Joint Studies for New and Mitigated Energy Systems


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The ETSAP partnership and the extended network of IEA-ETSAP tool started in 1978. The success of this nearly unique collaboration community can be attributed to the contributions of the 20 Contracting Parties, the dedication of the experts involved in IAE-ETSAP, and the efforts of the modelling community experts.

The editors wish to thank all those actively involved in IEA-ETSAP as well as those working with the ETSAP Tools who have contributed to this amalgamation of the accomplishments of the last three years.
Preface

This report summarizes the advancements, applications, and accomplishments within the community of MARKAL and TIMES users during Annex XI “Joint Studies for New and Mitigated Energy Systems”. It orderly collects short summaries of books or book chapters, peer-review articles, research papers/reports (or long abstract), Ph.D. theses, presentations and online information appeared in the period 2008-2010. It provides many examples of policy relevant application of the MARKAL and TIMES modelling platform and its continued spread to new users, as well as the ongoing advancement of the methodology to meet the requirements for integrated energy planning in these challenging times.

The final report of previous annexes, along with update information on the Implementing Agreement for a Program of Energy Technology Systems Analysis of the International Energy Agency - the text of the Implementing Agreementare, the text of the Annexes, instructions to get the software, the members list, the user`s guides, the factsheets of the Energy Technology Data Source, the proceedings of the biannual workshops, etc. - are available on line at www.iea-etsap.org. You are welcome to post questions, comments and proposals to the forum http://www.iea-etsap.org/forum/default.asp.
Summary

The Energy Technology Systems Analysis Program (ETSAP) is an Implementing Agreement of the International Energy Agency (IEA), first established in 1976. It functions as a consortium of member country teams and invited teams that actively cooperate to establish, maintain, and expand a consistent multi-country energy/economy/environment/engineering (4E) analytical capability. Its backbone consists of individual national teams in nearly 70 countries, and a common, comparable and combinable methodology, mainly based on the MARKAL - TIMES family of technical-economic models, permitting the compilation of long term energy scenarios and in-depth national, multi-country, and global energy and environmental analyses. More on IEA-ETSAP activities, tools and users can be found at www.iea-etsap.org.

This report of the Annex XI “Joint Studies for New and Mitigated Energy Systems” summarizes over 350 references published between 2008 and 2010, including 86 peer-review articles, 7 Ph.D. theses, 9 books or book chapters, 120 research papers and reports, as well as numerous presentations.


Most presentations were discussed at the IEA-ETSAP workshops, whose proceedings are posted at http://www.iea-etsap.org/web/Workshop.asp. By statute, ETSAP meets twice a year to exchange experiences, discuss ways to improve the tools and manage the common activities. Local experts are invited to these meetings so that they are exposed to the paradigm and can interact with the ETSAP participants from their country. These meetings are also held in non-Annex I countries and they often lead to collaborative model building projects with local and third party funds.

In this report, the studies and projects are organized by geographical coverage of the different models always following the same structure: a first part for the description of models and methodologies and a second part for the presentations of their various applications. Section 1 introduces the Global Models, including the IEA Energy Technology Perspective (ETP) model, the original TIMES Integrated Assessment Model (TIAM), several derived TIAM models from different modelling teams, the Global TIMES Model of the European Fusion Development Agreement (EFDA), the TIMES G5 model and the Global Multi-regional MARKAL Model (GMM). Section 2 deals with Regional Models, mainly the Pan-European TIMES model, as well as MARKAL-TIMES Models for Europe, Asia and North America. Section 3 is dedicated to a large number of applications from National Models of 32 countries. Section 4 contains applications of Sub-National Models for Western China, Reunion Island (France), Lombardy (Italy), Pavia (Italy), Southwest region (Sweden) and Kathmandu Valley (Nepal). Finally, Section 5 presents Local Models for rural areas and cities in Austria and Germany, as well as other local studies in rural areas such as Val d’Agri in Italy, other bigger cities such as Madrid (Spain), Beijing, Guangdong and Shanghai (China) and New York City (United States).
Section 1 - Global Models

The IEA Energy Technology Perspective (ETP) model.

This global 15-region model permits the analysis of fuel and technology choices throughout the energy system. For this analysis, the IEA Secretariat co-operated with a number of modelling groups with national and/or regional MARKAL and TIMES models for individual countries and regions have been used to assess the potential for CO₂ emissions reductions in China, OECD Europe and the United States. Using a techno-economic approach that assesses costs and benefits, ETP 2010 examines least-cost pathways for meeting energy policy goals while also proposing measures to overcome technical and policy barriers.

The most vital message of ETP 2010 is that an energy technology revolution is within reach. Achieving it will stretch the capacities of all energy-sector stakeholders and entail substantial upfront costs, but over the long term these will be more than offset by the benefits. Governments, investors and consumers around the world need to take bold, decisive action to initiate and advance change in their respective spheres of influence – and increase their commitment to working together.

The original TIMES Integrated Assessment Model (TIAM)

TIMES (The Integrated MARKAL-EFOM System) was conceived as a descendent of the MARKAL and EFOM paradigms, to which several new features were added to extend its functionalities and its applicability to the exploration of energy systems and the analysis of energy and environmental policies. The starting version of the global model was developed by the Canadian team – Richard Loulou, Maryse Labriet, Amit Kanudia – while working at GERAD (1999-2000). The seed of TIAM was embodied in the initial version of the global models developed by US-EIA (SAGE), IEA (ETP) and EFDA. These models cover 15 regions; 2100 is the time horizon. The following new features have been added to TIMES: linearised climate equations; multi-stage stochastic programming; new formulation for the forcing equation (linear approximation of forcing), allowing greater flexibility and power to the ETSAP-TIAM; and the possibility of binding each and every component of the cost objective function.

Extensive testing of TIAM was done in 2008-2009, through more than 100 runs of the model, as part of REACCESS project, but also as part of several other EC sponsored projects (TOCSIN, PLANETS) and other projects sponsored by the French Government, by ETSAP, and by the partners’ own funds. These projects also contributed to make desirable changes and additions to the already extensive TIAM database. The resulting 16 region TIAM model, has become the standard TIAM version since March 2009.

The TIMES model and its ETSAP-TIAM incarnations are the result of a multiyear multi-partner effort, resulting in a set of tools for the analysis of long term energy and emission issues based on techno-economics. The outcomes of many studies using the original TIAM model were already published in peer-reviewed journals, research reports and conference proceedings. Some examples are summarized in this section:

- How crucial is cooperation in mitigating world climate? In order to study the conditions for a World self-enforcing agreement on climate change, we model cooperative and non-cooperative World climate strategies with an integrated version of the 15-region techno-economic MARKAL model in which abatement costs and climate related damages are both included.

- Uncertainty and the role of hedging strategies for climate mitigation. In this research, we argue that the stochastic programming approach is well adapted to the treatment of major uncertainties, in spite of the limitation inherent to this technique due to increased model size when many outcomes are modeled. The article presents methodological details of the modeling approach, and uses realistic instances of the ETSAP-TIAM model to illustrate the technique and to analyze the resulting hedging strategies.

- Alternative climate targets under differentiated cooperation regimes. This article analyzes the feasibility of attaining a variety of climate targets during the 21st century, under alternative
cooperation regimes by groups of countries simulated via the ETSAP-TIAM technology based, integrated assessment model.

- OPEC oil strategies in a climate regime. This paper presents an analysis of the optimal oil production quotas of OPEC under a worldwide climate regime imposing a limitation on the radiative forcing. The analysis is conducted using a multi-region detailed energy-economy-environment bottom-up model (TIAM) where the demand laws for oil and its substitutes are implicitly defined as the result of a global supply-demand equilibrium in the World energy system, including the trading of energy forms and emission permits.

- Coupling bottom-up and top-down models to investigate cooperative climate policies. In order to assess the cooperation between industrialized and developing countries in the design of a comprehensive worldwide climate policy to limit the global long-term temperature increase to 2°C, we developed an iterative procedure to link the global technology-rich optimization energy model TIAM and the global general equilibrium model GEMINI-E3.

- Coupling Bottom-up and Top-down Models to Investigate Uncertainties. In this paper, we propose a dual approach, based on the combined use of stochastic programming in TIAM and Monte Carlo analysis to deal with these uncertainties in a coupled techno-economic analysis. These emission scenarios are then subject to an economic assessment, using a Computable General Equilibrium (CGE) model, GEMINI-E3, specifically designed to assess world climate change policies both at the microeconomic and the macroeconomic levels.

- World climate strategies (SynsCOP15). This research exploits three complementary models – the techno-economic TIMES Integrated Assessment Model (TIAM), the GEMINI-E3 macroeconomic model and the GENIE climate model – in a coordinated manner. This integrated framework is used to represent and evaluate the energy, emissions, technology, economic consequences as well as the climate impacts at global and regional levels of the several policy scenarios as proposed before and after the 15th Conference of the Parties (COP15) of the UNFCCC in December 2009.

- Energy security in EU scenarios from the PLANETS (Probabilistic Long-Term Assessment of New Energy Technology Scenarios) project. The project aims to assess the impact of technology development and deployment at world and European levels to foresee the best technological hedging policy in response to future environmental and energy policies.

- Future role of renewable energy technology for climate stabilization. In an effort to address these changes and better understand their impact on the evolution of the global energy system, the Renewable Energy Technology Deployment (RETD) Implementing Agreement of the IEA has defined its own scenario, in collaboration with the ETSAP Implementing Agreement. This report presents the results of that work. The RETD ACES Scenario was modeled using the ETSAP-TIAM3 model.

- The Role of Renewable Energies in Global Scenarios. This paper aims to test the ETSAP-TIAM global energy system model and to try out how far it can go towards a global 100% renewable energy system with the existing model database. Existing analysis with TIAM shows different ways of reaching the 2 °C target and also how uncertainty on different factors influences the optimal solution.

- Non-fossil energy technologies in 2050 and beyond. In facing energy security challenges the EU has in recent years adopted a fairly ambitious energy and climate change policy. These targets will require drastic changes in the energy systems of all countries in both the short and the long term. The scenarios for the EU27 countries plus Norway, Switzerland and Iceland (EU27+3) were examined using the global energy system model TIAM-World.

- GHG mitigation targets and potentials in large emerging economies. The outcome of the UN climate change negotiations at the COP15 in December 2009 was the Copenhagen Accord, which countries voluntarily can acknowledge alongside supplying their voluntary actions
combating climate change. On this background, this paper intends to analyse the pledges made by large emerging economies regarding their GHG-emission reductions in 2020 in light of their estimated potentials and costs for the same, both looking at existing national and international literature and presenting new results from the global ETSAP-TIMES Integrated Assessment Model (TIAM).

- Reinforcing the EU dialogue with developing countries on climate change mitigation. The FP6 TOCSIN project has investigated the strategic dimensions of RD&D cooperation and the challenge of creating incentives to encourage the participation of developing countries in post-2012 GHG emissions reduction strategies and technological cooperation. We investigated the possibility and consequences of a 3.5 W/m² radiative forcing scenario.

- Meeting global GHG emissions reduction targets: EMF24 scenarios. This presentation introduces sample of results of global GHG emissions reduction targets from the TIAM model in the EMF24 analysis framework: Technology Strategies for Achieving Climate Policy Objectives.

Other TIAM models were developed from the original ETSAP-TIAM model by different research groups; examples of studies using these different versions of TIAM are also presented.

**The original TIMES Integrated Assessment Model (TIAM)**

In the VTT version an additional region for Finland has also been tentatively implemented, and another new region for the other Nordic countries is under preparation. VTT has completed some enhancements to the TIAM model, in particular related to the modelling of GHG emissions and their climate change impacts. Studies with the TIAM-VTT model are:

- Global scenarios for effective climate change mitigation. The achievement possibilities of the EU 2°C climate target have been assessed with the ETSAP TIAM global energy systems model. Cost-effective global and regional mitigation scenarios of carbon dioxide, methane, nitrous oxide and F-gases were calculated with alternative assumptions on emissions trading.

- The role of CCS and renewables in global climate scenarios. The need for global and regional clean energy technology investments by 2050 are evaluated in climate policy scenarios with the bottom-up global ETSAP TIAM energy system model. The impacts of the assumed regional CO₂ storage potentials as well as bioenergy and wind power potentials on investments are also investigated by sensitivity analysis.

- Energy security in EU demand and supply scenarios. This work focuses on energy security in EU demand and supply scenarios of renewables and the dependence on Russian energy.

- Effort-sharing and coalitions in global climate scenarios. The post-2012 climate policy framework needs a global commitment to deep GHG emission cuts. This paper analyses reaching ambitious emission targets up to 2050 and how the economic burden from mitigation efforts could be equitably shared between countries. Being simple and transparent, the EVOC tool of Ecofys GmbH was used for calculating emission allocations, while and ETSAP-TIAM, a sophisticated but complex global energy system model of the TIMES family was used for creating the scenarios.

**The derived TIAM-FR Model**

Some improvements investigated in TIAM-FR include modification of demand drivers, modification in carbon storage potential (deep ocean and coalbed methane recovery), implementation of new technologies (fossil power plants with CCS, coal-biomass co-firing power plants with and without CCS, CHP), modification of costs (bioplants with CCS, geothermal new technologies). Studies with the TIAM-VTT model are:

- Global versus regional climate policies and technological limits. The aim of these studies is to discuss the long-term analysis of post-Kyoto commitments issued from Copenhagen/Cancun
Agreements, with the modelling tool ETSAP-TIAM-FR. More precisely, we investigate different coordination schemes for regions pledging in CO₂ mitigation targets during the period 2005-2050. This paper compares global efforts of CO₂ mitigation with regional climate policies expressed through targets pledged to UNFCCC and, finally discusses the impact of the development of CO₂ storage technologies in the energy mix in 2050.

- Implementing water allocation in the TIAM-FR energy model. In the context of a growing world population, leading to increasing demands and competition for water and energy, it is vital to develop long-term strategic policies that consider the interconnections between the water and energy sectors. The main aim of this study is to show how issues concerning water consumption and water withdrawal can be incorporated into energy system models, thereby facilitating discussions about possible futures concerning both aspects. Water commodities and technologies in the energy model TIAM-FR have been implemented in two step, in order to study separately the two part of the water-energy nexus.

**The derived TIAM-ECN Model**

Here is a list of major developments related to TIAM-ECN between 2009-2010: extensive changes have been made to the structure of a number of sectors (e.g. oil, coal and gas production, renewable resources as well as the residential and commercial end-use sectors), modeling of emissions has been improved by adding CO₂ emissions from deforestation and N₂O emissions from agriculture within the explicitly modeled flows, modeling of technology diffusion has been improved both on the level of resource use as well as on the end-use level, review of the technology data for storage type specific, regional storage potentials, review of the data on the power sector, review of the regional potentials for wind and solar energy, review of the transport sector structure and the data for the H2 production and transport technologies. There is an ongoing activity aiming at updating and improving structurally the modeling of bioenergy resources and potentials. Studies with the TIAM-ECN model are:

- The impact of uncertainty in long-term climate mitigation scenarios. There are large uncertainties concerning the large scale implementation of the CCS technology, one being the regional availability of storage sites for the captured carbon. We approach the issue from an energy system perspective and use an energy system model TIAMEC to study a set of scenarios covering a range of climate targets and technology futures, from two angles; 1) a sensitivity analysis consisting of a number of scenarios that assume perfect foresight for the decision making and 2) using a stochastic programming set-up, which allows the model to consider all included potential future states simultaneously.

**The derived TIAM-UCL Model**

The core aim of the Energy Systems research theme in the UKERC II project is developing a global optimisation model to analyse accelerated decarbonisation of the global E3 (energy-environment-economy) system, with a comprehensive investigation of costs and benefits of the different decarbonisation options. This adds to work carried out in UKERC I placing the detailed analysis of the UK in a global context, which was not possible with the UK MARKAL model, the main tool developed under UKERC I. The TIAM-UCL model development has two phases. The major tasks (the first phase) is breaking out UK from the 15 region model and model calibration (calibrating UK and Western Europe regions). Once the 16R TIAM-UCL has been successfully calibrated, the model has been enhanced (the second phase) through technical improvements such as adding new drivers, new resources, climate change policies (cap-and-trade, carbon tax), supply resource cost curves etc. Studies with the TIAM-UCL model are:

- The role of demand reduction in global climate change mitigation. This paper investigates the role of demand reduction in meeting global CO₂ reduction targets using the elastic demand version of the TIAM-UCL global model under different long-term low carbon energy scenarios during 2005-2100.

- Carbon tax vs. cap-and-Trade: Implications on developing countries emissions. This paper investigates the roles of carbon tax and cap-and-trade policies to mitigate global CO₂ emissions; these policies are analysed using the 16 Region TIAM-UCL global model.
• Demand, burden sharing and resources. This presentation introduces an analysis of burden sharing agreements for the UK under global decarbonisation trajectories.

**The derived TIAM-IER Model**

Studies with the TIAM-IER model are:

• Interdependencies between market power, resource availability and demand options. This presentation deals with interdependencies between market power, resource availability and demand options. A sensitivity analysis is performed with the soft coupling of TIAM and LOPEX.

• Natural gas supply for Europe. Using the same approach, this presentation concentrates on the natural gas supply for Europe. The main question is: what is the maximum profit of the natural gas exporting countries to Europe?

**The Global TIMES Model of the European Fusion Development Agreement (EFDA)**

The EFDA Times Model (ETM) is a multi-regional, global and long-term energy model of economic equilibrium, responsive to energy technology innovations, domestic and international trade energy policies, climate change mitigation and environment objectives. It has been developed within the European Fusion Development Agreement (EFDA) framework starting in 2004 and forms part of the TIMES family of energy models. In ETM the world is divided into 15 regions linked by energy and emissions permit trading variables. Time horizon will be 2100. Studies with the EFDA model are:

• Revised assessments of the economics of fusion power. A new energy economics model is employed to analyse the potential market performance of fusion power in a range of future energy scenarios and this shows that there can be a significant role for fusion in a future energy market. Possible implications for fusion’s role in a future energy market are then explored, using a sophisticated energy scenario tool, known as the EFDA/TIMES model.

• The future role of fusion power under endogenous technological learning. This dissertation addresses the impact of different endogenous learning approaches on the role of fusion power. To broaden the scope of endogenous learning descriptions, new approaches have been developed and implemented in the TIMES model generator.

• An analysis on the future costs of fusion power stations. There have been a wide range of studies of costs, varying primarily in the assumed materials and technology as well as assumptions about the fusion performance in scientific terms. This range is implemented in the EFDA Times Model (ETM) with the early generation plants assumed to be available in 2050, evolving to an advanced, mature plant over the following 30 years.

• Modelling CCS, nuclear fusion, and large-scale district heating. These presentations focus on modelling the infrastructure development for heat recovery from CCS and fusion in EFDA-TIMES and TIAM. CCS can be a driver for the development and expansion of large-scale district heating systems, which are currently widespread in Europe, Korea and China, and with large potentials in North America.

• The role of nuclear energy in long-term climate scenarios. Our objective is to analyze the role of nuclear energy in long-term climate scenarios using the World-TIMES (The Integrated MARKAL-EFOM System) bottom-up model.

• Global transportation scenarios in a multiregional energy model. The aim of this study is to assess the potential impact of the transportation sector on the role of fusion power in the energy system of the 21st century. For the present study a new transportation module has been linked to the EFDA-TIMES framework in order to arrive at a consistent projection of future transportation demands.

**The TIMES G5 model**

TIMES-G5 is a five-region, bottom–up, and process-analytic energy system model, developed at the Institute of Energy Economics and Rational Use of Energy (IER), University of Stuttgart in Germany, for the
analysis and projection of long-term energy futures on a national, regional, and global basis. The TIMES-G5 model disaggregates the globe into 25 European nations (EU25), the rest of the OECD countries (R_OECD), the rest of the non-OECD countries (R_NOECD), India, and China, as five separate regions. The model includes the modelling horizon from 1990 to 2100, containing 19 periods having unequal time spans of 5, 8, and 10 years, and six smallest time segments (i.e., day–night basis for three seasons). Studies with the TIMES-G5 model are:

- Uncertainty in the learning rates of energy technologies. This study examines the uncertainty in learning rates (LRs) of some energy technologies under endogenous global learning implementation and presents a floor-cost modeling procedure to systematically regulate the uncertainty in LRs of energy technologies. This work is executed using a multi-regional and long-horizon energy system model based on “TIMES” framework.

- Endogenous implementation of technology gap. Together, three methodologies have been developed in this study. The first methodology is global learning without a technology gap. The other two methodologies are about global learning with technology gaps, in the form of the knowledge deficit and time lag concepts. The methodologies are examined inside a multi-regional energy system model (TIMES) to understand the behavior of technologies, subject to uncertainty of learning rates.

**The Global Multi-regional MARKAL Model (GMM)**

GMM belongs to the MARKAL (MARKet ALlocation) family of models. GMM was further enhanced starting from the original version. Model improvements dealt with an extension of the number of world regions, the representation of alternative fuel chains (hydrogen and biofuels) and the personal transport sector, as well as the representation of endogenous technological learning (ETL). Studies with the GMM model are:

- An energy-economic scenario analysis of alternative fuels for personal transport. This paper deals with the long-term prospects of alternative fuels in global personal transport. It aims at assessing key drivers and key bottlenecks for their deployment, focusing particularly on the role of biofuels and hydrogen in meeting climate policy objectives. The analysis is pursued using the Global Multi-regional MARKAL model (GMM), linked to the Model for the Assessment of Greenhouse Gas Induced Climate Change (MAGICC).

- Supporting hydrogen based transportation. In this article we analyze the potential influence of selected factors for successful market penetration of hydrogen fuel cell vehicles in hydrogen based private transportation economy. Using a world scale, full energy system, bottom-up, optimization model (Global MARKAL Model—GMM), we address the possibility of supporting the fuel cell vehicle technology to become competitive in the markets.

**Section 2 - Regional Models**

**The Pan-European TIMES model**

This model results from the outcome of a number of projects over the last years. First, TIMES was used in the framework of the NEEDS (New Energy Externalities Developments for Sustainability) project (2004-2008) which was funded by the 6th Framework Programme, to create a model for EU-27, Iceland, Norway and Switzerland. In this model the energy systems of each one of the thirty countries are modelled separately in detail. This framework is completed by integrating LCA and External Cost into an Energy Model. Then, this model has been used as a starting point for building the RES2020 Pan-European TIMES (PET) model, and the models in the REACCESS project and REALISEGRID projects. All these models are characterised by a multi-period structure (base-year: 2000, last milestone year: 2050).

The RES2020 application of the model focused on the analysis of the renewable energy targets in EU27. This led to a more detailed representation of renewable energy sources and four alternative scenarios for achieving the targets for renewables and GHG emissions in 2020: a more detailed analysis of the availability factors for wind turbines, new decentralised electricity production technologies and further enhancements.
in the representation of biomass and biofuels, for instance on the differentiation of crop types and waste and residues sources to be used for the production of biofuels.

In the REACCESS project the PET model was recalibrated in detail to reproduce the 2005 statistics as a base year. In the framework of this project the PET model run together with the TIAM model (16 regions world model) and the REACCESS Corridor Model (RECOR) that link the two, in order to study the effects on the energy system of EU competing with the Rest of the World for scarce and uncertain supplies of energy sources. The PET model has 30 regions, the TIAM model 15 regions (16 minus EU+), so that the resulting integrated model has 45 regions, a heretofore unheard-of size for any technology-based energy model.

The REALISEGRID FP7 project, aims at developing a set of criteria, metrics, methods and tools to assess how the transmission infrastructure should be optimally developed to support the achievement of a reliable, competitive and sustainable electricity supply in the EU. In the framework of this project, four scenarios have been implemented with a TIMES model which includes EU27, Iceland, Switzerland, Norway and the Western Balkan region (EU27++). The geographical scope of the model has been extended to the Western Balkan adding to the model six new regions (Albania, Bosnia and Herzegovina, Croatia, FYR of Macedonia, Montenegro and Serbia. The representation of the endogenous electricity and gas trade across European countries was improved in the framework of this project, by including more precise information on the efficiency and costs of grid and trade infrastructure and on other points.

Studies using the Pan-European TIMES model are:

- Technologies, fuels and sector analysis in climate and energy policy scenarios for Europe. Stabilising the concentration of CO₂ in the atmosphere at a level of 450 ppm in order to keep global temperature increase below 2°C requires an ambitious climate policy. This study analyses the role of different technologies in the EU-27 with regard to efficiency improvements, fuel switching and energy saving measures under such a climate policy target.

- Future European gas supply. A steady increase of natural gas demand can be observed in Europe over the last decades. With the help of a cost-minimization model of the European gas supply system, the gas flows and the infrastructure capacity development up to the year 2030 are analyzed.

- Evaluation of the RES Directives implementation in EU27 for 2020 (RES2020 Project). The project aims at analysing the present situation in the RES implementation, defining future options for policies and measures, calculating concrete targets for the RES contribution that can be achieved by the implementation of these options and finally examining the implications of the achievement of these targets to the European Economy. A number of future options for policies and measures were defined and studied with the use of the TIMES energy systems analysis model, in order to analyze the quantitative effects on the RES development.

- EU 20-20 policy implications on the EU energy system. Presentations focusing on the evaluation of the EU Energy and Climate Package as proposed by the Commission in January 2008 by studying the impacts on the EU energy system.

- Energy corridors and security of supply in Europe (REACCESS Project). An example of policy assessment within the REACCESS project is the analysis of the interplay between the global goal of mitigating climate changes and the European goal of reducing dependence and vulnerability of the energy system.

- Transmission infrastructure development to support sustainable electricity supply. The REALISEGRID FP7 project aims at developing a set of criteria, metrics, methods and tools to assess how the transmission infrastructure should be optimally developed to support the achievement of a reliable, competitive and sustainable electricity supply in the EU.

- Contribution of alternative fuels and power trains for climate targets in the EU27. Within this study, a technology oriented, linear optimization model of the EU energy system is applied in order to analyze the cost optimal contribution of the transport sector to the achievement of
GHG reduction targets until 2050. A special focus lies on the analysis of the penetration of alternative fuels and vehicle technologies under ambitious GHG reduction targets.

- Perspectives of CCS power plants in Europe: Under different climate policy regimes. The target of this work is to analyse capture economics of CCS power plants and their contribution to GHG reduction in the European energy system under climate policy conditions.

- Perspectives of CCS power plants in Europe: Under uncertain power plant parameters. The perspectives of power plants with CCS in Europe are analysed with the Pan-European TIMES model (TIMES PanEU) incorporating technical and economic uncertainties of CCS technologies by the use of the Parametric Programming routine.

- Technology analysis of emission reduction potentials in the industrial sector in the EU-27. This study analyses the emission reduction potentials of the industrial sector at different carbon prices.

- Effect of a White Certificate Trading Scheme in the EU-27. The improvement of energy efficiency and thereby a reduction of energy consumption is one of the key goals of the energy and climate policy strategy of the European Union as stated in their EU 20/20/20 targets. One way of achieving this reduction target could be the implementation of a European wide white certificate trading scheme. This study examines the effect of a restriction on the total consumption of either final or primary energy on the European energy system.

- Analysis of potentials and costs of CO₂ storage in the Utsira aquifer in the North Sea. The FENCO ERA-NET project “Analysis of potentials and costs of storage of CO₂ in the Utsira aquifer in the North Sea” has studied the national and regional cost-effectiveness of CCS in five countries of North West Europe. The focus was on the feasibility of storing CO₂ into the Utsira formation as part of national or regional CO₂ mitigation strategies. The project have used the Pan European TIMES (PET) model and national MARKAL/TIMES models for the United Kingdom, the Netherlands, Germany, Denmark and Norway.

- Renewable heat: A policy and techno-economic assessment of EU2020 targets. We created cost curves for the implementation of renewable energy technologies in Flanders, for electricity production as well as for heat production. This presentation focuses on the status of renewable heat in the NREAP’s, the Flemish renewables cost curve and different subsidy mechanisms for renewable heat.

- Multivariate techniques for the analysis of partial equilibrium energy models results. In this paper, multivariate statistical techniques are used to analyse the data output of partial equilibrium energy models developed in the framework of the NEEDS Project, with the aim of emphasising their informational content and reducing redundancies.

**MARKAL Models for Europe**

Studies using MARKAL Models for Europe are:

- Exploring the implications of an EU-wide ‘ Tradable White Certificate’ scheme. Based on three evaluation criteria (cost-effectiveness, environmental effectiveness and distributional equity) this paper analyses the implications of implementing a European-wide ‘ Tradable White Certificate’ (TWC) scheme targeting the household and commercial sectors. MARKAL is applied to a database that depicts the reference energy system of Western Europe (EU15+).

- Assessment of the European energy conversion sector under climate change scenarios. In this dissertation, the European energy conversion sector and with special focus, the electricity generation sector were analyzed regarding the impacts of climate change on the energy infrastructure, and possible GHG emission reduction pathways, in respect of costs, and energy system parameters, such as technology choices and capacity installation. EuroMM was developed in the course of a dissertation at the Paul Scherrer Institute, in context of the European ADAM project, where it was used to analyze climate change adaptation and
mitigation scenarios for the European energy conversion sector. EuroMM disaggregates Europe (i.e., EU-27 plus Norway and Switzerland) into 18 regions.

MARKAL Models for Asia

Studies using MARKAL Models for Asia are:

- Energy security in the Greater Mekong Sub-region Countries. The paper evaluates effects of energy resource development within the Greater Mekong Sub-region (GMS) on energy supply mix, energy system cost, energy security and environment during 2000–2035. A MARKAL-based integrated energy system model of the five GMS countries was developed to examine benefits of regional energy resource development for meeting the energy demand of these countries (Cambodia, Laos, Myanmar, Thailand and Vietnam).

- Effects of cross-border power trade between Laos and Thailand. This paper analyzed the effects of hydropower development in Laos and power trade between Laos and Thailand on economy wide, energy resource mix, power generation capacity mix, energy system cost, environment, as well as, energy security. A MARKAL-based model for an integrated energy system of Laos and Thailand was developed to assess the effects of energy resource development and trade to meet the national energy demands of the two countries.

- Clean energy in the South East Asian Nations countries. This paper focuses on energy system development of the three largest Association of South East Asian Nations (ASEAN) countries: Indonesia, Philippines and Vietnam. This paper examines and quantifies the role of clean and advanced energy technologies for efficient local resource exploitation and improving energy security and environmental conditions. The main focus is on the power sector.

- The ESMOPO (Europe – South-east Asian Energy Modelling and Policy Programme) project. The ESMOPO (2005-2007) is co-financed by the European Union through EC-ASEAN Energy Facility Program. The project considers three ASEAN countries: Indonesia, Philippines and Vietnam. The project aims at developing country specific energy system models in the MARKAL modelling framework in order to identify country specific appropriate energy technologies and to quantify their implications in terms of energy savings, fuel substitution, investment and pollutions avoided. The main focus is on renewable and advanced fossil technologies.

- The POEM modelling framework. The main focus of the study is on India and China. The primary objective is to develop a portfolio of policy options including both international and national policies as well as institutional frameworks for international cooperation for these two emerging economies to engage them in climate protection measures under a post-2012 regime. The methodology involves the application of integrated modelling framework, on a soft-linking approach primarily, with common assumptions, iterative work procedure and a focus on co-benefits (local environment, health and energy security).

MARKAL-TIMES Models for North America

Studies using MARKAL-TIMES Models for North America are:

- Overview of the unconventional oil production up to 2030 using TIMES-Canada. Our main objective in this presentation is to analyze the evolution of conventional and unconventional oil production and exportations on the 2030 horizon in Canada, with their associated costs and GHG emissions. The development of the oil sector is analyzed under three socio-economic growth scenarios using the new energy model TIMES-Canada. The study is part of a more general research project realized with strong support and collaboration from the Office of Energy Research and Development (OERD) of Natural Resources Canada. TIMES-Canada covers the energy system of the 13 Canadian provinces and territories having their own reference energy system (RES), but linked together through energy, material and emission flows.
• Multi pollutant studies: Integrating climate and air quality planning in Maryland. This report was undertaken by the Northeast States for Coordinated Air Use Management (NESCAUM) and the Maryland Department of the Environment (MDE). To assist states in moving to an integrated multi-pollutant planning approach, NESCAUM developed a reference case scenario that accounted for Maryland’s Renewable Portfolio Standards (RPS). NESCAUM then provided preliminary analysis of implementing the Regional Greenhouse Gas Initiative (RGGI) program as described in the Maryland Healthy Air Act, and the Maryland Clean Cars Act. Using outputs from NE-MARKAL, NESCAUM then conducted a preliminary health benefits assessment using the Co-Benefits Risk Assessment Model (COBRA).

• Exploring the benefits of insulation investment and home weatherization. This presentation explores the potential for energy savings and economic and environmental benefits in residential heating sector in New Englang using NE-MARKAL. The unconstrained case is a policy case representing the availability of a low interest loan for insulation purchases.

• Multi pollutant studies: A sensitivity analysis of transportation policy. This analysis first examines the multi pollutant implications of policy scenarios being considered in the northeast such as LDV efficiency standards, technology mandates and incentives and second performs a robust sensitivity analysis where 500 to 1000 model runs were preformed.

Section 3,4 & 5 – National, Sub-National, Local Models
There is a large number of references related to different applications of national models. By listing the most significant key words related to these studies, the table below gives a brief idea of the topics covered in 32 countries, as well as the number of references for each country in the last column.

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<td>Ireland</td>
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1. Studies and Projects using Global Models

1.1 The IEA Energy Technology Perspective (ETP) model

1.1.1 Model and methodology

The primary tool used for the analysis of the ETP scenarios is the IEA ETP model (1,2). This global 15-region model permits the analysis of fuel and technology choices throughout the energy system. The model’s detailed representation of technology options includes about 1 000 individual technologies.

The ETP model belongs to the MARKAL family of bottom-up modelling tools (Fishbone and Abilock, 1981). MARKAL has been developed over the past 30 years by the ETSAP, one of the IEA Implementing Agreements. MARKAL is a linear programming model that represents the entire energy system of a country or a region. Such a system includes the extraction, transformation, distribution, end-uses, and trade of various energy forms and some materials. Each economic sector is described by means of technologies, each of which is characterized by its economic and technological parameters. End-use demands in the base case are based on socio-economic assumptions and are specified exogenously by the user in physical units over a future horizon. The objective function is to minimizing the total discounted system cost while respecting environmental and technical constraints. The main model outputs are future investments and activities of technologies at each period. An additional output of the model is the implicit price of each energy form, material and emission, which is equal to its opportunity cost (shadow price). The model tracks GHG and criteria air contaminant (CAC) emissions from fuel combustion and processes. Emission reduction is brought about by technology and fuel substitutions (which lead to efficiency improvements and process changes in all sectors), by carbon capture and sequestration and by endogenous demand reductions.

Additional analysis has been undertaken for China, India, OECD Europe and the United States. Some regions in the ETP model are large, and cover a range of areas with vastly different energy resource availability and energy demands. In such cases, the use of regionalised country models can add value. For this analysis, the IEA Secretariat co-operated with a number of modelling groups with national and/or regional models. The insights from their models, which are based on the same approach as the ETP model, were used to refine the analysis.

The ETP scenarios have been developed using a combination of four approaches:

- Global perspective: the Baseline scenario for 2007 to 2030 is based on the Reference Scenario of the IEA World Energy Outlook 2009. This scenario has been further elaborated to include the period 2030 to 2050 using the Energy Technology Perspectives (ETP) model. The ETP model of global energy supply and demand has been used to analyse the BLUE scenarios for the period 2007 to 2050.

- Country/regional perspective: MARKAL and TIMES models for individual countries and regions have been used to assess the potential for CO₂ emissions reductions in China, OECD Europe and the United States.

- Sector perspective: the IEA Secretariat has developed sector models with country and region-level detail for industry, the residential and commercial sectors, and the transport sector. These spreadsheet models are detailed simulation tools that serve as repositories for information from experts and different models. They also serve as a communication tool between the modelling groups.

- Technology perspective: the present and future characteristics of technology options and their potentials have been assessed on the basis of expert information from the IEA Implementing Agreements and other sources.
1.1.2 Studies and scenarios

Using a techno-economic approach that assesses costs and benefits, the book (1,2) examines least-cost pathways for meeting energy policy goals while also proposing measures to overcome technical and policy barriers. ETP 2010 analyses and compares various scenarios.

- The ETP 2010 Baseline scenario follows the Reference scenario to 2030 outlined in the World Energy Outlook 2009, and then extends it to 2050. It assumes governments introduce no new energy and climate policies.

- In contrast, the BLUE Map scenario (with several variants) is target-oriented: it sets the goal of halving global energy-related CO₂ emissions by 2050 (compared to 2005 levels) and examines the least-cost means of achieving that goal through the deployment of existing and new low-carbon technologies (Figure 1). The BLUE scenarios also enhance energy security (e.g. by reducing dependence on fossil fuels) and bring other benefits that contribute to economic development (e.g. improved health due to lower air pollution).

Figure 1. Key technologies for reducing CO₂ emissions under the BLUE Map scenario

A wide range of technologies will be necessary to reduce energy-related CO₂ emissions substantially.

1.1.3 Results

1.1.3.1 General findings

Current trends – as illustrated by the Baseline scenario – are patently unsustainable in relation to the environment, energy security and economic development. Ongoing dependence on fossil fuels (especially coal) continues to drive up both CO₂ emissions and the price of fossil fuels. Oil prices, for example, are assumed to reach USD 120 per barrel (in 2008 prices) by 2050.

But this carbon-intensive future is not a given. Using a combination of existing and new technologies, as envisaged in the BLUE scenarios, it is possible to halve worldwide energy related CO₂ emissions by 2050. Achieving this will be challenging, and will require significant investment. But the benefits in terms of environmental outcomes, improved energy security and reduced energy bills will also be large. Oil prices in these scenarios are assumed to be only USD 70 per barrel (in 2008 prices) by 2050.

- A portfolio of low-carbon technologies, with costs of up to USD 175/tCO₂ when fully commercialised, will be necessary to halve CO₂ emissions by 2050. No one technology or small group of technologies can deliver the magnitude of change required.

- Widespread deployment of low-carbon technologies can reduce global oil, coal and gas demand below current levels by 2050. Even so, fossil fuels will remain an important element of the world’s energy supply for the foreseeable future.

- Increasing energy efficiency, much of which can be achieved through low-cost options, offers the greatest potential for reducing CO₂ emissions over the period to 2050. It should be the highest priority in the short term.
• Decarbonising the power sector, the second-largest source of emissions reductions, is crucial and must involve dramatically increasing the shares of renewables and nuclear power, and adding CCS to generation from fossil fuels.

• A decarbonised electricity supply offers substantial opportunities to reduce emissions in end-use sectors through electrification (for example, switching from internal combustion engine vehicles to electric vehicles (EVs) and plug-in hybrids (PHEVs), or from fossil fuel heating to efficient heat pumps).

• New low-carbon technologies will be needed to sustain emissions reductions beyond 2030, particularly in end-use sectors such as transport, industry and buildings. The future is inherently uncertain and always will be. Trends in economic growth (and therefore energy use and emissions) and technology development are difficult to predict. A portfolio approach to low-carbon technology development and deployment can help deal with this uncertainty.

1.1.3.2 Sectoral findings

About 84% of current CO₂ emissions are energy-related and about 65% of all GHG emissions can be attributed to energy supply and energy use. All sectors will need to reduce dramatically their CO₂ intensity if global CO₂ emissions are to be halved. However, this does not mean that every sector needs to cut its own emissions by 50% (Figure 2). Each sector has different growth prospects under the Baseline scenario and a different range of low-carbon options that can be deployed to reduce emissions.

For advancing deployment of both existing and new technologies across all sectors, a key message is the need for rapid action that takes account of long-term goals. Without a long-range perspective, there is a risk that inappropriate and costly capital investments made in the near term could undermine future emissions reduction targets or will need to be scrapped well in advance of their normal life cycles.

Figure 2. Global CO₂ emissions in the baseline and BLUE Map scenarios

Power sector. It bears repeating that decarbonising the power sector will be at the heart of efforts to make deep cuts in global CO₂ emissions. The power sector currently accounts for 41% of energy-related CO₂ emissions. The Baseline scenario projects a doubling of these emissions over the period to 2050, because of continued reliance on fossil fuels. By contrast, the BLUE Map scenario achieves almost a 90% reduction (compared to 2007 levels) in the carbon intensity of electricity generation, with renewables accounting for almost half of global production and nuclear for slightly less than one-quarter. The other key change is that most remaining electricity production from fossil fuels has much lower CO₂ emissions thanks to widespread adoption of CCS. The BLUE Map scenario requires investment of USD 32.8 trillion (40% more than the USD 23.5 trillion needed in the Baseline scenario), more than half directed towards new power generation plants.

Electricity networks. Although system-scale demonstration is still needed, the flexibility of smart grids (which integrate both electricity and thermal storage technologies) appears to support balancing of variable generation and demand, better management of peak loads and delivery of energy efficiency programmes. Smart grids can contribute to reducing CO₂ emissions from both electricity generation and
use. In developing countries, smart grids will facilitate expansion of electricity services, and show significant potential to reduce transmission and distribution losses.

**Industry.** Direct emissions from industry account for around 20% of current CO₂ emissions. Achieving deep cuts in CO₂ emissions will require the widespread adoption of current best available technology, as well as the development and deployment of a range of new technologies (such as CCS, smelting reduction, separation membranes and black liquor gasification). Successful application of CCS in a number of energy-intensive industrial sectors (e.g. iron and steel, cement, chemical and petrochemical, and pulp and paper) represents potentially the most important new technology option for reducing direct emissions in industry.

**Buildings.** Direct emissions from buildings account for around 10% of global CO₂ emissions; including indirect emissions from the use of electricity in the sector increases this share to almost 30%. The low retirement rate of buildings in the OECD and in economies in transition, combined with relatively modest growth, means that most of the energy and CO₂ savings potential lies in retrofitting and purchasing new technologies for the existing building stock. In developing countries, where new building growth will be very rapid, opportunities exist to secure significant energy savings (rather quickly and strongly) through improved efficiency standards for new buildings. This will buy time to develop and deploy less mature and currently more expensive technologies that can play an important role in the longer term. For space and water heating, these include highly efficient heat pumps, solar thermal systems, and combined heat and power (CHP) systems with hydrogen fuel cells.

**Transport.** The transport sector is currently responsible for 23% of energy-related CO₂ emissions. Given the increases in all modes of travel, especially passenger light duty vehicles (LDVs) and aviation, the Baseline scenario shows a doubling of current transport energy use by 2050 and slightly more than a doubling of associated CO₂ emissions. While absolute reductions in transport emissions from 2007 levels are possible in OECD countries, strong population and income growth in non-OECD countries will make it extremely difficult to achieve absolute emissions reductions in the transport sector. In the BLUE Map scenario, by 2050 emissions in OECD countries are about 60% less than in 2007, but those in non-OECD countries are 60% higher on a well-to-wheel basis.

Prospects are good for cutting fuel use and CO₂ emissions from LDVs by improving the efficiency of ICEs, and through vehicle hybridisation and adoption of PHEVs, EVs and fuel-cell vehicles. In the BLUE Map scenario, biofuels, electricity and hydrogen together represent 50% of total transport fuel use in 2050, replacing gasoline and diesel. Biofuel demand for light-duty ICE vehicles begins to decline after 2030 owing to a strong shift towards electricity and hydrogen fuels. In contrast, biofuels use rises rapidly for trucks, ships and aircraft through 2050, replacing middle distillate petroleum fuels.

**Carbon capture and storage (CCS).** CCS in industry, fuel transformation and electricity generation accounts for 14% of the emissions reduction in the ACT scenario and 19% in the BLUE scenario, leading to the capture of 5.1 GtCO₂ to 10.4 Gt of CO₂ (3). In the BLUE scenario, 54% of the CO₂ capture takes place in the power sector (Figure 3) which is a lower percentage than in the ACT scenario (68% of all CO₂ emissions reductions) as the stringency of the BLUE scenario requires that CCS be deployed more extensively outside of the electricity sector. The BLUE scenario sees much more extensive uptake of CCS in the fuel-transformation sector (refineries, synfuel production, blast furnaces) and in manufacturing industries, for example in cement kilns, ammonia plants and industrial combined heat and power (CHP) units.

Storage is initially mainly associated with EOR. By 2025, it is roughly evenly divided between aquifers and depleted oil and gas fields, including enhanced oil and gas recovery (EOR and Carbon Sequestration and Enhanced Gas Recovery – CSEGR). By 2030, storage in deep saline formations (DSF) will dominate. Total cumulative storage over the period 2000–2050 amounts to 80 Gt, a small share of the total global storage potential. For the BLUE scenario, the share of DSF increases faster due to the higher financial incentive.
Energy technology roadmaps (1,4) provide a solid analytical footing that enables the international community to move forward on specific technologies. To date, the IEA has published the following low-carbon energy technology roadmaps: CCS, cement sector, electric/plug-in hybrid electric vehicles, nuclear power, concentrating solar power, photovoltaic power, wind energy. Each roadmap summary provides the reader with a summary assessment of the featured technology and the steps needed to accelerate the technology’s adoption as required to deliver the outcomes in the BLUE Map scenario.

The CCS example is provided here. CCS will need to contribute nearly one-fifth of the necessary emissions reductions to achieve cost-effective GHG stabilisation. If CCS technologies are not used, the overall cost to achieve stabilisation will increase by 70%. Achieving rapid CCS demonstration and deployment is a tremendous global challenge. While five commercial-scale operational CCS projects are providing evidence that these technologies are viable at scale, several dozen additional commercial-scale projects are needed in a variety of countries and sectors (Figure 4).

Without CCS, overall costs to halve emissions by 2050 rise by 70%. This roadmap envisions 100 projects globally by 2020 and over 3,000 projects in 2050.

- This roadmap’s level of project development requires an additional investment of over USD 2.5 to USD 3 trillion from 2010 to 2050, which is about 6% of the overall investment needed to achieve a 50% reduction in GHG emissions by 2050.
- The developed world must lead in the next decade by investing an average of USD 3.5 to USD 4 billion annually between 2010 and 2020. However, CCS technology must spread rapidly to the rest of the world through expanded international collaboration and financing.

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1 The roadmap summaries were developed using the ETP 2008 BLUE Map scenario, with the exception of solar CSP, solar PV and nuclear power. These roadmaps are consistent with current ETP 2010 scenarios: solar PV and CSP on the BLUE high Renewables variant, nuclear on the BLUE Map scenario. As a result, the numbers in the roadmap summaries may differ slightly from the results reported in other chapters of this book.
for CCS demonstrations in developing countries at an average annual level of USD 1.5-2.5 billion between 2010 and 2020.

- CCS is more than a strategy for “clean coal”. CCS technology must be adopted by biomass and gas power plants, in the fuel transformation and gas processing sectors, and in emissions-intensive sectors like cement, iron and steel, and chemicals manufacturing.
- The milestones in this roadmap will only be achievable via expanded international collaboration. New efforts to provide developing country knowledge/technology transfer are needed. Industry sectors with a global reach should also expand their CCS collaborative efforts.

**1.1.3.2 Regional trends analysis: focus on OECD Europe**

ETP 2010 (1,2) undertook a more detailed analysis of CO₂ trends and abatement options for four countries or regions that will have a major role in reducing global emissions: OECD Europe, the United States, China and India. Each will have very different starting points and future trajectories in terms of their CO₂ emissions and develop in different ways in both the Baseline and the BLUE Map scenarios.

As an example of regional results, this presentation (4) focused on the OECD-Europe region. OECD Europe’s CO₂ emissions to 2050 in the Baseline and BLUE Map scenarios are shown in Figure 5. CO₂ emissions reduce by 2.9 Gt or 72% in 2050 in the BLUE Map scenario as compared with the Baseline scenario. Measures in the end-uses sectors contribute 66% of the CO₂ savings. On the end-use side, efficiency improvements deliver 33% of the overall CO₂ savings followed by fuel switching to electricity and natural gas (12%), CCS in industry and fuel transformation (12%) and the increased use of biofuels (9%). The power sector contributes 34% of the overall emissions reduction between the Baseline and BLUE Map scenarios in 2050, with around 12% each from renewables and CCS and a further 7% from nuclear. End-use sector measures contribute nearly two-thirds of the emissions reductions between the Baseline and BLUE scenarios in 2050.

**Figure 5. Contributions to emissions reductions in OECD Europe**

![Figure 5. Contributions to emissions reductions in OECD Europe](image)

**Note:** Unlike otherwise indicated, all material derives from IEA data and analysis.

**1.1.4 Conclusion**

A truly global and integrated energy technology revolution is essential to address the intertwined challenges of energy security and climate change while also meeting the growing energy needs of the developing world. ETP 2010 shows that key players, from both public and private sectors, are starting to take the steps needed to develop and deploy a very broad range of new low-carbon technologies. Action can be seen in all of the most important sectors, and across most regions of the world.

Clearly, financing remains a substantial challenge as does identifying appropriate mechanisms to accelerate the deployment of low-carbon technologies in major developing countries. A related issue is that several sources predict a severe skills shortage, which could quickly become a major barrier to deployment across all sectors and in all regions. There is an urgent need to properly assess the skills required, considering regional situations and human resource availability, and to develop
recommendations on how to fulfil these needs. The roadmaps and transition pathways presented in ETP 2010 aim to overcome existing barriers and spur much-needed RDD&D in the very near term and throughout the period to 2050.

In short, the most vital message of ETP 2010 is that an energy technology revolution is within reach. Achieving it will stretch the capacities of all energy-sector stakeholders and entail substantial upfront costs, but over the long term these will be more than offset by the benefits. Governments, investors and consumers around the world need to take bold, decisive action to initiate and advance change in their respective spheres of influence – and increase their commitment to working together.

The options for emission reductions can be grouped into distinct categories (3), indicated in Figure 6:

- 1. Costs are relatively flat up to the ACT scenario (USD 50–100 per t of CO₂ reduced).
- 2. Costs increase significantly to reach the BLUE target (above USD 200 per t).
- 3. Without energy efficiency and/or CCS, the marginal cost would increase considerably.

Figure 6. Marginal abatement cost curve across the full suite of scenarios*

*Scenarios highlighting the significant role of assumed rates of technological progress.

1.2 The original TIMES Integrated Assessment Model (TIAM)

1.2.1 Model and methodology

TIMES (The Integreated MARKAL-EFOm System) was conceived as a descendent of the MARKAL and EFOM paradigms, to which several new features were added to extend its functionalities and its applicability to the exploration of energy systems and the analysis of energy and environmental policies (5,6). It is useful to distinguish between a model's structure and a particular instance of its implementation. A model's structure exemplifies its fundamental approach for representing and analyzing a problem—it does not change from one implementation to the next. All TIMES models exploit an identical mathematical structure. However, each model instance will vary according to the data inputs. The suite of tools has been used for several global and local analyses over the recent past.

The starting version of the global model was developed by the Canadian team – Richard Loulou, Maryse Labriet, Amit Kanudia – while working at GERAD (1999-2000). The seed of TIAM was embodied in the initial version of the global models developed by US-EIA (SAGE), IEA (ETP) and EFDA. These models cover 15 regions (Figure 7); 2100 is the time horizon.

TIAM comprises several thousand technologies in all sectors of the energy system. It is characterized by several technical and economic parameters and by emission coefficients for the three main GHG’s: CO₂, CH₄, and N₂O. The following new features have been added to TIMES: linearised climate equations; multi-stage stochastic programming; new formulation for the forcing equation (linear approximation of forcing), allowing greater flexibility and power to the ETSAP-TIAM; and the possibility of binding each and every component of the cost objective function.
Extensive testing of TIAM was done in 2008-2009, through more than 100 runs of the model, as part of REACCESS project, but also as part of several other EC sponsored projects (TOCSIN, PLANETS) and other projects sponsored by the French Government, by ETSAP, and by the partners’ own funds. These projects also contributed to make desirable changes and additions to the already extensive TIAM database. The resulting 16 region TIAM model (Figure 7), has become the standard TIAM version since March 2009 (7,8).

Figure 7. Definition of the TIAM regions

![TIAM-16R and TIAM-15R regions](image)

- **Europe**: EU27+Switzerland+Norway+Iceland (from ex-WEU and ex-EEU)
- **Russian Federation**: from ex-FSU
- **Central Asia & Caucasus**: Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, Uzbekistan, Armenia, Azerbaijan, Georgia (from ex-FSU)
- **Other Eastern Europe**: Belarus, Moldova, Ukraine, Albania, Bosnia-Herzegovina, Croatia, Macedonia, Montenegro, Serbia-Kosovo (from ex-FSU and ex-EEU)

OPEC and Non-OPEC countries are separated in primary and secondary sectors to appropriate strategies and oil price control by OPEC countries.

Figure 8 sketches the RES applicable to each of the TIAM regions (5).

Figure 8. Sketch of the TIAM model’s RES

The main elements of TIAM’s RES are now briefly described (5):

- **Energy supply sector**: Each primary energy form is extracted from multiple layers of reserves (fossil, biomass) or of resource potentials (non-fossil energy such as wind, hydro, shallow, deep and very deep geothermal, etc.), each with a potential and a specific unit cost. This constitutes a supply curve for each energy form. The primary energy resources
and forms modeled in TIAM are: coal (4 resources, 2 forms), crude oil (21 resources, 4 forms), natural gas (11 resources, 1 form), and solid biomass (8 resources, 6 forms).

- Energy trade: The following types of energy are endogenously traded between the 15 TIAM regions: coal (brown and hardcoal), crude oil, refined petroleum products (gasoline, diesel, heavy fuel oil and naphta), natural gas, liquefied natural gas, and atmospheric emissions (see below). The prices of these energy forms are therefore endogenously computed by the model; the impact of environmental policies on energy and permit trade is thus taken into account.

- Energy transformation: crude oil is transformed into 15 RPP’s via refinery processes; solid biomass may be transformed into alcohols; coal and natural gas may be transformed into hydrogen via gasification or reforming (hydrogen might also be produced by electrolysis); natural gas is liquefied and LNG is gasified and via appropriate processes.

- Energy conversion: Electricity is produced by a large number of technologies, each of which takes as input one or more primary resources, such as coal, gas, heavy oil, wind, hydro, etc.

- Energy consumption sectors: End-use sectors include Residential, Commercial, Industry and Transportation. Each has several independent demands for energy services. Each energy service may be satisfied by an array of end-use technologies in competition.

- Emissions and emission reduction options: TIAM models emissions of the following GHG: CO₂ from energy consumption, CH₄ from energy consumption (including leakages) as well as from some nonenergy sectors (landfills, manure, wastewater, non-energy biomass burning, enteric fermentation and rice cultivation) and N₂O from energy consumption as well as from adipic and nitric acid industries. All GHGs emissions are also merged into a single CO₂-equivalent emission, based on their global warming potential, and used as input into the climate module (see Sect. 6). Emission mitigation may be accomplished in a number of ways:

  ⇒ Via energy substitutions;
  ⇒ Via improved efficiency of installed devices;
  ⇒ Via specific non-CO₂ abatement devices (e.g., CH₄ flaring or utilization for electricity production, suppression of leakages at natural gas transmission level, N₂O thermal destruction, anaerobic digestion of wastes with gas recovery, etc.);
  ⇒ Via sequestration (CO₂ capture and underground storage, biological carbon sequestration);
  ⇒ Via demand reductions (in reaction to increased carbon prices). Although agricultural GHG emissions are accounted for, some of them have no abatement options (i.e., CH₄ emissions from wastewater, biomass burning, enteric fermentation, and rice paddies). Endogenous trade of all emissions is available, allowing permit trading.

Due to its detailed technological nature, TIAM is able to simulate almost any type of emission abatement measure, be it a regulation, a tax, a cap and-trade system, a portfolio standard, etc.

Subsequent presentations (7,8) illustrated the recent developments related to the ETSAP-TIAM multi-regional and integrated model, including:

- New macro-economic growths;
- Addition of emissions: CO₂ from land-use (MIT data), N₂O from agriculture (EMF-22);
- Adjustment of the exogenous forcing of the climate module;
• Addition/modification of technologies: Biomass fired power plants with CCS -Low-emitting technologies for aviation (H2), navigation (alcohol), train (elc) -Energy flexibility in Agriculture;

• Other modifications as normal maintenance tasks, such as an appropriate computation of the associated gas, a new structure for biomass resources and biofuel production, with energy crops from agricultural and forestry residues, wood for energy and the nuclear fuel cycle.

The principal characteristics of the TIMES model and of its global incarnation as ETSAP-TIAM are presented and discussed in the first part of a two-part article (5). The article stresses the technological nature of the model and its economic foundation and properties. The article stays at the conceptual and practical level, while a companion article is devoted to the more detailed formulation of TIMES equations. Special sections are devoted to the description of four optional features of TIMES: lumpy investments, endogenous technology learning, stochastic programming, and the climate module. The article ends with a brief description of recent applications of the ETSAP-TIAM model. This article (6) is a companion to “ETSAP-TIAM: the TIMES integrated assessment model. part I:model structure”. It contains three sections, presenting respectively: the simplified formulation of the TIMES Linear Program (Sect. 1), the details of the computation of the supply demand equilibrium (Sect. 2), and the Endogenous Technology Learning Formulation (Sect. 3). The full details of these three formulations are available in the complete TIMES documentation at www.etsap.org/documentation.

The TIMES model and its ETSAP-TIAM incarnations are the result of a multiyear multi-partner effort, resulting in a set of tools for the analysis of long term energy and emission issues based on techno-economics. The outcomes of many studies using the original TIAM model were already published in peer-reviewed journals, research reports and conference proceedings. Some examples are summarized below. Other TIAM models were developed from the original ETSAP-TIAM model; these additional versions of TIAM are presented in the next sections.

1.2.2 Studies with the ETSAP-TIAM model

1.2.2.1 How crucial is cooperation in mitigating world climate?

In order to study the conditions for a World self-enforcing agreement on climate change, we (9) model cooperative and non-cooperative World climate strategies with an integrated version of the 15-region techno-economic MARKAL model in which abatement costs and climate related damages are both included. Based on the empirical finding of linear cumulative climate damages, the computation of Nash equilibrium can be reduced to solving a series of 15 independent linear programs, one per region. Moreover, assuming interregional transfers to share the global surplus of cooperation, our work adopts the point of view of dynamic partial equilibrium computation coupled with cooperative game-theoretic principles.

Scenarios

The base scenario is consistent with the storyline behind the A1B scenario of IPCC and the analysis is performed with CO2 limits. We computed four different transfer schemes, characterized by specific axiomatic properties reflecting different burden sharing rules: Nucleolus (NU), Shapley Value (SV), Germain-Toint-Tulkens’ solution (GTT) and equalization of total abatement cost per GDP (TAC).

Results

The most important cost-effective options identified by MARKAL to balance the damage costs, are the following ones. CO2 capture and sequestration in deep aquifers, as well as forestry sequestration account for more than the half of emissions reduction in 2050 in non-cooperative and cooperative cases, because of their low costs. Consequently, combined cycle gas turbine (CCGT) without and with CO2 capture dominates in the initial periods and bridges the transition to more advanced fossil and zero-
carbon technologies such as the efficient and cheap coal Solid oxide fuel cell (SOFC) with CO₂ capture becomes available (Figure 9).

**Figure 9. World primary energy (left) and electricity production (right)**

Adopting the point of view of the cooperative framework, we now turn to analyze whether transfers can be defined to ensure the stability of the grand coalition. Transfers between regions result from the sharing of the World surplus of cooperation over non-cooperation, where the noncooperative case is modelled by the individual Nash solution and the cooperative case is modelled by the social optimum. These transfers, or side-payments, are equivalent to the sharing of the burden of reducing CO₂ among the different regions. Figure 10 shows the allocation of the World gain of cooperation and the amounts of transfers between the four regions, for the four allocation rules.

**Figure 10. Allocation of the gain of cooperation over non-cooperation**

The four burden-sharing rules, inspired by cooperative game-theoretic principles, lead to contrasted allocations and transfers that guarantee the stability of the World cooperation. This offers flexibility in the choice of the preferred sharing of the burden, which will depend on the properties of the allocations that the decision-makers would prefer in the light of international negotiations. In fact, the more asymmetric the regions (when damage costs are unevenly distributed among regions), the higher the free-ride incentives but also the flexibility in sharing the cost of cooperation (contrasted allocations of the gain).
The results illustrate how the non-cooperative strategy is closer to the base case than to the cooperative strategy, and the amount of side-payments sufficient to guarantee the stability of the cooperative strategy are calculated with four different rules.

**1.2.2.2 Uncertainty and the role of hedging strategies for climate mitigation**

In this research (10,11), we argue that the stochastic programming approach is well adapted to the treatment of major uncertainties, in spite of the limitation inherent to this technique due to increased model size when many outcomes are modeled. Although the example treated uses the classical expected cost criterion, the paper also presents, and argues in favor of, altering this criterion to introduce risk considerations, by means of a linearized semi-variance term, or by using the Savage criterion. Risk considerations are arguably even more important in situations where the random events are of a ‘one-shot’ nature and involve large costs or payoffs, as is the case in the modeling of global climate strategies.

The article presents methodological details of the modeling approach, and uses realistic instances of the ETSAP-TIAM model to illustrate the technique and to analyze the resulting hedging strategies. The paper makes a distinction between random events that induce anticipatory actions, and those that do not. The first type of event deserves full treatment via stochastic programming, while the second may be treated via ordinary sensitivity analysis. The distinction between the two types of event is not always straightforward, and often requires experimentation via trial-and-error. Some examples of such sensitivity analyses are provided as part of the TIAM application.

**Scenarios**

The instances modeled and analyzed assume several alternative global temperature targets ranging from less than 2°C to 3°C. The 2.5°C target is analyzed in some more details.

For a given temperature target, the two selected uncertain parameters are: i) the climate sensitivity $C_s$ (four possible values), and ii) the vector of energy service demands resulting from the future economic growth (two possible values). The combination of these two uncertainties leads to 8 possible States of the World (SoW). However, after conducting stochastic optimizations with the 8 SoW’s, it was observed that the impact of economic uncertainty on the hedging strategy before 2040 was quite negligible.

Therefore, we decided to eliminate economic growth as an explicit uncertainty in our main runs, and to assess the impact of uncertain economic growth on the hedging strategy as one kind of sensitivity analysis. The resulting event tree, with only $C_s$ as the uncertain parameter, has 4 branches, as shown in Figure 11.

**Figure 11. The reduced event tree**
Results

The base case GHG emission trajectory as well as the atmospheric GHG concentration reached in 2090 (Figure 12) are fairly close to the B2 Emission Scenario proposed by the IPCC. As for sector emissions in the base case, the electricity and transportation sectors are the highest GHG contributors in 2000 (more than 40% of total GHGs), and the electricity and industry sectors become the highest contributors at the end of the horizon (more than 48% of total GHG).

Figure 12. Atmospheric concentration [CO2-eq] under hedging and perfect forecast strategies

The situation is radically different under the 2.5 °C temperature constraint, since both the electricity and industry sectors are able to reduce to almost zero (less than 3% of total GHG) their emissions in the most stringent branch, mainly thanks to CCS in the electricity sector, and switching to electricity in the industrial sector. Based on emissions, the PFCs=5°C strategy is also the deterministic strategy that is closest to the optimal hedging strategy before 2040. Atmospheric concentration obtained with the lowest value of Cs (Figure 13) is lower in Hedging than in Base although no target was imposed on this branch of the Hedging. This is because hedging actions taken pre-2040 push concentration downward. Again, PFCs=5°C is the PF strategy that is closest to Hedging before 2040. In the base case, the temperature increase in 2090 is in the range from 1.4 °C to 2.4 °C, depending on Cs (Figure 13). In all hedging branches, temperature peaks within the 22nd century, and then declines, so that the equilibrium temperature is always lower than the maximum observed temperature from 2000 to 2200. This might not necessarily be the case for other temperature scenarios, or if a slower emission decline was assumed after 2100.

Figure 13. Temperature increase 2000–2200*

* Assuming emissions linearly decrease to 0 from 2100 to 2200

Amongst the most noticeable results, the model reveals that the smallest achievable temperature increase is close to 1.9 °C, albeit at a very large cost, by a combination of energy switching, capture and storage of CO2, CO2 sequestration by forests and non-CO2 emission reduction options. Moreover, the
impact of uncertainty of the climate sensitivity parameter $C_s$ is major, requiring the implementation of early actions (before 2040) in order to reach the temperature target.

In other words, the “wait and see” approach is not recommended. Robust abatement options include: substitution of coal power plants by hydroelectricity, sequestration by forests, CH$_4$ and N$_2$O reduction. Among them, several options appear also to be super-hedging actions i.e. they penetrate more in the hedging strategy than in any of the perfect forecast strategies (e.g. hydroelectricity, CH$_4$ reduction), proving that stochastic analyze of future climate strategies might give insights that are beyond any combination of the deterministic strategies. In contrast, the uncertainty of the GDP growth rates has very little impact on pre-2040 decisions. This insensitivity is a pleasant surprise, as it shows that the hedging strategy for only one random parameter ($C_s$) is also a quasi-optimal strategy when the two types of uncertainty are present.

The comparison of hedging with perfect forecast strategies shows that a deterministic strategy with $C_{s}=5\, ^\circ$C is closest to the hedging strategy. However, the two differ in several key aspects, and this confirms the relevance of using stochastic programming in order to analyze preferred climate policies in an uncertain world where the correct climate response is known only far into the future. Sensitivity analyses are undertaken on: the date of resolution of uncertainties, the exogenous radiative forcing, the very long term emissions, the price elasticities of demands, and nuclear development.

1.2.2.3 Alternative climate targets under differentiated cooperation regimes

This article (12) analyzes the feasibility of attaining a variety of climate targets during the 21st century, under alternative cooperation regimes by groups of countries simulated via the ETSAP-TIAM technology based, integrated assessment model. The article discusses the pros and cons of the stochastic programming treatment of forcing targets.

Scenarios

Five climate targets of increasing severity are analyzed, following the EMF-22 experiment. Each target is attempted under two cooperation regimes, a First Best scenario where all countries fully cooperate from 2012 on, and a Second Best scenario where the World is partitioned into three groups, and each group of countries enters the cooperation at a different date, and implement emission abatement actions in a progressive manner, once in the coalition.

In addition to the 10 separate case analyses, the article proposes a probabilistic treatment of three targets under the First Best scenario, and shows that the three forcing targets may in fact be interpreted as a single target on global temperature change, while assuming that the climate sensitivity $C_s$ is uncertain.

Results

Figure 14 shows net GHG emissions and the Kyoto forcing trajectories. The emissions results confirm the earlier observation that the 2.6 W/m$^2$ target is very difficult to satisfy, requiring very drastic emission reductions very early. In 2050, the First Best scenario calls for a global reduction of 65% of 2010 emissions in order to satisfy the 2.6 W/m$^2$ targets. And when groups 2 and 3 are entering late (the 2-Best scenario), the 2050 reduction is 50% of the 2010 level, but now the brunt of the early reduction effort is borne by OECD countries.

It seemed interesting and useful to attempt an alternative interpretation of the targets, by examining them simultaneously, as the manifestation of a single temperature target, subject to alternate outcomes of a random variable, the Climate Sensitivity parameter $C_s$. To illustrate and test this approach, we selected the First Best scenario and the three alternate RF targets with overshoot, and we sought the single temperature target (if such exists) that is equivalent to them. By examining the RF trajectories issued from the 3 separate scenario runs, we discovered that the 2.45 °C target on temperature increase fulfills this condition, as long as we assume specific values for the climate sensitivity parameter $C_s$. We were therefore able to replace the three alternate RF targets by that single temperature target, while acknowledging the randomness of $C_s$. Since the uncertainty on the target is assumed resolved in 2040, it
follows that the stochastic programming (hedging) strategy is unique from 2005 to 2040 inclusive, and branches out after 2040.

**Figure 14. GHG emissions and Kyoto forcings for the 10 cases**

![GHG emissions and Kyoto forcings for the 10 cases](image)

*The extension of the forcing trajectories beyond 2100 assumes emissions that decline linearly to 0 from 2100 to 2400.

GHG emissions in Hedging are from 4 to 7% larger than those of the 1B-2.6 over deterministic scenario from 2010 to 2040, confirming that the severe 2.6 forcing target has a strong influence on emissions in the hedging strategy. However, this relatively minor difference in emissions provokes a 40% decrease in the GHG shadow prices in hedging relative to 1B-2p6 over, at all years until 2040 (Figure 15).

**Figure 15. GHG prices**

![GHG prices](image)

The analysis shows that under some climate targets, it is not optimal to improve energy efficiency, but rather to take advantage of certain technologies that help to reach the climate objective, but that happen to be less energy efficient than even the technologies in the reference scenario. This is particularly observable in the power generation sector and in some end-use sectors.

The probabilistic interpretation of the multiple climate targets seems promising. The hedging strategy was itself shown not to be a naive average of deterministic ones, and to present a mix of abatement actions that could not easily be found otherwise. The application of stochastic programming to larger sets of uncertainties and scenarios would be desirable, albeit computationally cumbersome.

**1.2.2.4 OPEC oil strategies in a climate regime**

This paper (13,14) presents an analysis of the optimal oil production quotas of OPEC under a worldwide climate regime imposing a limitation on the radiative forcing. The analysis is conducted using a multi-region detailed energy-economy-environment bottom-up model (TIAM) where the demand laws for oil and its substitutes are implicitly defined as the result of a global supply-demand equilibrium in the World energy system, including the trading of energy forms and emission permits.
Scenarios
Reference Scenario runs: We first run TIAM with no quotas, i.e. we compute a competitive equilibrium as if OPEC were not a cartel (run noted RE for Reference). We then conduct a series of runs (named RE-X), each of which imposes a fixed set of production reductions to X% of the OPEC oil production levels observed in the RE run, where X varies from -60% to +40%.

Climate Scenario runs: Similarly, we first conduct a run with no quotas (competitive equilibrium) but including a constraint on Radiative Forcing equal to 3.5 W/m² in 2100 (run noted CL). This is a severe constraint that is expected to contain the increase in average global temperature within 2°C through the 21st century. We then conduct a series of runs with oil production quotas, named CLX, each of which imposes a quota reduction or increase equal to X% of OPEC’s oil production in the CL run, X varying from -70% to +30%. The smaller range chosen for these runs is sufficient to detect the optimal strategy.

We recall that OPEC’s optimal quotas were found to be at 80% of the corresponding competitive equilibrium values in both the Reference and the Climate scenarios. However, the absolute values of the equilibrium oil production levels are of course different in the two contrasted scenarios.

Results
The two export profiles (Figure 16) stay rather close together, with only a slight decrease in the Climate scenario, whereas world consumption decreases dramatically. This is no surprise, since a decrease in oil consumption mainly (negatively) affects the more expensive producers, which are in non-OPEC countries. An additional cause may be that OPEC oil is conventional, and its extraction emits less GHG’s than non conventional oil, which is produced exclusively in non-OPEC countries.

The OPEC profits are significantly higher in the Reference case than in the Climate NPV, indicating a probable preference of OPEC for a situation without any climate regime.

Figure 16. OPEC exports and global consumption in the two optimal OPEC strategies

A comparison of the global cost due to the climate constraint with and without OPEC quotas shows that the optimal quota strategy of OPEC decreases the global cost of climate mitigation by 159 B$ or about 1.4%, which is not very significant. We may conclude that OPEC’s quotas have a minor influence on the conduct of a global climate strategy.

The climate constraint makes oil a less desirable commodity, hence thea lower price in the Climate case compared to the Reference case until the second part of the time horizon (Figure 17) where the increase of the oil price in the Climate case reflects the high price of carbon at the end of the century. The OPEC strategies have an important impact of the oil prices, the latter increasing up to 40% in the optimal OPEC strategies compared to the global competitive strategy.

The analysis shows that OPEC’s quota strategies have a strong impact on oil prices with and without a world climate regime, but OPEC’s market power, measured as the impact on global welfare, remains moderate, and consequences of OPEC’s quotas on emissions and climate are very limited. In the climate scenario, OPEC would derive no advantage in ooding the oil market: the severe climate target is more important in determining oil demand than OPEC’s production strategies. Finally, OPEC’s quotas slightly
reinforce (positively) the energy and technology decisions taken to mitigate the GHG emissions; however, OPEC’s profits being lower in the Climate scenario, OPEC may be reluctant to engage in a strict global emission reduction agreement (considering a decision based on oil profits alone).

**Figure 17. Oil prices in the two optimal scenarios**

![Oil prices in the two optimal scenarios](image)

**1.2.2.5 Coupling bottom-up and top-down models to investigate cooperative climate policies**

In order to assess the cooperation between industrialized and developing countries in the design of a comprehensive worldwide climate policy to limit the global long-term temperature increase to 2°C, we developed (15,16,17) an iterative procedure to link the global technology-rich optimization energy model TIAM and the global general equilibrium model GEMINI-E3. Such a novel coupling methodology combines the precise representation of technology choices and their impact on climate change, and a coherent representation of the welfare gains or losses associated with the techno-economic choices. The coupling framework and algorithm are illustrated in Figure 18.

**Figure 18. Coupling framework**

![Coupling framework](image)

**Scenarios**

The climate target is defined by a maximal radiative forcing of 3.5 W/m² in any time, corresponding to a maximal global temperature increase of 2°C compared to pre-industrial times. The coupling methodology has been used to evaluate two kinds of climate cooperative agreements between countries.

- First, a global cooperative climate agreement (first best policy). Although idealised, this solution contributes to identify the best technology and energy decisions for the World to limit the GHG emissions; however, it does not indicate which country should pay for the identified mitigation options. This scenario is called S1.

- Second, two different partial cooperative climate agreements where only the energy intensive sectors of developing and emerging countries participate to the climate mitigation targets.

  ⇒ Scenario 2 (S2) Climate Agreement Limited to the Energy Intensive Industries: Using the same target of 3.5 W/m², all sectors of the OECD countries are covered by the climate agreement while in Non-OECD countries, only energy intensive industries (including electricity generation and upstream) are covered.

  ⇒ Scenario 2B (S2B) Climate Agreement Limited to Electricity Generation: All sectors of the OECD countries are covered by the climate agreement while in Non-OECD countries, only electricity generation is covered. The modeling of scenario 2B with
the target of 3.5 W/m² turned out to be infeasible. Therefore, the target used for this scenario was relaxed to 4.0 W/m². S2B can therefore not be compared to the other scenarios (S1 and S2) since the climate targets are different.

Results
The most important results related to S2 follow. First, the global techno-economic cost (obtained from TIAM in the Coupled-Models) of the Climate Agreement Limited to the Energy Intensive Industries (S2) is 1.5 times higher than the cost of the Climate Agreement based on all sectors (first-best solution S1); it increases even more in OECD (factor 1.8) since these countries have to do more mitigation efforts, but it increases also in Non-OECD (factor 1.3). In other words, all regions, including the Non-OECD countries, face a higher total cost when only the Intensive Energy sectors of the Non-OECD countries participate in the climate agreement (Figure 19), resulting in more costly strategies. CO₂ price in 2050 reaches 421$/tCO₂ in S2, compared to 286$/tCO₂ in S1.

Figure 19. Comparison of CO₂ emissions in reference, S1 and S2

The most important results related to S2B follow. The corresponding CO₂ price reaches 313 $/GtCO₂ in 2050. In terms of energy technologies, the Non-OECD countries do not increase their electricity consumption compared to the Reference case, but of course, the structure of the electricity generation is modified in favor of low-emitting power plants. Biomass fired plants with CCS play a crucial role. In terms of industrial production (not covered by the Climate agreement), developing and emerging countries, including China and India, reduce their imports and increase their exports compared to the Reference, while the opposite occurs in OECD countries: there is delocalization of the production (outputs of GEMINI-E3 in the Coupled-Models). Some delocalization of gas extraction to Non-OECD countries is also observed (outputs of TIAM in the Coupled-Models), but without provoking an important increase of emissions in these countries.

The assessment of globally and partially cooperative agreements (equivalent to a global Emissions Trading System or to project-based technology cooperation) shows that drastic technology breakthroughs and implementations are required as soon as possible, especially in the larger emitting countries, and in all sectors of the economy; focussing only on the power sector is not sufficient. Moreover, some risk of delocalization of both gas extraction and energy-intensive industries exist in the case of partial agreements, but they result in a limited carbon leakage thanks to the reduction of oil extraction in all cases.

1.2.2.1 Coupling Bottom-up and Top-down Models to Investigate Uncertainties
In this paper (18) we propose a dual approach, based on the combined use of stochastic programming and Monte Carlo analysis to deal with these uncertainties in a coupled techno-economic analysis. The stochastic programming approach is implemented on a bottom-up integrated assessment model, TIAM [18], to propose a hedging emission abatement policy for the time horizon 2030, followed by four typical recourse abatement policies, compatible with a target of 2.1°C temperature increase in 2100,
under reasonable assumptions on the uncertainty on climate sensitivity (Cs). These emission scenarios are then subject to an economic assessment, using a Computable General Equilibrium (CGE) model, GEMINI-E3, specifically designed to assess world climate change policies both at the microeconomic and the macroeconomic levels.

**Scenarios**
We identify four classes of uncertainties related to climate, technology, economy and energy prices, respectively. We draw 2000 samples with Latin Hypercube technique from the parameter distributions. For each sample we proceed in two steps:

- In step one, we run a Business As Usual (BAU) scenario, without any climate policy;
- In step two, we perform a climate policy scenario.

At the end we have performed 4000 runs. One objective of this paper was to study the role of technology and especially the CCS in climate policies.

**Results**
A cursory reading of our results might suggest that this technology has a limited impact in our scenarios. This does not mean that this technology does not contribute to GHG abatement, but rather that the uncertainty surrounding its costs is of limited scope particularly in respect to the CO2 price.

Indeed, in 2030, in 74% of cases the cost of CCS is lower than the carbon price, the use of this technology is a viable proposition. Is it interesting to look at the percentage of effective GHG emission reduction via CCS in Figure 20. When the climate sensitivity becomes high the contribution of the CCS to the GHG abatement converges to 20%. The figure also shows that when the climate constraint is low, this share is much higher and may even exceed 100%. This result must be related to the hedging strategy that we have taken into account, when the climate sensitivity is very low, the investment in CCS done before 2030 lead to an amount of CO2 sequestration above the GHG abatement required in 2050.

**Figure 20. Percentage of emission reductions effected via CCS in 2050 in respect to the GHG emissions in Gt C-eq.**

Several conclusions emerge from this work:

- The main uncertainty is related to the climate sensitivity, and it is necessary to determine its value as soon as possible. Indeed we showed that if the climate sensitivity is too high, simply, the climate target cannot be achieved in the CGE model. We also showed that the cost of climate policy is also very dependent on the climate sensitivity, when the GHG emission constraint is below 7 GtC-eq in 2050, the cost increases very rapidly reflecting the difficulty in reaching the climate target.
- Concerning the technological aspects of climate policy, we found that the availability of carbon free technologies is also determinant and that there is no single silver-bullet to combat carbon emissions. Thus, according to the model, CCS alone cannot provide the solution to the problem of GHG emissions increase and we must promote the development of a basket of carbon free technologies. Our simulations have shown
however that other factors are liable to affect the success and the cost of climate policy. The price of oil and behind it the behaviour of OPEC affects the possibility of reaching a target climate. The economic development of Asia is also a decisive factor in the cost and the success of a climate policy.

- Finally, we found that in 9% of runs the climate target cannot be reached, this means that if mitigation policies should be implemented, climate change adaptation policies must also be set up in parallel in case it would be simply impossible to achieve the target.

1.2.2.2 World climate strategies (SynsCOP15)

This research (19,20) exploits three complementary models – the techno-economic TIMES Integrated Assessment Model (TIAM), the GEMINI-E3 macroeconomic model and the GENIE climate model – in a coordinated manner. This integrated framework (Figure 21) is used to represent and evaluate the energy, emissions, technology, economic consequences as well as the climate impacts at global and regional levels of the several policy scenarios as proposed before and after the 15th Conference of the Parties (COP15) of the UNFCCC in December 2009.

The advantages of the approach is to combine the strengths of the different models: 1) Detailed technological representation of the energy system of TIAM-World (until 2100), 2) General equilibrium effects of GEMINI-E3 (until 2030) and 3) Flexible framework of GENIE describing the regional impacts of GHG concentrations (until 2100).

Figure 21. The Integrated Framework

Scenarios

In the first phase of the project, several scenarios (Table 1) have been evaluated to simulate different arrangements proposed before COP15 in Copenhagen, representing both first-best (full cooperation amongst all countries) and second-best scenarios – such as a complete failure in negotiations, an agreement within subgroups of countries (OECD, OECD+Russia, G20).

Table 1. Copenhagen Accord followed by world cooperation to reach 2°C in 2100*

<table>
<thead>
<tr>
<th>Scenario/Target</th>
<th>2020</th>
<th>2030</th>
<th>2050</th>
<th>2100</th>
</tr>
</thead>
<tbody>
<tr>
<td>CPH Failure</td>
<td>Lower pledges</td>
<td>As 2020</td>
<td>Full Coop from 2040</td>
<td>Full Coop from 2040</td>
</tr>
<tr>
<td>CPH Forever</td>
<td>Lower pledges</td>
<td>As 2020</td>
<td>Full Coop from 2040</td>
<td>Full Coop from 2040</td>
</tr>
<tr>
<td>CPH Plus</td>
<td>Higher pledges</td>
<td>Interpolation 2020-2050</td>
<td>-80% wrt 1990 in Annex 1 - 50% wrt BAU in other</td>
<td>Full Coop from 2055</td>
</tr>
<tr>
<td>Only 2050</td>
<td>No climate target</td>
<td></td>
<td></td>
<td>Full Coop from 2055</td>
</tr>
<tr>
<td>First-best</td>
<td>Full Coop from 2010</td>
<td>Full Coop from 2010</td>
<td>Full Coop from 2010</td>
<td>Full Coop from 2010</td>
</tr>
</tbody>
</table>

*In all Second-Best scenarios, permit trading limited to 20% of the emission reduction

Results

In terms of climate impacts, none of the 2020-2030 policies (Copenhagen targets forever, improved targets by 2050 etc.), is sufficient to limit the long-term temperature to 2°C (Figure 22).

Amongst the main conclusions, the analyses show that given the temporal dynamics of the climate and the mitigation options available in the models used for the analysis, early action is required and more
efforts than the pledges proposed by the Copenhagen Accord must be immediately applied after 2020 in order to succeed in limiting the long-term temperature to 2°C.

Figure 22. Surface average temperature increase in all a scenarios

1.2.2.3 Energy security in EU scenarios (from PLANETS project)

PLANETS (Probabilistic Long-Term Assessment of New Energy Technology Scenarios) is a research project (21,22) funded by the European Commission under the Seventh Framework Programme with the scope of devising robust scenarios for the evolution of energy technologies in the next 50 years. The project aims to assess the impact of technology development and deployment at world and European levels to foresee the best technological hedging policy in response to future environmental and energy policies. A suite of energy-economy-climate models (Table 2) is expected to generate the projection scenarios, using state-of-the-art methodologies that include stochastic analysis. The model portfolio spans varieties of regional coverage, technological detail and economic interrelations. The PLANETS team consists of eight partners from eight European Countries (France, Germany, Italy, Lithuania, Netherlands, Sweden, Switzerland, UK).

Table 2. Models overview

<table>
<thead>
<tr>
<th>Model Name</th>
<th>DEMETER (CNIMAN)</th>
<th>GEMINI-E3 (ORDECSYS)</th>
<th>PEM-TEAMS (USTUTT)</th>
<th>TIAM (KANLO)</th>
<th>TIAEMEC (ECN)</th>
<th>WITCH (FEEM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model Type</td>
<td>Global E3 optimal growth model</td>
<td>Top down, CGE model</td>
<td>Bottom Up</td>
<td>Technology: BU, with price-elastic demands</td>
<td>Bottom up, linear optimization, social planner</td>
<td>Top down, optimal growth, fully dynamic</td>
</tr>
<tr>
<td>Geographical coverage</td>
<td>One world region</td>
<td>World 28 regions</td>
<td>World, 15 regions</td>
<td>Global (15 regions)</td>
<td>World, 12 regions</td>
<td></td>
</tr>
<tr>
<td>Energy sector description, link with economic activity</td>
<td>2 energy sources 1. Fossil fuels 2. Non-fossil fuel energy</td>
<td>5 energy fuels/sectors: coal, crude oil, refined oil products, natural gas, electricity</td>
<td>Public and Astrophysic, Electricity and Heat, hard link with end use demand</td>
<td>Very detailed technological description. Link with economy via a) own price elasticities of demands for energy services, and b) linkage with CGE model (GEMINI-E3)</td>
<td>A technologically rich description of the energy sector, including all relevant technologies. Link to economy only through demand elasticities.</td>
<td>7 power generation technologies, 5 fuels. Hard linked with economy.</td>
</tr>
<tr>
<td>Timescal, calibration year</td>
<td>Calibration 2005, Timescale: 2010-2200</td>
<td>To 2050, one year timesteps, calibrated at 2001</td>
<td>2000-2030 5 year steps, and 2040, 2050, 12 time slices all periods</td>
<td>2005-2100, Base year=2005</td>
<td>Until 2100, calibrated for 2005</td>
<td>To 2200, 5 years timesteps, calibrated at 2005</td>
</tr>
</tbody>
</table>

Scenarios

PLANETS will research the future of energy systems by examining environmental and energy policies at the European and global level in their capacity to influence the deployment of new technologies with respect to a mutually agreed Business-As-Usual scenario. The project will also analyse the linkage between European and world perspectives of energy technology futures and forecasts, in particular in
terms of economic competitiveness and the capacity to export clean technology adoption. These presentations (23,24,25) give an overview of scenarios (Table 3) and preliminary results.

Table 3. Scenarios analysed in the PLANETS research project

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Summary</th>
<th>Targets</th>
<th>Codes</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>First Best (FB)</strong></td>
<td>All regions cooperate fully (and trade) from 2012 onward to achieve the target(s) efficiently</td>
<td>Two targets: 3.2 W/m², 3.5 W/m²</td>
<td>FB-3p2, FB-3p5</td>
</tr>
<tr>
<td><strong>Second Best (SB)</strong></td>
<td>Each group of countries has an emission commitment until 2050, with different starting date of commitment, and then all countries join the global climate coalition.</td>
<td>Until 2050: Fixed commitments</td>
<td>SC1-3p2, SC2-3p2</td>
</tr>
<tr>
<td><strong>Variant (Var)</strong></td>
<td>Same as Second Best, but trading limited to 20% of reductions</td>
<td>Until 2050: Fixed commitments</td>
<td>Var1-3p2, Var2-3p2</td>
</tr>
</tbody>
</table>

Results (preliminary)

There is a remarkable similarity of results from different models, with some significant differences (Figure 23): bottom-up models with a lot of technological flexibility achieve targets with lower global costs. In particular, Coal+CCS and Biomass+CCS play large roles and help reduce policy costs and GHG prices.

Figure 23. Policy costs as % of GDP

In the TIAM model, 67 energy channels are available to import gas, coal, and oil products into EU, from several regions in the ROW. Another useful and interesting result (26,27) concerns the impact of increasing reliability on the total amount of energy imported by EU. We observe that energy imports slightly increase in 2025 and decrease significantly at later periods when reliability increases. The decrease ranges from 30% in 2030 to about 20% in 2055. This is an important result showing the resilience of the EU energy system in the medium and long terms.
First, it appears that the supply of energy can be guaranteed with a known probability, under the very mild assumption that the mean of the random availability factors be known, or bounded at some level higher than half of the range. Second, such reliability is achieved at what may be considered moderate an extra cost, not exceeding 0.7% of the total EU energy cost. Moreover, the results, in addition to ensuring a degree of reliability, contribute very significantly to reduce the concentration of supply sources, a feature that is desirable in itself.

1.2.2.4 Future role of renewable energy technology for climate stabilization

Several changes require a reevaluation of modeling algorithms, as the global energy system enters this period of dramatic change. The changes include: the need for rapid decarbonization of the energy system; the shift from centralized to decentralized infrastructure; accelerating technological change and the increasing potential for disruptive technological changes market penetration, and cost reductions in solar photovoltaics (PV) that result in grid price parity; and the convergence of energy security issues with climate change mitigation and adaptation.

In an effort to address these changes and better understand their impact on the evolution of the global energy system, the Renewable Energy Technology Deployment (RETD) Implementing Agreement of the IEA has defined its own scenario, in collaboration with the ETSAP Implementing Agreement. This report (28, 29, 20) presents the results of that work. The RETD ACES Scenario was modeled using the ETSAP-TIAM3 model, a partial equilibrium, technology-rich, economic optimization model.

Scenarios

The RETD ACES Scenario (Achieving Climate and Energy Security) targets reductions in GHG emissions consistent with stabilizing GHG concentrations in the atmosphere at 400 ppm\(^2\) carbon dioxide equivalents (CO\(_2\)-eq) by 2100. Of equal importance, the RETD ACES Scenario also places constraints on the global trade of energy commodities to reflect the rising importance of energy security and the linkages between energy security and climate change. In order to evaluate the results of the RETD ACES Scenario, an internally consistent Reference Scenario was developed: a hypothetical baseline from which comparisons can be made.

Results

In the Reference Scenario, GHG emissions continue to grow, from about 40 gigatonnes (Gt) CO\(_2\)-eq to 70 Gt by 2060 (Figure 24). In the RETD ACES Scenario, GHG emissions fall steadily, reaching just 9 Gt CO\(_2\)-eq by 2060, a roughly 75% reduction from 2010 levels. These emissions encompass the impact of all energy and non-energy sector emission sources and sinks contained in TIAM, which include land use change and reforestation (the latter acts as a sink). In 2060, net CO\(_2\) emissions reach zero. The system is able to achieve carbon neutrality because of ongoing reforestation and other GHG mitigation options, even though the energy sector as a whole and land use change remain net CO\(_2\) emitters through 2060 and beyond. Despite these dramatic reductions in GHG emissions, GHG concentrations still do not reach 400 ppm CO\(_2\)-eq by 2100, instead reaching approximately 420 ppm, after peaking at approximately 490 ppm CO\(_2\)-eq in 2035. One factor behind the challenge of reaching 400 ppm by 2100 is the GHG emissions contribution of agriculture, even though the RETD ACES Scenario includes relatively optimistic assumptions about the emissions of non-energy GHGs. The GHG reductions are achieved primarily through reductions in CO\(_2\) emissions from the energy sector. Compared to the Reference Scenario, total final energy consumption in the RETD ACES Scenario is 22% lower in 2060. This difference is due to two factors: (i) increasing efficiency of energy transformation and use, and (ii) reduced demands due to higher energy prices and improved access by consumers to energy usage information via the Smart Grid.

\(^2\) In running the model, it was not possible to achieve this target. Rather, the model converged on a concentration of about 420 ppm by 2100, with concentrations falling at a rate of about 1 ppm per year in 2100.
In addition to greater efficiency, there is a rapid decarbonization of energy supply. Consumption of coal at plants that are not equipped with CCS technology is dramatically reduced. In terms of primary energy demand, total coal consumption falls by over 25% by 2060, but coal use without CCS falls by almost 85%. The situation for oil is similar. For energy purposes, natural gas use rises from about 93 EJ in 2010 to 227 EJ in 2060, of which 74 EJ is equipped with CCS. The net effect is that total primary energy demand for all non-RE resources rises modestly but the GHG emissions from these resources fall (Figure 25). Simultaneous, RE becomes the most important energy source sometime between 2030 and 2040, when it passes 50% of all primary energy supplies, up from about 20% today.

In the RETD ACES Scenario, no other sector is more transformed than electricity. There is a rapid reduction in the use of fossil fuels for power generation, except where this usage is also accompanied by CCS, which is assumed to be available commercially starting in 2020. RE becomes the largest contributor to electricity generation and capacity sometime before 2030, with RE generation rising from about 22% in 2007 to 61% by 2030. All RE technologies grow significantly, although wind and PV see the greatest growth in capacity through 2060 (Figure 26).

After 2030, the global electricity mix is composed mainly of (i) fossil fuels with CCS (still mildly carbon positive), (ii) nuclear power and RE (essentially carbon neutral) and (iii) biomass with CCS (quite strongly carbon negative). The availability of carbon negative electricity results in significant fuel switching to electricity in all sectors of the economy where this is technically possible.

The total direct energy system costs of the RETD ACES Scenario are larger than the comparable costs resulting from the Reference Scenario by approximately $14.3 trillion (discounted at 5%) over the next 50 years. The total incremental cost of the RETD ACES Scenario compared to the Reference Scenario is only about 1% of total cumulative GDP. Given the wide range of benefits that will result from the RETD
ACES Scenario, one can reasonably conclude that the value of these as-yet-to-be quantified benefits should exceed this comparatively modest incremental investment in climate change mitigation.

**Figure 26. Renewable electricity capacity in the RETD ACES scenario through 2060**

* Biomass CCS used only for the purpose of CO₂ removal is excluded.

The results of this project are both encouraging and sobering. The future as described by the RETD ACES Scenario is both technically and economically feasible, and may in fact be economically superior to a future characterized by inaction. Achieving this future will require immediate, sustained and concerted investment in technology development and infrastructure. EE and RE are the keys to achieving the climate and security goals of the scenario. These messages are consistent with several other similar independent analyses. In order to achieve the goals of the RETD ACES Scenario, immediate steps must be taken to transform the energy sector from one dominated by large centralized fossil-fuel infrastructure, to one dominated by RE generation and characterized by a greater a mix of both centralized and distributed energy generation. The role of enabling technologies, including Smart Grid and CCS, will be critical to this transition. The success of this evolution will also depend on the sustainability of increased bioenergy utilization and the reversal of the trend of deforestation. The results of the modeling also point to the importance of non-energy GHG reductions and sinks.

### 1.2.2.5 The Role of Renewable Energies in Global Scenarios

This paper (30,31) aims to test the ETSAP-TIAM global energy system model and to try out how far it can go towards a global 100% renewable energy system with the existing model database.

Existing analysis with TIAM shows different ways of reaching the 2 °C target and also how uncertainty on different factors influences the optimal solution. The main conclusion from existing analysis with TIAM is that the 2 °C target is possible to reach, but it will be expensive. Another very important point is that if uncertainty on the value of the climate sensitivity (Cₜ) is taken into account then the optimal strategy calls for early action compared to a full foresight optimisation using the most probable value of Cₜ.

**Scenarios**

Forcing renewables and energy savings in TIAM was done through using the following three scenarios:

- **Reference scenario:** Standard assumptions, climate policyfree.
- **Alternative scenario I:** CO₂-concentration in the atmosphere is restricted to 400 ppm.
- **Alternative scenario II:** The price for GHG emissions is fixed to 400 Euro per tonne CO₂e globally (CO₂e price).

**Results**

As can be seen from Figure 27, the world is close to utilising the full resource potential of geothermal already in 2050 in both alternative scenarios, in contrast to the reference scenario. Hydro and biomass
are both utilised at between 75% and 90% of their potential in the alternative scenarios, which are very much larger shares than in the reference scenario. In 2050 there is still plenty of potential for increased energy production from wind.

**Figure 27. Renewable resource utilisation (2050)**

In summary it is clear that a 100% renewable energy system was not achieved in neither of the scenarios examined, yet the system came very close to some of the resource limits. However, there is still a large unutilised wind potential, as well as potentials for solar, tidal and wave to enter the system.

1.2.2.6 *Non-fossil energy technologies in 2050 and beyond*  
For many countries energy security concerns are accompanied by a preference for renewable options which can reduce their dependence on imported oil and gas, as well as helping to meet environmental policy objectives. In facing these challenges the EU has in recent years adopted a fairly ambitious energy and climate change policy. These targets will require drastic changes in the energy systems of all countries in both the short and the long term. In the following discussion (32), focus is on long-term scenarios for the EU countries, up to the end of this century. The scenarios for the EU27 countries plus Norway, Switzerland and Iceland (EU27+3) were examined using the global energy system model TIAM-World.

**Scenarios**

To keep the global mean temperature rise below 2°C we need, according to the IPCC, to reach global stabilisation at 450 ppm CO₂eq, which means that global GHG emissions must be halved by 2050 and in fact reduced even more in the OECD countries. According to the analyses presented in this report, it will be difficult for the European countries to meet these targets as mitigation options from the energy sector alone do not seem to be sufficient, but have to be supplemented by action from other sectors, for example the agricultural sector. On the other hand, the Danish case described in this report shows that Denmark stands a good chance of meeting the mitigation goals and of being able to phase out fossil fuels rapidly and thus reduce GHG emissions at the pace needed.

**Results**

**Main point for renewable energy technologies are (Figure 28):**

- Solar energy can be used to generate heat and electricity all over the world. Our technical ability to exploit this resource has improved dramatically in recent years, and by 2050 the IEA forecasts that the PV and CSP technologies will each produce 11% of the world’s electricity.
- With increased focus on offshore deployment combined with the radically different conditions compared to onshore, it is likely that completely new concepts will emerge. Wind energy has the potential to play a major role in tomorrow’s energy supply, cost-effectively covering 30-50% of our electricity consumption.
- Hydropower is a mature technology close to the limit of efficiency, in which most components have been tested and optimised over many years.
- Wave energy can be seen as stored wind energy. Globally, the potential for wave power is at least 10% of total electricity consumption. An ambitious yet realistic goal for Danish wave power by 2050 could be around 5% of electricity consumption.
- Biomass presently covers approximately 10% of the world’s energy consumption. A realistic estimate of the total sustainable biomass potential in 2050 is 200-500 EJ/yr covering up to half of the world’s energy needs in 2050.
- The potential for geothermal energy is substantial since suitable aquifers are available, and the technology is an excellent match for the district heating systems already widely used.
- Many types of electricity storage will be of great importance in the coming decades. A shift to sustainable energy sources will also require mobile storage technologies for vehicles. Capturing electricity from wind and solar sources in a concentrated form, these will need to deliver driving ranges similar to those of modern gasoline and diesel vehicles. In future storing energy as hydrocarbons synthesised from hydrogen, made by the electrolysis of water, and carbon dioxide extracted from the atmosphere may become viable. There is also considerable technical and economic potential for heat storage.
- The need for an energy supply with low fossil fuel dependence and low GHG emissions has led to renewed interest in nuclear energy. The next generation of nuclear energy systems, Generation IV, may be deployed from 2040 onwards. Fusion research is now taking the next step with the construction of ITER. If everything goes according to plan, the first commercial fusion power plant will then be commissioned by 2050.
- Carbon capture and storage (CCS) can be used on power plants and industrial furnaces. Denmark still has a good chance of exploiting CCS, with plenty of geological storage capacity both onshore and offshore. With an increase in wind energy, Danish coal-fired power plants will provide the baseload and can operate flexibly even with CCS.

Figure 28. Developments in non-fossil technologies 2010-2050
By 2050, the sum of the potential of all the low-carbon energy sources exceeds the expected demand. The challenge for a sustainable global energy system with low CO₂ emissions by 2050 is therefore to utilise this potential in the energy system to the extent that it can be done in an economically attractive way.

It will not be possible to develop the energy systems of the future simply by improving the components of existing systems. Instead, we need an integrated process that will optimise the entire system, from energy production, through conversion to an energy carrier, energy transport and distribution, and efficient end-use. A future intelligent power system requires investment now, since uncertainty among investors is already hindering progress towards a higher share of renewable energy. If we do not make this investment, future generations may look back in disbelief that for so long we tolerated an antiquated energy system without putting in place the improvements that were already possible.

1.2.2.7 GHG mitigation targets and potentials in large emerging economies

The outcome of the UN climate change negotiations at COP15 in December 2009 was the Copenhagen Accord, which countries voluntarily can acknowledge alongside supplying their voluntary actions combating climate change. Much has been discussed regarding whether these pledges are “sufficient” and whether they are “fair”. On this background, this paper (33) intends to analyse the pledges made by large emerging economies regarding their GHG-emission reductions in 2020 in light of their estimated potentials and costs for the same, both looking at existing national and international literature and presenting new results from the global ETSAP-TIMES Integrated Assessment Model (TIAM).

Scenarios

The countries studied in this paper are China, India, Brazil and South Africa – the BASIC group. These countries currently account for approximately 28% of the world’s GHG emissions (2005), 9.5% of the world’s economy and 33.41% of the world’s population. These shares are projected to increase by 2020.

In the Copenhagen Accord, the countries agree to work to limit the increase in global temperature to 2°C above pre-industrial levels. According to the IPCC, to stay within this limit will require GHG emission reductions of between 50 and 85% in 2050.

Results

Recent studies on GHG emissions in 2020, BAU, pledges and 2°C target (Figure 29):

- At best: high pledges meet required reductions for 2°C target
- At worst: 14 Gt CO₂e gap

Figure 29. Pledges contributions to GHG emission reductions
Sources: Lowe et al. (2010), climateinteractive.org/scoreboard, Stern and Taylor (2010), Houser (2010), Project Catalyst (2010), Rogelj et al. (2010), Elzen et al. (2010)

Some analyses of the pledges made by India and China conclude that the pledges of their reductions only amount to what the countries would expect to emit in 2020 in a BAU scenario or slightly below, meaning that there is no real commitment in the pledges (Figure 30).

**Figure 30. Relative emissions in four scenarios in 2020**

This conclusion however, varies greatly with assumptions on GDP trajectories. At the same time, studies of mitigation potentials and costs in these countries (Figure 31) indicate that their potential for emission reductions is larger than what they have submitted as voluntary targets, which indicates that a globally optimal mitigation path would require even larger efforts of them than what they have pledged so far.

**Figure 31. System costs of climate scenario (3.5 W/m² costs 2005-2100)**

The effort made by the BASIC countries to combat climate change will therefore be of high importance, as the ambitious goal of staying below 2°C is impossible without severe reductions also by these countries. However, the optimal path for them to take is not necessarily clear cut, as research on integrated policies for sustainable development and GHG emission strategies shows. One of the main concerns for developing countries regarding emission targets seems to be that they may have to lower their ambitions for economic growth and development. However, research shows that this needs not be the case, and that policies and strategies taking into account both sustainable development priorities and GHG emission targets, may achieve more optimal paths and outcomes.

### 1.2.2.1 Other studies with the ETSAP-TIAM model

**Reinforcing the EU dialogue with developing countries on climate change mitigation**

The FP6 TOCSIN project (34) has investigated the strategic dimensions of RD&D cooperation and the challenge of creating incentives to encourage the participation of developing countries in post-2012 GHG emissions reduction strategies and technological cooperation. We investigated the possibility and consequences of a 3.5 W/m² radiative forcing scenario. The 3.5 W/m² target requires a 50%-65% reduction of global emissions by the end of the century compared to 2000 emissions. As a 3.5 W/m²
scenario will require very dramatic emission reductions, not just in future decades but almost immediately, TIAM simulations indicate that China and India will both need to begin to see large scale penetration of CCS by 2015-2020. Considering the lags associated between a decision to build a new power station and it coming online, the decisions needed for deployment by 2020 must be taken almost immediately in order to see any perceptible change in overall generation mix and to have an impact on near term emission trajectories.

**Meeting global GHG emissions reduction targets: EMF24 scenarios**

This presentation (35) introduces sample of results of global GHG emissions reduction targets from the TIAM model in the EMF24 analysis framework: Technology Strategies for Achieving Climate Policy Objectives. EMF 24 focuses on international and domestic climate policy intervention scenarios focusing on technology strategies for achieving climate policy objectives. These scenarios (Table 4) will enable the community to exercise enhanced modeling capabilities that were focused on in previous EMF studies on the international trade implications of climate policies, the representation of technological change, and the incorporations of multi-gas mitigation and land use emissions and mitigation policy alternatives.

**Table 4. Scenarios analyzed with TIAM for EMF-24**

<table>
<thead>
<tr>
<th>Technology Dimension</th>
<th>Energy Intensity</th>
<th>Reference</th>
<th>Low</th>
<th>Reference</th>
<th>Low</th>
<th>Reference</th>
<th>Low</th>
</tr>
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<tbody>
<tr>
<td>CCS</td>
<td>On</td>
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<td>Off</td>
<td>On</td>
<td>Off</td>
<td>Off</td>
<td>Off</td>
</tr>
<tr>
<td>Nuclear energy</td>
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<td>Off</td>
<td>On</td>
<td>Off</td>
<td>Off</td>
<td>Off</td>
</tr>
<tr>
<td>Wind &amp; Solar</td>
<td>Adv</td>
<td>Adv</td>
<td>Ref</td>
<td>Ref</td>
<td>Ref</td>
<td>Ref</td>
<td>Ref</td>
</tr>
<tr>
<td>Bioenergy potential</td>
<td>High</td>
<td>High</td>
<td>High</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
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</table>

<table>
<thead>
<tr>
<th>Policy Dimension</th>
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<th>Reference</th>
<th>Low</th>
<th>Reference</th>
<th>Low</th>
<th>Reference</th>
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<th>Low</th>
<th>Reference</th>
<th>Low</th>
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<tbody>
<tr>
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<td>2</td>
<td>3</td>
<td>4</td>
<td>15</td>
<td>16</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>550 CO2 e</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
<td>20</td>
<td>21</td>
<td>29</td>
<td>30</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>Idealized G8</td>
<td>37</td>
<td>38</td>
<td>10</td>
<td>22</td>
<td>23</td>
<td>24</td>
<td>39</td>
<td>40</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Muddling through</td>
<td>11</td>
<td>12</td>
<td>13</td>
<td>14</td>
<td>25</td>
<td>26</td>
<td>31</td>
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</table>

Other TIAM models were developed from the original ETSAP-TIAM model by different research groups; examples of studies using these different versions of TIAM are presented below.

1.3 The derived TIAM-VTT Model

1.3.1 Model and methodology

The global TIMES model is a large and complex multi-regional energy system model. The basic version of the model consists of 15 world regions, with an additional distinction of the resources and production of primary energy in OPEC and non-OPEC countries within each region. In the VTT version (36) an additional region for Finland has also been tentatively implemented, and another new region for the other Nordic countries is under preparation. VTT has completed some enhancements to the TIAM model, in particular related to the modelling of GHG emissions and their climate change impacts. The VTT version of the model includes a complete modelling of all anthropogenic emissions and control technologies of methane (CH4), nitrous oxide (N2O) and the F-gases of the Kyoto protocol.

1.3.2 Studies with the TIAM-VTT model

1.3.2.1 Global scenarios for effective climate change mitigation

The achievement possibilities of the EU 2°C climate target have been assessed with the ETSAP TIAM global energy systems model (36). Cost-effective global and regional mitigation scenarios of carbon dioxide, methane, nitrous oxide and F-gases were calculated with alternative assumptions on emissions trading.
Scenarios
In addition to the baseline and 2°C scenarios, some stochastic scenario analysis concerning the climate sensitivity was also committed (Table 5).

Table 5. Assumptions on the uncertainty of climate sensitivity to the doubling of atmospheric CO₂ concentration

<table>
<thead>
<tr>
<th>Climate sensitivity (°C)</th>
<th>Probability</th>
<th>Temperature adjustment lag (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5</td>
<td>0.2</td>
<td>15</td>
</tr>
<tr>
<td>3.0</td>
<td>0.4</td>
<td>40</td>
</tr>
<tr>
<td>4.5</td>
<td>0.2</td>
<td>67</td>
</tr>
<tr>
<td>6</td>
<td>0.2</td>
<td>80</td>
</tr>
</tbody>
</table>

Results
The following figure presents the results for the regional development of CO₂ emissions in the baseline and 2°C scenarios (Figure 32). In the mitigation scenarios, an 85% reduction in CO₂ emissions is needed from the baseline, and very significant changes in the energy system towards emission-free sources take place during this century. The single largest technology group providing emission reduction during the study period was CCS technologies, contributing a 5.5 Pg CO₂ emission reduction by 2050 and 11.8 Pg CO₂ reduction at maximum in 2100. Forestation measures were the second largest group of measures with a maximum use of 7.7 Pg CO₂ in 2080. The largest contributing regions were developing Asia (ODA) by 2.5 Pg CO₂, Central and South America by 1.4 Pg CO₂ and Africa by 0.8 Pg CO₂ in 2080.

The results illustrate quite well the significance of the uncertainties in climate sensitivity with respect to the necessary climate change mitigation efforts (Figure 33). In the scenario experiment it was assumed that the uncertainties in the sensitivity of climate to GHG concentrations would be fully resolved around 2050. Due to the uncertainties involved before that point, the optimal hedging strategy would support strong immediate actions to reduce global emissions, so that the total emissions would be reduced by about 40% by the year 2040. If it then nevertheless turns out that the climate sensitivity to the doubling of CO₂ concentration compared to pre-industrial levels is only 1.5°C, then no more efforts would be needed in order to stabilize the temperature increase below 2.8°C. However, in this case it might actually be worth to strive at stricter targets with respect to global warming.

Figure 32. Development of global CO₂ emissions in the baseline scenario and in the 2°C scenario
1.3.2.2 The role of CCS and renewables in global climate scenarios

The need for global and regional clean energy technology investments by 2050 are evaluated in climate policy scenarios with the bottom-up global ESAP TIAM energy system model (37). The impacts of the assumed regional CO₂ storage potentials as well as bioenergy and wind power potentials on investments are also investigated by sensitivity analysis.

Scenarios

In the sensitivity analysis runs, we assumed 40% reduction in global and regional maximum potentials for bioenergy and wind power, and 40% reduction in global and regional CO₂ storage potentials.

Results

Figure 34 shows the investments needed for selected technologies in electricity production. The annual capital expenditure is based on the assumptions for technology investments including technology learning. In the baseline scenario the use of fossil fuels, especially coal, increase rapidly while in the policy scenario the renewables and nuclear dominate. The annual capital expenditures in 2050 for both wind power and energy production with CCS were about 200 billion € per year. For biomass fired energy production the calculated annual investments in 2050 were around 400 billion € per year. It should be noted that global investments in nuclear power would more than double by 2050 even though investments in new nuclear capacity were constrained according to the existing policies in developed countries.

The sensitivity analysis for the scenario runs showed that assumed maximum regional potentials of biomass use would have great impact on future investments for bioenergy technologies. Bioenergy production competes in land use with food production and according to our own research the estimates used could be too optimistic. One on the single major technologies to tackle climate change was CCS, which accounts for about 10 Gt CO₂ per year emission reduction in 2050. The sensitivity studies for CO₂ storage potential indicated that approximately 1500 Gt potential did not change the pathway to achieve the 2°C limit. The results of the study indicate that the demand of both wind and bio energy as well as the utilization of CCS will strongly grow under strict climate policy scenarios. This can be seen both in terms of electrical capacity and annual capital costs. Although the falling fossil base electrical capacity will be relatively large until the mid of the century, its monetary value in term on annual capacity costs will be relatively low.
Figure 34. Global investments in heat and power generation in 2020, 2030 and 2050 in the policy scenario

Left figure: Annual capital expenditure with 10% interest rate. Right figure: Global electrical capacities (nominal). The thin vertical lines describe the range of the results from sensitivity studies, where bioenergy resources, wind energy resources and CO2 storage potential were decreased by 40% each in its own scenario.

1.3.2.3 Energy security in EU demand and supply scenarios

This presentation focuses on energy security in EU demand and supply scenarios of renewables and the dependence on Russian energy.

Scenarios

Baseline
- No new climate policy after 2012
- GDP growth assumptions based on ETSAP TIAM data
- No constraints for new oil or gas production, constraints for new nuclear based on the existing policies for the EU-30 countries

2 C-scenario
- Maximum temperature increase by 2100 limited to 2 C degrees
- Ghg emission reduction target for Annex 1 countries: -20% in 2020, -70% in 2050 and -90% in 2090 compared to 1990 emissions
- Global emissions trading with "CDM policy" for Annex 1 countries: max. 20% in 2020 and max. 50% in 2050 of target by purchasing allowances

2C gas-scenario
- 2 C scenario with constrained natural gas production and trade between world regions

Results

The Figure 35 shows the EU-30 gas import needs by 2050. In the 2°C gas scenario, most of gas is imported from Russia. In 2050 the gas import from Africa and Middle East decreases down to zero. The gas consumption is at its highest level in 2020 in all the scenarios.

With ambitious climate policies the assumptions of maximum production capacities of gas up to 2020 would have great impact on energy mix in the EU-30 area. New gas production in the EU-30 area:
- In 2050 the assumed maximum potentials of renewables (especially wind and biomass) would be critical with ambitious climate policies.
- The use of indigenous energy sources didn't change remarkably with 20% ghg reduction target. With 70% reduction target in 2050 the share of renewables increased up to 45%.
1.3.2.4 Effort-sharing and coalitions in global climate scenarios

The post-2012 climate policy framework needs a global commitment to deep GHG emission cuts. This paper (39,40) analyses reaching ambitious emission targets up to 2050 and how the economic burden from mitigation efforts could be equitably shared between countries. Being simple and transparent, the EVOC tool of Ecofys GmbH was used for calculating emission allocations, while and ETSAP-TIAM, a sophisticated but complex global energy system model of the TIMES family was used for creating the scenarios.

Scenarios

This study has analysed global effort sharing of climate change mitigation with Triptych and Multistag effort sharing rules and two mitigation scenarios aiming at -10% and -50% reductions from 1990 levels by 2050, leading to concentrations of 550ppm CO₂-eq and 485ppm CO₂-eq by 2100, respectively. The targets were assumed to be globally binding from 2020. For calculating the resulting concentrations, radiative forcing and mean temperature increase (using 3°C climate sensitivity) up to 2100, the emission target of 2050 was assumed constant for the period between 2050 and 2100. If further reductions would be made post-2050, though, concentrations below 485 and 550 ppm would be attainable by 2100. With the 485 ppm target the temperature stabilizes during the century, whereas with the 550 ppm target it is still increasing in 2100 and would probably stabilize around 2.5°C later on.

Results

Figure 36 presents the emission allocation, relative to 2000 emissions, in 2020 and 2050 for the 15 different countries or country groups in TIAM. The approaches allocate, respectively, 10–50% reductions for Annex I in 2020 and 60–95% reductions in 2050.

Of all the eight different mitigation scenarios created, the moderate growth B2 scenarios with both reduction targets are used for illustrating the mitigation measures. Figure 37 portrays the emission profiles in both cases, separately for combustion and process emissions. As can be seen, the electricity sector provides the largest cost-efficient mitigation potential.

Figure 38 presents regional mitigation and emission trade costs in 2020 and 2050. Both effort sharing rules allocate costs for Annex I countries in 2020 (with the exclusion of Eastern Europe), costs around zero for more developed non-Annex I countries, and gains for least developed countries as a result of selling emission allowances. In 2050, Annex I countries, especially Australia and Russia (as a part of FSU) with the 485ppm target, face relatively high costs. Also most non-Annex I countries face positive costs, and only India and Africa are able to gain financially from the effort sharing.
Figure 36. Emission allocation, relative to 2000 emissions, in 2020 and 2050*

* The bars present the median of the four economic growth scenarios.

Figure 37. Global GHG emissions with the 550 ppm (left) and 485 ppm (right) mitigation targets

Figure 38. Regional mitigation costs relative to their baseline GDP in 2020 (left) and 2050 (right)*

*The error bars correspond to the range of values with four baseline scenarios.

The scenarios indicate a large low-cost mitigation potential in electricity and industry, while reaching low emission levels in international transportation and agricultural emissions might prove difficult. The
two effort sharing approaches, Triptych and Multistage, were compared in terms of equitability and coherence. Both approaches produced an equitable cost distribution between countries, with least developed countries having negative or low costs and more developed countries having higher costs. There is, however, no definitive solution on how the costs should be balanced equitably between countries. Triptych seems to be yet more coherent than other approaches, as it can better accommodate national circumstances. Last, challenges and possible hindrances to effective mitigation and equitable effort sharing are presented. The findings underline the significance of assumptions behind effort sharing on mitigation potentials and current emissions, the challenge of sharing the effort with uncertain future allowance prices and how in efficient markets might undermine the efficiency of a cap-and-trade system.

1.4 The derived TIAM-FR Model

1.4.1 Model and methodology

Here, some improvements investigated in TIAM-FR (41)

- Modification of demand drivers
- Modification in carbon storage potential (deep ocean and coalbed methane recovery)
  - Implementation of new technologies (Fossil power plants with CCS, Coal-biomass co-firing power plants with and without CCS, CHP)
  - Modification of costs (Bioplants with CCS, Geothermal new technologies)

1.4.2 Studies with the TIAM-FR model

1.4.2.1 Global versus regional climate policies and technological limits

The aim of these studies (41) is to discuss the long-term analysis of post-Kyoto commitments issued from Copenhagen/Cancun Agreements, with the modelling tool ETSAP-TIAM-FR. More precisely, we investigate different coordination schemes for regions pledging in CO2 mitigation targets during the period 2005-2050. This paper compares global efforts of CO2 mitigation with regional climate policies expressed through targets pledged to UNFCC and, finally discusses the impact of the development of CO2 storage technologies in the energy mix in 2050.

Scenarios

A baseline business as usual (BAU) scenario without any emission constraints was first calculated. We defined scenarios according to the CO2 mitigation targets expressed to UNFCC for the Copenhagen Agreement in January 2010 by Europe (Western+Eastern), the United States of America, Australia, Canada, Japan, China and India for 2020. In addition, the international community appears to converge on long-term objectives, namely a CO2 mitigation of 60% to 80% by 2050. Concerning the United States and Canada, we consider targets that they also pledged a CO2 mitigation target of 30% by 2025, 42% by 2030 and 83% by 2050.

To a better understanding of the various targets, we translate these pledges to the same reference year and follow the same type of reduction, i.e. emission mitigation (Table 6).

Table 6. Understanding the targets

<table>
<thead>
<tr>
<th>Regions</th>
<th>On 1990 scale</th>
<th></th>
<th>On 2005 scale</th>
<th></th>
</tr>
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<tbody>
<tr>
<td></td>
<td>2020</td>
<td>2050</td>
<td>2020</td>
<td>2050</td>
</tr>
<tr>
<td>Europe</td>
<td>-20%</td>
<td>-80%</td>
<td>-18%</td>
<td>-79%</td>
</tr>
<tr>
<td>Japan</td>
<td>-25%</td>
<td>-80%</td>
<td>-32%</td>
<td>-82%</td>
</tr>
<tr>
<td>Australia</td>
<td>+9%</td>
<td>-77%</td>
<td>-13%</td>
<td>-82%</td>
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<tr>
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<td>-0.3%</td>
<td>-80%</td>
<td>-17%</td>
<td>-83%</td>
</tr>
<tr>
<td>Canada</td>
<td>+3%</td>
<td>-79%</td>
<td>-17%</td>
<td>-83%</td>
</tr>
<tr>
<td>China</td>
<td>+301%</td>
<td>+109%</td>
<td>+73%</td>
<td>-10%</td>
</tr>
<tr>
<td>India</td>
<td>+332%</td>
<td>+86%</td>
<td>+110%</td>
<td>-10%</td>
</tr>
</tbody>
</table>
Another scenario expresses global constraint that consists in reducing CO₂ emissions by 50% in 2050 compare to the year 2000, in line with the consensual 2°C objective expressed to UNFCCC and the Fourth Assessment Report of IPCC (IPCC, AR4). For 2050, all regions are concerned by this global target but they are not constraint at a beforehand determinate level of CO₂ emissions. We then create different scenarios to analyze different scheme of international coordination on climate policies over the period 2005-2050.

- First series:
  - Optimistic: This international scenario represents the fix and optimistic CO₂ mitigation targets of the COP 15 commitments expressed for 2020 and optimistic assumptions for 2050.
  - Pessimistic: This international scenario represents the fix and pessimistic CO₂ mitigation targets of the COP 15 commitments expressed for 2020 and pessimistic assumptions for 2050.

- Second series:
  - COP15: A regional scenario considering post COP15 pledges in 2020 and assuming new targets for 2050. The lowest CO₂ mitigation targets by 2020 and the higher assumptions in 2050.
  - COP15plus: A coupled regional and global scenario in line with the consensual 2°C objective: The lowest CO₂ mitigation targets by 2020 and, the limitation of the world CO₂ emissions to 50% in 2050 by comparison with 2000.

Results

In the long-term, the impact of the climate policies is more noticeable in terms of global CO₂ emissions, whether the scenario is optimistic or pessimistic, even though the effects of the ambitious target for 2050 are more significant compared to the BAU scenario. Then, as we can see in Figure 39, in 2050, carbon constraints involve a decrease in emissions of more or less 20 Gt CO₂ (following optimistic or pessimistic targets for that year) in comparison with BAU. In the medium term, the situation is different, with a less marked effect for all carbon constrained scenarios in 2020. The level of global CO₂ emissions decreases by about 5 Gt in 2020 in comparison with the BAU scenario.

Fig. 39. Regional CO₂ emissions (Gt CO₂)

Additional constraints imposed on the energy system involve variations in energy and technology choices. However, impact is weak on the total volume of primary energy consumption, which noticeably increases, especially in 2050 and for all the scenarios. The environmental constraints lead to an increase
of renewables to shares of 41.2% and 46.2%, depending on more or less ambitious scenarios for 2050, against 32.9% in the BAU scenario (with a marked increase essentially for biomass).

We can suppose that the choice between gas and coal is influenced by the CCS development, to the detriment of gas. Indeed, environmental constraints lead to the development of CCS technologies, as showed in Figure 40. In 2050, between 8.2 and 10.55 Gt of CO2 should be sequestrated to reach the carbon emission mitigation target, depending on the stringency of the climate target.

Figure 40. CO₂ storage (Gt)

For addressing the problem of global climate change, CCS technologies are expected to be deployed but could the investment in CCS technologies in order to avoid around 10 Gt of CO2 emissions be feasible? So, we investigate new scenarios with limited CCS technologies expressing pessimistic views of their future development. As we can see in Figure 41, we add a constraint on regional CCS deployment on the Pessimistic and Optimistic scenarios.

The impact of the CCS constraint on the energy mix is particularly noticeable on the development of renewables. Wind, solar, geothermal energy and waterpower reach 30.5% in optimistic scenario and renewables represent 54.5% if we consider them as a whole with biomass and alcohols. In 2050, the solar deployment yet results to the CCS limit. Indeed, 27 200 TWh are produced from solar technologies in the optimistic scenario with CCS limit against 7 300 TWh in the optimistic scenario without CCS limit. So, without constraint on the deployment of CCS technologies, fossil fuels will continue to dominate energy production even if this is in a lesser extent, due to the potential of CCS technologies. However, if we limit these, renewables become increasingly competitive and their use needs to be expanded considerably.

Figure 41. CO₂ storage (Gt) in optimistic and pessimistic scenario with added constraint on CCS deployment

A key feature of the Copenhagen agreement is the participation of the United States and non-Annex I countries, especially China, as they represent a large share of the global CO2 emissions. This analysis shows on the one hand that the impact of American and Chinese targets is weak by 2020 and essentially
marked on long-term and on the other hand that the carbon marginal cost varies strongly according to countries. That is the reason why there were great expectations for an international agreement at the last UNFCCC (COP 15) which was held at Copenhagen in December 2009. For the long term, a noticeable convergence seems exist as regard the will of regions to reduce their CO2 emissions. But, as the result of the Climate Change Conference confirms, the deal on medium term targets is far from being sealed. Nevertheless, even if an international coordination is difficult to be established, the global carbon stakes stay the same and continue to be crucial.

What is also interesting to note is the analysis of global versus regional climate stake. The commitments pledged by the states in COP15 scenario do not dramatically reduce emissions in 2020, and are not sufficient in the context of the pathway expressed by COP15plus scenario, to reach the global UNFCCC objective. To achieve the overall objective of 2°C, a wider CO2 mitigation is required and particularly, developing countries will have to participate to the CO2 emissions reductions efforts (Figure 42). Thus, it is expected that fast developing and developing countries participate actively in the emissions reduction effort by setting binding targets as soon as 2020. In this context, not only a higher contribution of fast developing countries is expected but also the necessary participation of developing countries and so, an international cooperation is required to reach the global climate target. The problem is about the fair and plausible level of their contribution firstly according to growth and development perspectives and secondly, according to their technological options. Indeed, the technological progress is also a determinant issue.

Figure 42. CO2 emissions reductions compare to the BAU (Gt)

<table>
<thead>
<tr>
<th>Regions</th>
<th>2020</th>
<th>2050</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>S1</td>
<td>S2</td>
</tr>
<tr>
<td>Industrialized</td>
<td>-1.2</td>
<td>-1.5</td>
</tr>
<tr>
<td>Developing countries</td>
<td>-0.2</td>
<td>-1.5</td>
</tr>
<tr>
<td>World</td>
<td>0.1</td>
<td>2.3</td>
</tr>
<tr>
<td></td>
<td>-1.3</td>
<td>-5.3</td>
</tr>
</tbody>
</table>

Rq: S1 = COP15 and S2=COP15plus

In this context, we studied energy mix evolution from 2005 to 2050 in light of these scenarios (Figure 43).

Figure 43. World power mix (%)
important role to play in the future energy mix. Most of those studies focus on BECCS global potential whereas it is of interest to understand where this mitigation will be deployed. This key issue will strongly depends on regions’ biomass resources and storage sites endowment. The aim of this specific study is to assess the global and regional potential of BECCS up to 2050 and to compare it to the deployment of CCS in the power generation. This analysis is conducted with the global multiregional TIAM-FR optimization model. Investigated climate policy scenarios led to a considerable expansion of renewable energy and CCS and BECCS technologies in the power sector. CCS from fossil fuel is mainly deployed in fast developing countries, well endowed with coal and, BECCS is highly distributed in developing countries even if biomass resources are widely available in all regions. This response to carbon constraint is however dependent of the consideration of CO2 negative emissions and of the incentives and appropriate policies created by States. In addition, it required the development of a regulatory framework, sustained R,D&D and infrastructures investments.

This topic (post-Copenhagen, regional impacts of global carbon stakes,) has been presented in several conferences (42,43,44,45,46,47,48,49,50,51,52,53)

1.4.2.2 Implementing water allocation in the TIAM-FR energy model

Water and energy are both considered as strategic issues in our societies. Even though policies related to these resources generally dealt with separately, they are highly interconnected. Indeed, energy is required to maintain water supplies and water is essential to produce energy (Figure 44). Water use for energy can be close to 60% of the total use of water in high-income countries like France (57%) and the United States (40%). For upstream chain energy activities or cooling systems necessary for the production of electricity, huge quantities of water may be used: one part is consumed, the other is returned to the source.

The selection of technologies used in the energy sector may have a large impact on water. So, in the context of a growing world population, leading to increasing demands and competition for water and energy, it is vital to develop long-term strategic policies that consider the interconnections between the water and energy sectors. The main aim of this study (54,55,56,57) is to show how issues concerning water consumption and water withdrawal can be incorporated into energy system models, thereby facilitating discussions about possible futures concerning both aspects.

**Figure 44. Water for energy and energy for water**

Water commodities and technologies in the energy model TIAM-FR have being implemented in two step, in order to study separately the two part of the water-energy nexus.

**Scenarios: Water for Energy**

A number of scenarios with different policy measurements concerning water were developed and evaluated. Furthermore, impacts of different cooling systems utilizing large amounts of water were considered through scenario specifications. Different types of cooling systems were evaluated; open loop systems, closed loop systems and dry systems.

Scenarios for new installations, no change of existing power plants water factors.

- BAU (Business as usual scenario): Water factors for new installations = water factors for existing installations
- CL: New installations use only closed loop systems (better efficiency enables to decrease the temperature difference)
- CL+NR: New installations use only closed loop systems and better efficiency allows decreasing the ow needed in the cooling system

**Results**

Policies on water consumption concern both the upstream and downstream of the energy chain. The introduction of new legislations concerning cooling systems was found to lead to decreased water withdrawals and increased water consumption (Figure 45). Technological choices (CCS or FGD) were found to have a large impact on water consumption, consolidating the importance of considering the interconnection between the water and energy sectors.

**Figure 45. Fresh water withdrawals and consumption**

![Graph showing fresh water withdrawals and consumption](image)

**Scenarios: Energy for Water**

All water uses were integrated in terms of a water reference system detailing water resources, water consumption levels by different technologies, and water demand (58). The considered processes are water pumping from two source of freshwater, surface or groundwater, desalination technology, drinking treatment and wastewater treatment.

The TIAM model provides a comprehensive framework to estimate water demand for both agricultural, and non-agricultural sectors (municipal and industrial sectors) in 2050 (Figure 46). The proposed TIAM-FR model was used to optimize water allocation considering of opportunities for water reuse or non-conventional water use, to explore alternatives futures for water to 2050. Water supply and demand TIAM model thought outcomes under the business-as-usual scenario of Middle East region (Figure 47).

**Figure 46. Interaction between the energy system and the water system in TIAM-FR**

![Diagram showing interaction between energy and water systems](image)
These assumptions were made:

- Water supply and demand TIAM model thought outcomes under the business-as-usual (BAU) scenario of Middle East region, a region of extremes, the driest and most water scarce areas of the world.
- Base year: 2005; Long term horizon 2050
- The FAO-Aquastat database was compared with the end-use sectors of the demands for energy services in TIAM-FR. Three sectors are in common: agricultural, municipal and industrial sectors.

The water demand scenario was built with the following average growth rate (Table 7).

**Table 7. Average growth rate for water demand**

<table>
<thead>
<tr>
<th>Water Demand per sector</th>
<th>2005</th>
<th>Average Growth Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rainfed agriculture</td>
<td>8.3E+11</td>
<td>0.4%</td>
</tr>
<tr>
<td>Irrigated agriculture</td>
<td>1.1E+11</td>
<td>0.9%</td>
</tr>
<tr>
<td>Municipal</td>
<td>2.3E+10</td>
<td>2.5%</td>
</tr>
<tr>
<td>Industrial</td>
<td>1.4E+10</td>
<td>2.5%</td>
</tr>
</tbody>
</table>

**Results**

To assess an optimal water-energy mix under BAU scenario for the water scarce Middle East context, the model allows us to define such a constraint that is the available conventional water for the 2005 year. Because of these constraint, the model allocate non conventional water which is needed to supply the demand. This is the share between conventional and non-conventional water that is decided by the model. Non conventional water resources can substitute part of the scarce natural conventional resource but at an energy cost. We made an improvement of the TIAM-FR model with the development of a Water module:

- Allowing the linkage between water and energy in a first multiregional world model
• Providing a new tool to discuss interactions in the long run for different scenarios on water and energy.

This assessment of an energy value of water may contribute to consider water as a non-renewable resource and to adopt its weak sustainability assumption. This approach enables to appreciate the water saving potential and the associated technological strategies.

1.5 The derived TIAM-ECN Model

1.5.1 Model and methodology

Here is a list of major development related to TIAM-ECN between 2009-2010 (59):

• Extensive changes have been made to the structure of a number of sectors (e.g. oil, coal and gas production, renewable resources as well as the residential and commercial end-use sectors) in order to simplify the structure of the model in places where it was considered unnecessarily complex.

• Modeling of emissions has been improved by adding CO₂ emissions from deforestation and N₂O emissions from agriculture within the explicitly modeled flows. This has great relevance also for Europe, since many European long term climate mitigation strategies rely, at least to an extent, on existing emissions trading/CDM potential in the developing world, therefore making the accurate global description of emission sources and sinks quite important.

• Modeling of technology diffusion has been improved both on the level of resource use (i.e. modeling growth, peak and decline for oil and gas production) as well as on the end-use level. These changes allow us to make more robust conclusions concerning the temporal patterns of technological change, also in Europe, where many technologies may find their early markets.

• For CCS, we have done a review of the technology data and have updated our estimates for storage type specific, regional storage potentials. Accurate regional data enables us to answer more detailed questions concerning the characteristics of CCS diffusion on the regional level, instead of reporting more aggregate and stylistic global results alone.

• Data on the power sector has been reviewed and updated. This sector plays a key role in the energy sector and is the most important sector for early climate change mitigation.

• Regional potentials for wind and solar energy have been reviewed and updated. These two renewable sources of energy represent the currently perhaps most successful (wind) and the most promising (solar) sources of carbon free energy and are therefore especially important for the outcomes of the long term scenarios.

• The transport sector has been reviewed, and based on this review its structure as well as the data have been updated based on a literature review. Additionally, the data for the H2 production and transport technologies has also been updated. Future tasks include a similar update on the production and distribution of other synthetic fuels that can be used for transport.

• We have used the stochastic version of the model. An example of such a study was demonstrated within the PLANETS project, where the impact of uncertainty in climate targets and CO₂ storage availability for long-term climate mitigation was studied.

• Part of the resources in 2010 has been used for developing a model development strategy for the next few years. It is expected that such a strategy can do both, help us direct future acquisition activities, as well as give more general, long term directions for the day-to-day development activities.
There is an ongoing activity aiming at updating and improving structurally the modeling of bioenergy resources and potentials. If possible, we would like to model the interactions between regional bioenergy, deforestation and reforestation potentials (and activities) in more detail. Such an improvement in the model would give us a powerful tool to tackle some of the hot topics being discussed within the European energy and climate policy discourse. For example, due to the global scope of our model, we would be able to endogenize the climate consequences of large scale biofuel imports to Europe from the developing world.

1.5.2 Studies with the TIAM-ECN model

1.5.2.1 The impact of uncertainty in long-term climate mitigation scenarios

One potential key technology for bridging the transition from the current fossil dominated energy system to a more sustainable one in CCS. However, there are large uncertainties concerning the large scale implementation of this technology, one being the regional availability of storage sites for the captured carbon. We approach (60,61) the issue from an energy system perspective and use an energy system model TIAMEC to study a set of scenarios covering a range of climate targets and technology futures, from two angles; 1) a sensitivity analysis consisting of a number of scenario that assume perfect foresight for the decision making and 2) using a stochastic programming set-up, which allows the model to consider all included potential future states simultaneously.

Scenarios

More and less stringent targets can be interpreted to represent the same temperature target, under different assumptions concerning the climate sensitivity. In order to keep the number of scenarios required feasible, we define three alternative targets: 5.5 W/m2, 4.0 W/m2 and 3.2 W/m2. Since the 3.2 W/m2 target is fairly stringent and might dominate the results, we study how sensitive the stochastic results are to the choice of the most ambitious target considered possible. We do this by changing the value of the lowest target from 3.2 to 3.6 W/m2 for the sensitivity analysis.

The stochastic scenario includes all three climate targets (3.2, 4.0 and 5.5 W/m2) as well as the two possible futures for the storage volume. However, the six different combinations of targets and storage volumes are exclusive, i.e. only one of the six will materialize in 2050. Thus probabilities need to be assigned to each of the six world states post-2050 (Table 8).

Table 8. Likelihoods for the combinations of climate target and storage volumes after their resolution in 2050

<table>
<thead>
<tr>
<th>Potential for CO₂ storage</th>
<th>Low</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>Climate target, W/m²</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.5</td>
<td>17.5%</td>
<td>7.5%</td>
</tr>
<tr>
<td>4</td>
<td>31.5%</td>
<td>13.5%</td>
</tr>
<tr>
<td>3.2</td>
<td>21.0%</td>
<td>9.0%</td>
</tr>
</tbody>
</table>

Results

If there was a single marginal mitigation cost that stays constant throughout the timeframe studied, postponement of mitigation would be preferable to the model, due to the 5 % discount rate. If, however, it is assumed that mitigation potential in the future is reduced and costs increased, action needs to be taken already early on. These types of dynamics are seen also in our CO₂ emission results (Figure 48). The most stringent target, 3.2. W/m², requires the CO₂ emissions to start decreasing immediately, with the steepness of the decrease slowly leveling off close to the end of the century.
CCS offers a possibility for relying on the existing, fossil fuel dominated production structures slightly longer. There is, however, uncertainty concerning certain aspects of CCS, such as storage potentials and leakage from storage. Figure 49 illustrates the results for the use of these technologies. What is first noticeable is that the level of climate ambition plays a key role for the diffusion of CCS technologies. What is also noteworthy is that although before 2050 the use of CCS is strongest in the 3.2 W/m² perfect foresight scenario, the cumulative use of CCS over the whole 21st century is most widespread in the scenario with the target of 3.6 W/m². A possible reason for this is that by the end of the century staying below the 3.2 W/m² target requires already completely carbon free measures, rather than ones where part of emissions is still released due to a capture rate of some 90%. Finally, a robust conclusion can be made for the perfect foresight scenarios: The more stringent the target, the larger the share of cumulative CCS activity across the century takes place before 2050.

Perhaps the clearest indicator for the costs of the mitigation regime is the shadow price of CO₂, which can be interpreted as the market price for emission permits, assuming a global mitigation and trading regime, without any transaction costs or limits to emission trade. Figure 50 presents results for this indicator: if a 3.2 W/m² climate target is possible, the value of emission permits is considerably higher than in any other scenario. This also shows why the model is using the precautionary approach to its hedging; if it did not “prepare for the worst”, in the stochastic case the carbon price could easily explode and approach infinity (in other words, reaching the climate target would be infeasible).

Figure 49. Use of CCS. Panel b uses the variant, with 3.6 W/m² target
Figure 50. Emission price, right panel focusing on the scenarios without the 3.2 W/m² target*

* Ranges show the difference between high and low storage estimates

We find that if a very stringent target is a possibility, it dominates the solution; if deep reductions are not started as soon as possible, the target may become unreachable. However, reaching the stringent target comes at an exceedingly high price, indicating that e.g. adaptation measures, or even climate damages, might be preferable to the very high mitigation costs this target suggests.

1.6 The derived TIAM-UCL Model

1.6.1 Model and methodology

The core aim of the Energy Systems research theme in the UKERC II project is developing a global optimisation model to analyse accelerated decarbonisation of the global E3 (energy-environment-economy) system, with a comprehensive investigation of costs and benefits of the different decarbonisation options. This adds to work carried out in UKERC I placing the detailed analysis of the UK in a global context, which was not possible with the UK MARKAL model, the main tool developed under UKERC I. The Energy System research team in the UCL Energy Institute developed the 16 Region TIAM-UCL global model (named as TIAM-UCL), under the UKERC II research activity, by breaking out the UK from the Western Europe (WEU) region in the 15 Region ETSAP-TIAM model (62). A simplified representation of the TIAM-UCL model structure is presented in Figure 51.

Figure 51. The TIAM-UCL global model structure

The TIAM-UCL model development has two phases. The major tasks (the first phase) is breaking out UK from the 15 region model and model calibration (calibrating UK and Western Europe regions). The underlying data for the base year calibration in TIAM-UCL is the IEA Extended Energy Balances of OECD
and non-OECD countries. Energy services demands for different end-use sectors and drivers of projections of them during the model period 2005-2100 are created for the UK region. Once the 16R TIAM-UCL has been successfully calibrated, the model has been enhanced (the second phase) through technical improvements such as adding new drivers, new resources, climate change policies (cap-and-trade, carbon tax), supply resource cost curves etc. Development of the database of the IEA Extended Energy Balances helped to recalibrate all 16 regions in the TIAM model to the IEA primary energy production/consumption, final consumption and electricity generation data (2005). The TIAM-UCL model and its variants will be applied to a wide range of policy analyses, research collaborations and academic publications from 2010.

1.6.1 Studies with the TIAM-UCL model

1.6.1.1 The role of demand reduction in global climate change mitigation

Though world leaders did not reach any agreement in Copenhagen in setting CO2 reduction targets for individual countries or for major emitters, politicians agreed that inaction makes its consequences more irreversible and there must be substantial cuts in CO2 emission. There are different options to reduce CO2 emissions: efficiency improvement, low carbon alternative fuels, sequestration (CCS) and demand reduction. This paper (63) investigates the role of demand reduction in meeting global CO2 reduction targets using elastic demand version of the TIAM-UCL global model under different long-term low carbon energy scenarios during 2005-2100. In the elastic demand version of the partial equilibrium model, energy services demands will respond to price changes. The elasticities used in TIAM-UCL model are long-run elasticities and are the same as used in the ETSAP-TIAM model.

Scenarios

There are three different scenarios defined for this analysis: the first is the Reference Case (REF) where CO2 emissions are not constrained. The other two are the Low Carbon Scenarios, in which annual CO2 emissions are constrained for both developed as well as developing countries to meet the atmospheric CO2 concentration targets (Table 9). The low carbon scenarios are analysed under the assumption that cap-and-trade is in effect—any country can buy emissions from other countries in order to meet their target.

Table 9. Scenario definition

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Reduction target compared to 2005 emission level</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Annex 1</td>
</tr>
<tr>
<td></td>
<td>2050</td>
</tr>
<tr>
<td>Reference Case (REF)</td>
<td>-</td>
</tr>
<tr>
<td>LCS540: Low Carbon Scenario 540 ppm</td>
<td>-80%</td>
</tr>
<tr>
<td>LCS450: Low Carbon Scenario 450 ppm</td>
<td>-80%</td>
</tr>
</tbody>
</table>

*Emits more than 2005 emission

Results

Results of the decomposition analysis indicate that the contribution of demand reduction to overall CO2 reduction, when comparing the elastic demand low carbon scenarios with the base case, is in both scenarios around 5%. (Figure 52).
While the contribution of demand reduction tends to be highest in early periods (2020-2030) with up to 8% due to the lack of cost-efficient low-carbon technologies, the demand share decreases to half of the share towards the end of the 21st century. This can be explained with the greater availability of low-carbon technologies. Demand reduction can play a significant role within a limited scope next to more important measures, in particular structural shifts towards carbon-free energy technologies. CO\textsubscript{2} reduction target is met by greater contribution of sequestration for which the technology has not been proved yet.

Sensitivity analysis will be carried out with limited/delayed availability of sequestration options. Though demand reduction is one of the cost effective options it needs a behaviour changes as well as it cost the society in terms of welfare losses due to the un-served energy services demand. Welfare loses due to demand reduction will be analysed in the paper. TIAM-UCL provides marginal CO\textsubscript{2} abatement cost (MAC). Analyses show that the demand reduction (elastic demand version of the model) reduces MACs compared to the standard version by up to 15% in the LCS540 and up to 24% in the LCS450 during 2030-2100.

1.6.1.2 Carbon tax vs. cap-and-Trade: Implications on developing countries emissions

In the same context, a key issue is to find a way to engage developing countries under any emerging agreement that also ensures full participation of developed countries in climate change mitigation. This paper (64) investigates the roles of carbon tax and cap-and trade policies to mitigate global CO\textsubscript{2} emissions; these policies are analysed using the 16 Region TIAM-UCL global model.

Scenarios

Five main scenarios are defined (Table 10): one is the Reference (REF) Scenario, to which no climate change policies are applied; two different scenarios under each cap-and-trade policy and tax policy are defined.

Table 10. Scenario definition

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Reduction target compared to 2005 emission level</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Developed countries</td>
</tr>
<tr>
<td></td>
<td>2050</td>
</tr>
<tr>
<td>REF: reference case</td>
<td></td>
</tr>
<tr>
<td>CAP-80: Low Carbon Scenario under cap-and-trade policy targeting only developed countries</td>
<td>-80%</td>
</tr>
<tr>
<td>CAP-450: Low Carbon Scenario under cap-and-trade policy targeting all regions to achieve a target of CO2 only concentration of 450 ppm</td>
<td>-80%</td>
</tr>
<tr>
<td>Scenario</td>
<td>Description</td>
</tr>
<tr>
<td>---------------------------</td>
<td>-----------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Tax-50: Low Carbon Scenario with low CO2 tax policy</td>
<td>Same tax is applied to all regions. CO2 tax of US$ 50/t is applied from 2020.</td>
</tr>
<tr>
<td>Tax-200: Low Carbon Scenario with high CO2 tax policy</td>
<td>Same tax is applied to all regions. CO2 tax of US$ 50/t from 2020, US$ 1000/t from 2030 and US$ 200/t from 2050 is applied.</td>
</tr>
</tbody>
</table>

**Results**

Developing countries' contribution to emission in 2100 in the CAP-80 Scenario is about 70%, about the same as observed in the REF Scenario. The contribution increases to 79% under the CAP-450 Scenario (Figure 53), where both developed and developing countries are targeted. At least 40% of the global emissions during the second half of the century are actually emitted in China, which meet its reduction target by buying credit from other regions.

**Figure 53. Global CO$_2$ emissions under the CAP-450 during 2005-2100**

Emission trading is unilateral under CAP-80 Scenario when only the developed countries are targeted. When all the regions' emissions are constrained under CAP-450 Scenario with full emission trading option, developing countries also adopt emission reduction targets resulting in bilateral trade (Figure 54). Buyers in early periods become sellers in the later periods. Developing countries (China and Middle-East) become buyers while developed countries (Australia, Canada, Japan and Western Europe) become sellers.

**Figure 54. CO$_2$ emission credit buyers and sellers under the CAP-450 Scenario**

Total global discounted energy system costs under different scenarios are presented in Figure 55. The global discounted energy system cost under cap-and-trade policy scenarios and tax policy scenarios are incomparable as the later include tax collected in the total energy system cost. Change in Regional energy system cost (right) shows that these two policies cost more to developing countries than the developed countries.
Important finding is that when the mitigation target is high, meeting a 450ppm CO₂ only concentration target, in which developing countries are also included, some developing countries become buyers and some developed countries become sellers. China becomes the buyer from 2030 and emission trading (buying credits from other regions) account for 15% and 12% of China’s CO₂ reduction in 2050 and 2100 respectively. In developing countries, energy system and infrastructure is being developed/built, if we target those countries later, it will cost more as they will be locked into inefficient/high carbon energy system. Applying a high carbon tax (under tax policy) in developing countries in the near term may not be appropriate as their immediate goal is economic development, which may be affected by high energy prices. But, they will be better off when providing financial and technology support to invest in clean energy infrastructure under a cap-and-trade policy when their economy is being developed.

Figure 55. Discounted energy cost and percentage change as compared to REF Scenario

1.6.1.3 Demand, burden sharing and resources

This presentation (65) introduces the latest work using TIAM-UCL, i.e. an analysis of burden sharing agreements under the UK under global decarbonisation trajectories. The scenarios experiment the following rules: converging per capita GHG emissions, converging GHG intensity of GDP, differentiate developed and developing countries and limited purchase of GHG permits to 10% of gross emissions.

1.7 The derived TIAM-IER Model

1.7.1 Studies with the TIAM-IER model

1.7.1.1 Interdependencies between market power, resource availability and demand options

This presentation (66,67) deals with interdependencies between market power, resource availability and demand options. A sensitivity analysis is performed with the soft coupling of TIAM and LOPEX. The methodological approach of linking an oil market and an energy system model can be illustrated as follow (Figure 56).
Scenarios
Several scenarios have been analysed from a reference scenario with long-term equilibrium on oil market regarding the sensitivity of oil price on factors on the supply side:

\[ \Rightarrow \text{EOR+TPROG: Increasing recovery factor from 50\% to 60\% plus technological progress in oil supply (cost reduction of 0.5\%/year)} \]

\[ \Rightarrow \text{UNCONV: More optimistic assumptions on growth in production of unconventional oil (oil sands, oil shale)} \]

\[ \Rightarrow \text{FT+BIOFUEL: More optimistic assumptions on growth in production of liquid fuels by Fischer-Tropsch conversion of coal, natural gas or biomass and of methanol/ethanol} \]

In addition, analysis were carried on for 1) sensitivity of oil price on oil demand (LOW DEMAND) - Lower GDP growth, 2) Sensitivity of oil price on OPEC behaviour (OPEC): Disintegration of OPEC and 3) sensitivity of oil price on climate policy (CO2): Introduction of a CO2 price of up to 350 $/t by 2050

Results
In the reference scenario, the price peak in 2030 of 150 $/bbl caused by the decline in conventional non-OPEC production and, at the same time, non-sufficient supply from unconventional oil and alternative liquids allowing OPEC to exercise market power (Figure 57). After 2030 OPEC’s influence decreases by increased production from unconventional (oil sands) and alternative fuels (FT fuels). Other findings:

- The OPEC cartel behaviour represents the largest price component.
- Improvements in oil recovery reduce scarcity and lead thus to lower prices.
- Rate by which unconventional and alternative fuels can be introduced is also critical for price reductions, since:
  \[ \Rightarrow \text{Conventional oil can be saved -> scarcity rent becomes lower (smaller price impact)} \]
  \[ \Rightarrow \text{OPEC’s market power shrinks (major price impact)} \]
  \[ \Rightarrow \text{But, lower prices also imply higher overall liquid fuel demand} \]
Factors reducing price and at the same time demand are: substitution options for oil on the demand side, lower economic growth, CO₂ mitigation measures (however, overall price for burning oil increases).

Figure 57. Oil prices and climate policy

1.7.1.2 Natural gas supply for Europe

Using the same approach, this presentation (68) concentrates on the natural gas supply for Europe. The main question is: what is the maximum profit of the natural gas exporting countries to Europe? The profit of the gas exporting countries are modeled as add on-costs, while the profit of the exporting countries equal (gas price Europe – gas cost) x import quantities. The variation of the add on costs depending of different cost profiles. The climate policy scenario is modeled by the introduction of a CO₂ price of up to 350 $/t by 2050.

1.8 The Global TIMES Model of the European Fusion Development Agreement (EFDA)

1.8.1 Model and methodology

The EFDA Times Model (ETM) is a multi-regional, global and long-term energy model of economic equilibrium, responsive to energy technology innovations, domestic and international trade energy policies, climate change mitigation and environment objectives (69). It has been developed within the European Fusion Development Agreement (EFDA) framework starting in 2004 and forms part of the TIMES family of energy models. In ETM the world is divided into 15 regions linked by energy and emissions permit trading variables. Time horizon will be 2100.

The reference energy system includes five energy consumption sectors (residential, commercial, agriculture, industrial and transportation) and two energy supply sectors (electricity production and upstream/downstream). Technologies, in the ETM, are divided into technologies working at the base year and the future potential technologies entering the energy system during the whole period of study. All of them are very well characterized by a number of technical, environmental and economic parameters. Energy demand drivers (annual growth rates of population, GDP, number of households ...) are provided exogenously, then driver projections are performed using the GEM-E3 (general equilibrium model for Europe and the World) model and finally, demands for energy services are linked to the drivers’ projections. That means that ETM has the capability of estimate the response of the demands to changes introduced in the model.

In ETM, the different regions are connected by inter-regional exchange process. Trade in ETM can be bi-lateral between two regions and multi-lateral between several supply and demand regions. In a bi-lateral trade, there is one inter-regional exchange process between the two regions, thus, there is a balance between both regions. A multi-lateral trade however, is based on a common marketplace for a commodity which has several producing and consuming regions. A new region for the marketplace is created and each region has an only inter-regional exchange process between itself and the marketplace region.
1.8.2 Studies with the EFDA model

1.8.2.1 Revised assessments of the economics of fusion power

As part of the PPCS (Power Plant Conceptual Study) in Europe, published in 2005, an assessment was made of the likely economic performance of the range of fusion power plant concepts studied. Since that time, new work has been carried out, within the fusion programme, and particularly in the EU DEMO study, that changes a number of the important assumptions made in the PPCS. The impact of the new results, emerging from the EU DEMO studies, on the role of fusion in the future energy market is described. A new energy economics model is employed to analyse the potential market performance of fusion power in a range of future energy scenarios and this shows that there can be a significant role for fusion in a future energy market (70). Possible implications for fusion’s role in a future energy market are then explored, using a sophisticated energy scenario tool, known as the EFDA/TIMES model.

Scenarios

First, we have performed a run with atmospheric carbon concentration constrained to be less than 550 ppmv. Next, having observed that fusion now enters the picture at the end of the century, we explored the effect of varying fusion costs in two further runs in which the carbon constraint is retained. In one, fusion costs are increased by 20%, while, in the other, costs are reduced by 20%; both investment and maintenance (fixed and variable) costs are adjusted by this percentage.

Results

Figure 58 shows a base case scenario for global electricity production. This illustrative calculation suggests that the largest contribution towards the end of the century is from coal technologies, with the remainder coming from fission, renewables and gas. Fusion does not enter in this case.

Figure 58. Contributions from different sources to the global electricity production in the base case

Figure 59 shows the contributions from the various fuel sources to electricity generation at 2100 for all four cases. It can be seen that, although fusion was absent in the unconstrained case, it plays a role comparable to fission or wind in other cases.

Figure 59. Contributions from different sources to the global electricity production at 2100 for the four scenarios
In these early results, fusion’s role is very sensitive to costs. If there are no growth constraints, increasing costs by 20% reduces the final market share by 66%, whilst reducing costs by the same amount increases final market share by 152%. Whilst the level of fusion’s market share is comparable to earlier work, the cost sensitivity is greater here, perhaps as a result of removing constraints in the electricity sector.

1.8.2.2 The future role of fusion power under endogenous technological learning

This dissertation (71) addresses the impact of different endogenous learning approaches on the role of fusion power. To broaden the scope of endogenous learning descriptions, new approaches have been developed and implemented in the TIMES model generator. These new approaches add two new features that can be used to model the economic and technical parameters of technologies endogenously. For the first time, the performance improvement of a parameter is linked to the acquired utilisation experience, and the endogenous improvement of a technical technology parameter is implemented.

For the assessment of the impact of endogenous learning features, a single-regional global energy system model (TUG-IPP-Model) has been developed using the TIMES model generator. The TIMES model generator allows the user the implementation of additional sets of equations, without having to change the main code. This feature has been used to implement the new modelling features Learning-By-Using and Advanced Technological Learning. The introduction of non-linear relationships into a linear optimisation model has been solved by using Mixed-Integer-Programming techniques. In this approach, standard TIMES equations have been replaced by new ones, and the learning process is controlled via binary variables.

Scenarios

The impact of some key parameters has been taken into account by a systematic variation of these parameters, which are the applied CO₂ abatement policy, assumptions on the maximum fusion capacity growth, the available non-renewable resources and a set of available technological options (CO₂ sequestration, fast breeder reactors and hydrogen as an energy carrier).

Eight different learning scenarios have developed, to demonstrate the impact of four different learning approaches on the role of fusion power in the TUG-IPP-model. In these learning scenarios, only fusion power, a larger subset of technologies, or all electricity producing technologies have been treated as endogenous learning technologies. For these technologies, one of three different parameters, two economic and one technical, were assumed to be improving with increased experience.

A total of 4608 scenarios have been calculated, to evaluate the impact of different learning scenarios and the variation of the key parameters on the model results and the role of fusion power. For only 82 scenarios – all of them from the LBD-2 and LIC-Cp scenarios – no solution was obtained.

Results

The distribution of the fusion share of all these scenarios is plotted in Figure 60. Without CO₂ abatement policies, the results for this performance indicator lie between 0 and 4%. Only under the presence of either cumulative CO₂ emission constraints or CO₂ taxes, higher values can be achieved. Here, the pattern is similar for both types of policy; the distribution has three peaks, at 10%, 14-16% and 22-24%, which can be assigned to the three values for the fusion capacity growth rate, 5%, 7% resp. 9%. The values for these peaks are obtained from three quarters of all scenarios.

Without endogenous learning treatments, the role of fusion power is mainly determined by the willingness to reduce the CO₂ emissions from energy technologies. It has been shown that fusion power plants as the only endogenous learning technology are not deployed in a different pattern as they are in case of exogenous learning. On the other hand, the endogenous treatment of more technologies does not exclude fusion from scenarios it is otherwise used in. Only in scenarios in which the economic advantage of fusion power is only lightly above uncompetitive alternatives, endogenous learning can
make a difference. The main impact on the model results is still exerted by other assumptions, i.e. the willingness to avoid CO₂ emissions, and the limits that restrict the build-up of the fusion power capacity. The main goal of using endogenous learning treatments, which is assuring the consistency between prior assumptions and model results has been achieved, although only on the basis of a single technology.

Figure 60. Distribution of the fusion shares obtained in all learning scenarios

1.8.2.3 An analysis on the future costs of fusion power stations

There have been a wide range of studies of costs, varying primarily in the assumed materials and technology as well as assumptions about the fusion performance in scientific terms. Whilst a wide range of plants have been studied, the overnight capital costs vary from typical values of 4$/Wₑ for early generation plants to around 25$/Wₑ for mature, advanced fusion plants. This range is implemented in the EFDA Times Model (ETM) with the early generation plants assumed to be available in 2050, evolving to an advanced, mature plant over the following 30 years (69). From 2004 till now, ETM has been constantly updated and improved within successive SERF projects with the collaboration of different Euratom associations. Last version has been developed in December 2009 and preliminary results for different environmental scenarios are presented in this work.

Scenarios
Two framework scenarios are defined as follows (with conservative assumptions on fusion costs, energy demand and uranium resources):

- Base case scenario (SC1): there is no limit to CO₂ emissions
- 450ppm scenario (SC2): a limit of 450ppm in CO₂ eq concentrations is set by 2050

Results
These results have to be taken as very preliminary. Results show that in a base case scenario, with no measures for CO₂ emission reductions, coal technologies play a dominant role in the global power production in 2100. Fission technologies supply also an important amount of the global electricity by 2100 experiencing a big increase from 2040. In this scenario, fusion does not enter the energy system.

When CO₂ emission restrictions are imposed, the global energy system composition changes completely. In a 450ppm scenario (SC2), coal technologies disappear in 2035 being mainly replaced by nuclear fission technologies which experience a great increase until 2070. Afterwards, this share starts decreasing to end in a small share in 2100 due to uranium resources exhaustion. Fission technologies are then replaced by the fusion power plants that starting in 2070 are responsible of almost half of the global electricity production in 2100. Fusion technology, in the beginning, is going to be expensive when comparing with other mature technologies. However, the panorama changes completely when CO₂ emission restrictions are introduced.
1.8.2.4 Modelling CCS, nuclear fusion, and large-scale district heating

These presentations (72,73) focus on modelling the infrastructure development for heat recovery from CCS and fusion in EFDA-TIMES and TIAM. CCS can be a driver for the development and expansion of large-scale district heating systems, which are currently widespread in Europe, Korea and China, and with large potentials in North America. If fusion will replace CCS in the second half of the century, the same infrastructure for heat distribution can be used. This may support the penetration of both technologies. Sensitivity analyses of biomass and CCS in EFDA-TIMES (Figure 61) show that fission is limited only by uranium resources. When an additional arbitrary constraint is set, Max 25% nuclear fission in all regions, CCS appears in the mid-21 Century, when nuclear fission is constrained. The experience from the previous studies with EFDA-TIMES show that constraints on nuclear fission are essential. Otherwise, nuclear fission will dominate the market.

Our objective (74) is to analyze the role of nuclear energy in long-term climate scenarios using the World-TIMES (The Integrated MARKAL-EFOM System) bottom-up model. World-TIMES is a global model that optimizes the energy system of 15 regions over a 100-year horizon (2000–2100).

Scenarios

The base year period (2000) of the model is calibrated to the IEA statistics and balances for that year (IEA, 2000). The future energy demands are projected to the 2100 horizon using various socio-economic drivers, which are consistent with the storyline behind the B2 family of IPCC scenarios. The B2 scenario already shows a level of nuclear production lower than all other IPCC marker scenarios until 2080. We present energy and emission results for climate scenarios for two levels of CO2 concentration (450 and 550 ppmv by 2100). We have modeled an alternative base case, in which the lower constraints used to calibrate nuclear production to the IPCC B2 marker scenario are reduced arbitrarily by 60%.

![Figure 61. Sensitivity analyses of biomass and CCS](image)

1.8.2.5 The role of nuclear energy in long-term climate scenarios

Results

Although fuel substitutions are occurring later in the 550-ppmv scenario (after in 2050) than in the 450-ppmv scenario (already large in 2030), all scenarios suggest a major transition to nuclear energy in 2100 to, respectively, 50%, 51%, and 68% of the total electricity production (Figure 62).

Under the 450-ppmv scenario, the nuclear market size is particularly large in 2100. This means more than 6000GW of new nuclear installed capacity by 2100. Advanced LWRs will still dominate the market, but their total capacity will not increase compared to the base case (4500GW in 2100). In fact, the incremental increase in nuclear capacity over the base case comes mainly from nuclear fusion: 1500GW in 2100. Although nuclear fusion reactors are not entering the market as soon as they become available (2050), they quickly capture parts of the market, from 3.6% in 2080 to 23% in 2100. With the 60% reduction, the alternate base case shows a nuclear level production lower than all IPCC marker scenarios. Applying the 450-ppmv constraint to this alternate base case illustrates very similar emission...
reduction strategies in the electricity sector. However, since the global reduction effort required to reach the 450-ppmv target is more significant in the alternate base case, the cost of the entire system is 100 billion dollars (B$) higher in the alternate 450-ppmv scenario (1295B$ compared to 1195 B$).

Figure 62. Electricity production by type in 2100 in both base cases and 450-ppmv scenarios

Nuclear energy technologies satisfy a large portion of electricity production in many regions. Other renewable technologies might play a more important role but need further cost reductions or new regulations to penetrate the market in substantial proportions. Carbon sequestration and endogenous demand reductions for energy services are also significantly contributing to reach environmental target.

1.8.2.6 Global transportation scenarios in a multiregional energy model

The aim of this study (75,76) is to assess the potential impact of the transportation sector on the role of fusion power in the energy system of the 21st century. For the present study a new transportation module has been linked to the EFDA-TIMES framework in order to arrive at a consistent projection of future transportation demands.

Scenarios

We have evaluated our model assuming the following set of energy scenarios:

- Demand scenario: We have considered both the transportation demand scenarios Continuous Growth and Modal Split.
- Technological scenario: We consider two distinct technological transportation scenarios, the Hydro and the Electro scenario. In both cases we assume a transition from the dominant use of fossil energy carriers towards a hydrogen or electricity dominated infrastructure, respectively. Starting in the region with the highest present value of GDP we impose the transition towards an alternative infrastructure to happen in all world regions at similar levels of GDP. For the Electro case, however, we eventually impose only a 50% share of the road traffic volume since this technology might also in the future not be suited to satisfy the demand for individual long distance travel.
- Policy scenario: In addition to the base case, we consider two climate scenarios, namely the stabilization of the global atmospheric CO₂ concentration at levels of 550 ppm and 450 ppm, respectively.

Results

In the base case, an ongoing dependency on liquid fossil fuels can be observed in spite of the depleting resource base (Figure 63). This situation nonetheless is consistent with todays estimates of fossil fuel availability. As expected both in the Hydro and Electro cases higher consumption levels of hydrogen and electricity for transportation purposes can be observed. At the same time the consumption of gasoline
and in particular diesel declines. This is also the case in the 450 ppm scenario, however, not implying any specific transition away from fossil energy carriers. The levels of hydrogen and electricity use in the 450ppm case is even slightly higher than in the Hydro and Electro scenarios, implying an even faster transition towards alternative fuel vehicles as anticipated in the transportation scenarios. Consequently, also the sector of electricity generation will be affected more rigorously by the climate constraints.

The levels of electricity generation for both climate scenarios is shown in Figure 64 together with the contribution of fusion power plants. Obviously the decarbonization of the electricity mix substantially helps to create a market for fusion power. This, however, is sensitive to the assumptions on the economics of future fusion power plants.

Our results show that the penetration of fusion power plants is only slightly sensitive to transportation fuel choices but depends strongly on assumed climate policies. In the most stringent case considered here the contribution of electricity produced by fusion power plants can become as large as about 50% at the end of the 21st century. This statement, however, is still of preliminary nature as the EFDA-TIMES project has not yet reached a final status.

**Figure 63. World use of transportation fuels for various transportation/climate scenarios.**

![Figure 63](image)

**Figure 64. Total electricity production for the 550ppm and 450ppm cases with the contribution of fusion power**

![Figure 64](image)
1.9 The TIMES G5 model

1.9.1 Model and methodology

TIMES-G5 is a five-region, bottom-up, and process-analytic energy system model, developed at the Institute of Energy Economics and Rational Use of Energy (IER), University of Stuttgart in Germany, for the analysis and projection of long-term energy futures on a national, regional, and global basis. The TIMES-G5 model disaggregates the globe into 25 European nations (EU25), the rest of the OECD countries (R_OECD), the rest of the non-OECD countries (R_NOECD), India, and China, as five separate regions. The model includes the modelling horizon from 1990 to 2100, containing 19 periods having unequal time spans of 5, 8, and 10 years, and six smallest time segments (i.e., day–night basis for three seasons). Figure 65 shows the overall RES provided in the TIMES-G5 model, how the commodities are transformed from one form to another, and the inter-connectedness of various technologies through transformations.

Figure 65. Simplified version of the reference energy system (RES) in the TIMES-G5 model.

1.9.2 Studies with the TIMES G5 model

1.9.2.1 Uncertainty in the learning rates of energy technologies

This study (77) examines the uncertainty in learning rates (LRs) of some energy technologies under endogenous global learning implementation and presents a floor-cost modeling procedure to systematically regulate the uncertainty in LRs of energy technologies. This work is executed using a multi-regional and long-horizon energy system model based on “TIMES” framework. This work has implemented the global learning methodology, in which all regions participate (regional cluster) in a common learning process by adding their cumulative capacity to reduce the specific cost of a learning technology. In addition, the floor-cost approach is used to deal with the uncertainty of LRs, the last segment presenting the floor cost of the technology. In this approach, the optimization server is provided with the total cumulative cost and the corresponding cumulative capacity of all kink points of MIP segmentations.

Scenarios

Nine technologies - biogasification (BIOG), integrated gasification combined cycle(IGCC), combined-cycle gas turbine (CCGT), molten carbonate–fuel cell (MCFC), solid oxide fuel cell (SOFC), solar PV (SOLPV), wind onshore (WON), wind offshore (WOF), and geothermal heat pump(GEO) - are considered for learning. Different PRs have a wide range of specific costs and cumulative capacities for reaching the same value of cumulative capacity and specific cost, respectively (Figure 66). Thus, the model results will be influenced largely by the uncertainty of PRs, such as maximum PR (MaxPR) and minimum PR (MinPR), because the optimization subroutine discourages technologies with high-learning investment.
Results
Cumulative-capacity development by dissemination of learning technologies across the various world regions has been observed to be different among the learning scenarios, and a reference case is depicted in Figure 67. The cumulative capacities of IGCC, SOLPV, and WOF remain approximately the same at the global level in all learning scenarios. This occurs because IGCC development reaches its maximum value at a comparatively lower investment cost, whereas SOLPV and WOF are intended to satisfy the minimum renewable electricity generation. Cumulative-capacity development of the WON technology shows cost-effectiveness, and thus has an emerging potential under uncertainty in LR scenarios with lesser learning investment. CCGT penetrates more in learning scenarios such as WON and it penetrates more towards the later periods. Generally, MinPR induces more diffusion of learning technologies than MaxPR in terms of the early accomplishment of the floor cost through lowest learning investment.

Figure 66. Variations of specific costs with uncertainty in the learning rates*

*while starting from the same unit-specific cost and same specific cost; 2005 refers to the specific cost in the year 2005; ‘a’ stands for the same unit-specific cost at the starting point; and graphs without 2005 and ‘a’ as captions are step wise linearized curves

Figure 67. Cumulative-capacity development of learning technologies in the model horizon
All regions receive an economic advantage to learn in a common domain, and resource-ample regions obtain a marginal advantage for better exploitation of the learning technologies, due to a lower supply-side fuel-cost development. The lowest learning investment associated with the maximum LR mobilizes more deployment of the learning technologies.

### 1.9.2.2 Endogenous implementation of technology gap

Together, three methodologies have been developed in this study (78). The first methodology is global learning without a technology gap. The other two methodologies are about global learning with technology gaps, in the form of the knowledge deficit and time lag concepts. The methodologies are examined inside a multi-regional energy system model (TIMES) to understand the behavior of technologies, subject to uncertainty of learning rates. The floor cost approach on piecewise linear approximation in mixed integer programming (MIP) has been implemented to handle the uncertainty in learning rates, where the technology does not decline below a certain value of specific cost.

**Results**

The discounted objective values of a global energy system for three learning scenarios (such as MinPR, MedPR, and MaxPR) vary considerably, and reflect the differentiated specific cost development of the learning technologies (Figure 68). A difference in the trillion range of investment cost among scenarios is influenced by many factors, such as the difference in period-wise investment cost mobilized by learning rates; the floor costs of some learning technologies being marginally different within learning rates; cross cutting of the investment cost development by learning technologies; and the minimum renewable electricity production from learning technologies forcing the system to produce electricity, irrespective of higher learning investment subject to learning rates. The increase in objective value of knowledge-deficit scenarios is also caused by the additional cost imposed to knowledge deficit of developing regions on learning technology utilization.

**Figure 68. Objective value of different scenarios**

Cumulative capacity development through the dissemination of learning technologies across world regions has been observed differently among learning scenarios, and a base case is depicted in Figure 69. The cumulative capacity of IGCC and wind offshore holds approximately the same values on global level in all learning scenarios. WOF is meant to satisfy the minimum renewable electricity generation. The cumulative capacity development of WON and CCGT technologies show cost-effectiveness, and have emerging potential under uncertainty in learning rate scenarios with less learning investment, leaning more towards later periods for global learning without a knowledge deficit. Generally, MinPR induces more diffusion of learning technologies than MaxPR does.
The discounted objective values of the knowledge deficit and time lag approaches for a medium progress ratio is maximal for the time lag approach, and minimal for the knowledge-deficit approach, as found in the model run from 1990 to 2025 with only 8 periods (Figure 70). The difference in the objective value is very small, but the increase in objective value is caused by the learning investment incurred for minimum capacity development of the learning technologies.

Global learning recommends the technological path inducement of learning technologies (such as IGCC, CCGT, WON, SOLPV, and GEO), which appear promising from the cost-economic factor for motivation of their development, and should be enabled by all possible market mechanisms available. However, the time lag approach of the technology gap strongly favors the technologies of IGCC, CCGT, and WON.

Global learning selects highest learning technologies in maximum uncertainty of learning rate scenario, whereas any form of technology gap retards the global learning process and discourages the technologies deployment. Time lag notions of technology gaps prefer heavy utilization of learning technologies in developed economies for early reduction of specific cost. Technology gaps of any kind should be reduced among economies through the promotion and enactment of various policies by governments, in order to utilize the technological resources by mass deployment to combat ongoing climate change.

1.10 The Global Multi-regional MARKAL Model (GMM)

1.10.1 Model and methodology

GMM belongs to the MARKAL (MARKet ALlocation) family of models, i.e. a group of bottom-up, perfect foresight cost-optimization models that identify least-cost solutions for the energy system under given sets of assumptions and constraints and for a given time horizon. GMM was further enhanced starting from the original version (79). Model improvements dealt with an extension of the number of world regions (Figure 71), the representation of alternative fuel chains (hydrogen and biofuels) and the personal transport sector, as well as the representation of endogenous technological learning (ETL).
reference energy system (RES) of GMM is depicted in Figure 72 and covers the entire energy system from the extraction of resources, to conversion of primary energy carriers, to the use of final energy carriers in end-use technologies across different demand sectors.

Figure 71. The six world regions in GMM

Figure 72. Simplified Reference Energy System (RES) as applied in GMM

1.10.2 Studies with the GMM model

1.10.2.1 An energy-economic scenario analysis of alternative fuels for personal transport

This paper (79) deals with the long-term prospects of alternative fuels in global personal transport. It aims at assessing key drivers and key bottlenecks for their deployment, focusing particularly on the role of biofuels and hydrogen in meeting climate policy objectives. The analysis is pursued using the Global Multi-regional MARKAL model (GMM), linked to the Model for the Assessment of Greenhouse Gas Induced Climate Change (MAGICC).

Scenarios
The analyses conducted in this section focus on three key climate stabilisation scenarios: 650 ppmv, 550 ppmv and 450 ppmv CO₂ concentration in the atmosphere.
Results

With increasingly stringent climate policy targets, however, biofuels vehicles gradually lose market share, while hydrogen fuel cell vehicles become increasingly important. Figure 73 now presents hydrogen and biofuels production throughout the scenarios investigated above. It shows that hydrogen production increases with increasingly stringent climate policy targets, reaching up to 171 EJ of hydrogen production by the year 2100 under the strongest climate policy target. Trends observed for biofuels are less obvious. Any climate policy target imposed leads to an earlier and stronger deployment of biofuels, even though not so much in personal transport, but rather in other sectors such as other transport. However, for the strongest climate policy target (and to a lesser extent also for the 550 ppmv climate policy scenario), the trend is reversed in the second half of the century, which is when hydrogen becomes available on a larger scale.

Figure 73. Total hydrogen (left) and biofuels (right) production under different climate policies in all end-use sectors

Inevitably, this poses the question: ‘where will hydrogen come from?’ Figure 74 compares the shares of the different hydrogen production technologies across the different climate policy scenarios, highlighting once more that coal gasification is the most competitive technology, providing for example for almost all hydrogen production under a mild climate mitigation policy.

Figure 74. Hydrogen production across climate policy scenarios

It was found that one key to the deployment of hydrogen in the first place is the availability of low- or zero-emissions technologies for hydrogen production, and coal gasification with CCS (and electricity co-production) was identified as a highly promising technology in this regard, along with nuclear hydrogen production.
production and wind power parks dedicated to hydrogen production via electrolysis. The other key to a successful deployment of hydrogen is the build-up of a network for hydrogen delivery.

In any case, hydrogen appears likely to be a long-term option for transport under the assumptions in our analysis, as it represents a radical departure from today’s transport fuel chains, and there is still a considerable need for RD&D and an analysis of the potential of individual technologies, in particular fuel cells. However, facilitating hydrogen requires efforts today.

1.10.2.2 Supporting hydrogen based transportation

In this article (80) we analyze the potential influence of selected factors for successful market penetration of hydrogen fuel cell vehicle technology in a hydrogen based private transportation economy. Using a world scale, full energy system, bottom-up, optimization model (Global MARKAL Model—GMM), we address the possibility of supporting the fuel cell vehicle technology to become competitive in the markets.

Scenarios

In a series of optimizations we evaluate the potential influence of governmental supports and the internalization of externalities related to CO2 and local pollution emissions originating from the transportation sector, as well as preferential crediting options and demonstration projects promoting fuel cell vehicles. In the sensitivity analysis we assume that governments are willing to initiate the switch towards a more sustainable transportation system by firstly internalizing the external costs related to the CO2 emissions coming from the production of fuel and the operation of vehicles followed by the externalities related to local pollutants.

We therefore performed a series of optimization experiments varying the tax level. First and in order to assess “demand pull” options, we directly support hydrogen systems by different means of compensating mobile fuel cell vehicle customers with a fixed reimbursement for every kW of fuel cells purchased. The “learning investments” strategy assumes promoting fuel cell vehicles by means of a series of demonstration cars at more favorable prices to the end consumer.

Results

This set of initially supported demonstration projects and the corresponding reduced specific cost is introduced in GMM in a sensitivity assessment and defines the potential influence of this strategy. The diagram below illustrates the outcomes of this strategy (Figure 75). The results are very optimistic as a minimum amount of “learning investments” in form of demonstration vehicles could render hydrogen fuel cell cars competitive. This is again explained as a consequence of the high learning rate assumed and the significant number of cumulative doublings obtained.

Figure 75. Demonstration projects - illustration of market penetration
Our analysis started with increasing of costs of environmentally unfriendly technologies. This was achieved by introduction of environmental penalties for externalities. The result of this part of the analysis has shown that introduction of a carbon tax of 50US$/ton CO₂ provides a benefit to hydrogen cars. Another option would be to internalize for externalities related to local pollutants. Not the full range of external cost has to be internalized in order to help the penetration of hydrogen fuel cell cars.
2. Studies and Projects using Regional Models

2.1 The Pan-European TIMES model

2.1.1 Model and methodology

The model and results presented in this paper (81,82) are the outcome of a number of projects over the last years, that have developed and used the PanEuropean TIMES model.

2.1.1.1 The NEEDS - TIMES Pan European Model.

TIMES was used in the framework of the NEEDS (New Energy Externalities Developments for Sustainability) project (2004-2008) which was funded by the 6th Framework Programme, to create a model for EU-27, Iceland Norway and Switzerland (Figure 76). In this model the energy systems of each one of the thirty countries are modelled separately in detail. This model has been used as a starting point for building the RES2020 Pan-European TIMES (PET) model, and the models in the REACCESS project and REALISEGRID projects. The PET model is designed to explore the development of the EU+ energy system till 2050.

Figure 76. Geographical scope of the PET model

In the Pan European TIMES model, the level of analysis per sector of economic activity in each country, is rather detailed. On the demand side the useful energy demand per use in the residential, commercial, agricultural, industrial, and transport sectors is analysed in detail (81):

- **Residential:** The energy service demands that are being considered in the residential sector are space heating, space cooling, water heating, cooking, lighting, refrigeration, cloth washing, cloth drying, dish washing, other electric uses (equipment) and other energy uses. Furthermore three building categories are used for the demands for space heating, space cooling and water heating, namely multi apartment building, single house in urban areas and single house in rural areas.

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• **Commercial**: The energy service demands considered in the commercial sector are quite similar to the residential sector and include space heating, space cooling, water heating, cooking, refrigeration, lighting, public lighting, other electric uses (equipment), other energy uses. Furthermore the energy service demands for space heating, space cooling and water heating are divided into two building categories, namely small and large commercial buildings.

• **Agriculture**: Agriculture is not analysed in detail, but is represented as a single energy service demand satisfied by a single technology that consumes a mixture of fuels.

• **Transportation**: The transportation sector is analysed into road and rail transport of passengers and freight, domestic and international navigation as well as domestic and international aviation. Passenger’s road transport is divided into short and long distance car transport, urban busses, intercity busses and motorcycles. Passenger’s rail transport is divided into urban Metro transport and intercity train transport. Freight transport is divided into road transport by trucks and intercity rail transport. The aviation and navigation are split to domestic and international, without further analysis of alternative technologies.

• **Industry**: The industrial sector is analysed in detail following an initial division into energy intensive industries and other industries. The energy intensive industries are: Iron and Steel, Aluminium, Copper, Ammonia, Chlorine, Cement, Lime, Glass, Paper. For each one of these industrial branches a detailed description of the production processes is being used in the model. Other non-ferrous metals, other chemicals, other non-metallic minerals, and the remaining industries are represented using the same generic structure with the energy uses of steam, process heat, machine drive, electrochemical processes and other processes.

Demands are specified by three conceptually different pieces of information (82):

• The list of energy service demands: There are 70 exogenous demands for energy services.

• The base year: The original version of the model in NEEDS was calibrated to 2000 data.

• Values for all milestone years till 2050: The construction of the reference useful energy demand projections was based on the general equilibrium model GEM-E3 (EU22 countries).

On the supply side, the electricity and heat production is analysed in detail, the refineries are modelled using a generic refinery structure and the mining and extraction of primary energy resources are modelled using a cost-supply curve (81).

• Electricity and Heat production: The electricity production sector is divided into public power plants and CHP plants, and auto production electricity power plants and CHP plants in the industrial and commercial sector. The high, medium and low voltage grids are included in the model, with different type of technologies being able to produce at different voltage, modelling distributed generation. Annual flows of electricity are split by season - spring R, summer S, fall F, winter W - and daily load profiles – night 12 hours, day 11 hours, peak 1 hour.

• Primary resources: The mining of each primary energy resource is modelled using a supply curve with three cost steps. Biomass is modelled, but not in detail regarding the production processes.

The following air emissions species are represented explicitly in the PET model (82): Carbon Dioxide (CO₂), Carbon Monoxide (COX), Methane (CH₄), Sulphur dioxide (SO₂), Nitrogen Oxides (NOₓ), Nitrous Monoxide (N₂O), Particulate (PM 2.5=PMA and PM 10=PMB), Volatile Organic Compounds (VOC), Sulphur hexafluoride (SF₆) and Fluoro Carbons (CxF). Each of them can be emitted either from combustion (suffix N added to the code) or from processes.
Each single region model was represented by the same RESy (Figure 77); however some energy chains were not active in some regions (82). The Pan European model is constructed by linking together the 29 country models (and the rest of the world), by means of trade variables. The Pan-European TIMES model is more than the sum of the national models as it allows to reflect links between countries and impose constraints at the European level, reflecting the possible coordination of policies across borders.

Figure 77. High level RES of the PET single region models

This framework is completed by integrating LCA and External Cost in Energy Model. All these models are characterised by a multi-period structure (base-year: 2000, last milestone year: 2050) and will include, in the Pan-European model, the most important life-cycle emissions, materials, and costs analysed by other NEEDS research streams (life cycle assessment and ExternE). This version (83) was used for the work carried out in research stream 2a, ‘Modelling internalisation strategies including scenario building’, co-ordinated by the IMAA, CNR.

2.1.1.2 The RES2020 Pan European TIMES model

The RES2020 application of the model focused on the analysis of the renewable energy targets in EU27. This led to a more detailed representation of renewable energy sources and four alternative scenarios for achieving the targets for renewables and GHG emissions in 2020:

- A more detailed analysis of the availability factors for wind turbines has been performed using data from the production of the existing wind parks.
- New decentralised electricity production technologies have been included in the technology database of the model. These include CHP plants and Integrated Gasification Combined Cycle (IGCC) power plants using black liquor in the Pulp and Paper Industry, wave power plants, tidal power plants, and small CHP power plants using biomass as a fuel.
- Further enhancements were made in the representation of biomass and biofuels in the model (84), for instance on the differentiation of crop types and waste and residues sources to be used for the production of biofuels (Figure 78).
2.1.1.3 The REACCESS Pan European TIMES model

In the REACCESS project the PET model was recalibrated in detail to reproduce the 2005 statistics as a base year (81). In the framework of this project the PET model run together with the TIAM model (16 regions world model) and the REACCESS Corridor Model (RECOR) that link the two, in order to study the effects on the energy system of EU competing with the Rest of the World for scarce and uncertain supplies of energy sources. While the detailed technological nature of the paradigm is an advantage for the REACCESS project (82), it also leads to model sizes that offer a significant challenge to even the best performing computers, due to the size of the resulting model. The PET model has 30 regions, the TIAM model 15 regions (16 minus EU+), so that the resulting integrated model has 45 regions, a heretofore unheard-of size for any technology-based energy model. We adopted the integration framework shown in Figure 79 (85).

Figure 79. Integration framework of the REACCESS model

Modeling energy corridors

This report (82) and several presentations (86,87) summarizes the work undertaken for the identification and characterization of the energy corridors, collecting data on present and planned
and/or expected situations of oil, gas, coal, biomass, nuclear fuels and new energy vectors as far as resources, primary and secondary productions, and transportation through “captive” and “opensea” routes, from any part of the World towards not only Europe but also the other World regions that are competing with Europe for these supplies. Particular efforts have been devoted to the spatial analysis of the identified energy corridors, by using GIS tools (ArcView) (Figure 80): NG pipeline (20 corridors), Oil pipeline (2 corridors); Oil ship (95 corridors); Coal ships (8 corridors); Refined products ships (66 corridors); LNG ships (78 corridors); Nuclear ships (6 corridors); Biomass (20 corridors); Electricity (37 corridors); Hydrogen (12 corridors). To describe the corridors, data collected include a very large number of elementary infrastructures, plants, fields, etc. Similarly, the chokepoints, narrow channels along widely used global sea routes, were modelled. Once the starting and destination ports have been identified, the route with the highest shipping density between these two points has been assumed. Alternative paths related to the same pair of ports have been identified.

Figure 80. Ship routes and pipelines

![Ship routes and pipelines](image)

Because supply corridors are very complex entities, their representation required the creation of a new type of TIMES process that generalizes the trade processes already existing in the model generator. The new process (called corridor) describes a corridor as a set of branches that may have almost any topology, each branch having its own investment and activity variables, and those variables being linked logically by a set of flow conservation equations. The new process type was coded in the GAMS code of TIMES and is now a permanent feature of the TIMES generator. Figure 81 shows the typical flows in and out of a corridor.

This generic example shows a gas pipeline that is supplied by two non-EU regions (Region1 and Region2) and feeds four EU+ countries (A, B, C and D). NG_x, NG_y and NG_z are gas streams from different countries/basins in Region1, feeding this corridor. The feeders from each supply point are then aggregated into a single commodity and fed to the corridor. These streams can also feed other corridors, as well as satisfy local consumption. A similar situation exists in Region2. The output (named GASNAT) in EU+ countries goes to meet the final energy demand for natural gas. The EU+ gas demands in each country may also be met by domestic production and/or supply from other gas corridors. In the case of complex gas and oil pipelines, there are a few important modeling details that are not apparent in Figure 81.
In addition, one political risk elemental parameter is attached to each branch of each corridor. When available, the technical risk parameters will also be attributed to each branch.

Implementing risk parameters
The most innovative aspects of the tools developed by the project are linked not only to the number and the detail of the description of the energy systems, but to the exploration of some risk dimensions related to the energy supply routes to Europe and Member States inside long term scenarios (2010-2050). For the evaluation of the risk parameters in REACCESS, two dimensions have been explored (88):

- For the technical risk, two approaches have been taken into account: the risk for people safety and for the environment and the unavailability of the infrastructure. These kinds of risk are considered as additional costs related to the use of the process or corridor.
- For the non technical (political-economic), four dimensions have been taken into consideration: economy-driven, intrinsic energy, political-institutional and socio-political risk.

Risk representation in the RECOR model
Finally, the integration of overall cost and overall risk in the RECOR1 model was also successfully tested, along the lines of the MiniMax approach selected for the representation of systemic risk. The specific task of minimizing a Max expression is greatly facilitated thanks to the model enhancements (made by our VTT partner), which allows the user to create the risk component of the objective very simply, by specifying a new attribute called ACTBET, equal to the risk parameter attached to that process.

In order to test the approach we considered the entire set of corridors (oil open sea corridors, and gas captive corridors). For the gas corridors, it is observed that the inclusion of risk has smoothed the flows across the various corridors: total imports are reduced by the inclusion of the risk objective (in itself, this is a risk reduction action). The reductions range from 4% to close to 20% compared to REF.

2.1.1.1 The REALISEGRID Pan European TIMES model
The REALISEGRID FP7 project, aims at developing a set of criteria, metrics, methods and tools to assess how the transmission infrastructure should be optimally developed to support the achievement of a reliable, competitive and sustainable electricity supply in the EU. In the framework of this project, four scenarios have been implemented with a TIMES model which includes EU27, Iceland, Switzerland, Norway and the Western Balkan region (EU27++).
In framework of the REALISEGRID project, the PET model has been a general review of input parameters and data that indirectly drive them. For instance, taking into account recent economic downturns imply a review of the development profiles of demands for energy services in the first projection years. The second even more demanding task was to update all energy flows to the 2005 energy balances, as well as the assignment of final consumptions to the detailed end uses. In parallel the geographical scope of the model has been extended to the Western Balkan adding to the model six new regions (Albania, Bosnia and Herzegovina, Croatia, FYR of Macedonia, Montenegro and Serbia).

The representation of the endogenous electricity and gas trade across European countries was improved in the framework of this project, by including more precise information on the efficiency and costs of grid and trade infrastructure and on other points. The model also include the re-gasification plants to take in account the liquefied natural gas imported by ships (existing and planned plants).

2.1.2 Studies using the Pan-European TIMES model

2.1.2.1 Technologies, fuels and sector analysis in climate and energy policy scenarios for Europe

Stabilising the concentration of CO₂ in the atmosphere at a level of 450 ppm in order to keep global temperature increase below 2°C requires an ambitious climate policy. This study (89,90) analyses the role of different technologies in the EU-27 with regard to efficiency improvements, fuel switching and energy saving measures under such a climate policy target. The analysis is carried out using the regionalised Pan-European TIMES energy system model. Thereby limited resources and import potentials of various energy carriers, competition among different sectors and the country-specific differences in energy demand are taken into account.

Scenarios

In total, five scenarios are analysed within the scope of this study:

BAU Reference

- No limits on CO₂ emissions
- Minimum use of renewable energies in line with national policies
- Nuclear phase out in corresponding countries

450 ppm Climate protection

- 71% CO₂ emissions until 2050 (compared to 1990)
- Nuclear phase out in corresponding countries

OLGA_NUC Climate protection + security of supply + enhanced nuclear energy

- 71% CO₂ emissions until 2050 (compared to 1990)
- Reduction of the net imports (oil 30% and gas 40% until 2050 compared to 2010)
- Nuclear phase out in corresponding countries

OLGA_NUC Climate protection + security of supply + enhanced nuclear energy

- 71% CO₂ emissions until 2050 (compared to 1990)
- Reduction of the net imports (oil 30% and gas 40% until 2050 compared to 2010)
- Options for enhanced utilization of nuclear energy

450 ppm_100 Climate protection + high oil price scenario

- 71% CO₂ emissions until 2050 (compared to 1990)
- Nuclear phase out in corresponding countries
- Oil price of 100$2000/barrel from 2010 onward and gas price adoption

Results

In the case of the climate protection scenarios, the given target of 1310 Mt CO₂ will be reached in 2050 (Figure 82). The reduction starts first in the conversion sector, then households and commercial and then in the industrial sector. The contribution of emission reductions of the conversion sector turns out to be lower under the condition of restricted imports of oil and natural gas because these energy carriers can be substituted more easily in this sector than in the enduse sectors.
To explain the reasons for emission reduction compared to the reference scenario, the reduction value is split up into different components (Figure 83). Fuel switching followed by the use of CCS technology is mainly responsible for mitigation of emissions in the case of stand alone emission reduction targets (450 ppm scenario). Caused by the high share of electricity generation based on coal, the share of CCS increases in the security of supply scenario (OLGA) and the influence of the fuel switch abates. Energy efficiency just contributes in the longer run to the GHG mitigation because the increased use of renewables and CCS leads to a compensation of energy efficiency gains. The contribution of renewables to reach the emission reduction in 2050 is comparable in all scenarios. The request of security of supply leads to a higher amount in 2030 in the particular scenarios. If extended commissioning of nuclear energy plants is an option, this option is used in EU-27 to attain the CO₂ mitigation targets due to its cost effectiveness (cf. OLGA_NUC).

Till the year 2030, the CO₂ prices develop moderately in the climate protection scenarios. In 2030, they are 94 h/ton CO₂ in the case of stand alone emission reductions (450ppm) and 72 h/ton CO₂ in the OLGA scenario. Where the use of nuclear energy is continued, they go down to 53 h/ton CO₂. Just when the reduction target for EU-27 is higher than 60% compared to 1990, the prices are above 100 h/ton CO₂.

In the case of climate protection polices and limited use of nuclear energy, the most important measures for the reduction of GHG are an increased use of renewables, CCS, fuel switching and the intensified application of electricity in the end use sectors. Efficiency improvements play an additional role when security of supply is taken into account.

**2.1.2.2 Future European gas supply**

A steady increase of natural gas demand can be observed in Europe over the last decades. With the help of a cost-minimization model of the European gas supply system (91), the gas flows and the
infrastructure capacity development up to the year 2030 are analyzed. The model used in this analysis covers the natural gas system of the member states of the European Union plus Algeria, Armenia, Azerbaijan, Belarus, Bosnia-Herzegovina, Croatia, Georgia, Iran, Kazakhstan, Macedonia, Norway, Russia, Serbia and Montenegro, Switzerland, Turkey, Turkmenistan, and Ukraine. In addition, Egypt, Libya, Nigeria, Oman, Qatar and the UAE have been considered as LNG exporters in the model.

Scenarios
For a given demand vector of natural gas in the different countries and given capacity values for pipelines and LNG facilities, the model determines the flows within the gas system in such a way that the total discounted system costs are minimized. To study the future development of the gas supply system up to the year 2030, in a second analysis the model has been given the possibility to invest in pipeline and LNG infrastructure. For Libya, also the offshore Green Stream pipeline between Libya and Italy has been taken into account. In the considered time horizon from 2004 to 2030 European gas consumption (excluding FSU) is assumed to be growing at an average annual rate of 1.6% compared with 3.5% between 1990 and 2004.

Results
The resulting pipeline capacities and gas flows in the year 2030 are shown in Figure 84. The Ukraine will remain the country with the largest gas transit volume. In 2030, 143 bcm of gas are shipped from Russia through the Ukraine to Europe compared with 116 bcm in 2004. Further major import routes from Russia to Europe are the expanded Yamal pipeline with 44 bcm of gas entering Poland and Lithuania as well as the NEGP pipeline with 27 bcm of gas flowing to Germany in 2030.

The scenario analysis reveals that Europe’s dependency on gas imports will increase indeed in the future, but cost effective options exist to diversify its supply mix. For pipeline gas such policy strategies could be increased gas imports from Northern Africa, mainly from Algeria with supply costs in the range of 32–55 $/1000m^3$, and gas shipments from the Central Asian countries Azerbaijan, Kazakhstan and Turkmenistan (supply costs between 47 and 59 $/1000m^3$).

In the latter option, the gas either has to be shipped through Russia, which means that the dependency on Russian gas supply is merely replaced by a dependency on the Russian pipeline infrastructure, or new pipelines via Turkey and South East Europe, as the suggested Nabucco pipeline have to be built. Despite higher costs, the Nabucco pipeline can reduce Europe’s dependency from Russia and, therefore, may also strengthen the position of European countries in gas price negotiations with Russia. Besides this diversification of pipeline gas imports, LNG, being imported today only by a few countries in Europe, can be a strategy to be more seriously considered by other European countries, which currently solely rely on pipeline imports, to diversify their gas supply options.
2.1.2.3 Evaluation of the RES Directives implementation in EU27 for 2020 (RES2020 Project)

The project RES2020 (Monitoring and Evaluation of the RES Directives Implementation in EU27 and Policy Recommendations for 2020) aims at analysing the present situation in the RES implementation, defining future options for policies and measures, calculating concrete targets for the RES contribution that can be achieved by the implementation of these options and finally examining the implications of the achievement of these targets to the European Economy (92,93,94,95,96,97,98,99,100). A number of future options for policies and measures were defined and studied with the use of the TIMES energy systems analysis model, in order to analyze the quantitative effects on the RES development.

Scenarios

It was decided to run four alternative scenarios in order to examine the achievement of the renewable targets set by the European Union for 2020. The scenarios that were elaborated are:

- Reference Scenario: where there is no enforcement of the targets for renewable energy sources in 2020. The support mechanisms that are modeled for renewables are investment subsidies and feed-in tariffs in the Member States that employ them.

- RES Reference Scenario: where the target for renewable energy sources per Member State and the corresponding targets for CO₂ emission in 2020 are enforced. The total CO₂ both from the ETS and non-ETS sectors, has a reduction, of 18% from the 1990 level. The biofuels target is imposed as a lower bound for all the Member states, to be 5.75% in 2010 and 10% in 2020.

- RES Trade Scenario: where the target for renewable energy sources per Member State and the corresponding targets for CO₂ emission in 2020 are enforced and the trade of Green Certificates is also possible.

- RES Trade-30 Scenario: with the same assumptions as the RES Trade Scenario, but enforcing a 30% reduction target for CO₂ emissions over the whole of the European Union.
Results

The projections for primary energy supply, already reveal several key outcomes of the model analysis. Policies on renewables and emissions reduce the demand for primary energy and its final use - especially by 2020. The use of renewables increases clearly already in the baseline and this increase is further emphasized, when a renewables target is imposed. Addition of more stringent emission targets does not significantly further alter the share of renewables. Coal consumption is clearly reduced due to the renewable and climate targets. There is no major change in the absolute consumptions of nuclear, gas or oil, neither across the scenarios nor between the year 2000 and 2020.

Final energy use of non-renewables and renewables is further specified in Figure 85. Some remarks on these figures:

- Consumption of non-renewable final energy peaks in 2015, if a renewable policy is in place. The use of renewable final energy carriers, however, increases throughout the time frame for all scenarios.
- The relative shares of the different non-renewable energy carriers remain exactly the same across the scenarios. This means that since oil, gas and non renewable electricity are the non-renewable energy carriers with the highest consumption, in absolute terms, they also make up for most of the reductions that result from the policies.
- The use of renewable final energy is more than doubled already in the BaU scenario. By 2020, a renewable policy will have brought in another 30% more renewables on top of what is achieved in the BaU scenario.
- In the BaU scenario, renewable electricity and biofuels have the largest absolute increase. The additional renewables induced by specific targets is mostly coming from bioenergy, covering more than 50 % of the additional renewable energy beyond the baseline.
- In the RES-T scenario, slightly less renewables are introduced when compared to the RES scenario. In short, the RES scenario may have some surplus RES production compared with the 20% target, while the RES-T scenario meets this target exactly.

Figure 85. Final energy use of a) non-renewables and b) renewables

In the BaU scenario, the electricity production from renewables is projected to more than double by 2020; the energy and climate targets are applied lead to a further increase of circa 15 – 20 % on top of the BaU scenario. The share of renewables in electricity production amounts to slightly more than 35% and is relatively robust between the different RES scenarios. The mix of renewable technologies in power production is mainly based on wind, hydro and biomass (Figure 86):

- In 2000 more than 80 % of all renewable electricity generation was based on hydro. Since there is little further potential for increasing hydro power, its production in absolute
numbers remains almost constants and its relative share decreases to slightly over 30 % by 2020.

- In all scenarios, wind power is the main renewable electricity source by 2020, covering about 45 % of total renewable generation in all scenarios by 2020.
- In the RES scenarios, policies further increase renewable electricity generation, and especially generation from wind. Also the use of biomass for power generation becomes more important. Other non-hydro sources play a minor role.
- The introduction of virtual trade of surplus renewable certificates leads to less renewable electricity production, at the expense of biomass and wind.
- In the 30% GHG scenario, there is some reduction in fossil power generation. Of the total electricity production from coal power plants, 55% is produced in plants equipped with CO₂ capture and storage.

**Figure 86. Net Electricity generation from renewable energy sources**

![Net Electricity generation from renewable energy sources](image)

In the BaU scenario, total CO₂ emissions increase quite modestly, by circa 5 % over the 20-year time frame (Figure 87). In the ETS sector, the decarbonisation is mainly due to the power production sector, where the emissions are reduced some 13 %. In the non-ETS sector, most of the sectors increase their emissions lightly, with the transport sector being responsible for the highest increase.

- In the RES scenario, the power sector is responsible for at least 55 % of the mitigation efforts. In order to reach this emission reduction, the model applies a shadow price for CO₂ emissions of circa 50 €/ton.
- The difference between the RES and RES-T scenarios are almost negligible, indicating that virtual trade of excess certificates does not affect overall CO₂ emissions.
- When mitigation requirements are increased to 30 %, the relative importance of the power sector increases even more, its share being now some 65 % of the total mitigation. Of the next two most important mitigation sector, the importance of industry increases with the more ambitious climate target, whereas the relative contribution from the residential sector is reduced. These emission reductions are induced by a CO₂ shadow price of 80 €/ton.

In terms of discounted costs, the overall increases caused by the policies are quite minor. Total discounted system costs increase 0.22% in the RES-ref scenario, with its RES target and 20% emission reduction target. With certificate trading of the surplus certificates, this difference is even smaller, some 0.18%. If emission target is made more demanding, costs are 0.49% higher than in the BaU scenario.
In order to check the robustness of the outcomes for several key assumptions, we executed a modest sensitivity analysis on the model. For the analysis on biomass availability, key findings are:

- In primary and final energy, a reduced availability of biomass leads to a minor response in total energy use, as average costs of the alternative RES source (more expensive biomass, or other RES technologies) are higher than that of the original biomass.
- In total, final renewables use decreases, since countries that have some RES production in excess of the 20% target, because some options are simply costcompetitive against fossil options, lose this surplus when biomass is constrained.
- However, with a reduction of biomass potential, total (absolute) renewables use in power (Figure 88) and heat actually increases at the expense of biofuels, particularly in 2020 (as cellulosic feedstock for 2nd generation biofuels is likely to be diverted to heat and power production).
- When biomass availability is reduced, biomass use decreases less than proportionally. This illustrates that for many biomass resources, sheer availability is not the constraint, and the loss of availability is (partly) compensated by the use of other more costly types of biomass.
- Key substitutes for biomass-based technologies that increase their share when biomass is constrained are solar-PV and ocean energy (in the electricity sector), and solar-thermal in the heat sector (where biomass maintains its dominant role). In the transportation sector, hydrogen experiences a slight increase.
- Overall CO2 emissions do not increase when biomass availability is constrained.
- The limitation of biomass availability clearly leads to higher renewable costs related to reaching the 20% RES objective. For example, a 50% reduction of biomass availability leads to an increase in renewable costs of several tens of percent, compared to the RES-ref scenario.
The main conclusions that can be drawn from the results presented in the previous sectors are:

- Policies reduce overall energy demand, and suggest a potential decoupling of economic growth and energy demand: energy use peaks between 2015 and 2020.
- In terms of fossil resources, the energy and climate targets lead to a shift away from coal and oil, while natural gas use remains relatively stable.
- The costs of the 20% renewable energy and GHG reduction targets are relatively minor; total discounted system costs increase 0.22% in the RES-ref scenario.
- A virtual trade mechanism of the surplus of renewable certificates can lead to moderate changes in renewable energy production among the member states. Virtual trade of the excess certificates leads to a reduction of additional costs for renewables of more than a quarter, and a reduction of almost one fifth of total additional costs for meeting the 20% renewable energy and GHG reduction targets.
- Higher climate mitigation ambitions, in the form of a 30% GHG emission reduction target, lead to a minor increase of renewable energy in the mix. This addition, however, comes against a significant cost increase of more than 50% compared to the RES-ref scenario. Additionally, other technologies, such as CCS, lead to a more than doubling of overall additional costs.
- Of the efforts needed to meet the RES target of 20% by 2020, slightly more than 40% is delivered in the heat sector, ca 40% comes from power production, while around 15% is delivered as biofuels.
- The RES targets lead to renewables supplying more than 35% of total electricity production by 2020, almost 20% of total heat production, and 10% of road transport fuels.
- The deployment of renewable energy technologies is relatively robust towards changes in assumptions on the availability of biomass and wind energy.

2.1.2.4 EU 20-20 policy implications on the EU energy system

In the same context, this presentation (101,102) focuses on the evaluation of the EU Energy and Climate Package as proposed by the Commission in January 2008 by studying the impacts on the EU energy system.
**Scenarios**

Baseline case (REF)
- No emission reduction measures
- Nuclear phase out according policy of respective EU countries
- Minimum renewable energy use

BEST climate policy on global trade
- EU 20-20 target
- GHG emission reduction from 2020 linear to -39% by 2050

Second Best
- EU 20-20 target
- GHG emission reduction from 2020 linear to -50% by 2050

Second Best VAR
- EU 20-20 target
- GHG emission reduction from 2020 linear to -50% by 2050
- Limit the ETS part to stress the Non-ETS sector

**Results**

Figure 89 compares the net electricity generation installed capacity for the four scenarios.

**Figure 89. Net electricity generation installed capacity [GW] in the EU27**

The economic development or in general the requested demand influence on the same level the future energy system as the technology development and availability. With a limitation of nuclear CCS become a very important technology. In the period between 2030 and 2050 the level of the GHG reduction target for the EU27 depends on the possibility of cost effective world wide reduction potentials. In general additional policy measures which are reducing the flexibility of the energy systems are not cost efficient. Over 90 % of the fossil fuels will be imported in the EU27 till 2050 (58 % in 2000). The overall import dependency growth up little more than 70 % (61 % in 2000).

The same kind of analysis were done for Germany in (103). The target of the integrated energy and climate program of the German government is a 30 % reduction of the GHG emission by 2020 related to the year 1990.
2.1.2.5 Energy corridors and security of supply in Europe (REACCESS Project)

An example of policy assessment within the REACCESS project is the analysis of the interplay between the global goal of mitigating climate changes and the European goal of reducing dependence and vulnerability of the energy system (85).

Scenarios

Keeping into account that the model is huge, with more than 3 million variables, only a few scenarios could be possibly built and analysed. Only two mitigation pathways are represented here; Week and strong mitigation pathways are analysed imposing a mild or severe CO2 equivalent tax. The risk dimension is examined with the help of the EU energy system risk indicator. The inaction, when the risk indicator is not constraint, is compared to the optimal action from the EU wide perspective. The four main scenarios indicated below have been compiled and analysed:

<table>
<thead>
<tr>
<th>S-RISK</th>
<th>Free</th>
<th>Reduced</th>
</tr>
</thead>
<tbody>
<tr>
<td>Climate Change Mitigation Low</td>
<td>REF</td>
<td>RISK</td>
</tr>
<tr>
<td>Climate Change Mitigation High</td>
<td>CLIM</td>
<td>RISK-CLIM</td>
</tr>
</tbody>
</table>

Results

As expected, the task of participating to the mitigation of global climate changes turns out to be much more expensive for Europe than reducing the risk of the EU energy system security, as it increases the total system cost of about 5% yearly in the decade 2020-2030. However the climate change mitigation effort makes the extra cost of reducing the risk lower than in the absence of this climate objective. Reducing the energy security risk of EU27 to the same level as in the RISK scenario implies total system cost increases of about 0.2%, i.e. a cost increase from 5% to 5.3% on an annual basis in the decade 2020-2030. This cost of achieving higher energy security is lower when global climate changes objectives are in the EU27 agenda, due to synergies at several levels.

Like energy system security objectives, climate change mitigation objectives have the effect of reducing the EU27 dependence on total final energy consumption in most sectors and fuels, in particular on electricity, by using more efficient end-use devices and shifting consumers’ demands to less energy intensive sectors (Figure 90).

By reducing the total primary energy supply climate change mitigation objectives are indirectly as effective as energy security risk reduction policies: total fossil import in 2040 reduce in both scenarios from about 63 EJ (REF) to about 46-45 EJ (RISK or CLIM scenarios). The part of this reduction which is not due to energy efficiency improvements in the end-use sectors is achieved by harnessing more domestic resources, mainly renewable (Figure 91). This finding is in effect the proof that there is strong synergy between the risk and the climate objectives, as far as energy savings are concerned.

In contrast, the CLIM scenario is not very effective in achieving significant reductions in the concentration of foreign energy suppliers: the Herfindahl-Hirschman quadratic concentration index in 2040 reduces from 0.146 in REF to 0.127 in CLIM, which is not nearly as much reduction compared to the level of 0.084 achieved in the RISK scenario. If we now turn to the reverse impact of RISK on the CLIM scenario, we observe that the EU energy security risk avert policies have very limited effects on the global climate change mitigation objectives: in the risk avert scenarios (CLIM-RISK) CO2 permits cost just a few percent less than in the simple climate change mitigation case without risk considerations (CLIM). The analysis also proves that the energy systems of non-EU countries are not much affected by the risk consideration in EU, with or without climate strategies.

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4 To a level compatible with a CO2 stabilization concentration of 450 ppm at the end of the century and for EU27 halving the 1990 CO2 emissions from the energy system in 2030.
2.1.2.6 Transmission infrastructure development to support sustainable electricity supply

The REALISEGRID FP7 project aims at developing a set of criteria, metrics, methods and tools to assess how the transmission infrastructure should be optimally developed to support the achievement of a reliable, competitive and sustainable electricity supply in the EU.

Scenarios

Four scenarios were selected and the model runs for the period 2005-2030 in five years intervals (81). The most important drivers identified for the European energy system and its future developments are six: population and households (POP); development of the Gross Domestic Product (GDP); level of climate change mitigation (CCM); degree of improvement of energy technologies (TECH); availability of extra European oil and gas supply (GAS); and development of electricity cross-border infrastructures (ELC).

Some additional quantified description of the six drivers is useful in order to explain their impacts on the results of the four scenarios. The four scenarios and their main characteristics are (Table 11):
Table 11. The four scenarios and their main characteristics

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Driver</th>
<th>Optimistic</th>
<th>Competing</th>
<th>EU-centric</th>
<th>Pessimistic</th>
</tr>
</thead>
<tbody>
<tr>
<td>POP</td>
<td>HIGH</td>
<td>HIGH</td>
<td>LOW</td>
<td>LOW</td>
<td></td>
</tr>
<tr>
<td>GDP</td>
<td>HIGH</td>
<td>HIGH</td>
<td>LOW</td>
<td>LOW</td>
<td></td>
</tr>
<tr>
<td>Climate Change Mitigation</td>
<td>STRONG</td>
<td>STRONG</td>
<td>STRONG</td>
<td>WEAK</td>
<td></td>
</tr>
<tr>
<td>Technological Improvement</td>
<td>HIGH</td>
<td>HIGH</td>
<td>LOW</td>
<td>LOW</td>
<td></td>
</tr>
<tr>
<td>Gas</td>
<td>HIGH</td>
<td>LOW</td>
<td>LOW</td>
<td>LOW</td>
<td></td>
</tr>
<tr>
<td>Intra EU+ electric interties</td>
<td>BOUNDED</td>
<td>FREE</td>
<td>FREE</td>
<td>BOUNDED</td>
<td></td>
</tr>
</tbody>
</table>

Results
The results of the four scenarios are presented here at the aggregate level of EU36. Total CO2 emissions are directly determined by the CCM driver starting in 2020 in the first three scenarios and starting in 2030 in Pessimistic. In 2030, there are small additional reductions for the first three scenarios, but the Pessimistic now requires severe and rapid GHG reductions (the drop from 2025 to 2030 is 24%, a very large and sudden reduction over a five year period). The largest variations in emissions occur in two sectors: electric power generation, and industry (Figure 92).

Figure 92. Emissions of CO2 by sector (Mt/yr)

Total electricity generation
Figure 93) grows by 38% from 2010 to 2030 in the first two scenarios. In EU Centric and Pessimistic, the growth is 16% and 15% respectively, over the same time span. The much lower electricity growth shown for the last two scenarios is not fully explained by the 14 lower economic growth in these two scenarios: what in fact happens is that, facing a lower economic growth, the strategy to reduce emissions is qualitatively different in the two groups of scenarios. With low growth, there is less need to use the electricity sector as a privileged sector in which to implement reductions of emissions. This is an important finding, since it establishes that electricity production is over sensitive to the growth of GDP whenever a climate target is in effect.

Recall that the electricity interties within EU+ are the same in all scenarios until 2020. In 2025 and 2030, the model is free to increase interties capacities only in the Competing and EU Centric scenarios (Figure 94). For these two scenarios, the increase in intra EU+ electricity trade is clearly visible in 2025 and 2030, confirming that the model indeed makes good use of the additional capacity of the electricity interties.
Figure 93. EU+ electricity generation by type (GWh/yr)

Figure 94. Electricity trade in EU+ (TWh/yr). Imports from ROW are fixed in all scenarios

2.1.2.7 Contribution of alternative fuels and power trains for climate targets in the EU27

Within this study (105,105), a technology oriented, linear optimization model of the EU energy system is applied in order to analyze the cost optimal contribution of the transport sector to the achievement of GHG reduction targets until 2050. A special focus lies on the analysis of the penetration of alternative fuels (e.g. biofuels, hydrogen, electricity) and vehicle technologies (e.g. (plug-in) hybrid electric vehicles, battery electric vehicles, fuel cell electric vehicles) under ambitious GHG reduction targets. Since the TIMES PanEU model covers the whole energy system of the EU, pathways for the production of alternative fuels are modelled, too.

Scenarios

In order to analyze the cost optimal contribution of alternative fuels and power trains to the achievement of climate protection targets in the EU, five GHG reduction scenarios are considered (Figure 95), representing the probable range of GHG reduction the EU has to attain until 2050 in order to contribute to the achievement of the global 450 ppm target.
Results

The comparison of transport final energy consumption in the different scenarios (Figure 96) shows, that until 2020, the GHG reduction targets have only little influence on the composition of transport fuels. Even in the most ambitious GHG scenario (GHG_80), conventional crude oil based fuels like diesel, gasoline, kerosene and liquefied petroleum gas (LPG) still account for 95 % of transport final energy consumption. The reason lies in the comparably low CO2 price in 2020 that does not exceed 76 EUR/t of CO2.

However, in the following periods the consumption of biofuels, especially BtL fuels increases considerably in all GHG scenarios. In 2050, the share of biofuels in transport final energy consumption ranges from 28 % to 45 % in the GHG scenarios. The main consumers of biofuels are heavy duty vehicles for road freight transport and aviation, where the availability of other technical options for GHG reduction is limited. Beginning in 2040, an increasing consumption of electricity and hydrogen can be observed.
Looking at the deployment of alternative power trains for cars (Figure 97), it turns out that conventional internal combustion engines (ICE) remain the dominant technology until 2030 in all scenarios, being only slightly supplemented by hybrid electric vehicles (HEV). After 2030 and especially in the scenarios with high GHG reduction targets, plug-in hybrid electric vehicles (PHEV) become an important alternative technology option for cars. On the one hand, they benefit from the fact that their electric range (up to 60km) is sufficient for most of the daily driving, so that their combustion engine has to run only in exceptional cases. On the other hand, their investment costs are much lower than those of pure battery electric vehicles (BEV) because of their comparably low battery capacity. As a result, the share of PHEVs increases up to 29% of total car vehicle stock in scenario GHG_80 until 2050.

Figure 97. Deployment of alternative power trains for cars in the different scenarios (EU27)

2.1.2.8 Perspectives of CCS power plants in Europe: Under different climate policy regimes

In the next two decades capacity investments in Europe of about 200 – 400 GW are necessary to compensate decommissioning capacities and to satisfy growing electricity demand. In this regard the climate protection targets of the European Commission, aiming the stabilization of the CO2 concentration in the atmosphere at 450 ppm, represent a fundamental criterion for the commissioning of new power plants in the European energy sector. The target of this work (106,107) is to analyse capture economics of CCS power plants and their contribution to GHG reduction in the European energy system under climate policy conditions. The analysis will be conducted with the Pan-European TIMES energy system model (TIMES PanEU). For the modeling of varying CCS costs a fuel independent capture process is implemented in TIMES PanEU (Figure 98).

Scenarios

For the description of the results, five CCS cost variations will be discussed. They are named similar to GHG path naming, representing the capture costs reached in 2040 (CCS20, CCS30, CCS40, CCS50 and CCS60).
Figure 98. Modeling of the fuel independent CCS process in TIMES PanEU Model

Results

The results of the development of the carbon emissions in the public energy sector are displayed as difference of the CCS cost variations (CCS30, CCS40, CCS50, CCS60) to the least cost CCS option (CCS20) for each GHG path (Figure 99).

Figure 99. Difference of CO2 emissions compared to the variant with minimum CCS costs for the climate paths

In the periods 2040 and 2050 carbon emissions in the public energy sector are less sensitive to changes of CCS capture costs compared to 2030. Decreases of capture costs cause carbon emission reductions of maximum 18 Mt CO2. For GHG-60 path and GHG-65 path the total carbon emission from public energy sector are more sensitive to CCS cost changes than in 2040, since there is a higher flexibility in these paths in 2050 concerning the GHG reduction option than in 2040 or under more restrictive climate policy. Under certain conditions declining capture costs lead to an increase of carbon emissions in the public energy sector. The reason of this effect is the increase of electricity demand due to lower capture prices and consequently lower electricity prices, which results to a shift of carbon emissions from the public sector to end use sectors.

Regarding at the carbon captured by technologies of the public energy sector, a high sensitivity in the year 2030 can be observed as well. Most influence of the carbon price can be observed in 2030, due to the high sensitivity and changes of the emissions of the public energy sector into end use sectors in case of increasing carbon capture costs. However in 2030 neither changes of the climate target nor the costs of carbon capture lead to significant changes of the total electricity generation. In 2050 the electricity generation is dominated by natural gas and nuclear power plants, which produce together more than
half of the electricity independent from the GHG path and CCS costs. Changes of the fuel mix for
electricity generation primary concern coal, natural gas and renewable energies (Figure 100).

**Figure 100. Electricity generation compared to the variant with minimum CCS costs for the climate paths**

Under the GHG-60 path primary coal based electricity decreases with rising capture costs in 2050. In the
CCS20 variant, additional 261 TWh electricity from coal power plants are generated compared to the
CCS60 variant. Substitution effects from coal to natural gas as observed in GHG-60 in period 2030 play a
subordinated role in 2050. In 2050, especially in the GHG-71 path and the GHG-75 path, natural gas
based electricity is less substituted but primary saved due to a reduction of electricity demand.

2.1.2.1 Perspectives of CCS power plants in Europe: Under uncertain power plant parameters

The perspectives of power plants with CCS in Europe are analysed with the Pan-European TIMES model
(TIMES PanEU) incorporating technical and economic uncertainties of CCS technologies by the use of the
Parametric Programming routine (108). Thereby the analysis considers two different climate policy
regimes for Europe.

**Scenarios**

The climate paths are based on scenarios, which represent different possible outcomes of international
climate protection agreements and can be interpreted as different allocations of GHG emission permits:

- The first GHG reduction path (GHG-74) states a target for the EU-27+3 of 38 % in 2030
  compared to Kyoto base and a moderate further increase to 74 % reduction in 2050.

- The second GHG reduction path (GHG-83), which is more ambitious in the long run, reaches a
  reduction of 27 % in 2030 compared to Kyoto base and increases rapidly to 83 % in 2050 for the
  EU-27+3.

**Results**

The share of CCS technologies of total electricity generation in the EU-27+3 varies between 0% in 2020
and a maximum of almost 40 % (2500 TWh) in 2050 (Figure 101). Under the conditions of the GHG-74
scenario, CCS power plants gain already competitive in 2020 with a maximum share of 8 % (300 TWh) of
total electricity generation. In 2030, CCS technologies contribute at least to 13 % to electricity
generation, conversely to the GHG-83 scenario, in which a very low capture performance of CCS power
plants delays market entrance of CCS technologies. The maximum share of CCS at total electricity
generation reaches 28 % in 2030 at a CO₂ emission level of 330 Mt (GHG-74 scenario) in the public
electricity and heat generation sector and 14 % in 2030 at a CO₂ emission level of 690 Mt (GHG-83).
Consequently higher efficiencies and lower invest costs of CCS power plants can lead to additional electricity quantities from CCS in the EU-27+3 up to 270 TWh in 2020 in the GHG-74 scenario and up to 600 TWh per year for the time horizon to 2050. Concerning the fuel type of CCS technology in the GHG-74 scenario, a dominant share of solid fossils for the periods until 2040 can be stated, changing to natural gas in 2050 (Figure 102).

The market share of CCS power plants is highly influenced by climate policies. Under an ambitious climate policy regime (GHG-83), the electricity demand increases up to 6500 TWh in 2050 in the EU-27 plus Norway, Switzerland and Iceland (EU-27+3), with a high contribution of CCS power plants (almost 40 %). The technical and economic parameters of CCS power plants can determine the market share significantly. Thereby improvements of capture performance can bring additional electricity quantities to the system, satisfying the growing demand and substituting alternative electricity generation technologies, e.g. natural gas combined cycle without CCS.

Regarding the influence of future CCS power plant parameters the analysis shows that in early periods (2020 and 2030) reductions of invest costs have a higher impact on the electricity generation from CCS power plants since CCS power plants are primary based on solid fossil fuels, which economics are more sensitive to invest costs reductions than to efficiency improvements.

2.1.2.2 Technology analysis of emission reduction potentials in the industrial sector in the EU-27

This study (109,110) analysis the emission reduction potentials of the industrial sector at different carbon prices. Therefore, CO₂ prices of scenarios with different emission restrictions, especially in the periods of 2020 and 2030, ending up in a 450 ppm target at 2050, are calculated. The model used for this analysis is the energy system model TIMES PanEU.
Scenarios
The two scenario runs with a reduction target of -15% and -40% in 2020 compared to Kyoto base year. In the long run (2050), both of these restricting scenarios have the same target which equals a 450 ppm goal (-71% in 2050 compared to 1990).

Results
The industrial reduction potential plays the key role next to the conversion/production sector. In total, from the additional reduced emissions, 147 Mt are reduced by industrial supply processes and 154 Mt by production processes in 2030. All these mentioned different possibilities and the following effects influence the total use of fuels in the industrial sector. The use of coal (-879 PJ at 123 €/t compared to 27 €/t), gas (-655 PJ) and petroleum products (-105 PJ) are clearly decreasing, whereas the use of renewables (+1 725 PJ) is clearly increasing when the CO2 price gets higher. The different effects of more efficient technologies (leading to a lower total consumption) as well as the use of biomass and CCS (leading due to their lower efficiency to a higher consumption) compensate and the total consumption of fuels stays almost constant at a level of about 12000 PJ in the year 2030.

The final energy consumption balances district heat and electricity as energy carrier (with the conversion losses of industrial electricity generation in the conversion sector) while the total fuel consumption also balances the conversion losses of industrial electricity generation. The drivers for the emission reduction at industrial heat production are a switch to biomass (from coal and clearly from gas) and the use of CCS at industrial CHPs. Looking at the heat output by technology, there’s also a switch (Figure 103). At lower emission prices, the heat output from industrial boilers stays almost constant. Within this range, the share of renewables used is increasing. Afterwards, at a price above 65 €/t, boilers are substituted by heat from CHP’s and district heat. Both heat commodities are generated with an increasing share of renewables and at a higher CO2 price also from CCS.

Next to the industrial supply processes, the other way of industrial emission reduction are the production processes. The additional emission reduction in 2030 comparing the reductions at increasing CO2 prices compared to the lowest price of 27 €/t could be split up into the different industrial sub-sectors. The key sub-sectors concerning emission reduction in industrial production processes are the iron/steel and the cement industry.

Figure 103. Heat supply in the industrial sector in 2030 compared to the scenario with the CO2 price of 27 €/t

Main emission reduction possibilities in the iron/steel industry are efficiency improvements by process developments or changes, fuel switches or the use of CCS. One crucial change is the substitution of the standard blast furnace process by the electric arc process (Figure 104). This change is cost effective even at low CO2 prices and before 2030. That’s why the potential is already used in 2030 at a low CO2 price and even at higher price the use of electric arc stays constant. Next to this efficiency improvement, CCS
is used in the iron/steel industry. Especially at a carbon price between 56 €/t and 75 €/t the highest growth rates of this technology appear.

**Figure 104. Use of technologies in the iron and steel industry compared to the scenario with the CO₂ price of 27 €/t**

![Graph showing the use of technologies in the iron and steel industry](image)

The key results of this analysis are:

- Both supply processes (industrial generation of heat, steam, electricity, cooling) and production processes (like generation of steel or cement) have high potentials for emission reduction and on both fields reductions are necessary to reach ambitious climate targets.

- Clear distinctions of ways to reduce industrial emission between energy supply and production processes in the industrial sector have to be made. Key drivers concerning the production processes are efficiency improvements while key driver for the supply side is the increased use of renewables, mainly biomass for heat generation.

- The CCS technology plays also an important role at the reduction of industrial emissions, both in the supply side and in production processes.

- Focussing on the production side, the most important sub-sectors concerning the emission reduction are the iron/steel and the cement industry.

- Due to the increased use of renewables in industrial heat generation and the use of CCS, the efficiency in the supply processes is decreasing at higher CO₂ prices.

**2.1.2.1 Effect of a White Certificate Trading Scheme in the EU-27**

The improvement of energy efficiency and thereby a reduction of energy consumption is one of the key goals of the energy and climate policy strategy of the European Union as stated in their EU 20/20/20 targets. On way of achieving this reduction target could be the implementation of a European wide white certificate trading scheme. This study (111,112) examines the effect of a restriction on the total consumption of either final or primary energy on the European energy system. To analyse this impact, a TIMES-model based approach with different scenarios is used.

**Scenarios**

In general, a business as usual case (scenario: REF) is compared with other scenarios. These other scenarios contain a European wide certificate trade which leads to lower energy consumption due to improved energy efficiency and energy savings.
<table>
<thead>
<tr>
<th>Scenario</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>REF</td>
<td>Business as usual</td>
</tr>
</tbody>
</table>
| FEC      | -21% CO₂ reduction ETS sector 2020 (base 2005)  
            European wide restriction on final energy consumption |
| FEC_450ppm | -21% CO₂ reduction ETS sector 2020 (base 2005)  
             European wide restriction on final energy consumption  
             -71% CO₂ reduction till 2050 (base: 1990) |
| PEC      | -21% CO₂ reduction ETS sector 2020 (base 2005)  
            European wide restriction on primary energy consumption |
| PEC_450ppm | -21% CO₂ reduction ETS sector 2020 (base 2005)  
             European wide restriction on primary energy consumption  
             -71% CO₂ reduction till 2050 (base: 1990) |

**Results**

The different end use sectors contribute on a different level to reach the reduction target. Comparing FEC to REF, the strongest reductions occur in the household sector (Figure 105). Key driver are the efficiency potentials in generating space heat. Next to residential, the industry sector has the second strongest contribution to reach the reduction targets based on final energy consumption. Key drivers are changes in manufacturing technologies but also the supply of heat and electricity.

**Figure 105. Reduction of final energy by end use sector (scenario FEC compared to REF)**

A more detailed analysis is made for the industry sector (Figure 106). The focus is thereby on improvements of energy efficiency. In FEC, the total consumption is 3126 PJ lower in 2050 (FEC compared to REF). FEC_450ppm has a slightly higher consumption than FEC.

Analyzing the shares of the different energy carriers, it can be observed that in case of a climate constraint the use of renewables (7.0 % of final energy consumption industry in 2050 in FEC_450ppm to 3.6 % in FEC) and electricity increases while less coal and petroleum products are used. Furthermore under a white certificate scheme based on final energy, more district heat is used. Under conditions of a climate constraint, it is used more electricity due to the higher efficiency of electric applications (like a technology switch to electric arc furnace in the iron and steel industry) and the ongoing decarbonization of the public electricity generation. The increased amount of renewables mainly comes from biomass which is used for heat and steam supply.

**Figure 106. Scenario comparison FEC industry by energy carrier (EU-27)**
The energy efficiency improvements are measured and displayed in Figure 107. The increasing output in the industry has of course an increasing effect on the final energy consumption. In contrast, the energy efficiency improvements are reducing the energy consumption. Key drivers for these improvements are in the non-energy intensive sub sectors the more efficient cross-sectional technologies (like pumping system, fans, compressed air) and process optimization in the energy intensive branches.

**Figure 107. Scenario comparison reduced FEC of sector industry by improved energy efficiency (EU-27)**

A trading scheme based on final energy causes a shift of conversion losses into the public sector (reduced autoproducer). Furthermore, the main contribution to achieve the reduction targets comes from household and industry sector. Both sectors generate reductions in the heat supply (space and process heat) which are strengthened by process improvements occurring in the industry sector. Because all reductions have to be achieved in the end use sectors, the additional system costs are higher.

The specific costs show the potential price increase of fuel costs by the implementation of an energy consumption restriction. They differ between 1.19 € per GJ of final energy in 2020 to 0.78 € per GJ in 2050 (focusing on scenario FEC). This corresponds to a price increase of natural gas of 22 % in 2020 to 13% in 2050 both measured in real terms in €2000.

### 2.1.2.2 Analysis of potentials and costs of CO₂ storage in the Utsira aquifer in the North Sea

The FENCO ERA-NET project “Analysis of potentials and costs of storage of CO₂ in the Utsira aquifer in the North Sea” has studied the national and regional cost-effectiveness of CCS in five countries of North West Europe (113,114,115,116). The focus was on the feasibility of storing CO₂ into the Utsira formation
as part of national or regional CO₂ mitigation strategies. The following partners have been involved in the project: University College London, UK, Utrecht University, NL, University of Stuttgart, DE, Risø DTU, DK and Institute for Energy Technology, NO (coordinator).

The project have used the Pan European TIMES (PET) model and national MARKAL/TIMES models for the United Kingdom, the Netherlands, Germany, Denmark and Norway. Analyses were carried out on both national level and regional (North European) level and the model results were compared to study the advantages of a common European CO₂ infrastructure in contrast with national infrastructures.

Scenarios
The future role of the Norwegian Utsira formation as a storage location for CO₂ from North European countries depends on the actual properties of the formation, mitigation strategies, future energy costs, development of CCS technologies, public acceptance and political barriers. All the national energy system models give considerable differences in the CCS implementation dependent on the emission reduction targets. The national models have been analysed with both 20 % and 80 % emission reduction targets towards 2050.

Results
Under tight climate targets for Europe (C-80), the use of costly storages and long transport distances is necessary and the Utsira storage formation gains competitive and represents a valuable CO₂ storage option. The total electricity generation in the countries of the North Sea region (Germany, Denmark, the Netherlands, Norway and the UK) reaches almost 2000 TWh in 2050 (Figure 108). This development is characterised by the switch of the demand sectors from fossil fuel based technologies to electricity applications under a strong climate policy. The electricity generation changes towards a low carbon intensive structure with a high share of renewable technologies (56 % of total generation in 2050) and a widespread use of CCS technologies (38 % in 2050).

Figure 108. Electricity generation in the neighbouring countries of the North Sea

The CO₂ quantities captured increase from 50 Mt in 2020 to 570 Mt in 2050. CO₂ is primary captured from CCS technologies of public electricity and heat generation (90 % in 2050). Large CO₂ quantities are captured in Germany, reaching a level of 300 Mt in 2050.

CO₂ storage quantities exceed the quantities of carbon captured due to additional CO₂ amounts coming from Belgium and Poland to be stored in the Netherlands and Germany. In total almost 640 Mt CO₂ are stored in 2050 (Figure 109). The CO₂ is primary stored in saline aquifers with 40 Mt in 2020 increasing drastically to 240 Mt in 2030, and 400 Mt in 2050. Storage in onshore aquifers had a share of 45 % of total aquifer storage in 2050. CO₂ storage in hydrocarbon fields reaches a level of 100 Mt to 140 Mt for the period 2030 to 2050. The reason behind is cross-border carbon exchanges from Germany to the Netherlands.
Alternative infrastructure schemes for the Utsira connection in the North Sea have almost no influence on the energy system of the neighbouring countries of the North Sea. The total quantities remain on a level of 590 Mt in 2040 and 640 Mt in 2050 independent from the pipeline network layouts. However, the CO₂ quantities transported to Utsira differ slightly (Figure 110).
Table 12. Comparison of national and regional results –CO2 storage in Utsira (C-80)

<table>
<thead>
<tr>
<th>Country (Infra I)</th>
<th>2030</th>
<th>2040</th>
<th>2050</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regional</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>United Kingdom</td>
<td>12.3</td>
<td>56.4</td>
<td>73.5</td>
</tr>
<tr>
<td>The Netherlands</td>
<td>4.6</td>
<td>34.4</td>
<td>41.4</td>
</tr>
<tr>
<td>Germany</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Norway</td>
<td>8.7</td>
<td>1.7</td>
<td>2.2</td>
</tr>
<tr>
<td>Denmark</td>
<td>0.0</td>
<td>0.2</td>
<td>0.0</td>
</tr>
<tr>
<td>Total</td>
<td>25.7</td>
<td>90.0</td>
<td>116.2</td>
</tr>
<tr>
<td>National</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>United Kingdom</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>The Netherlands</td>
<td>0.0</td>
<td>2.4</td>
<td>105.2</td>
</tr>
<tr>
<td>Germany</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Norway</td>
<td>0.7</td>
<td>0.0</td>
<td>2.9</td>
</tr>
<tr>
<td>Denmark</td>
<td>0.0</td>
<td>2.0</td>
<td>1.4</td>
</tr>
<tr>
<td>Total</td>
<td>0.7</td>
<td>2.4</td>
<td>109.5</td>
</tr>
</tbody>
</table>

According to the PET model results, CO2 transport to Utsira from outside Norway would mainly originated in the UK (60 to 75 Mt/a in and 2050) and in the Netherlands (20 to 50 Mt/a in 2040 and 2050). The United Kingdom profit from the comparably short transport distance to Utsira and the Netherlands utilise the Utsira formation due to limited domestic low cost storage possibilities over time and the fact that the country appears to become a CO2 hub for the region. In Germany and Denmark the availability of domestic onshore saline aquifers determines the competitiveness of CO2 storage in Utsira. If these aquifers are not usable, Utsira will be a competitive storage option.

A main limitation for the use of the Utsira formation is the maximum annual injection rate for CO2. This appears as a stronger limiting factor than the total storage capacity. The maximum simulated injection rate that was found in the literature is 150 Mt CO2 per year. Under stringent mitigation targets the requirement of annual CO2 capture can exceed 150 Mt per year in the North European countries. To obtain a better understanding of the limitation of the Utsira formation as a possible storage location for North European CO2, further research on the injection rate capacity will be required.

2.1.2.3 Other studies with the PET model

Renewable heat: A policy and techno-economic assessment of EU2020 targets

Renewable heat, especially biomass, plays a very important role in the action plans of different Members States and can take up a share of more than 20% in the gross energy consumption for heating and cooling by 2020. We (117) created cost curves for the implementation of renewable energy technologies in Flanders, for electricity production as well as for heat production. This presentation focuses on the status of renewable heat in the NREAP’s, the Flemish renewables cost curve and different subsidy mechanisms for renewable heat.

There is a certificate system for electricity production (CHP certificates, Green electricity: PV, wind, ...) and subsidies, such as tax deduction for some green heat technologies (solar boiler, heat pumps), but no supporting system for biomass heat in Flanders. Do we need it? Probably! But what supporting mechanisms? While the existing supporting mechanisms are focused on technologies with high investment costs and returns based on MWh of production, the biomass heat production technologies are characterized with low investment costs and highly uncertain fuel cost. In addition, supporting mechanism based on fuel use/heat production can have perverse effects: poorly insulated house uses more energy.

Multivariate techniques for the analysis of partial equilibrium energy models results

In this paper (118), multivariate statistical techniques are used to analyse the data output of partial equilibrium energy models developed in the framework of the NEEDS Project, with the aim of emphasising their informational content and reducing redundancies. In particular, Cluster Analysis and Principal Component Analysis are applied to characterise final energy consumption (FEC) and CO2 emission by country (25 European countries) for two different scenarios (Business as Usual – BAU and CO2 450ppmv), and with reference to years 2000, 2015 and 2050.
The overall objective is to set up a general applicable procedure for characterizing data correlation structure and identifying suited indicators, in order to devise advanced tools for supporting decision making processes as well as for assessing the sustainability of energy-environmental strategies. This preliminary application of Cluster Analysis and PCA to partial equilibrium energy models outputs has proven to be useful for improving the post optimal analysis, allowing the users to find out model inconsistencies as well as to identify the key variables in order to devise sustainable and effective energy–environmental strategies.

2.2 Studies using MARKAL Models for Europe

2.2.1 Exploring the implications of an EU-wide ‘ Tradable White Certificate’ scheme

Recent developments in European energy policy reveal an increasing interest in implementing the so-called ‘ Tradable White Certificate’ (TWC) schemes to improve energy efficiency. Based on three evaluation criteria (cost-effectiveness, environmental effectiveness and distributional equity) this paper (119) analyses the implications of implementing a European-wide TWC scheme targeting the household and commercial sectors. MARKAL is applied to a database that depicts the reference energy system of Western Europe—hereafter EU15+. The Energy Information Administration (EIA) of the US Department of Energy (DOE) developed the database\(^5\). In this study, quantitative economic and environmental effects are the result of how the energy system of the EU15+MARKAL model reacts to the modelled TWC scheme.

Scenarios

By forcing the EU15+ energy system to meet a user-defined saving target (i.e. setting a maximum amount of final energy consumption compared to the baseline scenario), the analysis attempts to explore cost-effective potentials of cumulative energy savings capable of meeting different levels of mandatory policy ambitions when a TWC scheme is implemented. Thus, it is assumed full compliance, i.e. 100% ‘energy-saving effectiveness’\(^6\). To be taken also as a sensitivity analysis – and related E3 outcomes – different mandatory policy targets are analysed:

- Target-A means that an EU-wide supports the achievement of the indicative cumulative saving target of 1% per year (over 9 years) as set by the EEE&ES Directive.
- Target B means that an EU-wide aims at realizing already identified energy saving potentials (30%) for the household and commercial sectors - the achievement of target A is then implicit.
- Target-C aims at exploring a rather ambitious energy saving target (N50%) going beyond the ones identified in the literature - the achievement of target-A and B is then also implicit.

---

\(^5\) The EIA-DOE developed the System for Analysis of Global Energy Markets (SAGE) to examine a wide range of global energy issues; it integrates a set of regional models for the development of the International Energy Outlook, 2003. In SAGE, 15 regions are identified based upon political, geographical and environmental factors: Africa, Australia–New Zealand, Canada, Central and South America, China, Eastern Europe and Former Soviet Union, India, Japan, Mexico, Middle-East, Rest of Asia, South Korea, United States, and Western Europe. For each region, input information regarding energy service demands are developed using economic and demographic projections. 12 The entire documentation of the model and a detailed data implementation guide can be found at http://tonto.eia.doe.gov/ ftproot/modeldoc/m072(2003)1.pdf and http://tonto.eia.doe.gov/ftproot/modeldoc/m072(2003)2.pdf.

\(^6\) Energy efficiency is simply defined as decreased energy consumption while always keeping energy service demands satisfied. This evaluation criterion is defined herewith as whether obliged parties meet or not a mandatory energy saving target, i.e. effectiveness towards compliance level.
Results

Estimates of marginal life cycle energy saving costs were calculated from the absolute changes in energy system costs when adding extra units of energy saved under each time step as a result of pre-defined energy saving targets. For simplification, lower and upper bounds of marginal costs for each target applied are shown in Figure 111. Figures range from $-2$ to $8$ Euro cents/ kWh. Current minimum and maximum household energy fuel costs (excluding taxes and value-added tax [VAT]) of countries were used as benchmarks for comparison. Depending on the fuel saved, different cost effective potentials are identified.

One can observe minimum and maximum nominal electricity costs corresponding to Greece (lowest) and Denmark (highest), respectively. Based on these values, both target-A and -B are met cost-effectively, i.e. even if the lowest electricity costs (as in Greece) are used as a benchmark, there is up to 27% (ca. 5100 PJ or 1400 TWh) of technical potential of energy savings (compared to the baseline) by 2020 that generates net financial benefits. Minimum and maximum nominal costs for household gas consumption are also shown, corresponding to the UK (lowest) and Sweden (highest), respectively.

Figure 111. Marginal life cycle energy saving costs under different cumulative energy saving targets (2005–2020)*

*Household fuel costs (maximum and minimum values for electricity and gas in EU15+) are used as benchmarks to identify financial cost-effective potentials of energy savings under the modelled EU-wide TWC scheme.

Based on the results, cost-effective supply of TWCs is predominant in the household sector for all energy-saving targets applied. In terms of fuels, gas dominates the supply of TWCs. Regarding the sources of TWCs as regards energy service demand, results are shown in Figure 112. Overall, whereas space heating represents the dominant source of savings within the household sector; lighting and space heating are equally relevant within the commercial sector. As observed, trends are consistent in all scenarios — for both sectors and main fuels (electricity and gas).

Using a bottom-up model, quantitative results show significant cost-effective potentials for improvements, with the household sector, gas and space heating representing most of the TWC supply in terms of eligible sector, fuel and energy service demand, respectively.

If a single market price of negative externalities is considered, a societal cost effective potential of energy savings above 30% (compared to the baseline) is observed. In environmental terms, the resulting GHG emission reductions are around 200Mt CO2-eq by 2010, representing nearly 60% of the EU-Kyoto-target. From the qualitative perspective, several embedded ancillary benefits are identified (e.g. employment generation, improved comfort level, reduced ‘fuel poverty’, security of energy supply). Whereas an EU-wide TWC increases liquidity and reduces the risks of market power, autarky compliance strategies may be expected in order to capture co-benefits nationally. Cross subsidies could occur due to investment recovery mechanisms and there is a risk that effects may be regressive for low-income
households. Assumptions undertaken by the modelling approach strongly indicate that high effectiveness of other policy instruments is needed for an EU-wide TWC scheme to be cost-effective.

**Figure 112. Supply of TWCs — sources per eligible sector, fuel and energy saving demand under target-A**

2.2.2 Assessment of the European energy conversion sector under climate change scenarios

In this dissertation (120,121,122), the European energy conversion sector and with special focus, the electricity generation sector were analyzed regarding the impacts of climate change on the energy infrastructure, and possible GHG emission reduction pathways, in respect of costs, and energy system parameters, such as technology choices and capacity installation.

EuroMM was developed in the course of this dissertation at the Paul Scherrer Institute, in context of the European ADAM project, where it was used to analyze climate change adaptation and mitigation scenarios for the European energy conversion sector. EuroMM disaggregates Europe (i.e., EU-27 plus Norway and Switzerland) into 18 regions (Figure 113).

**Figure 113. Disaggregation of Europe into 18 regions which were considered in EuroMM**

In this model, power generation technologies from small scale CO2-free power generation units, to large scale conventional fossil power generation systems, an electricity transportation and distribution system, as well as fuel production technologies for fossil fuels, biofuels and hydrogen were implemented based on cost, availability and efficiency parameters. Additionally, the model included
special features on power plant availabilities, the use of water for cooling of thermal power capacity and incorporated estimates on river temperatures. The optimization model was solved as a mixed integer problem, to make lumpy capacity investments for large scale technologies available.

**Scenarios**

- Business as usual
- Adaptation: with higher global average temperatures in 2050
- Mitigation 1: 450 ppm CO₂-eq emissions target (50% probability of achieving 2°C target)
- Mitigation 2: 400 ppm CO₂-eq emissions target (80% probability of achieving 2°C target)

**Results**

In the analysis of mitigation scenarios it was found that the European electricity sector can reduce GHG emissions by up to 90% until 2050, under stringent climate targets. However, large changes to the energy infrastructure are necessary to achieve such targets (Figure 114). Especially the deployment of CO₂-free technologies such as wind power and the extension of the electricity grid for trade purposes are mandatory to reduce the costs of mitigating climate change. Furthermore, emissions reductions from other sectors are needed to ensure, stringent mitigation targets can be reached, allowing to stabilize climate change below 2°C increase until 2100.

**Figure 114. Electricity generation in adaptation and mitigation scenarios**

In the scenario analysis of adaptation, it has been found that especially southern Europe needs to prepare for warmer climate. It has been found that expected higher water temperatures of rivers are likely to decrease availability and efficiency of thermal power plants, and that reduced river runoff is likely to decrease the output of hydro power in the future, under a warmer climate. To cope with such instances, costly investments in advanced cooling technologies are mandatory in southern Europe. Nordic European countries on the other hand may profit from warmer temperatures, decreasing the energy consumption for space heating, and an increased precipitation is likely to favor additional output of hydro power.

**2.3 Studies using MARKAL Models for Asia**

**2.3.1 Energy security in the Greater Mekong Sub-region Countries**

The paper (123) evaluates effects of energy resource development within the Greater Mekong Sub-region (GMS) on energy supply mix, energy system cost, energy security and environment during 2000–2035. A MARKAL-based integrated energy system model of the five GMS countries was developed to examine benefits of regional energy resource development for meeting the energy demand of these countries.
Two sets of the models were developed to carry out the study. First, five separate national models based on MARKAL (i.e., for Cambodia, Laos, Myanmar, Thailand and Vietnam) representing the independent energy system of each country were formulated. Having developed the national energy system models, the second step in developing the integrated GMS–MARKAL model involves connecting infrastructures of the bilateral, regional and inter-country energy linkages within the GMS and with the rest of the world to the five national energy systems.

Scenarios

Four scenarios are studied; (i) base case, (ii) unrestricted energy trade case, (iii) individual emission reduction target case and (iv) joint emission reduction target case.

Two alternative options of CO₂ reduction by 5% of the emission level under the UNRTD case are considered for this purpose:

- (i) individual country CO₂ abatement target of at least 5% of the CO₂ emission from each of the study countries in the UNRTD case (i.e., the individual emission reduction target case, hereafter ‘‘IND-ERT’’) and
- (ii) the joint emission reduction target of 5% of the combined regional level emission from the five countries (hereafter ‘‘JOINT-ERT’’ case).

Results

As can be seen from Table 13, the total cost of the integrated energy system of the selected GMS countries as a whole (hereafter, GMS means all GMS countries except China) including the international energy linkages within the GMS under the base case is estimated as $1298 billion, which is 18% higher than that of the unrestricted case. This strongly indicates that the expansion of energy cooperation within the region is beneficial to the GMS as a whole in terms of a lower energy system cost.

Table 13. Total discounted energy system cost during 2000–2035 for the base case and UNRTD casea, 10⁹ US$.

<table>
<thead>
<tr>
<th>Case</th>
<th>Discounted energy cost</th>
<th>Cambodia</th>
<th>Laos</th>
<th>Myanmar</th>
<th>Thailand</th>
<th>Vietnam</th>
<th>Inter-country linkages</th>
<th>GMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base</td>
<td>Domestic energy production cost</td>
<td>9.1</td>
<td>19.8</td>
<td>68.8</td>
<td>623.3</td>
<td>387.2</td>
<td>1.1</td>
<td>1,109.3</td>
</tr>
<tr>
<td></td>
<td>Net imported energy</td>
<td>6.7</td>
<td>(5.0)</td>
<td>(11.4)</td>
<td>207.8</td>
<td>(9.2)</td>
<td>–</td>
<td>188.8</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>15.8</td>
<td>14.8</td>
<td>57.4</td>
<td>831.1</td>
<td>377.9</td>
<td>1.1</td>
<td>1,298.2</td>
</tr>
<tr>
<td>UNRTD</td>
<td>Domestic energy production cost</td>
<td>3.3</td>
<td>18.5</td>
<td>77.4</td>
<td>471.3</td>
<td>359.0</td>
<td>2.1</td>
<td>877.7</td>
</tr>
<tr>
<td></td>
<td>Net imported energy</td>
<td>6.4</td>
<td>(5.7)</td>
<td>(17.7)</td>
<td>215.1</td>
<td>(8.3)</td>
<td>–</td>
<td>189.8</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>9.8</td>
<td>12.8</td>
<td>50.7</td>
<td>632.3</td>
<td>350.7</td>
<td>2.1</td>
<td>1,067.5</td>
</tr>
</tbody>
</table>

a The numbers in parenthesis represents that the countries have net energy export.

As can be seen from Table 14, the implementation of CO₂ emission abatement policy under an unrestricted energy resource development and trade within the region would not significantly affect the integrated energy system cost. At the individual national levels, Laos would register the highest decrease in the energy system cost (11% more than that of the UNRTD case). The restriction of CO₂ emission among the five GMS countries is found to change theirs energy system. The biomass-based power generation technology would be the most cost-effective option for the energy systems of Cambodia, Laos and Thailand while wind and nuclear power generation technologies are appropriate for the energy systems of Myanmar and Vietnam, respectively. It is also found that the volumes of power exported from Laos and Myanmar under the CO₂ emission abatement target case are larger (i.e., 36% and 45% higher, respectively) than those in case of without a CO₂ emission constraint.

Table 14. Total discounted energy system cost during 2000–2035, 10⁹ US$

<table>
<thead>
<tr>
<th>Case</th>
<th>Discounted energy cost</th>
<th>Cambodia</th>
<th>Laos</th>
<th>Myanmar</th>
<th>Thailand</th>
<th>Vietnam</th>
<th>Inter-country linkages</th>
<th>GMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>IND-ERT</td>
<td>Domestic energy production cost</td>
<td>3.6</td>
<td>21.4</td>
<td>81.2</td>
<td>417.3</td>
<td>357.9</td>
<td>2.5</td>
<td>883.8</td>
</tr>
<tr>
<td></td>
<td>Net energy import cost</td>
<td>6.4</td>
<td>(7.1)</td>
<td>(99.4)</td>
<td>215.1</td>
<td>(7.4)</td>
<td>–</td>
<td>187.6</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>10.0</td>
<td>14.2</td>
<td>61.8</td>
<td>632.3</td>
<td>350.5</td>
<td>2.5</td>
<td>1,071.3</td>
</tr>
<tr>
<td>JOINT-ERT</td>
<td>Domestic energy production cost</td>
<td>3.3</td>
<td>20.7</td>
<td>78.9</td>
<td>419.2</td>
<td>358.4</td>
<td>2.3</td>
<td>882.8</td>
</tr>
<tr>
<td></td>
<td>Net energy import cost</td>
<td>6.5</td>
<td>(6.7)</td>
<td>(18.1)</td>
<td>214.5</td>
<td>(7.7)</td>
<td>–</td>
<td>188.5</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>9.8</td>
<td>14.0</td>
<td>60.8</td>
<td>637.7</td>
<td>350.7</td>
<td>2.3</td>
<td>1,071.2</td>
</tr>
</tbody>
</table>
All the five countries except Myanmar would benefit from the expansion of regional energy resource integration in terms of lower energy systems costs and better environmental qualities. An imposition of CO₂ emission reduction constraint by 5% on each of the study countries from that of the corresponding emissions under the unrestricted energy resource development in the GMS is found to improve energy security, reduce energy import and fossil fuels dependences and increase volume of power trade within the region. The total energy system cost under the joint CO₂ emission reduction strategy would be less costly than that under the individual emission targets set for each country.

### 2.3.2 Effects of cross-border power trade between Laos and Thailand

This paper (124) analyzed the effects of hydropower development in Laos and power trade between Laos and Thailand on economy wide, energy resource mix, power generation capacity mix, energy system cost, environment, as well as, energy security. A MARKAL-based model for an integrated energy system of Laos and Thailand was developed to assess the effects of energy resource development and trade to meet the national energy demands of the two countries.

Two main steps are followed to construct this integrated model. Firstly, a MARKAL model representing the energy systems of Laos and Thailand are developed. Secondly, infrastructures of the bilateral energy linkages (e.g., power grid transmission lines, natural gas pipeline, and lignite trade linkage) between Thailand and Laos are constructed. Altogether, there are two country-level energy systems and one system of physical trade linkages between these two countries combined in the model.

### Scenarios

Three scenarios were studied:

- **Low level (BASE):** The joint energy system development of Laos and Thailand during the planning horizon of 2000–2035 is evaluated under existing power trade agreements. The level of power purchased by Thailand from Laos is restricted to the level of 5.0 GW by 2011 as stipulated in the existing electricity purchase agreement between the two countries.

- **Medium level (HY60):** Laos and Thailand moderately expand their cross-border power trade beyond the level stipulated in the base case in that the hydropower development in Laos could be allowed up to 60% of the hydropower potential. The exploitable hydropower resource was limited to 40% of the maximum potential during 2000–2010 and gradually increases up to 60% by 2035. Any surplus hydropower after meeting the domestic demand in Laos was assumed to be available for export to Thailand.

- **High level (HY80):** The level of hydro-electric exploitation in Laos was set to increase from 40% of that country’s hydropower potential during 2000–2010 and rise up to 80% by 2035. All other things were similar to the HY60 case.

### Results

Discounted total cost of an integrated energy system of Laos and Thailand in the base case during 2000–2035 is found at $878 billion (Table 15), which is nearly the same as the case of high level of hydropower development in Laos (HY80). In terms of the relative energy system cost, the energy cost of Thailand in the HY80 case is estimated to 0.2% ($2055 million) because of the reduction of domestic power generation capacity and increasing power imported from Laos. On the contrary, the energy cost of Laos is found to increase by 10.6% ($1521 million). Though Laos would gain more revenue from more power export, the higher cost would stem from expansions of power generation capacity.
Table 15. Discounted energy system costs of Laos and Thailand (10. US$).

<table>
<thead>
<tr>
<th>Cases</th>
<th>BASE</th>
<th>HY60</th>
<th>HY80</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laos</td>
<td>Capacity (GW)</td>
<td>10.5</td>
<td>13.9</td>
</tr>
<tr>
<td></td>
<td>Export (TWh)</td>
<td>50.6</td>
<td>62.1</td>
</tr>
<tr>
<td></td>
<td>% exported power to Thailand as of the total export</td>
<td>75</td>
<td>97</td>
</tr>
<tr>
<td>Thailand</td>
<td>Capacity (GW)</td>
<td>137.6</td>
<td>134.2</td>
</tr>
<tr>
<td></td>
<td>Import (TWh)</td>
<td>47.4</td>
<td>70.7</td>
</tr>
<tr>
<td></td>
<td>% imported power to Thailand as of the total import</td>
<td>76</td>
<td>81</td>
</tr>
</tbody>
</table>

As can be seen from Table 16, total power generation capacity of Laos by 2035 in the HY80 case is expected to be 7.1GW higher than that of the base case. The percentage share of the power exported to Thailand is estimated to increase to 98% of the total power export (as compared to 75% in the base case). The result also shows that Thailand would have positive impact under the intermediate level of water resource in Laos (HY60) due to there would still be a substantial reduction in the energy system cost.

Table 16. Power generation capacity (GW), power export/import (TWh) of Laos and Thailand in 2035

<table>
<thead>
<tr>
<th>Country</th>
<th>Case</th>
<th>Investment cost</th>
<th>O&amp;M costs</th>
<th>Net imported energy cost</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laos</td>
<td>Base</td>
<td>7631</td>
<td>13,715</td>
<td>-7066</td>
<td>14,279</td>
</tr>
<tr>
<td></td>
<td>HY60</td>
<td>8208</td>
<td>15,016</td>
<td>-7943</td>
<td>15,281</td>
</tr>
<tr>
<td></td>
<td>HY80</td>
<td>8699</td>
<td>15,585</td>
<td>-8485</td>
<td>15,799</td>
</tr>
<tr>
<td>Thailand</td>
<td>Base</td>
<td>521,266</td>
<td>135,598</td>
<td>206,221</td>
<td>863,085</td>
</tr>
<tr>
<td></td>
<td>HY60</td>
<td>520,698</td>
<td>134,146</td>
<td>206,841</td>
<td>861,685</td>
</tr>
<tr>
<td></td>
<td>HY80</td>
<td>520,479</td>
<td>133,317</td>
<td>207,236</td>
<td>861,031</td>
</tr>
<tr>
<td>Cross-country linkages</td>
<td>Base</td>
<td>596</td>
<td>235</td>
<td>0</td>
<td>830</td>
</tr>
<tr>
<td></td>
<td>HY60</td>
<td>741</td>
<td>271</td>
<td>0</td>
<td>1012</td>
</tr>
<tr>
<td></td>
<td>HY80</td>
<td>806</td>
<td>287</td>
<td>0</td>
<td>1093</td>
</tr>
</tbody>
</table>

The results show that 80% exploitation of water resource in Laos would induce power trade between the countries. The integrated energy system cost is found to decrease marginally but it would mitigate the CO2 emission by 2% when compared with the base case. Thailand is expected to gain benefit from the increased level of power imported from Laos in terms of the lower energy system cost, better environmental quality and, greater diversification of energy sources. As compared to the base case, Laos would become the net energy exporter, earn significant export revenue, and improve the increase in revenue of energy export per increase in total energy system cost from the maximum exploitation of hydropower resource.

The analysis is found that the cross-border power trade policy would secure energy sources of supply for Laos and Thailand. Finally, this paper concluded that cross-border power trade policy between Laos and Thailand and expansion of hydropower development in Laos would generate significant benefits to them.

2.3.3 Clean energy in the South East Asian Nations countries

This paper (125) focuses on energy system development of the three largest Association of South East Asian Nations (ASEAN) countries: Indonesia, Philippines and Vietnam. This paper examines and quantifies the role of clean and advanced energy technologies for efficient local resource exploitation and improving energy security and environmental conditions. The main focus is on the power sector.

Within the Australian-ASEAN Energy Policy System Analysis Project (EPSAP) 4 a MARKAL model was developed for each of the ASEAN country’s energy systems. In the current study, these existing modelling frameworks are used as starting models which then have been considerably modified and upgraded for the purpose of the study.
Scenarios

In the Business-as-Usual (BAU) Scenario, the technology choices (for power generation) available to the model are reflecting technologies currently widely used in the studied countries. In the Technology Scenarios, additional fossil and renewable power generation technologies, which are, currently commercially available in the market or expected to be available within the time frame of the analysis, are available to the model. The technologies considered are presented in Table 17.

<table>
<thead>
<tr>
<th>Category</th>
<th>Fuel source</th>
<th>Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fossil</td>
<td>Coal</td>
<td>Supercritical pulsed coal combustion (Coal-SC)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Circulating fluidised bed combustion (CFBC)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Integrated gasification combined cycle (IGCC)</td>
</tr>
<tr>
<td>Fossil</td>
<td>Natural gas</td>
<td>Advanced combined cycle gas turbine (Adv-CCGT)</td>
</tr>
<tr>
<td>Nuclear</td>
<td>Uranium</td>
<td>Pressurized water reactors (PWRs)</td>
</tr>
<tr>
<td>Renewables</td>
<td>Biomass</td>
<td>Co-firing</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Combustion-power only</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Combustion-heat and power (Biomass-CHP)</td>
</tr>
<tr>
<td>Renewables</td>
<td>Wind</td>
<td>Onshore</td>
</tr>
<tr>
<td></td>
<td>Solar</td>
<td>Solar PV</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Solar-thermal</td>
</tr>
</tbody>
</table>

The objective is to identify the maximum potential reduction that can be achieved with the help of additional technologies. Hence, an additional constraint on CO2 reduction is imposed to the model. For each country, two scenarios are constructed targeting low and high CO2 emissions reductions. The CO2 reduction scenarios are simulated for both low and high oil price cases (Table 18).

<table>
<thead>
<tr>
<th>Policy constraints</th>
<th>Technology database</th>
<th>Indonesia</th>
<th>Philippines</th>
<th>Vietnam</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Low oil</td>
<td>High oil</td>
<td>Low oil</td>
</tr>
<tr>
<td></td>
<td></td>
<td>price</td>
<td>price</td>
<td>price</td>
</tr>
<tr>
<td>Business-as-Usual</td>
<td>No</td>
<td>No</td>
<td>IBAU-L</td>
<td>PBAU-L</td>
</tr>
<tr>
<td>Technology Scenario</td>
<td>No</td>
<td>Yes</td>
<td>IBAU-H</td>
<td>PBAU-H</td>
</tr>
<tr>
<td>CO2 reduction-low target</td>
<td>Yes</td>
<td></td>
<td>ITECH-L</td>
<td>PTECH-L</td>
</tr>
<tr>
<td>CO2 reduction-high target</td>
<td>Yes</td>
<td></td>
<td>ICO2-L1</td>
<td>PCO2-L1</td>
</tr>
<tr>
<td>CO2 reduction-high target</td>
<td>No</td>
<td></td>
<td>ICO2-L2</td>
<td>PCO2-L2</td>
</tr>
<tr>
<td>CO2 reduction-high target</td>
<td>No</td>
<td></td>
<td>ICO2-L3</td>
<td>PCO2-L3</td>
</tr>
<tr>
<td>Import reduction</td>
<td>Yes</td>
<td>IPERED-L</td>
<td>PENSEC-L</td>
<td>PENSEC-H</td>
</tr>
<tr>
<td>Primary energy reduction</td>
<td>Yes</td>
<td></td>
<td>IPERED-H</td>
<td>VPER-L</td>
</tr>
</tbody>
</table>

Results

In Indonesia, radical changes are seen in the power system in terms of future technology choices (Figure 115). In 2030, at the low reduction target, similar to 2020, CFBC and advanced CCGT are the most favourable technologies, which together generate about 75% of the total generation. When the reduction target is high, supercritical coal power with its higher efficiency replaces CFBC partly. Generation from advanced CCGT is even higher.

In Philippines, the major impacts are to be seen in the power sector (Figure 116): the share of sub-critical pulsed coal technology decreases due to its relatively lower efficiency; coal supercritical technology is the most favourable option followed by CFBC while IGCC remains uncompetitive; and advanced CCGT, offering 60% and 63% efficiency in 2020 and 2030, respectively, is replacing CCGT. In the low CO2 reduction case, the shares of renewables are 39% and 24% in 2020 and 2030, respectively, compared to 32% and 22% in the PBAU-L case. When the higher CO2 target is attempted in 2030, the share of renewables is only marginally higher.

In Vietnam, the CO2 reduction scenarios with additional technological options, the model selects supercritical coal power, CFBC, advanced CCGT, instead of sub-critical and CCGT technologies (Figure 117). When the reduction target is higher, it is only higher efficient supercritical technology which is
cost-effective for coal-based power plants. While hydro power makes additional contribution in 2020 to curb CO₂ emissions, in 2030, no additional contribution is possible as it already has hit the maximum potential in VBAU-L/H case.

Figure 115. Power generation in CO₂ reduction scenarios in low oil price case - Indonesia

Figure 116. Power generation in the CO₂ reduction scenarios in low oil price case - Philippines

Figure 117. Power generation in the CO₂ reduction scenarios and VBAU-L case - Vietnam
The paper concludes that there is a large potential market for clean and advanced energy technologies in the studied countries. If adopted, these technologies will bring several benefits like reduction in primary energy requirement, reduced investments requirement in the power sector and other parts of the energy infrastructure, reduced import of primary energy, reduced CO₂ emissions and local pollution, reduced energy system costs and marginal cost of electricity supply.

2.3.4 The ESMOPO Project and the POEM modelling framework

These presentations (126,127,128,129) introduced the ESPOMO and the POEM modelling framework.

2.3.4.1 The ESMOPO (Europe – South-east Asian Energy Modelling and Policy Programme) project

The ESMOPO (2005-2007) is co-financed by the European Union through EC-ASEAN Energy Facility Program. Target groups include a wide range of organisations involved in regional as well as global development, research and business activities, i.e. country-specific energy policy and decision making institutions, ASEAN, ASEAN energy industries, European Union, European energy industries and donor and lending organisations.

The project considers three ASEAN countries: Indonesia, Philippines and Vietnam. The project aims at developing country specific energy system models in the MARKAL modelling framework in order to identify country specific appropriate energy technologies and to quantify their implications in terms of energy savings, fuel substitution, investment and pollutions avoided. The main focus is on renewable and advanced fossil technologies.

Scenarios


- BAU-L (BAU-Low oil price case)
- BAU-H (BAU-High oil price case)

Technology scenario: Enhanced use of clean and advanced technologies (European technologies).

- TECH-L (BAU-L+Technology database)
- TECH-H (BAU-H+Technology database)

Results

Results from the technology scenarios are shown below: the cumulative CO₂ reduction potentials (Figure 118), as well as a priority list of clean and advanced technologies by countries (Table 19).

Figure 118. Cumulative CO₂ reduction potentials
2.3.4.2 The POEM modelling framework

Developing countries are reluctant to make any binding commitment as their per capita emissions are low and climate abatement measures conflict with their main priorities on socio-economic development. The question is if there is a way to simultaneously provide sufficient energy to support poverty alleviation and economic growth and achieve sufficient emission reductions.

The main focus of the study is on India and China. The primary objective is to develop a portfolio of policy options including both international and national policies as well as institutional frameworks for international cooperation for these two emerging economies to engage them in climate protection measures under a post-2012 regime.

By applying an integrated modeling framework, the study will explore possible multiple pathways which may exist for these countries to contribute into international climate initiatives without compromising their national development priorities. Specific objectives are:

- developing country-specific integrated modeling framework to analyse policies and identify multiple pathways to achieve socio-economic and climate targets
- identifying/designing international climate polices in post-Kyoto regime for future commitments and participations of emerging economies (India and China)
- designing national polices (in socio-economic sectors, energy and environment) compatible with the global climate targets
- designing and quantifying as much as possible the international co-operations needed to make the participation in a post-2012 regime acceptable at least in economic terms
- disseminating the results to potential users for use in future negotiations

The methodology involves the application of integrated modelling framework, on a oft-linking approach primarily, with common assumptions, iterative work procedure and a cocus on co-benefits (local environment, health and energy security). The relate global and national models to be applied are:

- the global climate model FAIR connected to global energy model TIMER,
- the global GE model DART,
- the global population and health model PHOENIX,
- a national macro-economic model (India),
- a national energy system model MARKAL (India)
- a national macro-economic model (China),
- a national energy system model MARKAL (India).

2.4 Studies using MARKAL-TIMES model in North America

2.4.1 TIMES-Canada: energy and climate policies in Canada

The main objective with this contribution (130,131) is to present a Canadian project that aim at developing a new inter-provincial energy model for Canada (TIMES-Canada), to illustrate the richness of the database and to show preliminary results for energy policy analysis. The study is part of a more
general research project realized with strong support and collaboration from the Office of Energy Research and Development (OERD) of Natural Resources Canada.

2.4.1.1 Model and methodology

TIMES-Canada covers the energy system of the 13 Canadian provinces and territories (Figure 119) having their own reference energy system (RES), but linked together through energy, material and emission flows. The model is calibrated to the base-year 2007.

Figure 119. Provinces and territories of Canada


The Reference Energy System (RES) of each province/territory is modeled in details (Figure 120). For example, it includes:

- A total of 52 end-use demand segments into five sectors (agriculture, commercial, industrial, residential and transportation) with repositories including a large number of new technologies available to replace existing stocks.
- All existing centralized and decentralized electricity plant units in Canada (over 3000 units), as well as units already planned for construction or refurbishment in future years.
- A new technology repositories including numerous thermal, clean coal, nuclear and renewable plants (hydro, wind, solar PV, tidal, wave, geothermal).
- Uranium reserves, Canada being the world’s most important producer.
- Recoverable coal reserves, modeled in details, namely bituminous, sub-bituminous and lignite in the Western region, as well as bituminous in the Atlantic Provinces, as well as proven reserves of anthracite at Mount Klappan (British Columbia).
- The technical potential for hydro, geothermal, tidal and wave, the overall capacity that would be possible to exploit technically. Canada still has important unexploited hydro potential, huge potential of wave and tidal power in the Atlantic Provinces and significant potential for geothermal power in British Colombia for high temperature electricity generation.
- The annual potential for solar and wind electricity generation taking into account geographical constraints (since these potentials are not limited by the availability of the resources).
The supply sector covers fossil fuels and biomass production, including primary production and secondary transformation processes (cokeoven gas plants, refineries) as well as oil and gas pipeline, mining processes, fossil fuel reserves and supply curves (see details below).

A trade module covering international exchanges between Canada and any other countries, by countries of origin/destination (exogeneously), and inter-provincial exchanges (endogenously) for crude oil, natural gas, refined petroleum products, coal and LNG.

**Figure 120. Simplified illustration of the reference energy systems in TIMES-Canada**

The primary resources of oil and gas are modeled through a supply curve with steps up to three levels. Each step is characterized by the cost of the resource and the amount of energy (annual) available at this cost. In addition, fossil fuel sources can have up to three categories: located reserves, enhanced recovery and new discovery. There are different primary production technologies for different oil products and reserves types, as different amount of energy is needed for extraction (e.g. located versus enhanced recovery for conventional reserves; mined versus in situ methods for unconventional reserves). The base year calibration process involved the analysis of the recent trends in the oil and gas industry, which required numerous data sources from governments, associations and companies. Some results of this exercise are presented below.

### 2.4.1.2 Overview of the unconventional oil production up to 2030

Our main objective in this presentation (130,131) is to analyze the evolution of conventional and unconventional oil production and exportations on the 2030 horizon in Canada, with their associated costs and GHG emissions. The development of the oil sector is analyzed under three socio-economic growth scenarios using the new energy model TIMES-Canada.
Scenarios

Demands are projected to the 2020 horizon in line with the socio-economic growth rates of the National Energy Board and extended to the 2030 horizon using a regressive approach. The oil sector is analyzed under three socio-economic growth scenarios:

- Central case: The crude oil price is assumed to reach US$ 90/bbl by 2020.
- Low case: The crude oil price is assumed to reach US$ 60/bbl in 2020.
- High case: The crude oil price is assumed to reach US$ 120/bbl in 2020.

Results (preliminary)

An important step was to calibrate the oil sector to a reference scenario that is consider the most accepted trend for the future, today. An in-deep research was performed, based on a detailed evolution of all east offshore projects and all oil sands projects, creating a bottom-up approach to build the supply of upstream primary energy sources up to 2030.

For eastern offshore projects, it was possible to build a distribution of the production trends by water-depth, a relevant approach considering that the production cost is directly correlated to depth. Most promising is production from Water Depth between 400-1000 feet. For western oil sands projects, detailed information was also collected from a large number of different sources about both mining and in-situ projects. These data were used to forecast oil sands production from projects currently been developed and the trend of future projects. It was also possible to build a distribution of the production trends by oil types and extraction approaches a relevant approach considering that the production cost is directly correlated to depth. From these results, is appears that production from oil sands will continue to grow, peaking close to year 2030, if we consider current trend and decay rate from oil sands projects. As for offshore production, it is expected to start by 2025. The resulting forecasts were used to calibrate the oil sector in the reference scenario of TIMES-Canada (Figure 121).

Figure 121. Oil production in the central case in Canada, 1995-2030

Future works will allow sensitivity analyses on techno-economic inputs to model technological considerations taken into account by Canadian and provincial energy policies. In particular, we are working together with our supporting organization, namely Natural Resources Canada, to set up a series of interesting matters such as new technology development (nuclear reactors, clean coal technologies, etc.), liquefied natural gas imports, biofuel and hydrogen production, electrification of transportation, etc.

In addition, the energy demands will be projected to the 2100 horizon using various socio-economic drivers, which are consistent with the storyline behind various families of IPCC scenarios. Finally, another important phase of this research project, funded by the Ministry of Economic Development, Industries and Exportations of Quebec, and realized in collaboration with the REACCESS project of the 7th FP-EU, will be to:

- Characterize and model energy supply corridors for the integrated Canadian market;
• Couple the TIMES-Canada model with the world model TIAM to analyze energy security policies (2030) and climate policies (2100) for Quebec and Canada in the international context.

2.4.2 NE-12 MARKAL: Climate and air quality planning in New England

Northeast States Center for a Clean Air Future (NESCCAF) developed a New England MARKAL energy system model originally encompassing the six New England states (NEMARKAL) to provide Northeast Center for Atmospheric Science and Policy (NCASP) with a powerful tool for planning current policy goals. However, NESCCAF saw the need to characterize the entire Northeast power market in order to accurately assess the potential benefits of such programs within this broader region.

NESCCAF contracted IRG (132) to expand the NE-MARKAL model database and framework to encompass Pennsylvania, New Jersey, New York, Delaware, Maryland, and the District of Columbia, so as to cover the entire planning region, including all the states involved in the Regional Greenhouse Gas Initiative (RGGI). The model will be housed at Northeast States for Coordinated Air Use Management (NESCAUM) and is available to all member states to examine policy issues of particular interest to them.

2.4.2.1 Model and methodology

Development of the NE-12 model was closely linked to several authoritative data sources. The NE-12 model has been fully calibrated to SEDS data for the base year, and a reference case developed that tracks AEO2006 regional results, and incorporates regional and national policies including state renewable portfolio standards and new CAFE standards. The model has also been extensively run and tested as part of the Renewable Energy and Efficiency Modeling Analysis Partnership (REMAP) model comparison project, sponsored by DOE, NREL, and EPA.

The following sections describe the development, data sources, and calibration of each sector of the model in more detail. They also note areas for possible future further development:

• The NE-12 Commercial sector demands were based on the 14 Commercial Demand Subsectors and the Residential sector demands on the 15 residential demand subsectors in NEMS and AEO.

• All industry demands are mapped into the following general end-use categories using MECS data: steam boilers, process heat, machine drive, electro-chemical, feedstock, and other uses.

• The end-use technologies supplying each of the end-use categories are defined by fuel type and are tied together by ADRATIOs that start at the current fuel share but relax over time to allow fuel switching to occur.

• The NE-12 Transportation sector models three highway demand categories: light duty vehicles (TL), heavy trucks (TH), and buses (TB), and uses dummy "other" demands to account for total fuel consumption in the sector. There are five size classes for LDVs and two for heavy trucks. Demand for air travel (TA), ships (TN), and rail (TR) have been aggregated.

• For combined heat and power (CHP) plants, there are two types of applications: independent CHP plants that primarily sell electricity to the grid (the steam can be used in a range of low to medium temperature applications) and industry CHP plants that are more tightly integrated with the industrial processes.

• Electricity trade in the model is represented by interstate bilateral trade links and is limited by two types of constraints: 1) bilateral trade constraints (capacity transfer limit between two states) and 2) joint constraints (limits on the simultaneous flows into or out of a state).

• There are some indigenous resource supplies (particularly coal). However, it was decided that the approach of single fixed-price resource cost should be continued. Imports of fossil
resources and refined petroleum products are available in unlimited amounts at AEO2006 reference case sector delivered prices. Available coal types have been simplified from the forty-plus types NEMS tracks.

- Hydrogen, nuclear and renewables: Cost curves for delivery of centralized and decentralized hydrogen are taken from an Argonne National Lab report. Nuclear fuel costs are taken from NEMS. Renewable resources are indigenous to each state, and supply data for renewables has been modeled in the same manner as was developed for NE-MARKAL.
- A similar issue exists for in-region refineries as for in-region fossil resource production. For NE-12, the technology characterizations for PADD-I could be used, with state level refinery capacity data from EIA’s Petroleum Supply Annual to establish the RESIDs for existing capacity. Dummy demand technologies have been added to track refinery energy consumption and corresponding emissions at AEO 2006 levels, but the refinery products simply considered as imports regardless of whether or not they might have originated within the region.

While NE-12 in its current form can serve as an adequate comprehensive model framework for examining energy and environmental issues for the states in the region, by definition a model needs to be a living entity that is subject to ongoing improvement, expansion, and evolution.

**2.4.2.2 Multi pollutant studies: Integrating climate and air quality planning in Maryland**

This report (133) was undertaken by the Northeast States for Coordinated Air Use Management (NESCAUM) and the Maryland Department of the Environment (MDE). Recognizing that climate change will become the major environmental policy driver over the next decade, MDE seeks to employ analytical approaches and techniques developed by NESCAUM that evaluate least-cost policy pathways for achieving Maryland’s climate goals while also yielding benefits to help the State address its other air quality challenges.

To assist states in moving to an integrated multi-pollutant planning approach, NESCAUM has developed a Multi-pollutant Policy Analysis Framework (MPAF), illustrated in Figure 122. The MPAF contains models that deal with: (1) energy economics -- the Northeast Market Allocation Model (NE-MARKAL) -- and regional economic impacts -- the Regional Economic Models, Inc. (REMI); (2) air quality and acid deposition -- the Community Multi-scale Air Quality Modeling System (CMAQ); and (3) health effects -- the Benefits Mapping and Analysis Program (BenMAP) or the Co-Benefits Risk Assessment Model (COBRA). The centerpiece of the framework is the NE-MARKAL model.

NESCAUM developed a reference case scenario that accounted for Maryland’s Renewable Portfolio Standards (RPS). NESCAUM then provided preliminary analysis of implementing the Regional Greenhouse Gas Initiative (RGGI) program as described in the Maryland Healthy Air Act, and the Maryland Clean Cars Act. Using outputs from NE-MARKAL, NESCAUM then conducted a preliminary health benefits assessment using the Co-Benefits Risk Assessment Model (COBRA). These analyses demonstrate the tools and approaches that MDE can use in the future to evaluate potential policy initiatives.

**Figure 122. NESCAUM’s multi-pollutant policy analysis framework**
Scenarios

NESCAUM developed three basic scenarios. Next, NESCAUM examined a more stringent carbon cap scenario for RGGI and then re-visited the Clean Cars Act, accounting for the lifecycle emissions of transportation fuels.

- The reference case provides the basis for comparison of different policy scenarios within the modeling framework. Some policies already in place in Maryland were built into the reference case, including the Maryland RPS and some mandated controls within the power sector based on the Healthy Air Act.

- The Healthy Air Act requires Maryland to participate in the RGGI:
  - The first mandatory market-based CO₂ emissions cap-and-trade program in the U.S. The 10 participating states, including Maryland, have agreed to cap CO₂ emissions from the power sector in 2008, requiring a gradual decrease over time until a 10 percent reduction in CO₂ to 2008 is achieved by 2018. RGGI is composed of CO₂ budget trading programs in each of the participating states that are linked through CO₂ allowance reciprocity.
  - NESCAUM conducted an additional analysis, using a more aggressive, 30 percent reduction in the RGGI cap relative to 2008 CO₂ levels.

- The Clean Cars Act: NESCAUM quantified the GHG emission reductions that would be achieved in the Northeast through adoption of the California light-duty motor vehicle GHG standards. These standards mandate that CO₂ emissions decline 16 percent relative to 2002 levels by 2016. NESCAUM’s analysis estimated state-specific CO₂ emissions from light-duty vehicles for 2009-2030 for the NESCAUM states.

Results

Results are presented for the RGGI scenarios. The NE-MARKAL model predicts that the RGGI cap on the power sector will be met primarily by substituting coal-fired electricity generation with gas generating units. By 2029, gas-fired generation is predicted to account for 55% of the state’s electric power generation, up from 23% in the reference case. Meeting the RGGI cap would also require a substantive shift away from coal-fired electricity generation (Figure 123). The predictions for renewable generation projects remain identical to the reference case, accounting for seven percent of the state’s electricity by 2029. This predicts that RGGI, as currently designed, would fail to encourage new renewable energy development.

Figure 123. Predicted power sector electricity generation

Because this is a preliminary analysis, NESCAUM has started to identify three areas where there are opportunities for future study.
• First, NESCAUM recommends expanding the analysis to include the other modules of the NESCAUM Multi-Pollutant Policy Analysis Framework, and to explore more policy scenarios contained in Maryland’s Climate Action Plan.

• Second, hand in hand with a more rigorous analysis, NESCAUM recommends that analytical enhancements should be pursued: (1) revisit the power sector (2) examine the transportation sector data and constraints (lower bound gasoline consumption); (3) examined in more detail the relationship between high electricity prices induced by a fix carbon cap and increased deployment of industrial sector combined heat and power (CHP) to the commercial sector; (4) examine the interaction between ethanol incentives and emissions of nitrogen oxides (NOx).

• Third, efforts should be focused on how to build capacity in-house at MDE so that it can engage in multi-pollutant planning using the suite of the tools within the NESCAUM Framework.

Figure 124 summarizes the grid mix over the modeling timeframe under a more aggressive cap in the RGGI region of 30% GHG reductions by 2030 relative to 2008 levels. The model responded to this hypothetical GHG cap scenario by implementing renewable electricity to a much larger extent, accounting for more than twice the share of generation in 2029, compared to the RGGI scenario. With an average annual rate of growth of 10%, renewable projects were predicted to be the second fastest growing source of electricity in Maryland under this more aggressive cap.

Because this is a preliminary analysis, NESCAUM has started to identify three areas where there are opportunities for future study.

• First, NESCAUM recommends expanding the analysis to include the other modules of the NESCAUM Multi-Pollutant Policy Analysis Framework, and to explore more policy scenarios contained in Maryland’s Climate Action Plan.

• Second, hand in hand with a more rigorous analysis, NESCAUM recommends that analytical enhancements should be pursued: (1) revisit the power sector (2) examine the transportation sector data and constraints (lower bound gasoline consumption); (3) examined in more detail the relationship between high electricity prices induced by a fix carbon cap and increased deployment of industrial sector combined heat and power (CHP) to the commercial sector; (4) examine the interaction between ethanol incentives and emissions of nitrogen oxides (NOx).

• Third, efforts should be focused on how to build capacity in-house at MDE so that it can engage in multi-pollutant planning using the suite of the tools within the NESCAUM Framework.

Figure 124. Predicted power sector electricity generation under a more aggressive cap (30% below 2008 by 2029)
2.4.2.3 Other studies using the NE-MARKAL model

Exploring the benefits of insulation investment and home weatherization

This presentation (134) explores the potential for energy savings and economic and environmental benefits in residential heating sector in New England using NE-MARKAL. The unconstrained case is a policy case representing the availability of a low interest loan for insulation purchases. The policy is represented by lowering the implicit discount rate to 3% and cumulative cap on total investment of 15% of New England’s households. Additional runs consider the interaction between investment patterns and insulation cost estimates. Investment patterns can a) starts high and fades out (high to low) or b) ramps up (low to high). The installed cost of insulation estimates considered are: a) $2,840 b) $3,500 c) $4,500.

In unconstrained case insulation investments are made predominantly in the first 5 years of the modeling time frame leading to the most significant energy savings. The savings to investment ratio is favorable as investments are made early (Figure 125):

- Unconstrained returns $1.50 for each dollar invested
- High to Low returns $1.30 for each dollar

![Figure 125. Net Economic Benefits, 2005-2030](image)

Multi pollutant studies: A sensitivity analysis of transportation policy

Currently there are two pilot multi pollutant studies which use MARKAL to weigh the trade offs between and synergies arising from state specific climate and air quality goals. This analysis (135) first examines the multi pollutant implications of policy scenarios being considered in the northeast such as LDV efficiency standards, technology mandates and incentives and second performs a robust sensitivity analysis where 500 to 1000 model runs were preformed. The key input parameters varied in each run were fuel prices and vehicle cost. The sensitivity analysis reveals a fuller range of multi-pollutant tradeoffs by providing a framework to understand the relationship between input assumptions and modeled results.
3. Studies and Projects using National MARKAL and TIMES Models

3.1 Bangladesh

3.1.1 The future choice of technologies and CO₂ emission reduction in the power sector

This paper (136) examines the impacts of CO₂ emission reduction on future technology selection and energy use in Bangladesh power sector up to 2035 considering the base year 2005. It also examines the implications of CO₂ emission reduction targets on energy security of the country. The analysis is based on a long-term energy system model of Bangladesh using the MARKAL framework.

Scenarios

The introduction of the CO₂ emission reduction targets (10% CO₂ reduction, 20% CO₂ reduction and 30% CO₂ reduction referred to hereafter as "CO210, CO220 and CO230" scenario, respectively) directly affects the shift of technologies from high carbon content fossil-based to low carbon content fossil-based and clean renewable.

Results

To summarize the extensive results, the primary energy mix in 2035 is selected as the principal metric (Figure 126). This provides a good indication of the types of choices made by the model to meet the various CO₂ emission reduction targets applied.

The energy security issue is analyzed in terms of changes in net energy import dependency and diversification of energy resources resulting from the selected CO₂ emission reduction targets. Import dependency based on the base scenario value of 100%, drops to 85%, 67%, and 48% in the CO210, CO220 and CO230 scenarios, respectively. On the other hand, the system cost increases slightly by 2.5%, 8% and 9% in 2035 compared to base scenario in the CO210, CO220 and CO230 scenarios, respectively. The system cost increases significantly in the short-term period (2005-2015) due to high investments in the deployment of solar PV based power generation.

Figure 126. Primary energy mix in 2035 and % change in cumulative (2005-2035) system cost*

* The colored bars (except yellow in the middle), provide the breakdown of primary energy use (PJ) for the base scenario in 2005 and all scenarios in 2035. The numbers above each bar indicate the total (expressed in PJ) and percentage of the cumulative coal use that is imported and the total cumulative (expressed in mton) and percentage of CO₂ emission reduction compared to the base scenario during the study period. Oil is not indicated as it is not selected for power generation during the study period. The center yellow bar in the three scenarios on the right in this figure shows the change in cumulative total system cost relative to the base scenario.

The results show that the introduction of the CO₂ emission reduction targets directly affect the shift of technologies from high carbon content fossil-based to low carbon content fossil-based as well as clean, renewable energy-based technologies compared to the base scenario. With the CO₂ emission reduction
target of 10-30%, the cumulative net energy imports during 2005-2035 would be reduced in the range of over 1400 PJ to 4898 PJ compared to the base scenario emission level. The total primary energy requirement would be reduced in the range of 5.5-15.2% in the CO₂ emission reduction targets and the primary energy supply system would be diversified compared to the base scenario.

3.2 Belgium

3.2.1 The role of transport pricing to achieve the EU climate change objectives

This paper (137,138) examines the effects of replacing current fuel taxes by a system of taxes that account better for all the different external costs of the different transport modes. One of the important implications of this reform is that current fuel taxes are decreased to a level of 80 euro/ton of CO₂ but that the mileage related taxes on car and truck use increase. Using the MARKAL–TIMES model for the Belgian energy sector, putting all sectors and technologies on equal footing shows that a fuel tax reform makes that it is not cost efficient to require large CO₂ emission reductions in the transport sector and that traditional car technologies will continue to dominate the car market in 2020–2030. We address two questions:

- What this new form of pricing transport modes and vehicles implies for the selection of car transport technologies in the long term?
- Whether the EU will ultimately be able to reach its overall GHG emission reduction targets given that the transport sector will undergo a dramatic policy shift?

Scenarios

Compared to emissions of 1990, a reduction of emissions with 20% (in 2020) up to 52.5% (in 2050) is required. These reductions are even more impressive when they are compared with a reference case where, in the absence of climate policy, emissions would have grown by some 15% in 2020 compared to 1990 and by some 50% in 2050. Moreover we assume that the nuclear power stations (that still produce more than 50% of electricity production in Belgium in 2005) are all phased out in 2030 and that no international permit trade is possible.

Results

Table 20 reports on the role of the transport sector in the reduction of CO₂ emissions.

Table 20. Role of transport sector in reduction of CO₂ emissions in Belgium

<table>
<thead>
<tr>
<th>Years</th>
<th>2010</th>
<th>2030</th>
<th>2050</th>
</tr>
</thead>
<tbody>
<tr>
<td>Marginal cost of CO₂ reduction (Euro/ton CO₂)</td>
<td>31</td>
<td>68</td>
<td>531</td>
</tr>
<tr>
<td>Percent reduction in transport sector compared to reference scenario (%)</td>
<td>-1</td>
<td>-17</td>
<td>-48</td>
</tr>
<tr>
<td>Percent reduction in national emissions country (%)</td>
<td>-18</td>
<td>-59</td>
<td>-76</td>
</tr>
<tr>
<td>Percent reduction of activity for car transport (%)</td>
<td>&lt;1</td>
<td>&lt;1</td>
<td>-7</td>
</tr>
<tr>
<td>Percent reduction of activity for truck transport (%)</td>
<td>-2</td>
<td>-5</td>
<td>-15</td>
</tr>
</tbody>
</table>

It is interesting to see what technologies are used in the transport sector to respond to very strong CO₂ emission reductions. We find that till 2020, the traditional cars (gasoline and diesel) remain cost effective. From 2030 onwards, the major change is the use of alternative fuels in conventional engines: bio-ethanol, biodiesel and CNG (compressed natural gas) in conventional combustion engines. Many fancy technologies are not cost effective when they are placed in a fair comparison with traditional car technologies. The gasoline and diesel parallel hybrid cars are more fuel efficient but this fuel efficiency comes at a higher cost. The electric technologies never penetrate because the electricity needs to be produced using conventional gas power stations.

An industrialized economy that wants to reduce its emissions of GHG at lowest cost, has more cost efficient options to reduce CO₂ emissions in other sectors than the transport sector. This holds even for very ambitious national targets (30–50%), extra reduction of emissions in the transport sector becomes only cost effective after 2030. This leaves us with the question on the future role of fuel efficiency
standards. This role may be more important when the world is not able to make a self-enforcing climate change agreement.

### 3.2.2 EU-objectives on climate change and renewable energy for 2020

In this paper (139) we analyze the impact for Belgium of the EU-objectives for climate change and renewable energy for 2020. The specific targets for Belgium are a reduction of 15% CO₂eq in 2020 compared to 2005 for the non-ETS sectors and a renewable target share of 13% in 2020. In addition, there is a target for renewable energy in the transport sector of 10% (biofuel target). The issue is studied with the Belgian TIMES model.

**Scenarios**

To evaluate the effect of the EU targets for Belgium, we consider 4 scenario’s, including the reference scenario. The Belgian Kyoto target and the nuclear phase-out are imposed in all scenarios. It is assumed that 7% of the reduction target in 2010 is achieved by buying permits abroad. Only CO₂ emissions are considered as the other GHG are not yet modelled. Table 21 reproduces the definitions and the specific assumptions for the different scenario’s.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>REF</td>
<td>Reference scenario with a CO₂ price for ETS-sectors of 24 €/t after 2020</td>
</tr>
<tr>
<td>REN</td>
<td>Same as REF + 10% biofuel target + 13% Renewable target</td>
</tr>
<tr>
<td>CLIM</td>
<td>A CO₂ price for ETS sectors of 39 €/t in 2020 and a CO₂ emission constraint for non-ETS sectors</td>
</tr>
<tr>
<td>CLIM_REN</td>
<td>Same as CLIM + 10% biofuel target + 13% Renewable target</td>
</tr>
</tbody>
</table>

**Results**

The result in the first column of Table 22 is the relative change of the total discounted energy system cost in TIMES over the entire modelling period until 2050. The result in the second column shows this cost as a ratio to the estimated GDP for Belgium in 2010 (Eurostat).

The CO₂ emissions for the different scenarios are given in Table 23. The CO₂ emissions are not reduced much when only the renewable and biofuel targets are imposed without any climate target, especially in the long term.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>%DIF</th>
<th>%GDP2010</th>
</tr>
</thead>
<tbody>
<tr>
<td>REN</td>
<td>1.4%</td>
<td>5.5%</td>
</tr>
<tr>
<td>CLIM</td>
<td>4.2%</td>
<td>16.2%</td>
</tr>
<tr>
<td>CLIM_REN</td>
<td>4.5%</td>
<td>17.5%</td>
</tr>
</tbody>
</table>
Table 23. CO₂ emissions in the different scenarios (in Mio.t and % reduction)

<table>
<thead>
<tr>
<th></th>
<th>2010</th>
<th>2020</th>
<th>2030</th>
<th>2040</th>
</tr>
</thead>
<tbody>
<tr>
<td>REF</td>
<td>122</td>
<td>149</td>
<td>186</td>
<td>200</td>
</tr>
<tr>
<td>REN</td>
<td>121</td>
<td>124</td>
<td>161</td>
<td>173</td>
</tr>
<tr>
<td>CLIM</td>
<td>119</td>
<td>107</td>
<td>89</td>
<td>80</td>
</tr>
<tr>
<td>CLIM_REN</td>
<td>119</td>
<td>101</td>
<td>87</td>
<td>79</td>
</tr>
<tr>
<td>REN</td>
<td>-1%</td>
<td>-17%</td>
<td>-14%</td>
<td>-14%</td>
</tr>
<tr>
<td>CLIM</td>
<td>-3%</td>
<td>-28%</td>
<td>-52%</td>
<td>-60%</td>
</tr>
<tr>
<td>CLIM_REN</td>
<td>-3%</td>
<td>-32%</td>
<td>-53%</td>
<td>-61%</td>
</tr>
</tbody>
</table>

For a specific evaluation of the renewable target for Belgium, different runs of the CLIM_REN scenario were done with a renewable target going from 10% to 20% in 2020. For the period after 2020, the target is slightly increased from 2020 values. With the increasing target on renewable, the share of biofuels increases: for a renewable target of 13% or more, the cost efficient share of biofuels is more than 10%. For a renewable target of 12% or less, the cost efficient share of biofuels is less than 10%.

In Figure 127, the black line represents the additional annual cost in the year 2020 compared to the situation where a 13% target is imposed. The other marginal cost curve is linear and represents the opportunity cost assuming an international price of a green certificate of 50 €/MWh. The cost of a target for a Member State is after all the price of an international green certificate multiplied with the target. With renewable shares that are higher than 13%, the average additional annual cost for one extra percentage of green energy amounts to 350 M€ (rounded). This conclusion is only valid for 2020, since it has been shown that the marginal cost decreases rapidly after 2025. These computations have been based on the CLIM_REN scenario that assumes a fixed, exogenous price for the ETS sectors.

For the total period (2010-2050), the addition of a renewable and biofuel target on top of the climate target increases only slightly the total cost of a climate only policy. This increase is however mostly concentrated around 2020 and can then be substantial compared to the no renewable case. The addition of the renewable target represents an increase of the annual cost of the energy system of some 4% compared to the reference in 2020.

Figure 127. Additional annual cost in the year 2020 compared to the proposed 13% renewable target

We have shown that the climate and renewable policies interact and that the cost of additional climate or renewable efforts can only be specified when both constraints are clearly specified. While both the climate target and the renewable target contribute to the reduction of the CO₂ emissions, the technological choice they induce can be different, e.g. carbon capture versus electricity production from renewables.
3.2.3 Other studies

3.2.3.1 CCS possibilities for Iron and Steel

This presentation (140) focus on CO₂ emission reductions in the iron and steel industry. It identifies that the CO₂ come at 80–90% from iron production, C containing reductants take O₂ out of pellets or sinter, pellets, sinter are produced mainly from raw iron ore and process emissions. A classical process generates at least 1 ton of CO₂/ton of steel. Reducing CO₂ is possible via: efficiency (today 95% ~ thermodynamics), recycle, low carbon reducing agents and fuels, electrolyse iron ore into metal and oxygen, CCS, use oxygen as a BF feedstock, shift reaction and physical absorption. The results show that: the local context is extremely important; a decrease in CO₂ emissions requires breakthrough technologies (no regret solutions are small), for the integrated EU steel mills, Oxy-fuelled BF with CCS exhibits the fastest deployment potential; the TIMES modeling shows that the differences between technologies are rather small.

3.2.3.2 Dealing with no-regret measures for households in Flanders

The emissions of GHG related to residential heating in Flanders have a significant share in the total Flemish emissions of GHG. An insufficient insulation level of the Flemish houses forms one reason of this high emission level. To estimate the cost-efficient reduction potential of the residential sector, the Environmental Cost Model was extended with the sector households (141). This way, cost curves for GHG can be calculated. The concept of the ECM can be summarized as follows: The demand for a certain domestic comfort level is translated into an energy consumption by taking into account the heating losses through the building envelope and the boiler efficiency.

Reduction measures can lower the heating losses or improve the boiler efficiency. The large reduction potential of cost-reducing or no regret reduction measures forms an interesting result of the residential cost curves. This means that those measures are cost-efficient at even negative CO₂-taxes or marginal costs. The presentation shows results on cost-efficient reduction measures in the residential sector (Figure 128).

Figure 128. Marginal abatement cost curve 2020 cost-efficient reduction measures?

![Figure 128](image_url)

3.3 China

3.3.1 The role of CCS to achieve near zero emissions coal

This paper (144) introduces some areas of recent R&D on CCS in China and focuses, in particular, on the Near Zero Emission Coal (NZEC) project, a China-UK CCS initiative. NZEC is being undertaken in three phases. The ultimate aim of NZEC, following Phase 3, is to have constructed and operated a coal-fired power plant with integral CCS in China.

In this paper, some of the early progress made in NZEC Phase 1 is described. Launched in November 2007, the objectives of Phase 1 are to build confidence in CCS and to explore technology options for
demonstrating coal-fired power generation with CCS in China. NZEC Phase 1 is divided into 5 work packages: 1) Knowledge sharing and capacity building; 2) Future energy technology perspectives; 3) Case Studies for CO₂ Capture; 4) CO₂ storage potential; 5) Policy Assessment and Roadmap.

As part of the feasibility study, an energy systems analysis using the China MARKAL model is being undertaken (145) to provide a perspective on the energy technologies that may be deployed in China to meet its energy needs. Based on growth forecasts and national plans for China, predictions will be made of the technologies and fuels that may be deployed to meet its future needs.

The role of coal and the various technology options for utilising that coal will be identified. An estimate of the CO₂ emissions arising from the utilisation of coal and the potential impact of their release to the atmosphere will be made. The potential for CCS to reduce CO₂ emissions to the atmosphere, and the cost and impact of deploying CCS will be examined. In this paper, the authors will provide a progress review of this analysis and present provisional results.

**Results**

The total power capacity in China is forecast to increase from over 700 GW in 2007 to 1500 GW by 2020, 2000 GW by 2030 and 2500 GW by 2050. Over the same period, the share of total power generation capacity provided by coal fired units is expected to decrease from the present 70+% to 65% by 2020, 60% by 2030 and 50% by 2050. Assume, somewhat optimistically perhaps, that the share of IGCC plants will reach 10%, 30% and 50% by 2020, 2030 and 2050, respectively.

Assume also that all the IGCC plants are fitted with capture, then carbon emission reductions will be 357 Mt CO₂, 1240 Mt CO₂ and 2188 Mt CO₂. The additional investment costs are estimated as US$44bn, US$90bn and US$63bn by 2020, 2030 and 2050 respectively. Detailed assumptions and estimation results are shown in Table 24. It is clear from this early analysis that CCS offers much promise.

**Table 24. Macro analysis on CCS application**

<table>
<thead>
<tr>
<th>Year</th>
<th>2020</th>
<th>2030</th>
<th>2050</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total capacity</td>
<td>1500</td>
<td>2000</td>
<td>2500</td>
</tr>
<tr>
<td>Share of coal-fired plant</td>
<td>65%</td>
<td>60%</td>
<td>50%</td>
</tr>
<tr>
<td>Share of IGCC in coal-fired plants</td>
<td>10%</td>
<td>30%</td>
<td>50%</td>
</tr>
<tr>
<td>Investment cost (US$/kW)</td>
<td>1500</td>
<td>1250</td>
<td>1000</td>
</tr>
<tr>
<td>Operation hour</td>
<td>5500</td>
<td>5560</td>
<td>5500</td>
</tr>
<tr>
<td>Efficiency</td>
<td>42%</td>
<td>45%</td>
<td>45%</td>
</tr>
<tr>
<td>Efficiency loss with capture</td>
<td>25%</td>
<td>20%</td>
<td>10%</td>
</tr>
<tr>
<td>Investment cost increased with capture</td>
<td>30%</td>
<td>20%</td>
<td>10%</td>
</tr>
<tr>
<td>Capture rate</td>
<td>90%</td>
<td>90%</td>
<td>90%</td>
</tr>
<tr>
<td>CO₂ emission before capture (MtCO₂)</td>
<td>411</td>
<td>1418</td>
<td>2461</td>
</tr>
<tr>
<td>CO₂ emission after capture (MtCO₂)</td>
<td>55</td>
<td>177</td>
<td>273</td>
</tr>
<tr>
<td>CO₂ emission reduction (MtCO₂)</td>
<td>357</td>
<td>1240</td>
<td>2188</td>
</tr>
<tr>
<td>Investment cost increase (US$bn)</td>
<td>44</td>
<td>90</td>
<td>63</td>
</tr>
</tbody>
</table>

**3.3.2 Recent MARKAL related modelling activities**

These presentations (142,143) summarize the following recent MARKAL related modelling activities: 1) Sustainable Energy Development Model for West China (W-SED); 2) 4-region China MARKAL; 3) Beijing MARKAL; 4) China MARKAL; 5) Development of models for climate change mitigation assessment. Results from the 4-region China MARKAL are first shown for a base scenario and two tax scenarios (TAX50 and TAX200), and then base case results from China MARKAL are presented(Figure 129).

The 4-region model did provide some valuable results which the single region is not able to provide. First is the regional picture of energy production and consumption, emission and etc. (Figure 130). Second is the energy trade among regions. The model shows energy trade among regions will change greatly under different scenarios. For example, coal trade among regions will significantly decrease while gas trade will have to increase dramatically in the carbon constrain scenarios compared with BASE, and
electricity trade will also decrease in the carbon constrain scenarios compared with BASE since nuclear power will play important role to supply electricity for EAST when carbon is taxed.

Figure 129. Primary energy consumption in the EAST region

Figure 130. Results from China MARKAL

3.4 Colombia

3.4.1 LNG investment options in the framework of regional energy integration

Energy integration is a common goal of energy policy in several Latin American countries. It is clear that a country that connects two sub-continents would be called to play a key role in the process of energy integration, in this case that country is Colombia. In this paper (146) the economic aspects of electricity and gas integration between Colombia and Central America are analyzed. The Colombian MARKAL model was adjusted to include demands for electricity and natural gas in Central America and the availability of recourses in that region.

The results show that the most favorable options to meet the requirements of electricity in Central America are water resources, and imports from Colombia. In some scenarios generating gas and coal generation complement the basket. In any case, oil is the worst option for generating electricity in Central America although it is now an important technology in this region. Similarly, the option of importing natural gas to meet the requirements of Colombia and export surpluses to support the creation of demand in Central America is financially viable in most scenarios. The flexibilities inherent in the project succeed in increase its value or in reducing the amount of losses as appropriate. The increased sensitivity is due to the uncertainty in gas reserves in Colombia. The uncertainty in the international prices of natural gas and oil does not change substantially the results. It is concluded that
the energy integration proposed has economic benefits for all countries considered and that Colombia could be an integrationist country in Mesoamerica.

3.5 Cuba

3.5.1 Scenario analysis for the power sector analysis for Cuba
The Cuban power sector faces a need for extensive investment in new generating capacity, under a large number of uncertainties regarding future conditions. To identify cost effective investment strategies under uncertainties, a supply and power sector MARKAL model was assembled (147,148). The implications of least-cost investment strategies for new capacity builds, investment spending requirements, electricity prices, fuel expenditures, and CO₂ emissions for each scenario were assessed.

Scenarios
Two scenarios were assessed, a business-as-usual (BAU) scenario assuming continued moderate electricity load growth and domestic fuel production growth, and a high growth (HI) scenario assuming rapid electricity demand growth, rapid increase in domestic fuel production, and a transition to market pricing of electricity. Within these two scenarios sets, sensitivity analyses were conducted on a number of variables: Higher/Lower gas prices; Lower coal prices; Limited rate of new investment; No LNG import available; Higher bagasse availability.

Results
Given the multidimensional uncertainty, the robustness of the key results is surprising. Natural gas was found to be the cost effective fuel for new power plants in both the core BAU and HI scenarios, and most of the sensitivity runs, absent free or deeply rebated oil. This remained the case even when natural gas prices were increased 40% above AEO2009 projected levels and oil prices were decreased 40% below AEO2009 levels (Figure 131). Renewable resources, including wind and bagasse, did not play a substantial role in the generation mix, due to their much higher capital costs, except in scenarios where access to natural gas was limited. Thus it is cost effective to replace the existing heavy fuel oil plants with new natural gas combined cycle plants as quickly as possible.

A review of the total discounted energy system costs shows that the BAU and HI scenarios differ dramatically in sensitivity to external conditions. In the BAU scenario, limited growth of domestic gas production causes a great vulnerability to gas price fluctuations. A 40% increase in gas prices increases system cost by 15% and an inability to import LNG increases system cost by 50%. In the HI scenario, the effect on system costs of increases in natural gas prices and restrictions on the rate of investment in new power plants is considerably less pronounced.

Figure 131. Electricity generation for the gas/oil price sensitivity cases
In both scenarios, the replacement of the existing plants leads to a sharp drop in CO₂ emissions. However, in the HI scenario cases (Figure 132) steady growth in natural gas consumption brings CO₂ emissions back up to 2010 levels by 2022.

**Figure 132. CO₂ emissions in four HI sensitivity cases.**

Natural gas was found to be the cost effective fuel for new generation across both scenarios and most sensitivity cases, suggesting that access to natural gas, through increased domestic production and LNG import, is a clear priority for further analysis in the Cuban context.

### 3.6 Finland

#### 3.6.1 Impacts of EU CO₂ emissions trading on electricity markets and electricity consumers

In this paper (149), the likely impacts of the EU emission trading system on the Nordic electricity market and on the position of various market actors are assessed. In its first phase, the EU CO₂ emission trading system includes power plants with thermal capacity greater than 20 MW, metals industry, pulp and paper industry, mineral industry and oil refineries. The impacts of emissions trading were studied with the VTT electricity market model and with the TIMES energy system model. The annual average electricity price was found to rise 0.74 EUR MW h (in the Nordic area) for every 1 € tonne CO₂.

**Scenarios**

In the base case, the installed capacity of nuclear power plants was assumed to remain constant after the commissioning of the fifth plant by 2010. In the alternative case, another new nuclear power plant was assumed to be commissioned in the year 2012. In addition to nuclear power, the scenarios included a wide range of other options for new low-emission generation, including wind and hydropower as well as various bioenergy and advanced CHP options.

**Results**

According to the results, the sixth nuclear power plant would have a considerable stabilizing impact on the prices of electricity from the year 2012 onwards. The results indicate that significant savings can be achieved in the total costs entailed in the emission trading system by additional investments in nuclear power generation. In comparison, the economic potential of other new low-emission options was found to be relatively limited, at least in the short term (Figure 133).
Figure 133. The total direct annual energy system costs entailed in the emission trading system*

* All costs, including taxes and subsidies on energy production, have been allocated to the end-use sectors according to sectoral energy demands. The three scenarios on the left correspond to the base case, and the three scenarios on the right to the increased nuclear power case. The allowance price assumed in each scenario is shown on the top line.

The increase in low-emission generating capacity entailed by nuclear power would also have a notable impact on the national emission trading balance, as illustrated in Figure 134. The purchases of emission allowances would decrease most significantly in separate electricity generation, but smaller impacts could be seen also in the district heat and power and industrial sectors.

Figure 134. National balance of trade in CO₂ emission allowances according to the TIMES model*

* The three scenarios on the left correspond to the base case, and the three scenarios on the right to the increased nuclear power case. The allowance price assumed in each scenario is shown on the top line.

Large windfall profits were estimated to incur to electricity producers in the Nordic electricity market. In Finland, metals industry and private consumers were estimated to be most affected by the electricity market price increases. Expanded nuclear power generation could limit the increases in the prices of electricity to one-third compared to those in the base case.

3.7 France

3.7.1 Modelling the different types of industries

3.7.1.1 Approach and methodology

Taking into account the importance of the industry in energy consumption and corresponding GHG emissions, this thesis (150) develops a coherent methodological framework for the estimation of the
evolution of the energy consumption of most intense energy industries by 2050. For a more complete analysis, the prospective approach of type MARKAL/TIMES gives a detailed description of all the energy intensive industrial sectors. It is mainly oriented towards the 29 European countries with a central place for France. Particular emphasis was placed on the pulp and paper, steel and cement industries. Disaggregation to the level of the boiler in the TIMES industry model allows more flexibility in the choice of technology, which ensures representation more refined industry (process modeling approach). For the rest of the industry where production is very diffuse and heterogeneous (multi-product and multiprocess), a modeling approach by use is more appropriate.

A different methodology has been developed (151) for modelling the non-energy intensive (NEI) industry. Regarding the segmentation of the industry, we use three main criteria: (i) the existing differences in magnitude of energy intensity across manufacturing sectors; (ii) the NEI sectors share of energy costs in value of production; the quantity of energy consumed by production site. We could consider that NEI sector should have a share of energy costs in production value below 3%, an energy intensity below 4 GWh/Meuros and an energy consumed per site below 10 GWh/site. We conclude that the best way to model the non-energy intensive in TIMES involve developing energy end use estimates by generic process units and defining of energy end uses families, but not developing a process flow and estimates of energy use by process step.

3.7.1.2 The response of energy intensive industries to environmental constraints

We use a prospective energy model (152) to assess the response of industry to environmental constraint. The modeling tool is the TIMES model. We include a full description of multi-option processes involved in the production of paper, glass, cement and steel, providing typical energy consumption in each process step. We identify, for each large energy-consuming industry and for different carbon constraints, the best technologies or optimisations to reduce production cost, and we calculate the energy savings potential and the corresponding CO₂ emission reductions.

Scenarios

- Influence of a carbon tax: This scenario supposes an environmental awareness slightly stronger than today. A carbon tax is imposed to all the industrial CO₂ emissions. The price level is fixed at a “reasonable” level, at about double the 2008 CO₂ price (14-30 Euro/t). We suppose a carbon tax of 50 Euro per CO₂ ton for the period of simulation (2000-2050).
- CO₂ mitigation obligations by a factor of 4: Factor 4 is a that refers to an increase by two of the well-being while dividing by two the use of natural resources. The expression, used within the framework of the GHG emissions, consists in stabilizing the atmospheric concentration of CO₂ at a 450 ppm level. To achieve this target in France, it is necessary to reduce the CO₂ emissions by a factor of 4 (2000-2050). We postulate here its application to the large energy consuming industries.

Results

Concerning the energy consumption in the carbon tax scenario, we can observe (Figure 135). During the first period, from 2000 to 2035, in the business as usual scenario, there is a rather constant level of energy consumption, despite the low growth of industrial production. This means that industry has adopted “naturally” energy efficient processes, because they are competitive. After 2035, energy consumption increases because of the steel production growth.

Change in the energy mix after 2030. Coal is replaced by natural gas. With a medium carbon tax (50 Euro/t), it is cheaper to adopt low carbonated energy when possible (coal → natural gas → electricity). Steel industry replaces the traditional blast furnace (coal consuming) by a direct reduction process consuming natural gas, where natural gas acts as a reducing agent for the iron ore.
Figure 135. Energy consumption with or without a carbon tax

![Energy consumption graphs](image)

Figure 136 presents the technological solutions for two main industrial sectors in the Factor 4 scenario:

- Steel industry has changed for a mix of a natural gas process and an electrical solution. We find the appearance of the Direct Reduction process, like in the carbon tax scenario. But we find also the emergence of a radical process change towards the electrolysis of the iron ore.

- Cement industry needs CCS.

- Glass industry is more balanced (both electricity, natural gas process and CCS)

- Paper industry adopts the airless drying process. This new technique allows a 70% reduction in steam use but with the use of more electricity (+15 to 20%).

The appearance of those new technologies, both low CO₂-emitting and high capital cost, is explained by the strong constraint in CO₂-emissions. We postulate for CCS a favourable set of conditions (limited cost for transport, no environmental problem, public acceptance, large volumes storage). We find a 79% CO₂ emission decrease in 2050 (Factor 4 versus Business as usual). Consequently, the cost of the CO₂ constraint could reach 300 Euro/t in 2050. It represents the CO₂ price to make the energy system optimal. Even with the availability of CCS technology, the model calculates a strong CO₂ price to oblige the industry to use all the technical possibilities (even at a high cost) to be able to reach the Factor 4 target.

Figure 136. Steel and cement industry response to factor 4 (process change)

![Steel and cement production graphs](image)

The comparison between a Factor 4 for the whole industry and a Factor 4 by sector shows a different behaviour of the industry branches in response to the CO₂ constraint. The application of Factor 4 for the whole industry leads to a more drastic reduction of the CO₂ emissions in the cement industry, at the benefice of the other sectors. There is a strong inertia of the industry energy system. Only a strong long-
The response of the aluminium industry to environmental constraints

The electro intensive character of the aluminium sector requires consideration. A TIMES (MARKAL) model allows us (153) to build the RES of the French aluminium sector in order to follow the evolution of the sector under different conditions of electricity prices and carbon taxes. The methodology applied is a “bottom up” one: the RES is described in detail with specific economic and technical parameters. In a prospective point of view, we added the possibility in the future to evolve towards more efficient technologies.

Scenarios

The business as usual (BAU) scenario observes the evolution of the sector without the availability of the new technologies at the considered horizon. The energy prices of reference scenarios is set up at 42 €/MWh for a duration of twenty four years. After that period, two price scenarios are considered: in the scenario ELEC1 the electricity price will be increased by 10 %, and then constant for the next 20 years, the second scenario (ELEC2) takes the same shape with an increase of 20%. This second scenario translates the hypothesis of stronger impact of the increase of the other energies prices on the electricity price.

We observed that the model results showed a strong carbon emissions reduction in all the considered scenarios, because of the decreasing demand and of the efficiency improvement due to the new technologies. We chose to observe the effect of a carbon tax at different levels in order to simulate the sector evolution for different carbon prices.

Results

The introduction of the new technologies is a key factor in the energy consumption reduction and they will be economically profitable even with no carbon pressure. In the scenario ELEC1, the primary production progresses from 2015 when a more efficient technology is available, towards the wettable cathode and waits until 2035 to upgrade to the combined technology of the inert anode and wettable cathode (yellow and orange bars in Figure 137). The secondary production is largely renovated from 2020 and nearly all the scrap available is recycled using the new technology (green bars in Fig. 7). All the performed scenarios gave similar technology emergence profiles. The recycling process uses ten times less energy than the primary production and the model always converges in order to maximise the recycling part.

Figure 137. Technology selection for the scenario ELEC1

The effect of the carbon tax does not modify globally the technologies chosen by the model but it influences mainly the timeline of the investment: the inert anode technology is anticipated for a carbon
tax over 150 €/tCO₂ (if extended to the PFCs gases) and more. In terms of emissions, a carbon tax over 150 € including the PFC, pushes the sector to decrease emissions from 2020, when the more efficient technique is available, of 40% of the BAU scenario (from 0.58 Mteq CO₂ to 0.33 Mteq CO₂).

Today, the emissions reduction in the aluminium production can be obtained through the recycling (that uses ten times less energy than the primary) and through the improvement of the existing techniques for the electrolysis. The inert anode technique and the wettable cathode are the major R&D challenges that could allow considerable changes in the energy consumption of the aluminium sector. A carbon tax can anyway stimulate the R&D efforts and accelerate the emergence of this techniques improving their profitability.

3.7.2 Households under carbon constraint and the burden sharing issue

As a member of the EU, France is concerned to achieve the global 20% reduction of CO₂ emissions in 2020 and the French government has inscribed a 75% reduction of CO₂ emissions by 2050 in its energy orientation law in 2005. How would such an overall carbon constraint be declined over the households? Describing household energy behaviour in long-term energy planning models such as TIMES is crucial to answer correctly to the question (154, 155).

The paper survey helps us to provide specific values of discount rates for each kind of technology and each type of households. So that we are able to model differentiated investment behaviour. Finally, thanks to this detailed description we are able to model the best suited technologies and the timing of investments in optimal technologies for each type of households. The model also provides information about arbitrations made by the households between investments in housing’s technologies and transportation’s technologies as we consider capital constraints.

Scenarios

We can then highlight the impact of a carbon tax on the different types of households or the effect of a global carbon constraint on residential and transports sectors.

Results

BAU almost reaches Factor 4, with fixed levels of demand. Air/Air heat pumps and thermal Insulation are cost-effective solutions to reduce CO₂ emissions (Figure 138). With a carbon constraint, -80% in 2050, we see wood technologies in 2030 (Electricity : 60g/kWh) and reinforced Insulation (Figure 139). Such a constraint needs policies to adress equity issue (Figure 140).
3.7.3  A long term prospective analysis of the Paris/Île-de-France transportation sector

A large part of the energy consumption in urban areas is dedicated to transportation with an important role in total GHG emission. As a consequence energy utilization in urban areas in general and in the transport sector in particular is a major issue for climate policies. This paper (156) presents a long-term prospective analysis of the contribution to GHG emission and energy consumption of Paris/Île-de-France personal-vehicles transportation sector based on a MARKAL/TIMES bottom-up model.

Results (preliminary)

Table 25 shows the area repartition of personal-vehicles depending on their types of motorisation.

<table>
<thead>
<tr>
<th>Type</th>
<th>Paris</th>
<th>Petite Couronne</th>
<th>Grande Couronne</th>
<th>together</th>
</tr>
</thead>
<tbody>
<tr>
<td>diesel</td>
<td>24.1%</td>
<td>31.9%</td>
<td>39.9%</td>
<td>35%</td>
</tr>
<tr>
<td>gasoline</td>
<td>74.2%</td>
<td>66.3%</td>
<td>56.8%</td>
<td>63.3%</td>
</tr>
<tr>
<td>electric</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>GPL, GNV, hybrid</td>
<td>0.4%</td>
<td>0.5%</td>
<td>0.5%</td>
<td>0.5%</td>
</tr>
<tr>
<td>others</td>
<td>1.3%</td>
<td>1.4%</td>
<td>0.9%</td>
<td>1.1%</td>
</tr>
</tbody>
</table>

We can see that the number of diesel cars increases when the size of the area increases and when the density of its population decreases (and conversely for gasoline cars). Gasoline cars are more numerous in Paris because those vehicles are preferred for small-distances hops. In 2001 the number of cars propelled by alternative fuels such as electricity, GPL, GNV is not significant. Table 26 shows the dependency of each sector on commodities consumption.
Table 26. Percentage of commodities consumption per sector, Île-de-France 2002 / DGEMP’06

<table>
<thead>
<tr>
<th>Sector</th>
<th>coal</th>
<th>fossil</th>
<th>gas</th>
<th>elec</th>
<th>wood</th>
<th>total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Industry</td>
<td>87.18</td>
<td>0.71</td>
<td>17.33</td>
<td>12.52</td>
<td>13.43</td>
<td>7.8</td>
</tr>
<tr>
<td>Residential/Service</td>
<td>12.82</td>
<td>13.92</td>
<td>82.5</td>
<td>80.64</td>
<td>86.57</td>
<td>46.33</td>
</tr>
<tr>
<td>Agriculture</td>
<td>0</td>
<td>0.6</td>
<td>0.17</td>
<td>0.13</td>
<td>0</td>
<td>0.39</td>
</tr>
<tr>
<td>Transport</td>
<td>0</td>
<td>81.77</td>
<td>0</td>
<td>6.7</td>
<td>0</td>
<td>45.48</td>
</tr>
</tbody>
</table>

The 2002 transportation sector was consuming close to 85% of the fossil fuels imported in Île-de-France and only 7% of electricity (mainly for public transportation). It also points out that the two most energy-consuming sectors are residential/service (with 46% of final energy consumption) and transport with 45% (24% for road transportation and 21% for air transportation).

Between 1991 and 2001, mobility of People living in Grande Couronne has increased by 8.6% while mobility in Paris only increased by 0.7%. We can also see that the population in Grande Couronne has increased by 9.8% while it increased only by 3.4% in Petite Couronne and by 2.6% in Paris. Cars mobility shows a steady increase while the other mobility are stable and decreasing for public road transportation.

### 3.7.4 Regional future use of biomass and biofuels

Future fossil fuels scarcity is a major energy concern. Our transport systems depend on liquid fuels and they are essential in our way of life. So, it is important to look at mid-term horizon what can the substitutions to these liquid fuels be. The aim of this study (157, 157b) is to assess the potential of biomass for energy uses for France by 2050 and to provide a path for biofuel technologies deployment.

To achieve this objective, we have developed a detailed MARKAL/TIMES model for biomass use as energy source in France. Using this methodology biomass has been studied as part of the European Union’s renewable strategy for 2020 in the RES2020 project.

### Scenarios

**Biomass resource scenarios.** We define three types of scenarios for wood availability. Two types for short rotation coppice (SRC) and two types of agricultural products availability and prices.

For wood:
- Business as usual (BAU).
- All for energy: consider that priority is given to energy uses against other industriel uses.
- Dynamic wood industry: wood industry also becomes more dynamic. The resource is less fully allocated to energy.

For agricultural products, the potential that have been produced are the potential reachable without any food industry competition. Two levels of prices have been considered.
- Business as usual (BAU).
- All for energy: consider that the demand for energy purpose is growing fast, but the food usage for the national market remains important.

For short rotation coppice (SRC):
- Mean availability
- String availability

We finally made six combinations from the resource availabilities described above:
- **P1:** BAU wood products, BAU agricultural products with low prices and no SRC.
- **P1b:** BAU wood products, BAU agricultural products with high prices and no SRC.
• P2: Dynamic wood products, all for energy agricultural products with high prices, and high availability for SRC.
• P2b: Dynamic wood products, BAU agricultural products with low prices, and high availability for SRC.
• P2b: All for energy wood products, all for energy agricultural products with high prices, and high availability for SRC.
• P3b: All for energy wood products, all for energy agricultural products with high prices, and mean availability for SRC.

End-use bioenergy demand scenarios. A central element for this study is the level of end-use demand for energy produced by biomass products. Three end-use demands have been retained: bio heat only, bio cogeneration heat, bio electricity by cogeneration, bio fuel. For these three energy carriers, we have defined three scenarios based on two demand level and with the following specificities:

D1: Final demand is 20 Mtoe for 2050. This scenario correspond to a pessimistic extension to 2050 of the objective that has been announced in the 10th operational comity for renewable energy development with environmental high quality (ComOP 10) provided in the fremae of the French “Grenelle de l’environnement”.

D2: Final demand is 40 Mtoe for 2050. The ComOP 10 target are reached in 2020. After this period, we consider a growing demand for bio electricity due to an important penetration of electric vehicles.

D3: Final demand is 40 Mtoe for 2050. The ComOP 10 target are reached in 2020. After this period, we consider a growing demand for bio jet fuel. It reaches 20% in the transport sector (air and road).

Results

This kind of results shows, for a moderate demand of bioenergies (D1: 20 Mtoe), the French development of the mix of biofuels technologies and the associated bioresources required. Let’s now examine what a more important demand in biofuel implies in a second scenario (D2: 40 Mtoe with bioelectricity). For this level of demand, the resources employed are again oriented towards the agricultural products (Figure 141). However, when the resources are limited (P1), the imports of cereals and ethanol are systematic even with a difference in the prices (P1 & P1b). these imports are completed with the apparition of Btl technology production with straw and wood as input. This choice is due to the better energy efficiency of this technology that need less resources to produce the demanded biofuel. This result shows the limitation of the French potential if the demand is growing. Indeed, the imports have been very constraint with a high price, and even with new technologies, the demand cannot be fulfilled. The potential must then be revised to fulfill such an energy demand level.

For the most important potentials, for biomasses (P2 & P3) (Figure 142), the imports and the use of Btl technology is largely reduced. The G2 ethanol technology is then employed due to his less important production cost. We also notice a certain amount of imports if the prices on agricultural products are higher.

Concerning the agricultural resources employed with the mix of technologies, Figure 143 is showing that with such a level of biofuel demand, all the French potential is necessary. The imports also show a lack of this resources when constraints are more severe. These results show the limits of the agricultural resources for a more important biofuel demand. It also shows the importance of the wood resource to fulfill the final demand.
Figure 141. Conversion technologies repartition for D2 scenario

Figure 142. Conversion technologies repartition for D2 scenario and P2 & P3 resources

Figure 143. Agricultural products resources for D2 & D3 scenarios
3.7.5 Carbon value dynamics: A key driver to support mitigation pledges at country scale

This paper (158) quantifies the dynamic evolution of carbon values for French climate and energy policy. Its time dependency over successive periods and the effects of setting intermediate targets are evaluated using a long-term optimization model. Addressing critical issues for France, we produce consistent energy, emissions and carbon value estimates with a 5-year time step.

**Scenarios**

A scenario with no abatement or demand policy is defined as the baseline for the comparison. A second scenario considers alternative organizational choices but without any explicit abatement policy.

- **Base-A** scenario builds on the standard demand projection, taking an upper boundary of 65 GW on nuclear and a maximum contribution of 20 Mt for CCS by 2050. The imported energy prices are in line with the WEO 2007 and there are no biofuel imports.

- **Base-B** scenario describes strong political and organizational measures leading to modified demands of energy services in the building and transport sectors. In the building sector, the main measures are capital replacement (destruction and rate of new construction) as well as tighter regulatory requirements for new buildings and higher insulation potential. In the transport sector the key parameters are modal splits.

All CO2 mitigation cases are then constructed around a scenario ENV60-ref, where a reduction by 20% in 2020 and 60% in 2050 relatively to 1990 is explicitly imposed as a constraint to the operating conditions described in scenario Base-B. Elastic variations in this scenario are very slight (strongly marginal) and their amplitude is limited to 2% in 2050.

A group of 3 additional scenarios investigates technical options: ENV60-CCS, ENV60-Nuc and ENV60-Biof. Over the modeling horizon, the reduction profile is defined by the target’s level in 2020 and a decrease at a constant rate towards a 60% reduction in 2050. The effect of endorsing lower intermediate targets in 2020 while keeping the same long-term goal is assessed in 2 additional scenarios: ENV60-Itar1 and ENV60-Itar2. Lastly, the range of elastic demand adjustments in 2020 and 2050 is considered in two scenarios: ENV60-Ela1 and ENV60-Ela2. The ENV60-bestW scenario then depicts the most favorable combination of all options (Table 27).

**Table 27. Alternative scenarios for a 60% reduction of CO2 emissions**

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Trade and technology</th>
<th>Smooth path: Intermediate target in 2020</th>
<th>Demand responsiveness</th>
<th>Most favorable combination</th>
</tr>
</thead>
<tbody>
<tr>
<td>ENV60-CCS</td>
<td>Nuclear max 65 GW, max CCS at 40 Mt, biofuel import not allowed</td>
<td>Lower intermediate target 1:15% reduction in 2020</td>
<td>Higher demand variations allowed 1:5% in 2020, 10% in 2050</td>
<td>Nuclear max 92.8 GW, max CCS at 40 Mt, biofuel import allowed, 10% CO2 reduction in 2020, higher variations allowed Ela-2</td>
</tr>
<tr>
<td>ENV60-Nuc</td>
<td>Nuclear max 92.8 GW, max CCS at 20 Mt, biofuel import not allowed</td>
<td>Lower intermediate target 2:10% reduction in 2020</td>
<td>Higher demand variations allowed 2:10% in 2020, 20% in 2050</td>
<td></td>
</tr>
<tr>
<td>ENV60-Biof</td>
<td>Nuclear max 65 GW, max CCS at 20 Mt, biofuel import allowed</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
**Results**

There is no single technically feasible primary energy mix or electricity mix that can meet the climate and abatement targets. Though feasible, the above energy system evolutions are not equivalent in terms of the implied level of effort, and the usefulness of a synthetic cost indicator such as the carbon value is obvious. When caps on the emission pathway are applied, the level and dynamic evolution of the carbon value are given by the dual value of the constraint. The five-year time line also makes it possible to see the effect of intermediate targets. All the calculated estimates of carbon values are shown in Table 28.

The carbon values derived here cover a large range and their underlying hypotheses illustrate the complexity of the debate on ambitious commitments at national levels: there is a feasible path toward low carbon values, but since real energy systems and policy options are constrained, there is a genuine risk of endorsing commitments that will lead to high value. Only estimates for the ENV60-bestW scenario are close to the proposed guideline value for 2030 and 2050, while calculated values for ENV60-ref are several times higher: 14 times higher in 2020 and more than 4 times higher in 2050. A central carbon value for our work is defined with the mean value of all scenarios, which peaks around 2020, then reaches a local minimum around 2035, and finally increases strongly again at the end when more efforts are required. The standard deviation is then used to define upper and lower boundaries. This approach is preferred to boundaries given by the minimum and maximum values for all scenarios, which would give more importance to the more optimistic and pessimistic estimates.

**Table 28. Evolution of carbon value estimates over time**

<table>
<thead>
<tr>
<th></th>
<th>2010</th>
<th>2015</th>
<th>2020</th>
<th>2025</th>
<th>2030</th>
<th>2035</th>
<th>2040</th>
<th>2045</th>
<th>2050</th>
</tr>
</thead>
<tbody>
<tr>
<td>ENV60-bestW</td>
<td>0</td>
<td>0</td>
<td>20</td>
<td>30</td>
<td>93</td>
<td>118</td>
<td>174</td>
<td>147</td>
<td>196</td>
</tr>
<tr>
<td>ENV60-CS</td>
<td>0</td>
<td>26</td>
<td>427</td>
<td>299</td>
<td>256</td>
<td>164</td>
<td>287</td>
<td>332</td>
<td>427</td>
</tr>
<tr>
<td>ENV60-Nuc</td>
<td>0</td>
<td>23</td>
<td>385</td>
<td>278</td>
<td>229</td>
<td>187</td>
<td>303</td>
<td>334</td>
<td>376</td>
</tr>
<tr>
<td>ENV60-Bef</td>
<td>0</td>
<td>26</td>
<td>333</td>
<td>287</td>
<td>243</td>
<td>284</td>
<td>312</td>
<td>580</td>
<td></td>
</tr>
<tr>
<td>ENV60-bar1</td>
<td>0</td>
<td>0</td>
<td>163</td>
<td>217</td>
<td>288</td>
<td>136</td>
<td>285</td>
<td>345</td>
<td>832</td>
</tr>
<tr>
<td>ENV60-bar2</td>
<td>0</td>
<td>0</td>
<td>43</td>
<td>134</td>
<td>276</td>
<td>129</td>
<td>264</td>
<td>326</td>
<td>800</td>
</tr>
<tr>
<td>ENV60-Ea1</td>
<td>0</td>
<td>17</td>
<td>171</td>
<td>161</td>
<td>235</td>
<td>158</td>
<td>212</td>
<td>295</td>
<td>382</td>
</tr>
<tr>
<td>ENV60-Ea2</td>
<td>0</td>
<td>17</td>
<td>104</td>
<td>147</td>
<td>177</td>
<td>164</td>
<td>151</td>
<td>219</td>
<td>325</td>
</tr>
<tr>
<td>ENV60-ref</td>
<td>0</td>
<td>27</td>
<td>444</td>
<td>390</td>
<td>250</td>
<td>170</td>
<td>299</td>
<td>345</td>
<td>831</td>
</tr>
<tr>
<td>Mean value</td>
<td>0</td>
<td>15</td>
<td>233</td>
<td>223</td>
<td>232</td>
<td>156</td>
<td>245</td>
<td>295</td>
<td>528</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>0</td>
<td>11</td>
<td>155</td>
<td>92</td>
<td>46</td>
<td>22</td>
<td>64</td>
<td>64</td>
<td>238</td>
</tr>
</tbody>
</table>

Our results are situated above the upper range of carbon value estimates of world models with an overlapping zone. We show that the official policy guideline value is only consistent with an optimistic combination of assumptions. The central estimates are 4 times greater than the guideline carbon value for 2050 and up to 14 times greater in 2020 because of short-term inertia that are costly to move. We also find that with intermediate objectives, the carbon value’s dynamic is more than a simple upward curve and that its variability is itself time dependent.

**3.8 Germany**

**3.8.1 Projecting energy market trends until 2030**

Against the background of a currently shrinking contribution from indigenous energy carriers as well as increasing efforts of climate protection, the Energy Outlook 2009 (*Energieprognose* 2009) (159) assesses the development of energy supply and demand in Germany up to 2030, and further makes an outlook up to 2050. An integrated, model-based approach is adopted to illustrate the German energy markets as part of the European energy system. This is to account for embedding the German power supply system into the European domestic market as well as to capture in an appropriate way the effects of transnational, EU-wide regulation approaches like the European Emission Trading System.

**Scenarios**

Two cases of energy supply in Germany are examined. They differ only in one aspect: The Reference Case assumes a legally regulated nuclear phase-out, whereas the Lifetime Extension Case, further divided into two variants, presumes an extension of the existing nuclear power plants’ lifetime to 40 and
60 years. Sensitivity analyses evaluate the impact of alterations of key influencing parameters such as the demographic and economic development. The prescribed EU energy and climate policy objectives for Germany are taken into account in the Energy Outlook 2009 (EU-wide Emission Trading System (ETS), energy efficiency objectives, a temporary prolongation of the CHP Act, a strengthened European integration of the electricity market and an increase in competition in the domestic gas market, etc.).

Results
The primary energy consumption in Germany drops by 21 % until 2030 compared to 2007 (Figure 144). This is accompanied by an annual increase of energy productivity by 2 %. Petroleum oil remains the most important primary energy carrier despite a consumption downturn. As a whole, the dependence on energy imports (share of the net import in primary energy consumption of fossil energy carriers) increases from approximately 73 % in 2007 to nearly 87 % in 2030.

Figure 144. Primary energy consumption in Germany

There is a slight shortfall in attaining the objective of a 30 % share from renewable energy in the electricity generation in 2020. Likewise, the predefined EU objective for Germany to have a share of 18 % from renewable energy in gross final energy consumption in 2020 is just missed by a 2 % shortfall. The goal stated in the Kyoto Protocol for Germany to reduce GHG emissions by 21 % by 2012 compared to 1990’s level is markedly exceeded. Until 2030, GHG emissions in Germany decrease by 44 % relative to 1990 (Figure 145).

Figure 145. GHG emissions in Germany

The extended operation of nuclear power plants leads to lower GHG emissions in Germany and lower CO2- prices in the European Emission Trading System than in the Reference Case. The goal achievements
for renewable energy remain unaffected. In contrast, the growth of CHP electricity generation is curbed. Despite retrofit expenses, nuclear power plants can be operated with low generation costs. In addition, the reduced costs for CO₂ certificates facilitate lower electricity prices, which are up to 9 €/MWh lower than those stated in the Reference Case. The less expensive electricity supply is coupled with positive feedback effects for the industrial production, employment and the overall economic development (Table 29).

<table>
<thead>
<tr>
<th>Table 29. Positive macroeconomic effects of lifetime extension</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lifetime Extension [a]</td>
</tr>
<tr>
<td>-----------------------</td>
</tr>
<tr>
<td>40</td>
</tr>
<tr>
<td>60</td>
</tr>
<tr>
<td>80</td>
</tr>
<tr>
<td>100</td>
</tr>
</tbody>
</table>

Source: IER

3.9 India

3.9.1 Assessment of demand for natural gas from the electricity sector

The sustained electricity deficit and environment policies have added to an already rising demand for gas. This paper tries to understand gas demand in future from electricity sector. This paper (160) models the future demand for gas in India from the electricity sector under alternative scenarios for the period 2005–2025, using bottom-up ANSWER MARKAL model.

Scenarios

The scenarios are differentiated by alternate economic growth projections and policies related to coal reforms, infrastructure choices and local environment. GDP is one of the key drivers; therefore we developed scenarios to explore the expected impact of GDP growth on energy use. In this paper, we report scenarios for the 5%, 6%, 7%, 8% and 9% GDP CAGR for year 2005–2025 period.

The policy analysis was done around the reference scenario which is our 6% growth scenario. The results for all three policy cases have been abbreviated to CR L, M, H for coal reforms low, medium and high, CBW for coal-by-wire, and SC for the sulphur controls scenario.

Results

The general trend across the five growth scenarios is an increase in gas demand for power in future (Figure 146). However, the future transitions reveal when economic growth is faster than RS growth of 6% as is in 7%, 8% and 9% scenario, gas demand is lower till 2020 after which the gas demand is higher than RS. The trend of gas in power sector can be explained by four main factors: demand for electricity, gas availability, relative prices of coal and natural gas and gas demand from other sectors.

Their future share in the power sector will depend largely on the relative prices of these two fuels. Gas-based plants have lower capital costs and higher generation efficiencies (Shukla et al., 2004), which gives them a competitive advantage of around US $ 4 per Mbtu over coal-based plants. The coal prices in nearly all the scenarios are close to US $ 3 per Mbtu (Figure 147) and this means that a market clearing price of gas till US $ 7 Mbtu will result in growth of gas-based generation. The tightening gas situation post-2015 results in an increase in the gas prices and these results in a fall in gas demand from base-load gas plants in 2025.
Figure 146. Demand for gas for power generation: growth scenarios

Figure 147. LRMC of coal and natural gas: growth scenarios

CR L, CR M, CR H and CBW scenarios show lower gas demand, whereas the SC scenario shows demand for gas rising post-2015. The trend in gas demand that emerge for three policy cases has been explained by—relative prices of fuel, environmental constraints and infrastructure availability. The three coal reforms and CBW scenario have lower coal prices (Figure 148). In the three CR scenarios coal prices go down due to a rightward shift of coal supply curve whereas in CBW it is due to the flexibility of infrastructure. The difference in gas demand from the RS scenario reduces as the difference in relative prices is reduced.

Local environmental (SO2 emissions) control promotes end of pipe solutions flue gas de-sulfurisation (FGD) initially, though in the longer term mitigation happens by fuel substitution (coal by gas) and introduction of clean coal technologies integrated gasification combined cycle (IGCC).

Figure 148. LRMC of coal and natural Gas: alternative policy cases
3.9.2 An outlook to energy consumption in large scale industries

Steel, aluminium and cement are the key manufacturing industries in India which provide inputs to various other sectors such as construction, transportation, power transmission, etc. This paper (161) makes a foray into the energy demand for these industries and explores the potential of any future reduction in their energy consumption.

Scenarios

This section also provides a projection of total energy consumption in 2031 using the MARKAL modeling technique under two alternative scenarios: Business as Usual (BAU), which assumes the continuation of ongoing practice and Efficient (EFF) scenario, which assumes that best practice, would be adopted gradually to reach energy efficiency. These two scenarios can be thought to represent the floor and ceiling, respectively, with respect to energy efficiency in Indian industries by 2031.

Results

We compare our projection results for the energy consumption in steel, aluminium and cement industries with other forecasted results. We observe that the Centre for Science and Environment (CSE) 2009 has estimated energy consumption for these industries in 2031 under the BAU and the “Low Carbon” scenarios. We observe that the CSE results are always below our results for all the industries. One possible reason for the same could be that the CSE study derives its estimates based on data collected through surveying various firms in respective sectors (as mentioned in their study). This is always likely to result in an under-reporting of energy consumptions by the firms. We compute emission saving potential in saving potential in these three key industries in the alternative scenarios in 2031 (Table 30).

Table 30. CO₂ emissions in the steel, aluminium and cement industries (million tonnes) in 2031.

<table>
<thead>
<tr>
<th></th>
<th>BAU</th>
<th>EFF</th>
<th>Emission saving potential (percentage)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel</td>
<td>1070.61</td>
<td>802.97</td>
<td>25</td>
</tr>
<tr>
<td>Alum</td>
<td>14,019</td>
<td>11.23</td>
<td>20</td>
</tr>
<tr>
<td>Cement</td>
<td>939</td>
<td>732.42</td>
<td>22</td>
</tr>
</tbody>
</table>

India is almost at par with world’s best efficiency level for the aluminium and cement sectors. However, there is still scope for further improvement in each of these sectors.

3.9.3 Nuclear and clean coal technology options for sustainable development

Due to the growing energy needs along with increasing concerns towards control of GHG emissions, most developing countries are under pressure to find alternative methods for energy conversion and policies to make these technologies economically viable. In this paper (162) Indian power sector has been examined by using MARKAL model for introduction of clean coal and advanced nuclear technologies with implementation of energy conservation potential.

Scenarios

Two alternative scenarios have been developed with respect to the base case. The first is the advanced technology scenario and the second is mixed scenario (with energy savings potential). In Advanced technology scenario only the penetrations of advanced nuclear and clean coal technologies (PFBC and IGCC) have been considered. The mixed scenario uses the energy saving potential in various sectors of Indian economy together with advanced technologies. The cases for various energy efficiency potentials (maximum saving potential, 15%, 10% and 5% savings) have been used as an energy demand input for MARKAL modeling.
Results

It is observed that coal is the dominant electricity generation technology in the BAU scenario followed by large hydro and nuclear. Wind contributes about 4%. The corresponding electricity generation in various scenarios is shown in Figure 149. The advanced nuclear technology becomes important after the year 2025 in all of the scenarios. Except energy conservation potential scenario, coal shows increasing pattern in all other scenarios. Due to reduced demand in energy conservation potential scenario advanced nuclear and clean coal technologies become major source of electricity generation. Therefore, conventional resources do not get significant allocation in the energy mix and the result is a very heavy reduction in CO₂ emissions.

Figure 149.Resource wise electricity generation in various energy savings potential scenarios

Introducing advanced technologies in Indian power sector can only solve the problem of energy security and not the sustainability. Since application of advanced technology reduce the CO₂ only about 16% which is not a sustainable solution for environmental protection. Now, if we introduce the energy conservation potentials together with advanced technologies there is a great reduction in CO₂ emission. Two scenarios, advanced technology and energy conservation potentials, are mixed together and CO₂ is reduced about 70% as compared to the base case in the year 2045.

3.9.4 Renewable energy for sustainable electrical energy system

Present trends of electrical energy supply and demand are not sustainable because of the huge gap between demand and supply in foreseeable future in India. The path towards sustainability is exploitation of energy conservation and aggressive use of renewable energy systems. This requires adequate policy guidelines and interventions in the Indian power sector. Detailed MARKAL simulations (163), for power sector in India, show that full exploitation of energy conservation potential and an aggressive implementation of renewable energy technologies lead to sustainable development.
Scenarios
Two alternative scenarios have been developed except for the base case. The two scenarios are: Renewable Technology and Aggressive Renewable Technology. In the Renewable technology Scenario, present government policy and implementation of renewable energy in power sector have been considered. For Aggressive Renewable Technology Scenario, the mandatory use of full potential available for renewables by the year 2045 has been considered.

Results
Figure 150 shows the resource-wise installed capacity in Renewable Technology Scenario with various energy conservation potential options. In all of the cases, the coal increases from the base year 2005 to 2015 and then stagnated up to the year 2040 in the first two cases. The next two cases show the coal stagnation up to the year 2035. After the year 2040 a slight increase has been observed up to the year 2045. A very interesting situation happens with the nuclear power. The nuclear power capacity in the base case scenario is 18% of the total installed capacity in the year 2045 while in the maximum savings potential case this becomes 33%.

Figure 150. Resource-wise installed capacity in various energy savings options in renewable technology scenario

The Renewable Technology Scenario shows the reduction in coal consumption and the corresponding carbon emission reduction (16%), but this reduction is not up to the mark for sustainability. The aggressive approach to use the renewables shows a huge reduction in coal use (installed capacity is only 80 GW) and the carbon emission reduces to 72% as compared to BCS in the year 2045. Exploitation of renewables with energy savings case shows an early reduction in carbon emissions. The Aggressive Renewable Technology Scenario with maximum energy savings reduces the same (72%) amount of carbon in the year 2045. The renewable energy shares more than 35% in the energy mix in both the alternative scenarios in the year 2045.

3.9.5 Parametric sensitivity analysis for techno-economic parameters in power sector
Sensitivity analysis is a technique that evaluates the model response to changes in input assumptions. This paper (164) examines the variations in technical as well as economic parameters that can mostly affect the energy policy of India. MARKAL energy simulation model has been used to analyze the
uncertainty in all techno-economic parameters. Various ranges of input parameters are adopted from previous studies.

**Scenarios**

Inputs included in the analysis are: discount rate, the future costs of natural gas and oil, the hurdle rate for new electric generation technologies, future nuclear investment cost, availability factor and efficiency improvement of clean coal technologies. Discount rate is the most important parameter for sensitivity analysis because this affect whole of the energy system cost and allocations. The considered range for other inputs is summarized in Table 31.

**Table 31. Input parameters considered for sensitivity analysis in MARKAL**

<table>
<thead>
<tr>
<th>Sensitive parameter</th>
<th>Unit</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discount rate</td>
<td>Percentage</td>
<td>6.5-15</td>
</tr>
<tr>
<td>Efficiency</td>
<td>Percentage</td>
<td>38-58</td>
</tr>
<tr>
<td>IGCC</td>
<td>Percentage</td>
<td>34-50</td>
</tr>
<tr>
<td>PFBC</td>
<td>Percentage</td>
<td>0.85-0.89</td>
</tr>
<tr>
<td>Availability</td>
<td>Fraction</td>
<td>0.80-0.90</td>
</tr>
<tr>
<td>IGCC</td>
<td>Fraction</td>
<td>0.85-0.90</td>
</tr>
<tr>
<td>PFBC</td>
<td>Fraction</td>
<td>0.80-0.90</td>
</tr>
<tr>
<td>Hurdle rate</td>
<td>Percentage</td>
<td>5-25</td>
</tr>
<tr>
<td>Fuel prices</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oil</td>
<td>US$/barrel</td>
<td>30-150</td>
</tr>
<tr>
<td>Gas</td>
<td>US$/thousand cubic feet</td>
<td>3-8</td>
</tr>
<tr>
<td>Nuclear investment cost</td>
<td>US$/kW</td>
<td>1160-3000</td>
</tr>
</tbody>
</table>

**Results**

The results are shown in Figure 151. With the low discount rates of 6.5%, the share of coal in the energy mix decreases from 283 GW in the base case (discount rate 8%) to 218 GW in the year 2045. This means conventional coal power plants does not remain important for future points of time due to heavy discounting. The large hydro was the most preferred electricity production technology in 6.5% discount rate scenarios.

Increasing efficiencies of PFBC prefers the other renewable energy technologies while in case of increasing efficiencies of IGCC prefers coal as energy technology. Availability factor increase of new technologies does not change the proportion in energy mix of various technologies. Due to market fluctuations, if the gas prices increases the gas proportion becomes zero in the energy mix and the large hydro also decreases. The uncertainty in investment cost of nuclear affect the nuclear penetration in the power sector. Very high cost gives no allocation in energy mix. The large hydro becoming most competitive and covers about 50% market of total installed capacity.
Figure 151. Resource wise installed capacity with various discount rate scenarios

(a) Resource wise installed capacity with 6.5% discount rate scenario. (b) Resource wise installed capacity with 10% discount rate scenario. (c) Resource wise installed capacity with 12% discount rate scenario. (d) Resource wise installed capacity with 15% discount rate scenario.

3.9.6 National energy map for India: Technology Vision 2030

This presentation (165) introduces India’s Energy Sector Options & Challenges as well as recent MARKAL Applications at TERI.

- National Energy Map for India: Technology Vision 2030 (Principal Scientific Advisor to the Government of India)
- Examining technological options & financing challenges for India (at COP 14 and COP -15)
- Detailed electricity sector analysis for MSEB
- Energy-Economic-Environment Modelling to support climate change assessment and policy-making in India (Ministry of Environment and Forests, Government of India)

The key focus of this study (166) was to examine the role that various technological options could play under alternative scenarios of economic growth and development, resource availabilities, and technological progress. After an extensive survey of existing models, the MARKAL (MARKet ALlocation) model was selected to examine the pathways for optimal energy supply to meet the endues services in the five energy-consuming sectors (agriculture, commercial, residential, industrial, and transport) under various scenarios.

Scenarios

Seven alternative scenarios were set up against the BAU scenario to examine variations with regard to economic growth and technological progress:

- LG (low growth) represents low GDP growth rate of 6.7%
• BAU (business-as-usual) represents energy development as per current government plans and policies, representing a GDP growth rate of 8%
• HG (high growth) represents a high GDP growth rate of 10%
• EFF (high efficiency) includes energy-efficiency measures spanning across all sectors
• REN (aggressive renewable energy) represents a high penetration of renewable energy forms
• NUC (high nuclear capacity) scenario considers an aggressive pursuit of nuclear-based power generation
• HYB (hybrid) scenario is a combination of the BAU, EFF, REN, and NUC scenarios
• HG-cum-HHYB (high-growth hybrid) represents a high growth rate of 10% in addition to the hybrid scenario

During the course of the study, it was felt that there was a strong need to focus attention on energy policy options in the transport sector. Accordingly, an additional set of policy scenarios was developed specifically for the transport sector in view of the country’s high dependence on oil import and the concerns due to rising oil prices.

• Enhanced share of public transport (PUB-PVT): Share of public transport increased to 60% in 2036 as against 51% in the BAU scenario
• Increased share of rail in passenger and freight movement vis-à-vis road (RAIL-ROAD):
  ⇒ Railway freight share increased from 37% in 2001 to 50% in 2036 as against 17% in the BAU scenario;
  ⇒ Railway passenger share increased from 23% in 2001 to 35% in 2036 as against 23% in the BAU scenario
  ⇒ Share of electric traction increased for rail passenger and freight to 80% by 2036 instead of 60% in the BAU scenario
• Fuel efficiency improvements (FUEL EFF): Fuel efficiency of all existing motorized transport modes increase by 50% from 2001 till 2036
• Enhanced use of bio-diesel in transport sector (BIO-DSL): Penetration of bio-diesel to 65 Mtoe by 2036
• Transport sector hybrid (TPT-HYB): Incorporates all the above-mentioned measures in addition to BAU

Results
Based on the analysis of the model results, the key interventions can be delineated as follows.
• Enhancing end-use efficiencies (intervention 1, I-1).
• Adopting advanced coal- and gas-based power generating technologies (intervention 2, I-2).
• Enhancing the exploitation of renewable and nuclear energy resources (intervention 3, I-3).
• Enhancing efficiency in the transport sector by modal shifts (intervention 4, I-4).

In 2031, each of the end-use sectors has a potential to reduce energy consumption between 15% and 25% of the energy use in the BAU scenario. However, given the relative weight of each sector in the total energy use, the industry and transport sectors have the highest potential for energy savings, amounting to 41% and 47%, respectively, in 2031.
The possibility of commercial energy saving due to advanced coal- and gas-based power generating technologies is represented by the area between I-1 and I-2 in Figure 152. The model results indicate that in order of economic merit, the preferred power generation technologies are: (1) large hydro; (2) refinery-residue-based IGCC (integrated gasification combined cycle); (3) imported-coal-based IGCC; (4) high-efficiency CCGT (combined cycle gas turbine) (H-frame gas turbine); (5) indigenous-coal-based IGCC; (6) normal CCGT; (7) ultra-supercritical boiler; and (8) supercritical boiler.

Figure 152. Scope for reducing commercial energy requirements

The consumption patterns in the transport sector indicate that despite rising oil prices, demands for passenger and freight movement have been rather inelastic with regard to fuel prices. In the BAU scenario, the total energy consumption in the transport sector is estimated to increase by about 14 times from 34 Mtoe in 2001 to 461 Mtoe in 2031 (Figure 153). The analysis of the transport sector indicates that although much of the fuel reduction possibility in this sector can be related to autonomous efficiency improvements of the transportation modes, efforts should be made to enhance rail-based movement and the use of public transportation. This will go a long way in reducing the transport sector’s dependence on oil. By targeting action on the demand as well as supply sides in the transport sector in the TPT-HYB scenario, a reduction of about 190 Mtoe of energy can be achieved in 2031 as compared to the BAU scenario.

Figure 153. Comparison of energy consumption in the transport sector across various scenarios

The results of the modelling exercise indicate that from the viewpoint of energy security and the need to reduce its dependence on imports of all the conventional energy fuels, the country needs to undertake all possible options on the demand and supply side simultaneously to reduce its total energy requirements as well as diversify its fuel resource mix. Towards this end, the economy would need to pursue an integrated approach to energy planning.

3.9.7  Sustainable transport for developing countries

Transport sector will play a growing role in CO2 emissions from India in future. Changes in urban form and modal switching are a key element of moving transport sector on a low carbon path. The paper
(167) proposed extensions in an integrated modeling framework used earlier for modeling low carbon scenarios. These involved adding in the ANSWER MARKAL model time costs and infrastructure costs to model the modal choices endogenously. The revised model framework was used to examine low carbon transitions along two pathways. The first pathway assumed a conventional development pattern together with a carbon price that aligns India’s emissions to an optimal 550 ppm CO₂e stabilization global response. The second emissions pathway assumes an underlying sustainable development pattern characterized by modal switching, recycling, demand reduction and many other measures typical of the ‘sustainability’ paradigm.

3.10 Ireland

3.10.1 Building the Irish model

UCC has secured research funding for a two year project entitled “Energy Modelling – Irish TIMES” to build an energy systems model for Ireland (168). The project will build on the Energy Policy and Modelling research carried out by UCC’s Sustainable Energy Research Group and is funded by the Environmental Protection Agency under the Climate Change Research Programme 2007 – 2013 (with co-funding from Sustainable Energy Ireland). ESRI will collaborate on the project, facilitating the model to be populated out to the year 2050. Irish TIMES will provide a range of energy system configurations for Ireland that will deliver projected energy demand requirements optimised to least cost and subject to a range of policy constraints for the period out to 2050. The PET-IE model from RES 2020 is used as starting point for Irish TIMES (2009 -2011) in order to: provide new capacity to answer policy questions, insights into technology options, build energy systems modelling capacity at UCC, contribute to the significant international TIMES research effort through IEA ETSAP.

3.10.2 Modelling ambitious renewable energy and CO₂ reduction targets

Due to growing concerns regarding the dangers associated with climate change, countries are setting increasingly ambitious targets for CO₂ emissions reductions as part of an overall policy response. This paper (169,170,171) focuses on reductions in energy-related CO₂ emissions in particular and explores how an optimal mix of technologies may be determined to deliver a pre-established target. The paper uses the TIMES energy systems model to address this question. It uses one country, Ireland as a specific case study but may be readily applied to other countries. Ireland has an ambitious target to reduce GHG emissions in non-ETS sectors by 20% below 2005 levels by the year 2020 (under Decision 2009/406/EC).

Scenarios

Two energy system configurations are developed in this paper, the Reference Energy System (IT-REF) and the non-ETS 20% reduction scenario (IT-NETS).

Results

Figure 154 compares the total final consumption (TFC) by fuel and by sector of IT-REF with the National Energy Forecasts. In 2005, energy use in industry represented 22% of TFC compared with transport which accounted for 39%. The absence of growth in energy use between 2005 and 2010 is due to the damping effect of the economic recession. Focussing on the results for 2020, the TFC in the Baseline forecast for 2020 (N-Base) reaches 15.0 Mtoe. Due to the energy efficiency targets in the Government White Paper on Energy that are assumed to be achieved in the White Paper forecast (N-WP) this reduces to 13.8 Mtoe. The results from IT-REF yield a TFC of 13.9 Mtoe, reflecting that here the Reference Energy System delivers slightly less energy efficiency than the Government targets hope for.
Moving to the energy system delivering the 20% emissions reduction, the Reference Energy System is responsible for 42.2 Mt CO₂ in 2020, representing a 10% reduction on 2005 levels. The non-ETS scenario results in 36.4 Mt CO₂, representing a 22% reduction relative to 2005 levels and 13.6% lower than IT-REF in 2020.

Figure 155 compares the two energy systems focussing on the contribution from renewable energy. Both scenarios suggest significant renewable energy growth relative to the low production levels in 2005. In the IT-NETS energy system, renewable energy production in 2020 is more than ten times the levels in 2005. Wind energy provides 40% of 2020 renewable energy production in IT-NETS, with biomass contributes 32% and biofuels 25%.

The initial results from the Irish TIMES model presented in this paper suggest that an ambitious emissions reduction target for Ireland in the period to 2020 can be achieved and which energy efficiency and renewable energy technologies could be deployed to deliver the target at least cost.
3.10.3 Comparing results with a power systems model

The focus of this work (172) is to investigate the added value of the inclusion of extra technical constraints for thermal generators and the high resolution portrayal of wind and load variability in a power system model. The PLEXOS model which can replicate at a high resolution (30 minute time steps) the chronological modeling of a power system is compared for a number of test years to results from TIMES. As more wind and variable generation comes online in future power systems the effects of their inherent generation characteristic must be properly captured and modeled.

This analysis therefore intends to benchmark the performance of the TIMES electricity modeling against detailed results of the PLEXOS software in the Irish power system. This is important to determine the capability of the TIMES model to accurately account for effects of large amounts of wind and variable resource on the power system. The Irish TIMES model is the energy system model for Republic of Ireland developed within the research project commenced in 2009 as a joint project between UCC’s (University College Cork) Sustainable Energy Research Group and the ESRI (Economic and Social Research Institute).

Scenarios

To validate this procedure a range of scenarios could be analyzed. The authors choose to validate the achievement of two of the most challenging climate targets that Ireland is going to face:

- ETS/NETS scenario: the 21% and 20% GHG emissions reduction (relative to 2005 levels) for emissions trading sectors (ETS) and for sectors outside the emissions trading scheme (non-ETS sectors).
- -80% CO₂ scenario: the 80% GHG emission reduction (relative to 1990 levels).

Achieving these targets could mean a deep transformation of the power system due to high levels of renewable energy generation and high electricity loads. It is therefore the aim of this paper to verify the feasibility of the optimal TIMES pathways.

Results (preliminary)

Types of power system modelling within PLEXOS includes capacity expansion planning, transmission planning, market analysis, operational modelling and portfolio optimisation. A case study for capacity expansion planning is showed (Figure 156) for the client Transpower NZ (ISO). The main facts are:

- Supply dominated by hydro in the South Island
- Load is in the North Island
- High-voltage DC (HVDC) interconnection between the two islands
- One half of the HVDC is being retired: Should it be replaced? If so, what size?
  ⇒ New transmission expensive, but there are limited thermal expansion options: coal is too “dirty” and natural gas supply is very limited.
  ⇒ Renewable options: Wind, Micro-hydro, Geothermal, Wave power.

This is solved using 35 year PLEXOS LT Plan with mixed-integer programming (run time more than 2 hours each case).
3.11 Italy

3.11.1 A business as usual scenario for the energy system

The aim of this article (173) is to present a new model for the Italian energy system implemented with a common effort in the framework of an integrated project under the Sixth Framework Programme. In particular, the main features of the common methodology are briefly recalled and the modelling structure, the main data and assumptions, sector by sector, are presented.

Scenarios

In compliance with the decisions taken for the Pan-European model scenarios, also for the Italy NEEDS-TIMES model the baseline (BAU) scenario is characterised by exogenous assumptions around drivers, energy prices and policies that follow a rather business as usual trend as derived with the help of the general equilibrium model GEM-E3. The macroeconomic and energy price background assumptions are in line with those reported in the latest DG TREN projections.

Results

Following the increase of energy demand, there is an increase of fuel consumption by all sectors (Figure 157) on the time horizon. In particular, heat, coal and renewables have the most remarkable increase (respectively, heat from 225 PJ of the baseyear to 562 PJ in 2050, coal from 195 to 485 PJ and renewables from 81 to 175 PJ). Natural gas, electricity, waste and oil products increase is respectively 47%, 39%, 13% and 7%. Methanol and hydrogen (others), are being used from 2010 in the transport sector, their contribution increasing from 19 PJ up to 82 PJ in 2050.

No Kyoto policies are considered in the baseline scenario therefore, following the consumption trend, CO₂ emissions increase 24% in 2050; the highest contribution is given by industrial sector that doubles its emissions between 2000 and 2050 (Figure 158). Also in transport sector there is a remarkable increase of emissions (+26%) due to the increase of oil products use. On the contrary, in the conversion sector there is a 14% reduction, due to an increased use of renewables (hydro, wind, and photovoltaic) for electricity production.
Final energy consumption is characterized by a growing demand of electricity by almost all sectors, fulfilled by more efficient thermal plants, co-generation and, many renewable power plants (among which hydro are still prevailing) in line with the national policies. Consumption is increasing for industry, commercial, agriculture and transport but not for residential that, on the contrary, shows a declining trend. In the transport sector there is still a high consumption of oil products, but it can be noted also an increasing consumption of biofuels according to the national directives.

3.11.2 Assessment of externalities related to global and local air pollutants

In the last 20 years a great interest of the scientific community has been devoted to identify and monetarise the damages on human health and on environment caused by energy-related activities and to give guidance for supporting the design of internalisation measures. Based on this background research, the integration of energy system analysis methods with externalities assessments represents a powerful tool to support a systemic multi-objective investigation, aimed at achieving a better resource management as well as at reducing environmental pollution. This chapter (174) is addressed to describe, from a methodological and an operating point of view, how strategic energy planning can benefit from external costs evaluation.

In particular the effects of external costs on the least-cost optimised energy system configuration were analysed (175,176) in a national case study with the NEEDS-TIMES Italy model, considering the externalities related to local and global air pollutants (NOx, SO2, VOC, particulates and GHGs).

Scenarios

After an exhaustive literature review and taking into account the results coming from the NEEDS project internal discussions, two sets of reference values were identified (Table 32):

- Ambitious scenario, updated values that take into account the recent policy decisions, representing a compromise between the combination of the values proposed by Research
Streams 1b (more ambitious scenario) and Research Streams 1a (preferred scenario) inside NEEDS project.

- Realistic scenario, values derived by the results of the scenario analysis with the NEEDS TIMES Pan EU model that are in line with the values in the World EW scenario.

### Table 32. GHG external costs (Euro/ton of CO₂eq)

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>2010</th>
<th>2015</th>
<th>2020</th>
<th>2025</th>
<th>2030</th>
<th>2035</th>
<th>2040</th>
<th>2045</th>
<th>2050</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ambitious</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO₂</td>
<td>23.5</td>
<td>31</td>
<td>46</td>
<td>51</td>
<td>74</td>
<td>87</td>
<td>100</td>
<td>146</td>
<td>198</td>
</tr>
<tr>
<td>CH₄</td>
<td>493.5</td>
<td>651</td>
<td>966</td>
<td>1,071</td>
<td>1,554</td>
<td>1,827</td>
<td>2,310</td>
<td>3,066</td>
<td>4,158</td>
</tr>
<tr>
<td>N₂O</td>
<td>7,285</td>
<td>9,610</td>
<td>14,260</td>
<td>15,810</td>
<td>22,940</td>
<td>26,970</td>
<td>34,100</td>
<td>45,260</td>
<td>61,380</td>
</tr>
<tr>
<td>Realistic</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO₂</td>
<td>23.5</td>
<td>27</td>
<td>29</td>
<td>32</td>
<td>34</td>
<td>37</td>
<td>50</td>
<td>66</td>
<td>77</td>
</tr>
<tr>
<td>CH₄</td>
<td>493.5</td>
<td>493.5</td>
<td>567</td>
<td>600</td>
<td>672</td>
<td>714</td>
<td>777</td>
<td>1,050</td>
<td>1,386</td>
</tr>
<tr>
<td>N₂O</td>
<td>7,285</td>
<td>7,285</td>
<td>8,370</td>
<td>8,990</td>
<td>9,929</td>
<td>10,540</td>
<td>11,470</td>
<td>15,500</td>
<td>20,460</td>
</tr>
</tbody>
</table>

Therefore, the following scenarios were defined, whose macroeconomic and energy price background assumptions are in line with DG TREN 2005 projections:

- **BAU (Business as Usual)**: The baseline scenario, in which all the exogenous assumptions around drivers, energy prices and policies follow a rather business as usual trend. No climate policy is considered.

- **BAU_GHG**: Baseline scenario assumptions with the internalisation of the externalities related to CO₂, CH₄ and N₂O only, using the “Ambitious scenario” values.

- **BAU_LAP**: Baseline scenario assumptions with the internalisation of the externalities related to local air pollutants only (SO₂, NOₓ, NMVOC, PM10 and PM2.5).

- **BAU_LAP-GHG**: Baseline scenario assumptions with the internalisation of the externalities on both local and global air pollutants, including CO₂ (“Ambitious scenario” values).

- **Kyoto_forever**: A climate policy scenario aimed to achieve the national Kyoto Protocol’s target (-6.5% of GHGs in the period 2008-2012 compared to the 1990 values). Thus, starting from the values of the reference scenario, a reduction of 448 Mton of CO₂eq was imposed yearly from 2010 to 2050 to model the GHGs stabilisation on the full time horizon. No tradable permits or flexible mechanisms are allowed to achieve the prefixed -6.5% target.

- **Kyoto_LAP**: The internalisation of the externalities on local air pollutants (SO₂, NOₓ, NMVOC, PM10 and PM2.5) was added to the Kyoto_forever scenario’s assumptions.

### Results

In fact, as shown in Figure 159, in BAU_GHG a 7.8% reduction of LAP emissions and a 15% reduction of GHGs is achieved without any policy on them. On the contrary, in BAU_LAP there is a 25% increase of GHGs. This consistent variation is, mainly caused by the increase of natural gas consumption due the production, by a Fischer–Tropsch process, of a synthetic diesel characterised by a very low sulphur and aromatic content and to the absence of CCS. On the other hand, the internalisation of the externalities on both LAP and GHGs foster a higher decrease of both local and global pollutant emissions (in BAU_LAP_GHG the LAP and GHG reduction percentages being respectively -42% and -14%).
The effects of internalisation of externalities in terms of renewables share in gross final consumption of energy are summarized in Table 33. It can be seen that introducing externalities without any specific constraint on GHG is not sufficient to speed up the use of renewables. In fact, the BAU scenario is far from the objectives set by the EU for increasing the share of renewable energy. The 17% target by 2020 is hardly achieved in the scenarios Kyoto_forever and Kyoto_LAP, whereas in 2050 the RES share increases above 20% only in the scenarios with an exogenous constraint on GHGs, achieving its maximum share in BAU_~LAP_GHG (24%).

Table 33. Impact of internalisation on the renewables share in gross final energy consumption (%)

<table>
<thead>
<tr>
<th>Scenario</th>
<th>% of renewables in final energy consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2000</td>
</tr>
<tr>
<td>BAU</td>
<td>4%</td>
</tr>
<tr>
<td>BAU_GHG</td>
<td>5%</td>
</tr>
<tr>
<td>BAU_LAP</td>
<td>5%</td>
</tr>
<tr>
<td>BAU_LAP_GHG</td>
<td>5%</td>
</tr>
<tr>
<td>Kyoto_forever</td>
<td>4%</td>
</tr>
<tr>
<td>Kyoto_LAP</td>
<td>9%</td>
</tr>
</tbody>
</table>

Results obtained for the Italy case study show that the internalisation of damage costs pushes the system towards a more efficient technology configuration leading, in general, to a reduction of air pollutants and to an increase of the total system cost. As concerns GHG reduction, introducing externalities on local air pollutants has a negative effect on the levels of CO$_2$ eq whereas GHGs externalities causes a consistent reduction of CO$_2$ eq on the long term, reaching -17% in 2050 (and -19% when both LAP and GHGs externalities are taken into account) although a less relevant reduction can be observed on the short term. Thus, if the stakeholder perspectives are mainly focused on the long term, then the introduction of joint externalities on both LAP and GHGs represent the most effective choice, in terms of air pollution reduction and total energy system costs (inclusive of e avoided damages). On the other hand, a post-Kyoto policy can be achieved only imposing an exogenous constraints on GHGs.

3.11.3 Analysis of possible deployment scenarios for hydrogen

The paper (177) analyses Italian hydrogen scenarios to meet climate change, environmental and energy security issues. An Italy-Markal model was used to analyse the national energy–environment up to 2050. About 40 specific hydrogen technologies were considered, reproducing the main chains of production, transport and consumption, with a focus on transport applications.

Scenarios

These two scenarios provide the starting point for analysing the potential of hydrogen and FC under a range of different assumptions.
• Base scenario is a business-as-usual scenario which includes only currently enacted energy policies, without widespread use of hydrogen (small quantities are used in niche markets).

• Alternative scenario includes a set of new policies and measures aimed at reducing emissions and improving energy security; widespread use of hydrogen is possible at the 2030 horizon and thereafter; the stock of hydrogen vehicles reaches more than 2 million vehicles at 2030.

Results
In terms of primary sources, it is observed that natural gas will continue its strong growth (by 2015 it becomes the first fossil source). Oil consumption is limited to transport sector but remains quite stable in the time horizon after a slight decrease for the first decade, thanks to its almost total exclusion for electric generation and industry use. In any case both coal and renewables play a minor role in the energy market, even in the long period.

With reference to Figure 160 the net predominance of hydrogen production in refineries is evident looking at the Alternative Scenario.

Figure 160. Hydrogen production in the alternative scenario

The main process is catalytic reforming of natural gas. In fact refineries allow lower costs due to the availability of all the facilities necessary for this process. However two other technologies seem in a position to compete with catalytic reforming process, in case CO₂ penalties are higher: 1) biomass gasification, which has the considerable advantage of distributed generation; 2) coal gasification together with CCS.

In the Baseline scenario the use of hydrogen can be found in rather distributed niches belonging to different sectors; for example, buses in transport, electric generation in peak hours and, obviously, in the industrial sectors where it is already used today. In the Alternative scenario (Figure 161) the consumption is concentrated in the transport sector for more than 80%. The use in the industrial and electricity generation sectors remains the same as in the Baseline, while the increased use in the transport sector is pushed by the excellent environmental performances of this energy carrier.

The Alternative scenario, fostering the use of more efficient technologies, determines a significant reduction of CO₂ emissions, i.e. 30/60 Mtons, respectively, in 2020 and 2030. Of course, by 2020, CO₂ reduction does not depend on hydrogen use, as its share on the energy market is small, but on an earlier choice of efficient technological options. The introduction of alternative fuels into road transport, despite their limited portion of total fuel consumption, widens the choices available to the consumers and contributes to keep fuel competition high. The resulting effect is that fuel prices are kept down for all fuels, including oil.
3.11.4 Cost-benefit analysis in the Italian electricity sector

3.11.4.1 Feasibility of the nuclear option

In the framework of the renewed interest in nuclear power expressed by a number of Member States, include Italy, this paper (178) want to show an alternative scenario of evolution of the Italian Power System in 2030. In this study we want also analyse the sensitiveness of the cost of the nuclear plant in comparison with the price of the fossil fuels, particularly natural gas, at the aim of knowing if there is a indifference line between the two. At the scope of evaluate the possible ways of development of the power system it is necessary to use a model approach. Such a model, based on the MARKAL-TIMES multi-region representation of the Italian electric system has been developed by CESI in the frame of the “Research on the electric system”, in co-operation with AIEE and with the Torino Polytechnic.

Scenarios

A Reference Scenario of evolution of electricity demand in Italy has been produced, and a Reference Scenario of evolution of power supply, disaggregated by type of technologies, with the forecast of CO₂ emissions and an assessment of the effective of the policies in progress to support the Renewable Energy Supply and energy efficiency. Then, on the basis of this Reference Scenario we consider the possibility of the entry in function of the nuclear production in Italy.

Finally, for an analysis of sensitivity, on the basis of the Nuclear Scenario, we put some variants on the hypotheses of base regarding the prices of fossil fuels in order to assess which kind of relation between these and the long run marginal cost of a nuclear plant is.

Results

The Reference Scenario (Figure 162) shows a regular trend, even if cyclic, of realization of new plants based on past trends and on possible projects in progress. In the research of the minimization of the comprehensive cost of energy system, the model chooses a system of supply with an important growth of CCGT plants, restricting the realization of coal plant. The RES show a good growth, at an average annual rate of 3%, stimulated from tools of policy of support in force and the increase of electricity demand. Under these hypotheses Italy doesn’t reach in 2020 the target of RES development.

In the Nuclear Scenario (Figure 163), despite the cautious hypotheses of the prices of fossil fuels and CO₂ allowances, the model chooses to install all the nuclear plants as it can, at the expense of the CCGC plants. In this way we obtain, in 2030, a reduction of 22 Mt of CO₂, of 6,500 M€ of the whole cost of the electricity production and of 10 Gmc/y of the consumption of natural gas.
Obviously this choice depends on the assumption of the prices of fossil fuels, and through the development of a series of alternative scenarios we obtain a line of indifference that shares an area in which is suitable the construction of nuclear plant, considering economic and risk elements, and another area in which is not suitable. Particularly the threshold of convenience in Italy is a price of Brent of 87-88 $/bbl. Under this price the model chooses of not installing nuclear plant while above of this the cost of the system obtain a saving that increases with higher price of the oil (Figure 164).

Figure 162. Total Electricity Supply by Source in the BASE Scanario (TWh)

Figure 163. Total electricity supply by source in the NUCLEAR scanario (TWh)

Figure 164. Annual electricity system costs (million euros): BASE scenario vs. NUCLEAR scenario
3.11.4.2 Impact of a return to the nuclear option using an electricity model

The objective of the study (179) is to analyse the impact of a “return” to nuclear generation in CO₂ emissions and fossil fuel consumption for the Italian electricity system and the economic implications (Competitiveness). The medium-long term target of the Italian government, in terms of electricity energy production, can be summarized with the slogan “25-25-50”, i.e. 25% nuclear, 25% renewable and 50% fossil fuel production.

Scenarios

- The “Base” scenario is the reference for building alternative scenarios and refers to a projection of the evolution of the Italian electricity demand and supply system according to “business as usual” trends including CO₂ reduction targets for 2020 and 2030.
- The “Nuclear” scenario, integrates the “Base” scenario with the possibility to install up to 7 EPR nuclear plants with a size of 1600 MW each;

Results

The results of the scenario analysis show that the introduction of nuclear power plants in the Italian electricity system allows to diversify the supply sources (Figure 165), produce energy at a lower cost than the one generated by fossil fuelled and RES plants and significantly reduce emissions of GHG (Figure 166).

Nuclear is just one of many options to be pursued together (development of renewable sources, increase of energy efficiency in end-uses, CCS) and it must not be considered as an alternative. The achievement of a so high share (25%) of nuclear generation inevitably implies significant changes in the balance of the Italian power system, i.e. a reduction of net imports from abroad and a dramatic reduction of investments in new large fossil fuelled power plants. Moreover, if policies to reduce demand by increasing energy efficiency in end-uses are successful, it will be difficult to sustain a so ambitious level of development of renewable sources and nuclear in the electricity sector.

Figure 165. Electricity generation portfolio in the base and the nuclear scenarios
Further works involve an evolution from MATISSE (electricity sector) to MONET (energy sector) to analyse the Italian regional energy system and the impact at the regional level. The MONET model is under construction and first working version should available around the middle of 2011.

3.11.4.3 Feasibility of the storage option

Those three main factors – M-shaped load/price curve, hydro pumped-storage potential saturation and wind energy penetration – make the Italian electrical system a very favourable environment for the development of electricity storage. In this study, (180) the AIEE research group analyzes the cost-benefit of the electricity storage technologies (available or near to maturity) penetration into the Italian electricity market: CAES – Compressed Air Energy Storage (both underground and surface storage), Flywheels, Super-Capacitors (ECC), Superconducting Magnetic Energy Storage (SMES), Sodium Sulphur (NAS) Battery, Polysulfide-Bromine (PSB) Battery, Vanadium Redox Battery (VRB), H2/FuelCell.

Results

Leaving the MARKAL-Times model of the Italian electrical system free to install the electricity storage technologies – under certain constraints – it select the CAES technology as the most competitive and decides to install about 5 GW of new CAES plants in 2050, starting with about 350 MW in 2020 (the plants construction begins three years before), not reaching the user-defined potential (Figure 167). It means that such choice represents the optimum for the Italian electrical system, i.e. the least-cost solution.

Figure 167. CAES total installed capacity into the Italian electrical system – CAES scenario

If the model is free to integrate surface storage CAES plants to the new wind farms, the optimum electricity storage total capacity grows to about 9 GW in 2050, 7 GW in 2030. In this scenario, the total electricity production from wind-farm in Italy can reach 30 TWh in 2050, 5 TWh more than in the b.a.u. scenario.
The new electricity storage technologies entering into the world energy market can find a room in the Italian electrical system, which needs at least 5 to 10 GW within 2050 in order to optimize its structure. The CAES technology integrated into wind farms seems to be the most competitive electricity storage technology, it depends on the assumption about the future development of the NAS batteries. The related investments can rise from about 300 million euros in 2015/2020 to over 5 billion euros in 2050; further investments should be made for technology development and demonstration.

### 3.11.5 Calibration and scenario analysis for the national energy strategy

A TIMES model for Italy has been developed from the ETSAP-TIAM model (Italy as extracted region from WEU) with 42 energy service demands (181). The model is calibrated to the base year 2006 and demands are projected to the 2060 horizon (with 2 year interval up to 2020). The first objective was to analyse National Energy Strategy with (as far as possible) transparency of both scenario analysis and the model, as well as with transparent interaction between modellers and policymakers. The model was use (182) to get estimation of potential impact and costs of policy measures and technology options, with technological detail comparable with major policy documents (EU directives, national plans), technology-by-technology abatement cost curves (“McKinsey type”) and soft-link of new model with GTAP-Italy and Italian SAM.

Some presentations (183,184) previously explains how integrating MARKAL-Italy with Italian SAM is useful for impact analysis. SAM (Social Accounting Matrix) is a comprehensive accounting framework within which the full circular flow of income from production to factor incomes, household income to household consumption and back to production is captured. Similarly, for GTAP (Global Trade Analysis Project), a multi-regional Applied General Equilibrium model that captures world economic activity in 57 different sectors of 113 regions, two kinds of equations (accounting relationships and behavioral equations) and allows to obtain the impacts of policies in terms of GDP and trade variation, sectoral impacts, allocation effects, etc. It allows computation of the economy-wide impacts of energy policies, such as carbon taxation or emission trading (i.e. carbon leakage).

### Scenarios

A six-step process was used for developing scenarios for the “National Energy Strategy”: 1) Identification and definition of issues to be analysed; 2) Selection of key-factors in the system 3) Hierarchy of key factors by: importance, uncertainty, critical uncertainties; 4) Development of “storylines” around key-factors and critical uncertainties with quantitative translation for open discussion; 5) Elaboration of scenarios through system models; 6) Sensitivity analysis of base scenarios.

### Results

First results produced for the BAU scenario (optimistic version) is showed in Figure 168 with an assessment through comparison with other estimates (model scenarios and sectoral analyses).

**Figure 168. Total final energy consumption by sector**
3.12 Japan

3.12.1 Integrated assessment for CDM activities using energy and life-cycle assessment models

The mid-term target for energy-related CO₂ emission reduction by 2020 in Japan is 25% from the level in 1990. This study (185,186) aims at developing a method for evaluating CDM activities in the next decades, focusing on investment in supply-side energy technologies in Asian countries. By combining energy systems analysis and life-cycle assessment, potential amount of CDM credit anticipated from those activities will be discussed with their costs and benefits including co-benefits, in the light of the contribution of technology development to Japanese global environment policies. Possible energy-related CO₂ emission reduction is analyzed for estimating necessary CDM credits by using MARKAL model for Japan.

By developing a method to assess potential of CDM activities, potential amount of CDM credits in China and India has been evaluated by applying GOAL model for Asia. Social surveys in China and India have been made to estimate income elasticity through willingness to pay for avoiding human health risks. Based on the results of this study, cost-benefit analysis considering co-benefits for CDM activity in China introducing a new advanced coal fired power plant has been done.

Results

Based on the analysis by the MARKAL, energy-related CO₂ emissions in Japan are estimated as shown in Figure 169. Energy-related CO₂ emissions in 2020 and 2050 can be reduced around 15% and 50% from the level in 1990. The difference between energy-related CO₂ emissions and the mid-term mitigation target in 2020 is around 10%, 120 million t-CO₂/year. However it does not mean necessary CDM credits in 2020. Subject to continuation of present framework, the difference can be filled by forest sink and the rests can be filled by credits from the Kyoto mechanisms, such as CDM, joint implementation and emissions trading. The share of each credit under the Kyoto mechanisms depends on its price.

Figure 169. Energy-related CO₂ emissions in Japan by trade-off coefficient between system cost and CO₂ emissions

3.12.2 Long-term scenario analysis of zero-carbon energy system

Nuclear power and renewable energy are expected to contribute significantly to this in the future in Japan. Therefore, in the present study (187,188), their roles in future zero-carbon electricity system was examined using long-term scenario analysis from 2005 to 2100 based on an integrated analysis model. The analysis is conducted in three steps to (1) estimate electricity demand and load pattern based on lifestyle and industrial structure in the future using a bottom-up simulation sub model; (2) plan the optimized power generation mix to satisfied obtained electrical demand and load subject to various constraints using an optimization sub-model (3) confirm the reliability of the obtained best mix power generation system by using an hour by hour simulation sub-model. The proposed optimization method is quite different to many models proposed in past studies such as MARKAL and AIM (Asia-Pacific Integrated Model), which aim to find the least cost solution.
Scenarios
The results give the schedule of nuclear and renewable energy development from 2005 to 2100 and show that they will contribute 60% and 40% respectively in terms of electricity production by 2100. Finally, the whole system is proven as technically feasible with the help of EV (Electric Vehicle) batteries and hydrogen for daily and seasonal electric storage respectively, operated based on smart control technologies.

Results
The simulation results are shown in Figure 170, in which the electricity demand is shown to increase from 1,000 TWh to 1,500 TWh from 2005 to 2100.

**Figure 170. Obtained final energy demand by using the bottom-up simulation model**

3.13 Malaysia

3.13.1 Review of MARKAL energy modeling
In this paper (189), an attempt has been made to understand and review the various emerging issues related to the MARKAL energy modeling. Implementation in more than 40 countries and by more than 80 institutions, including developed, transitional, and developing economies indicate wide acceptability. The need to develop comprehensive energy models and their related infrastructures as the energy scenarios in Malaysia have compelled Pusat Tenaga Malaysia (PTM) to consider the MARKAL for the long term energy planning. Developing of the model is still in progress.

Table 34 indicates that, of the 21 APEC Member Economies, more than two-thirds (15) have or are developing Economy-level MARKAL models. In addition, several cities and provinces in China (including Shanghai and Hong Kong, Guangzhou) have developed local energy planning frameworks using MARKAL. A number of China’s other major municipalities and provinces have expressed strong interest in similar undertakings. With this established network of users and Member Economy models, improved energy efficient technology characterizations should enhance the energy system planning activities currently in progress in the APEC region. The need to develop comprehensive energy models and their related infrastructures requires no further justification as the energy scenarios in Malaysia are dynamically changing according to national as well as international concerns and aspirations. The energy sector was once regarded as one as a sub sector is now considered as a major economic one within the Malaysian economy.

**Table 34. APEC member economies and MARKAL capabilities**

<table>
<thead>
<tr>
<th>Economy-Level MARKAL Models</th>
<th>Under Development MARKAL Models</th>
<th>No MARKAL Models</th>
</tr>
</thead>
<tbody>
<tr>
<td>Australia Canada China Hong Kong, China Indonesia Japan Korea Mexico Philippines Chinese Taipei United States</td>
<td>Malaysia New Zealand Thailand Vietnam</td>
<td>Brunei Darussalam Chile Papua New Guinea Peru The Russian Federation Singapore</td>
</tr>
</tbody>
</table>
3.14 Moldova

3.14.1 Energy efficiency and RES analysis

The paper (190,191) presents results of analyses of energy efficiency measures and renewable energy sources implementation in the Republic of Moldova using MARKAL model. Energy savings and costs are identified for implementation of renewable energy sources and Energy efficiency measures.

Scenarios

The following scenarios are considered for analyses:

- Reference Scenario (Business as Usual Scenario) with slower replacement of existing end use demand devices, energy prices according to WEO 2009.
- Renewable Energy Target Scenario (using IPA-derived target) -10% biofuels in 2020 for transport sector
- Energy Efficiency Scenario (with greater penetration of efficient end-use technologies)
- Renewable Energy Target plus Energy Efficiency Scenario combines RE&EE scenarios

Results

As a result of Energy Efficiency (EE) scenario run (scenario D_EE) the optimum solution decreased from 11,206 MEuro of Reference Scenario to 10,979 MEuro. We conclude that if all EE measures related to implementation of advances end-use devices will be implemented in the country, this will contribute to about 2% decreasing of system cost.

Figure 171 represents the differences of Electricity Generation by Fuel Group + Imports (PJ) for Renewable, Energy Efficiency and Renewable and Energy Efficiency Scenarios comparing to Reference Scenario. Implementation of Renewable Energy Sources (wind turbines of 1PJ/year by 2012 and 2 PJ/year by 2030) substitutes the demand of power generation by coal-fired power plants of about 2PJ per year starting with 2021 till 2030. Energy efficiency measures decrease the demand of electricity generation by coal of up to 3PJ/year by 2030, due to more efficient end-use devices with lower electricity consumption. Combined implementation of Renewable Energy together with Energy Efficiency measure reduces the demand in new wind power plants to 1.5PJ/year by 2030 and substantial reduction of coal fired power plants production of up to 4.7PJ/year by 2030.

Figure 171. Electricity generation by fuel group + imports, PJ

Comparing Reference Scenario with Renewable, Energy Efficiency and Renewable & Energy Efficiency Scenarios in terms of final energy by fuels we can conclude that: in Renewable Scenario the final energy consumption does not change, except a small replacement of electricity consumption by natural gas, mainly in 2015 (Figure 172); Energy Efficiency Scenario shows a substantial decreasing of demand of electricity of up to 3PJ/year by 2030 and reduction of gas consumption by 2PJ/year by 2030, due to
more efficient end-use devices; Combined application of Renewable and Energy Efficiency Scenario has very similar final energy consumption with Energy Efficiency Scenario, except for more reduction in heat demand comparing to Reference Scenario.

The main conclusions are: 1) Meeting renewable targets is cost-effective with application of advanced end-use technologies; 2) Key measures will be needed to shift investment from fossil to renewable generation; 3) Encouraging uptake of more efficient technologies is a priority issue as the economic potential for energy saving is significant; 4) Combining EE and RET scenarios leads to more efficient energy system; 5) Residential sector is most interesting for implementation of energy efficiency measures.

Figure 172. Energy balance - final energy by fuel, PJ

3.15 Nepal

3.15.1 Energy planning and policy analysis

Nepal is facing a difficult energy supply crisis. Against this backdrop, it has become very essential to have an integrated energy model (192,193) in the present context for proper planning and policy analysis so that the policymakers can be timely updated and given various policy options to take necessary energy related policies and decisions. One of the main research questions, therefore, in the presynopsis report was to develop a modelling framework for the energy sector of Nepal so that energy policy analysis could be conducted and based on the framework. In this regard, both the top-down and bottom-up energy demand models were analyzed.

- Energy Demand Projection using Model for Analysis of Energy Demand (MAED) developed by International Atomic Energy Agency (IAEA), Vienna, Austria.

Nepal – MARKAL energy modelling framework was developed and inputs of the useful energy demands from the end-use approach (MAED) were exogenously incorporated in.

Scenarios

Introduction of clean energy technology at reference Case (Table 35)

**Table 35. Traditional fuels and fossil fuels replaced by electricity and/or fossil fuels**

<table>
<thead>
<tr>
<th>Sub-sector</th>
<th>2020</th>
<th>2030</th>
</tr>
</thead>
<tbody>
<tr>
<td>Industrial and commercial</td>
<td>Traditional and fossil fuels decreased by 20%</td>
<td>*Decreased 30%</td>
</tr>
<tr>
<td>Residential Urban</td>
<td>Fuelwood share decreased by 50%</td>
<td>*Decreased by 75%</td>
</tr>
<tr>
<td>Residential Rural</td>
<td>Fuelwood share decreased by 10%</td>
<td>*Decreased by 30%</td>
</tr>
</tbody>
</table>
Policy interventions at reference case

- CFL penetration
  - Incandescent bulbs replaced by CFLs at the rate of 50 percent in 2020 and then linearly to 100 percent in 2030 industrial, commercial and residential sectors.
  - Transmission and distribution losses of electricity grid reduced from 25 percent in base year to 20 percent in 2015, and then linearly to 10 percent in 2030.

- Introduction of New Transportation Technology:
  - Electric and hybrid cars introduced. Diesel and petrol cars to be reduced by 10 percent of reference case in 2020, 20 percent in 2025, and 30 percent in 2030.
  - Electric cars will be substituting at the rate of 5 percent in 2020, 10 percent in 2025, and 15 percent in 2030.
  - Hybrid cars will be substituting the remaining as 5 percent in 2020, 10 percent in 2025, 15 percent in 2030.

- All combined policy measures:
  - All combined policy measures plus wind power plant and solar water heating system introduced. Compared to the reference case, there is a 50% reduction in energy demand in the all combined policy in 2030.

Results

The analysis of the output of the modelling framework indicates certain insights that Nepal without delay has to undertake certain energy policies/strategies on priority basis (Figure 173). Concrete policies such as making indigenous hydropower resources as the leading priority for development, discouraging usage of petroleum products, focusing on enhanced promotion and development of renewable energy sources such as biogas, solar PV systems, solar water heating systems, promoting biofuels and electric vehicles in the transport sector, and wind energy have to be formulated without delay. Apart from these, energy efficiency measures from the demand/supply side, such as switching of incandescent lamps to CFLs, and transmission efficiency have to be encouraged strongly. In spite of all these, by implementing the combined policy measures GHG emissions can be reduced by 25 million tons and this reduction can be used for carbon trading through Clean Development Mechanism (CDM).

Figure 173. Fuel mix at reference & combined policy cases
3.16 Norway

3.16.1 Regional modelling focusing on transportation sector and hydrogen

3.16.1.1 Introduction of hydrogen in the Norwegian energy system

These presentations (194,195,196) introduced the regional approach to model the transportation sector (Figure 174). The regions for MARKAL analysis are: Oslo, Rogaland, Telemark and their selection is based on the following criteria: 1) Variations in the local energy resources and energy end use demand were emphasised; 2) Large potential of wind power - possible to produce zero-emission hydrogen based on electricity from wind; 3) Access to natural gas pipeline (and CCS) – possible to produce hydrogen from natural gas. The models includes no possibility to import or export hydrogen into or out of a region or between regions. The growth from 2005 to 2050 in the transportation sector is in average about 40%.

Figure 174. Framework

The Norwegian energy system is characterized by high dependency on electricity, mainly hydro power. If the national targets to reduce emissions of GHG should be met, a substantial reduction of CO₂ emissions has to be obtained from the transport sector. This paper (197) presents the results of the analyses of three Norwegian regions with the energy system model MARKAL during the period 2005-2050. The MARKAL models were used in connection with an infrastructure model H2INVEST.

Scenarios

A series of scenarios were used with the regional models to determine how taxes, emission constraints and energy prices may affect the production and use of hydrogen and to identify the key parameters and conditions to make a profitable transition to hydrogen powered cars.

- Scenario A : “HyWays” Scenario A is based on the work of the HyWays project [4]. An important input is the deployment of hydrogen cars at different times and hence the investment cost of vehicles. Currently, natural gas is exempted from tax in Norway. No changes in energy policies are assumed, except that a tax, similar to the gasoline tax, on natural gas for transportation is included.

- Scenario B : “Neutral taxation” Scenario B is a No-tax scenario; a pragmatic approach and a reference for analyzing the effects of taxes on transport energy.

- Scenario C : “CO₂-reduction” In this scenario a restriction on CO₂ emissions starting in 2020 with a 20% reduction compared to 1990 level was assumed, followed by a reduction of 66% in 2030 and a linear decrease to 75% reduction in 2050. There were no restrictions on emissions in the period prior to 2020.

- Scenario D : “Fuel prices” A sensitivity analysis with a steep increase of the crude oil price to 200 $/barrel is assessed. The price of natural gas was assumed to be 70% of the crude oil price corresponding to 163 $/boe in 2010-2050. The increase for crude oil was applied for oil products, including the price of heavy distillate, light distillates, diesel, gasoline and
kerosene. In these analyses the electricity price and the prices of biomass were kept unchanged.

- **Scenario E**: “Technology costs” The investment costs of battery electric vehicles (PHEV), hybrids, and plug-in hybrids were reduced and the costs of hydrogen powered FC and ICE cars were increased. The investment cost of PHEV decreased by 24% in 2010 and approx. 10% in 2020-2050, compared to the other analyses. In 2010, the investment cost of hybrid cars decreased by 10% and in 2020-2050 by 3%. The investment cost of HFCV was doubled in 2010 and increased by approx. 10% in 2025-2050. In addition to changes in investment cost, for HFCV the fuel consumption increased by 30% and the maintenance cost increased by 133% in 2010, 62% in 2020 and 12% in 2030.

**Results**

Results compared with a reference case and based on the assumptions of World Energy Outlook with no new transport technologies (194): Figure 175 shows private private cars and hydrogen production for Oslo.

**Figure 175. Results for Oslo: private cars and hydrogen production**

**Private cars**

**Hydrogen production**

The results for each regional model are presented in Figure 176. The base case with the assumptions of the HyWays project (Scenario A) is compared with the alternative assumptions of scenario B-E.

**Figure 176. Snapshot on energy use (upper diagrams) and production of hydrogen (lower diagrams) (PJ/year)**
The studies of the three different types of regions point out the importance of the conditions of hydrogen production. In case of industry using large amounts of natural gas, SMR-plants will be able to produce hydrogen at a reasonable price and with strong limitations on CO₂ emissions even CCS will be used. On the other hand, if excess/cheap electricity is available, electrolysis would be the technology selected for hydrogen production. In a city region with few energy resources, the more energy efficient electrical cars are preferred since hydrogen only can be produced at high cost. In all analyses, high tax differences between fossil fuels and other fuels (hydrogen, electricity and bio fuels) must be implemented for new propulsion technologies to be competitive in the mid-term. With limitations on CO₂ emissions hydrogen cars would be used earlier and to a higher extent. Higher oil and gas prices decrease the use of hydrogen in 2020 and 2030 due to more expensive hydrogen production (electrolysis instead of SMR).

### 3.16.1.2 Coupling the model with a GIS for infrastructure analysis

The NorWays project (198) aims at providing decision support for introduction of hydrogen in the Norwegian energy system by modelling of energy system and hydrogen infrastructure at various spatial levels. GIS-based regional hydrogen demand scenarios and fuelling station networks have been generated, considering organic growth of regional hydrogen coverage and increasing density of hydrogen users over time. The project includes modelling at national, regional and local level, utilizing energy system modelling (MARKAL), well-to-wheel-studies and infrastructure analysis. The work is carried out in close cooperation with the EU hydrogen roadmap project HyWays.

To optimize the supply structure, the H2Invest model has been developed. For a given list of fuelling stations (location and demand per time), at each time step the model evaluates building central plants at a list of specified locations and delivering the hydrogen to the best suited fuelling stations, with onsite hydrogen production being the fallback option. An example of a hydrogen supply landscape in 2035 is depicted in Figure 177 right (corresponding to the demand in Figure 177 left and including production facilities, truck and pipeline routes, and onsite generation).

**Figure 177. Hydrogen demand 2035 (left) and hydrogen supply 2035 (right)**

Beside inventory lists discretised over time and space and GIS output data, the H2Invest model returns aggregate shares of hydrogen production, delivery, costs and specific GHG emissions. In all scenarios, decentralised production technologies, especially electrolysis, play a crucial role due to Norway’s low population density. The costs of hydrogen can be at a competitive level from a penetration rate of app. 5% (anticipated 2025). GHG emissions from hydrogen production depend on the production mix and can be influenced effectively by political measures such as a high CO₂ taxes or subsidies on renewable electricity.
3.16.2 Impacts of climate change on the Norwegian energy system toward 2050

The overall objective of this work (199,200,201) is to identify the effects of climate change on the Norwegian energy system towards 2050. Changes in the future wind- and hydro power resource potential, and changes in the heating and cooling demand are analysed to map the effects of climate change. The impact of climate change is evaluated with an energy system model, the MARKAL Norway model, to analyse the future cost optimal energy system.

Scenarios

Ten climate experiments, based on five different global models and six emission scenarios, are used to cover the range of possible future climate scenarios and of these three experiments are used for detailed analyses. In this study Exp. 3 and Exp. 4 represent the extremes of the future climate conditions, while Exp. 10 represents an average with a detailed analysis of precipitation data. Further, the climate change experiments are compared to a BASE experiment, representing no climate change. Figure 178 shows the projected hydro resources, with and without impact of climate change, for selected experiments.

Figure 178. Projected hydro resources with and without impact of climate change (TWh/year)

Results

The most important impacts of climate change on the Norwegian energy system are a lower demand for heating and a higher hydro power potential. Also, the cooling demand will be higher, but the changes in heating demand will be significantly higher than the change in cooling demand. The studied climate change will have a limited impact on the wind power potential. The possible total direct consequences of climate change will be reduced energy system costs and lower Norwegian electricity production costs.

Climate change will reduce the electricity consumption in the residential and in the commercial sectors, since electricity is the most important energy carrier used for space heating. Climate change will also lead to an earlier implementation of electricity and hydrogen fuelled vehicles; changes in the electricity demand and the hydro power production results in more available electricity at a lower production cost that is used by electricity vehicles and for production of hydrogen from water electrolysis.

The impact of climate change on the end-use demand and on the renewable resources gives increased net electricity export (Figure 179), and for most sensitivity cases presented reduced national investments in new renewable power production, such as offshore wind, tidal and wave power. Because hydro power has relatively low operational costs, the cost optimal solution utilises all the hydro power potential available at all time.

The magnitude of the net electricity export and investments in new renewable power depends on several parameters. Factors that reduce the net electricity export are limited export opportunities and less use of energy efficiency measures.

Despite significant uncertainties regarding the future climate, the climate experiments presented, based on different global models and emission scenarios, are comparable with regard to the impact of climate change on the Norwegian energy system, although the magnitude of the impact varies. Together with the detailed analyses with three of the ten experiments, this consistent trend in the results, supports
the conclusion that the impact of climate change should be considered in future investments in the Norwegian energy sector, and should be taken into account in future policy resolutions.

**Figure 179. Net electricity export in 2030 and 2050, TWh per year**

![Net electricity export graph]

### 3.16.3 Global technology learning and CO2 emissions under policy constraints

In this paper (202,203,204,205,206) it is argued that technology learning may be both a barrier and an incentive for technology change in the national energy system. The possibility to realize an ambitious global emission reduction scenario is enhanced by coordinated action between countries in national policy implementation. The analysis of the national measures are done with a bottom-up energy systems model of the Norwegian energy system (MARKAL) with input from a global model (ETP) and a national macroeconomic model (MSG6). The national policies to stimulate technology deployment are input to the MARKAL model.

**Scenarios**

Among the global scenarios in the ETP study, the REF, the ACT Map and the BLUE Map are selected. They are stabilising the CO2 emissions at today’s level and reducing the CO2 emissions 50% by 2050 respectively and represent a relatively optimistic view with respect to technology development.

The EU 20/20/20 target aiming at increasing new renewable energy, reducing energy demand through energy efficiency and reducing CO2 emissions all by 2020 are concrete, though the extrinsic national targets vary. Two different policy measures are included in this study: (1) subsidies for new renewable energy conversion technologies, renewable district heat generation (DH) and CCS and (2) improved building code to reduce energy demand.

**Results**

An overview of the national scenario results in 2050 with spillover from global technology learning is listed in Table 36. The impact of global technology learning is substantial. In the R-scenario the CO2 emissions are increasing from about 44 Mton in 2005 to about 60 Mton in 2050. New electricity generation capacity is then obtained from NGCC. The choice of new electricity generation technology in the technology in the “no additional policy”—A- and B-scenarios, new electricity generating capacity is dominated by OFW (Offshore floating wind power). The cost of OFW is heavily influenced by global technology learning. The influence of the measures on total annual CO2 emissions is only significant in the R-scenario though still very small.

There are also large differences in the IS (Investment support) depending on the global scenario. Using IS as measure of the national contribution to global technology development is illustrated for the R, A, A–H, AE and AE–H scenarios below. In the R-scenario the national CO2 incentive of 150 NOK/ton may initiate an IS. The IS is very small; however, because NGCC are selected to meet the increased electricity demand. The national subsidy, in the R–H scenario, shifts the investments to NGCC with CCS. Because it does not become commercially viable within the analysis period all of these investments contribute to IS. This increases the IS substantially (Figure 180). In the A scenario, with a CO2 tax at the level of the global CO2 incentive only, significant IS is provided. This may seem inconsistent with the definition of IS. Firstly, the decision to provide IS is internal to the optimizing routine and thus determined by the system cost for the whole analysis period. More important are probably the favourable conditions for wind
power in Norway compared to the global average. In 2015–2020 the IS is directed to onshore wind power. From 2025 when spillover of global technology learning reduces the investment cost, IS is directed to OFW.

Table 36. Results in 2050 with spillover of global technology learning and with the additional policy measure

<table>
<thead>
<tr>
<th></th>
<th>R</th>
<th>A</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>System cost (Billion NOK)</td>
<td>5375.0</td>
<td>5043.1</td>
<td>5011.5</td>
</tr>
<tr>
<td>L (low subsidy)</td>
<td>+3.5</td>
<td>+4.2</td>
<td>+4.1</td>
</tr>
<tr>
<td>H (high subsidy)</td>
<td>+17.5</td>
<td>+21.9</td>
<td>+13.8</td>
</tr>
<tr>
<td>B (building code)</td>
<td>+100.0</td>
<td>+102.0</td>
<td>+108.0</td>
</tr>
<tr>
<td>CO₂ (Mton)</td>
<td>No add. policy</td>
<td>59.8</td>
<td>48.4</td>
</tr>
<tr>
<td>L</td>
<td>−0.5</td>
<td>+0.2</td>
<td>+0.2</td>
</tr>
<tr>
<td>H</td>
<td>−4.1</td>
<td>+0.5</td>
<td>+0.4</td>
</tr>
<tr>
<td>B</td>
<td>−4.3</td>
<td>−0.1</td>
<td>0</td>
</tr>
<tr>
<td>El-production (TWh)</td>
<td>No add. policy</td>
<td>162</td>
<td>201</td>
</tr>
<tr>
<td>L</td>
<td>+1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>H</td>
<td>+2</td>
<td>+2</td>
<td>+2</td>
</tr>
<tr>
<td>B</td>
<td>−15</td>
<td>−26</td>
<td>−21</td>
</tr>
</tbody>
</table>

Figure 180. National investments support provided for the scenarios R, A and A–H and learning investments

It is found that implementation of technology subsidies increase the national contribution to early deployment independent of the level of spillover. In a special case with no spillover for offshore floating wind power and endogenous technology learning substantial subsidy or a learning rate of 20% is required. Combining the high learning rate and a national subsidy increases the contribution to early deployment. Enhanced building code on the other hand may reduce Norway’s contribution to early deployment, and thus the realization of a global emission reduction scenario, unless sufficient electricity export capacity is assured.

3.16.4 Regional TIMES model with high time resolution

In Norway, hydropower is the by far most dominant source of electricity production. However, the potential for further growth is limited and therefore other sources of power production such as wind and gas power plants has been constructed during the last years. In order to improve modelling and analysis of demand side options and especially options for substitution of electricity demand a regional TIMES model (207,208) has been developed by Institute for Energy Technology (IFE) on commission of the Norwegian Water Resources and Energy Directorate (NVE).

The overall aim of this modelling work has been to develop a model that could be used in connection with the hydropower/power market model Multi-area Power-market Simulator (EMPS). The basis of the modelling work has been the existing MARKAL models at IFE. These models cover a single region MARKAL model for whole Norway and regional models for selected counties (Oslo, Telemark and Rogaland).
All these models cover all sectors with analysing periods towards 2050. In order to develop a model that could be used in iteration with the EMPS model we have increased time resolution to cover all weeks during each year and five time slices per week, equally 260 time slices annually. The TIMES model covers seven regions in Norway with exchange of electricity between regions and with neighbouring countries. The seven regions are the same in the two models and are defined based on limitations in the transmission and production capacities.

**Scenarios**

When we use the model in connection with the EMPS model we apply electricity prices (spot prices) from the EMPS model for each region into the TIMES model. The TIMES model return electricity demand for each time slice to the EMPS model. When the TIMES model is applied in the stand alone version the possibility of storing water from a week to the next improves the model significantly, in a hydropower dominated system such as in Norway.

**Results**

The initial iterations on a single region applying electricity prices from the EMPS model into the TIMES model and vice versa showed good agreement with expected load curves/price development during the year (Figure 181). Ongoing work will focus on iterations with a complete TIMES model and corresponding EMPS model with all seven regions. Further work will focus on comparisons of results from the stand alone TIMES model and the iterations between TIMES and the EMPS model.

**Figure 181. Electricity prices and consumption**

The first iterations show reasonable responses from the TIMES model to changes in electricity prices. There are different responses in different regions due to existing stock of alternatives. Options for storage of hydropower (weekly) improves the models in hydropower dominated systems significantly.

### 3.17 Portugal

#### 3.17.1 Cost of energy and environmental policy in CO₂ abatement—scenario analysis to 2020

This presentation (209) introduced the different studies using TIMES-PT:

- Quantifying the Synergies and Antagonisms Between Energy and Environment Policy Instruments in Place – feed-in tariffs, EU ETS and on-budget aids to gas infrastructures;
- Energy and GHG Emissions – Evaluation of Long Term Scenarios for Portugal;
- Renewable Energy Sources Availability under Climate Change Scenarios – Impacts on the Portuguese Energy System;
- Evaluation of the Energy Savings Potential of the Portuguese Households;
- Competitiveness of Portuguese Industry in Post-Kyoto EUTS: Sector CO₂: MAC;
- Portugal Climate 2020: GHG Emission Scenarios in the Post-Kyoto regime
• H: technologies roadmap for Portugal for 2050
The role of cost-effective measures in Portugal for compliance with the EU climate-energy targets
• What is the contribution of “cost-effective measures” in the residential and commercial sectors for GHG emission targets?
• What are the hidden gains if changes in behaviour and technologies follow a perfect knowledge pattern?

This paper (210) quantifies the contribution of Portuguese energy policies for total and marginal abatement costs (MAC) for CO₂ emissions for 2020. The TIMES_PT optimisation model was used to derive MAC curves from a set of policy scenarios.

Scenarios
The reference scenario, hereafter mentioned as no policy scenario, considers the most relevant Portuguese energy policies in place. The other studied five alternative policy scenarios are identical to the policy scenario except for the level of implementation of some of the assumed policies, as follows.

1. No policy—excludes all policies assumed in the policy scenario.
2. Nuclear—policy scenario allowing nuclear power. Because Portugal has no nuclear power plants at the moment it is assumed that such plants will only be operating from 2015 onwards, since it is considered that at least 8 years will be necessary to select a site, train personnel and obtain the necessary permits.
3. Conventional coal—policy scenario allowing new conventional coal power plants.
4. No incentives to gas—policy scenario without incentives for combined cycle natural gas power plants.
5. No biomass—policy scenario with a cap on biomass domestic production and imports, which does not allow for biofuel production. The cap was set at 2005 levels the most recent value on total national biomass consumption. The objective is to assess what is the effect in MAC if biomass is not available in expected quantities.

Increasingly strict CO₂ emissions caps were set for each of the six policy scenarios to build the MAC curves for CO₂ emissions for 2020. The caps are constant for the 2020–2030 period and range from a maximum increase of CO₂ emissions of 90% (91141 Gg CO₂) compared to 1990 levels, to a maximum decrease of 60% (19188 GgCO₂). Besides the CO₂ cap for 2020–2030, all scenarios consider the Portuguese commitment under the Kyoto Protocol (and the EU burden sharing agreement), which corresponds to an increase of 27% of 1990 emissions in the first commitment period of 2008–2012.

Results
The CO₂ MAC curves for 2020 for Portugal obtained with TIMES_PT for the six policy scenarios are presented in Figure 182, comparing MAC for the same reduction effort vis-a-vis 1990 emissions, i.e. the same CO₂ emissions cap. The introduction of policies significantly increases MAC: the policy scenario has 91–42% higher costs than the no policy scenario, respectively, for the emission caps of +20% and -60% CO₂ from the 1990 levels. The two scenarios with nuclear power have cheaper MAC as nuclear power plays a major role in electricity generation. When allowed, the share of electricity generated from nuclear power is never less than 71% of the generated electricity, roughly to 8.5GW installed capacity. Such quantities of nuclear power are very likely unfeasible in Portugal due to concerns other than global warming, such as size of the territory and energy security issues.
Figure 182. Marginal abatement costs curves for the Portuguese energy system in 2020*

* As percentage reduction from 1990 levels (the negative sign corresponds to an increase in emissions).

Figure 183 depicts emission reductions for 2020 compared with emissions for each policy scenario without an emission cap. In the scenarios without nuclear power, clearly electricity generation has the highest cost-effective reductions; it bears 45–74% of the total CO₂ abatement, especially in the conventional coal and no incentives to gas scenarios. The reductions are due to the substitution of coal by wind and by new hydro power plants. The relative importance of the abatement made by the electricity sector decreases slightly as stringency of emission caps increases, but even for the more restrictive emission caps industry and CHP are always second in overall CO₂ abatement. In the scenarios without nuclear, industry and CHP are responsible for 14–35% of total abatement.

From a CO₂ emission mitigation perspective, the existing policies introduce significant inefficiencies, possibly related to other policy goals. The ban on nuclear power is the instrument that has the most significant effect in MAC.

3.17.2 Cost of counteracting policy instruments in place in Portugal

The disarticulation of energy and environment policy instruments generates inefficiencies that stretch already limited government budgets and hamper the efficiency of all policy instruments in place. This paper (211) presents such a quantitative bottom-up approach that estimates the losses or gains on cost-effectiveness of interacting policy instruments using TIMES_PT, a bottom-up optimization technology model implemented for Portugal. The paper quantifies the interactions between the following policy instruments in place in Portugal: 1) feed-in-tariffs; 2) CO₂ emissions trading, and 3) on-budget aids to gas
infrastructures. The analysis is made for the period 2000 to 2030 and the interactions are assessed in terms of energy system costs and CO₂ emissions.

Scenarios
Simulation of different combinations of existing policy instruments (Table 37):

- EU-ETS: Electricity generation, refineries and energy intensive industry; Allocation to maintain 2000 emissions; Allowance price 21€/t CO₂; Only buying is modeled.
- Feed-in tariffs: Subsidies to generated electricity (€cents/kWh) for wind 7.90, small hydro 8.20, biogas 10.50, wood waste 11.00, waves 28.00, PV 46.50€
- Aids to gas
  ⇒ Min. electricity generated from gas combined cycle (existing & new) corresponding to at least 1100 MW installed capacity in 2010-2030
  ⇒ In 2007 1176 MW in place and attributed permits for more 3200 MW

Table 37. Simulation from 2000 to 2030 – analysis of results for 2020

<table>
<thead>
<tr>
<th>Policy</th>
<th>Scenario</th>
<th>None</th>
<th>All</th>
<th>ETS</th>
<th>FI</th>
<th>Gas</th>
<th>ETS+FI</th>
<th>ETS+Gas</th>
<th>Gas+FI</th>
</tr>
</thead>
<tbody>
<tr>
<td>EU-ETS</td>
<td></td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Feed-in tariffs</td>
<td></td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Aids to gas</td>
<td></td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

Results
The most costly counteracting policy instruments are feed-in tariffs and aids to natural gas (Figure 184). Its combined implementation increases total energy systems costs by 1% compared to a case where only aids to gas are modeled, which corresponds to 0.14% of the GDP. The counter effects of these instruments lead, in 2020, to ranges of -12 to +4% on wind installed capacity, -26 to +6% on electricity generated from coal, and an increase in CO₂ marginal abatement costs of 0-8 €/t CO₂. On the other hand, the combined implementation of the EU-ETS and aids to gas leads to reduced CO₂ marginal abatement costs (from 31 and 29 to 21€/t/CO₂).

Figure 184. System costs (2030)

3.17.3 The impact of climate change mitigation options on air pollutants emissions

In Europe, climate change policies implemented to achieve the EU climate objectives are estimated to reduce the costs of existing air pollution abatement policies in EUR 10 billion per year and to reduce emissions by 10% for SO₂ and 8-10% for NOₓ and PM (EEA, 2006). The objective of the paper (212) is to present the modeling approach and results on the evaluation of the impacts of GHG mitigation options on the SO₂, NOₓ and PM₂.₅ emissions by 2030.
The technological bottom-up model TIMES_PT was used to assess the impact of different GHG mitigation levels in air pollutants. TIMES_PT models the Portuguese energy system from 2005 to 2030, and has been extended in order to include acidifying pollutants SO₂ and NOₓ (Dias, 2009) and fine particulate matter PM2.5.

**Scenarios**

The following baseline policy assumptions were taken into account: (i) the hydro installed capacity included in the National Plan for High Potential Hydropower Infrastructures (PNBEPH) (INAG, DGE, REN, 2007); (ii) at least 10% biofuels in diesel and gasoline in road transport consumption, from 2010 onwards; (iii) a minimum of 5% electric private cars from 2015 onwards; (iv) accomplishment of energy efficiency targets from the National Action Plan for Energy Efficiency (PNAEE, 2008) in the year 2015.

**Results**

The REF scenario indicates a reduction of 7% in GHG emissions by 2030, when comparing with 2005 values, with the power sector showing the major reduction (-15%). This is a consequence of the Portuguese policies and measures, as indicated previously, to accomplish the EU climate-energy package 2020 and also of an increase of the efficiency in energy supply and demand. Concerning the scenarios with GHG restrictions, the main reductions occurred in different sectors, being industry (44-54%) and transport (62-60%) sectors more cost-effective. The GHG MAC curve for 2030 for Portugal obtained with TIMES_PT is presented in Figure 185. Three different sections can be identified:

- (i) Until a restriction of -25%, costs increase smoothly, reaching 100€2000/ton CO₂eq.;
- (ii) the next section from -30 to -35%, presents costs between 100 and 300€2000/ton CO₂eq.;
- (iii) a significant increase of costs is observed for emission restrictions above -35%, with costs getting close to 800€2000/ton CO₂eq. abated. In this point (35% to 40% reduction) the marginal cost doubles for an increase in abated emissions of only 5%.

**Figure 185. CO₂eq marginal abatement cost curve for the Portuguese energy system in 2030**

![Graph](image)

The cost-effective options generated by the TIMES_PT model for the different restrictive GHG emissions scenarios result in different values of air pollutants emitted (Figure 186). The breakdowns of the measures selected by the model are very important to identify possible options that simultaneously reduce air pollutants and GHG emissions, promoting synergies that may allow reaching more ambitious targets and eventually, lower economic costs for mitigation of both environment problems.
Figure 186. Emissions of air pollutants in 2030 in the different GHG restrictions scenarios

The main option to comply with the GHG restrictions is the increase of electricity generated from renewable resources, from 49% in REF to 53% in GHG_35 and 67% in the GHG_50, mainly through solar and wind energy. Increase of biomass consumption is also an option, mainly in the industry sector, in GHG restrictive scenarios, with impacts in increasing levels of PM emissions. The introduction of CCS abatement technology in less restrictive scenarios than in more restrictive ones, evidence that at higher and ambitious GHG mitigation levels, is more cost-benefit to increase renewable electricity production than invest in end-of-pipe solutions.

The improvement of energy efficiency and fuel switches are sufficient in all scenarios to comply with the emissions levels for 2010 of SO2 and PM without using control technologies. NOx emissions comply with the stipulated levels through the introduction of abatement technologies, such as SCR and combustion modifications in kills and boilers in the industry sector.

3.17.4 Contribution of different exogenous assumptions on the uncertainty of GHG emission scenarios

The development of GHG emission scenarios, frequently using energy-economic-environment models, is fundamental for climate policy. The degree of scenario’s uncertainty depends on the assumptions implemented in the model as exogenous parameters. This paper (213) assesses the contribution of different exogenous parameters for the case study of the Portuguese energy system. The linear optimization technology model TIMES_PT is used to develop seven alternative GHG scenarios for 2020.

Scenarios

One of these scenarios (Baseline) includes a combination of assumptions on all exogenous parameters, while the others have variations of only one of them (Figure 187).

Figure 187. GHG scenarios for 2020
Results
The scenarios’ comparison concludes that the most relevant assumptions for overall uncertainty are the ones related to the socio-economic assumptions, followed by the assumptions on technology deployment. The availability of energy resources presents minor variations on GHG emission (less than 2% of the Baseline emissions) (Figure 188).

Figure 188. Compliance with energy climate policy package (2020)

GHG emission estimates are never more than 9% different from the BASE scenario, thus in overall terms it seems that the emission changes are not significant. But, these relatively small differences in GHG emission scenarios have an impact in compliance with the energy-climate policy package, especially regarding the RES target of 31% for 2020. The most relevant assumptions for overall uncertainty are the ones related to the socio-economic assumptions (DEM), followed by the assumptions on technology deployment (EFF). Up to what extent the larger differences between these scenarios and the BASE scenario are simply because some assumptions have a wider variation range than the others? Assumptions made within an actual policy driven process - such a wide range is intrinsic to the climate policy formulation process.

3.17.5 Forecasting of residential energy services demand for 2030

Forecasting energy services demand is a very challenging topic, either as a long-term or a short-term exercise, since it depends on several (in)dependent factors from economic to climate drivers. This work (214) proposes a bottom-up approach to develop energy services demand scenarios of the residential sector up to 2030 for Portugal. The results have been used as inputs of the technological economic model TIMES_PT to obtain final energy consumption.

Scenarios
The residential energy services demand forecast was driven by two socio-economic scenarios, based on different life styles and population growth assumptions: i) Trend Scenario (TS), characterized by the continuation of past recent trends, and ii) Change Scenario (CS), supported by a sharper economic growth with changes to a more efficient behavior.

Results
Through the analysis of the results of the energy services demand methodologies, it is expected that the need of energy in the residential increase (e.g. 60 and 79% in TS and CS respectively) (Table 38). This can be explained by the introduction of new electric equipments, more hours of use of computers and televisions, and the increase of electric appliances ownership and comfort levels.

Table 38. Energy services demand growth index (2005=100)
In the long term, the increase of energy efficiency offsets the energy demand growth. The modeling exercise suggests changes in the energy consumption profile, switching from biomass, heat, and LPG to natural gas, electricity and solar thermal. In the residential sector it is projected a stagnation of final energy consumption in TS, with 1% growth from 2005 to 2030. In CS there is a 13% growth in energy consumption due to different installed equipments and fuel choices made by the model.

The results show that final energy consumption in residential sector will grow very modestly, especially in the TS. However, this masks significant growth in the demand for energy services, explained by the use of more energy efficient equipments.

### 3.18 Russia

#### 3.18.1 Carbon emissions projections and reduction potentials

The purpose of the paper (215) is to estimate CO₂ emissions trends, potentials and costs of CO₂ mitigations in Russia. The analysis consist in: 1) developing a bottom-up TIMES model of Russian economy with extensive representation of energy consuming and producing technologies; 2) reviewing official and alternative scenarios of economic development and demand for energy; 3) comparison of energy and climate policy scenarios; 4) analysis of policy selection under uncertainty. On the current stage of the analysis we consider pathways of CO₂ emissions in the power and heat production sector up to 2030. We analyze official and alternative projections of socio-economic development of the Russian economy, and apply RU-TIMES model for policy scenarios comparison and emissions projection.

**Scenarios**

For example, these presentations (216,217) show carbon emissions projections for Russia in baseline and policy estimates:

- **Official (MED, 2008):**
  - Innovative (~6.5%/year 2009-2030), baseline
  - Energy & Raw material (~5.5-6.5%/year)
  - Inertial (~4.5%/year)
- **Crisis scenarios:** 3 years recession & 6.5%/year after or 4.5%/year after
- **Policy:** CAP & Trade; Carbon tax

**Results**

In the study we apply official and alternative projections of GDP growth, electricity demand, domestic prices for energy, extraction and exporting volumes of fossil fuels, and targeted structure of electricity and heat generation to calibrate RU-TIMES model, formulate scenarios and estimate CO₂ emissions trends (Figure 189). According to our estimates, even in the case of the most ambitious scenario for economic growth and electricity and heat demand growth, CO₂ emissions in power and heat sector won’t exceed 90% of 1990 level by 2020. There are few main reasons of expected CO₂ reduction in Russia: 1) Targeted growth of share of nuclear and large hydro (MED, EFA); 2) Targeted growth of renewables in power and heat production; 3) Efficiency growth of generating capacity due equipment upgrade.

Our survey of real cases of renewable technologies implementation in Russia shows high competitiveness of the technologies comparing to conventional fossil-fuel based techs, and short-term of pay-back of investments in renewables. Market of renewable energy in Russia is not in cost equilibrium. Cap and Trade policy allows reduce costs for producers with lower emissions pathway. According to IEA estimates, energy efficiency might contribute up to 40% in emissions reduction by 2050. Recent study of energy efficiency in Russia (IFC) found 40% potentials for energy efficiency growth in Russia. This provide additional room for improvements and GHG reduction.
3.18.2 Designing stochastic experiments with deterministic models

Deterministic models have strong assumption – perfect information. At the same time, some uncertain parameters might be crucial for decision-making. The uncertainties will be resolved later, but decision should be made now. As an example, in climate policy analysis with integrated assessment models, unknown parameter is a climate sensitivity; for reference energy systems (MARKAL/TIMES) important assumptions are future demand, prices, technologies, etc. Therefore there is a good reason to turn to stochastic models (218,219), as they allow incorporate probabilistic (random) elements into optimization process. Let's consider an example based on TIMES model for Russian energy system (power and heat sector). Instead of assigning certain values to unknown parameters for deterministic runs, specification of distributions of the parameters is required.

Scenarios

Assume we have a set of alternative deterministic rational scenarios. For example, a country takes a commitment for CO₂ emissions reduction. And the goal of experiment is to estimate an optimal CAP considering uncertainty of future fossil fuels prices and carbon prices. The possible set of scenarios can be a set of CAP levels from -10% to -30% of 1990 level with step 5%. I.e. we have 5 scenarios {-10%, -15%, -20%, -25%, -30%}. Our goal is to pick one scenario from the predetermined SET, taking to account the known risks and our risk aversion.

The next step is determining sources of uncertainties (prices, demands, technological parameters, etc.) and characterizing them with distributions. On the next step we have to define a policy-period. This is a period where we cannot change our decision and have to follow the chosen policy until end of the period. Continuing our example, let's assume that we've decided to take a “-10%” CAP.

The following step is sensitivity analysis for each of policy options (scenarios). The main idea is to estimate variance of objective variable as result of uncertainty for each policy scenario. It is important to do the sensitivity analysis with the fixed endogenous variables by fixing them on the optimal level from a deterministic run with mean (median) values of uncertain parameters.

Results

As a result of the sensitivity analysis we have distribution of multiple deterministic runs of a model with fixation of endogenous variable during the policy-period. Results of EV analysis for various risk averse parameter (RAP) are presented in Table 39.
The example demonstrates stochastic inference with the deterministic model. In case of RAP <7 the variation of future costs are not sufficient to choose another policy. Costs are minimal under CAP = -20%. But for the more risk averse decision maker with RAP>=7 more stringent policy (-30%) is preferable because it is less sensitive to fossil fuels prices variation.

Table 39. An example of mean-variance analysis for various risk averse parameters

<table>
<thead>
<tr>
<th>CAP</th>
<th>E=1SD</th>
<th>E=2SD</th>
<th>E=3SD</th>
<th>E=5SD</th>
<th>E=7SD</th>
<th>E=10SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>-10%</td>
<td>1,352.20</td>
<td>1,480.90</td>
<td>1,609.60</td>
<td>1,867.00</td>
<td>2,124.50</td>
<td>2,510.60</td>
</tr>
<tr>
<td>-20%</td>
<td>1,345.40</td>
<td>1,473.80</td>
<td>1,602.20</td>
<td>1,859.10</td>
<td>2,115.90</td>
<td>2,501.10</td>
</tr>
<tr>
<td>-30%</td>
<td>1,351.90</td>
<td>1,479.10</td>
<td>1,606.20</td>
<td>1,860.50</td>
<td>2,114.80</td>
<td>2,496.20</td>
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<tr>
<td>-40%</td>
<td>1,364.60</td>
<td>1,495.80</td>
<td>1,626.90</td>
<td>1,889.30</td>
<td>2,151.70</td>
<td>2,545.30</td>
</tr>
</tbody>
</table>

3.19 Slovenia

3.19.1 Modelling the national energy system within the European framework

The relationships between anthropogenic activities and the environment require a careful analysis of economic and technological implication of energy-climate policies, to redirect the energy systems towards a sustainable configuration. This implies the implementation of innovative decisional tools for policy assessment, to support the policy makers in the definition of effective energy-environmental strategies, coherent at different spatial scales. In this framework partial equilibrium models as the TIMES models generator, developed under the IEA-ETSAP Programme represent a powerful tool to analyse global, national and local issues and to support the formulation of comprehensive policies. These tools are utilized in the framework of the Integrated Project NEEDS of the VI Framework Programme to develop the energy system models of 30 EU countries, which are linked by energy and emissions trades in a multiregional approach.

Scenarios

In this paper (220) are presented the main results obtained at country level for the Slovenia energy system in the Business As Usual – BAU scenario that provides the optimised development of the energy system in agreement with the main national energy and environmental policies.

Results

In the following the main results produced by the NEEDS_SI TIMES model for the BAU scenario are presented. The primary energy consumption increases about 12% on overall until 2050, even if a slight decrease respect to the base year can be noticed in 2010 (about 3%) (Figure 190). Among fossil fuels, coal and natural gas use is highly increased, whereas oil and lignite use is quite constant (being respectively about 90 and 50 PJ per year). In particular oil is the most used energy carrier over the full time horizon. Also renewables (hydro, wind, photovoltaic) are remarkably increased (+127%) due to their role in electricity production in substitution of nuclear after the decommissioning.

According to the demand projections, the overall net imports increase about 34% with a remarkable increase of coal due to its use in CHPs and a quite constant import of oil products and natural gas. On the other hand, electricity export decrease 67% and the net electricity generated increases about 30%, reaching 17.6 TWh in 2050 (Figure 191). A slight decrease in 2025 of the import values can be noticed, due to a decrease of electricity demand in the industrial sector. Nuclear, hydro and lignite are the energy vectors most utilised for electricity production. After 2025, nuclear is substituted by hydro, wind and natural gas, taking into account that renewable use is fostered both by the regulations in force and by the EU directives on the promotion of electricity produced from renewables.
Final energy consumption increase 35% on the full time horizon, with the highest variations for coal and natural gas (respectively from 3 PJ to 28 PJ in 2050 and from 24 PJ to 50 PJ). As concerns the environmental aspects (Figure 192), without specific restrictions on GHGs the total CO₂ emissions increase about 4% on average compared to the base year with a remarkable increased contribution of Industry (from 14% to 34%) due to a larger use of coal. On the other hand, the contribution from Conversion and Transport decrease (their share being respectively 33% and 18% in 2050) whereas the contribution from Residential, Commercial and Agriculture) is quite constant (about 15% of the total).
3.20 South Africa

3.20.1 Technology learning for renewable energy: Implications for long-term mitigation scenarios

Technology learning can make a significant difference to renewable energy as a mitigation option in South Africa’s electricity sector. This article (221) considers scenarios implemented in a MARKAL energy model used for mitigation analysis. It outlines the empirical evidence that unit costs of renewable energy technologies decline, considers the theoretical background and how this can be implemented in modeling.

Scenarios

Two scenarios are modelled, assuming 27% and 50% of renewable electricity by 2050, respectively. The solution adopted for the long-term mitigation scenarios (LTMS) analysis was to conduct most of the analysis without learning in either the base or policy (mitigation) cases. However, an additional variation of the base case with technology learning was run, and policy cases for technologies for which learning data was available were reported against this base case. In order to assess the impact of increased utilisation of renewable technologies on GHG emissions, various levels of penetration of renewables for electricity generation were considered.

Results

In this scenario, 15% of electricity dispatched must come from domestic renewable resources by 2020. The technologies available include South African hydro, wind, solar thermal, landfill gas, PV and biomass. This is extrapolated to 27% by 2030, and remains at 27% until 2050. Each of these technologies has an upper limit of capacity that can be built over the period, and a maximum rate at which capacity can be added to any single technology type each year. This scenario sees the introduction of solar power towers, parabolic trough and wind. The extent to which each is introduced can be seen in Figure 193. The solar power tower comes into the mix from 2014 and reaches its limit of 30GW in 2045. The trough starts off much smaller, but reaches 16GW by 2050. Wind comes in gradually, mostly at 25% availability, reaching a peak of 15GW installed capacity in 2030, but declining to 7GW by 2050 likely due to other renewable options becoming more economically viable and the relatively short life-time of wind turbines.

Figure 193. Electricity generating capacity for renewables with learning

The mitigation cost is R52/ton CO₂-eq at a 10% discount rate, reducing emission on average by 42Mt CO₂-eq per year. Figure 194 shows the emission reductions in the renewable energy scenario, without technology learning. If technology learning is assumed for both the base case and the renewable case, the mitigation costs decline significantly, becoming negative at -R143/tCO2-eq. The total emission
reductions are also increased to 2757Mt CO\textsubscript{2}-eq over the period. Emission reductions increase with learning, even when compared to the base case with learning. Annual emission reductions are 15 Mt CO\textsubscript{2}-eq higher if technology learning is assumed. The dip in emission reduction towards the end of the period is due to the increased uptake of renewables towards the end of the period in the base case.

The results show a dramatic shift in the mitigation costs. In the less ambitious scenario, instead of imposing a cost of Rand 52/tCO\textsubscript{2}-eq (at 10% discount rate), reduced costs due to technology learning turn renewables into negative cost option. Our results show that technology learning flips the costs, saving R143. At higher penetration rate, the incremental costs added beyond the base case decline from R92 per ton to R3. Including assumptions about technology learning turns renewable from a higher-cost mitigation option to one close to zero. We conclude that a future world in which global investment in renewables drives down unit costs makes it a much more cost-effective and sustainable mitigation option in South Africa.

**Figure 194. Emission reductions from 27% renewables compared to the base case**

![Graph showing emission reductions with and without technology learning](image)

### 3.20.2 Long-term mitigation scenarios

The Long-Term Mitigation Scenarios (LTMS) process is mandated by Cabinet, led by the Department of Environmental Affairs & Tourism and project managed by the Energy Research Centre. The purpose is to outline different scenarios of mitigation action by South Africa, to inform long-term national policy and to provide a solid basis for our position in multi-lateral climate negotiations on a post-2012 climate regime. This Technical Summary (222,223) therefore provides the basis, in abridged form, for the scenarios – stories of possible futures. The Scenarios together with the underlying technical work are forwarded by the SBT to high-level discussions in the first half of 2008.

#### Scenarios

The limits of the framework are defined by Growth without Constraints (GWC) and Required by Science (RBS). They define the space within which mitigation action occurs. Current Development Plans (CDP) shows what implementing existing policy would achieve, if extended into the future. In the space between GWC and RBS, several action-oriented strategies are defined. They indicate what South Africa ‘Can Do’ or ‘Could Do’.

#### Results

Figure 195 shows combinations – initial wedges, X-wedges and economic instruments combined. It illustrates how far they close the gap between GWC and RBS. As can be clearly seen, a gap remains in all cases by 2050. The initial combined case, demonstrates that making use of all the net negative cost mitigation options allows space to include some with net positive costs. The main qualifier is that the emissions are reduced relative to the high baseline in GWC, but increase in absolute levels right up to 2050. Expressed in terms of the gap between GWC and RBS, the combined initial scenario has closed
just under than half (43%) of this gap in the year 2050. Extending the combined case with further positive cost wedges increases emission reductions, but only stabilises them from 2040 to 2050. A key difference to the initial combined case is that emission stabilise, albeit only right at the end of the period. The combined extended scenario closes the gap about tow-thirds (64%).

In all cases, however, the gap between GWC and RBS is not fully closed. Combined initial or even extended wedges stay well above RBS. Fundamental reasons are that rigorous quantitative analysis relies on known technologies (and cannot model the unknown or future), and does not capture behavioural changes which may be important to emission reductions in future. Economic instruments get close to RBS, but emissions rise in the end. A ‘golden triangle’ of remaining emission reductions needs to be addressed in other ways.

Figure 195. GWC, RBS and combined mitigation actions*

* The lines include the emission reductions not only in the energy sector, but also in other sectors.

Total mitigation costs over a 48-year period add up to substantial numbers. These numbers can be seen in relation to the size of the economy (GDP) or the energy system. As is seen in the results (Figure 196), combining a set of negative cost options – mostly energy efficiency in various sectors - would make the share of GDP more negative, so that the curve initial slopes downward. Figure 196 shows that a range of positive cost wedges, such as those in electricity generation or CCS, can be added and still remain below 0% of GDP. On their own, positive cost wedges would have total mitigation costs that are a positive percentage, when compared to economic output. But when added up cumulatively, then the total cost of the package represented by the runs is still net negative. They become positive overall when electric vehicles and hybrids (both positive cost with large reduction potential) are added in the last two runs. The sensitivity analysis shows that electric vehicles are more competitive at higher oil prices.

The results depend on the wedges chosen. This becomes clear when the industrial energy efficiency is included, or excluded. Industrial energy efficiency not only drives the overall costs further into negative territory, but it also adds a large amount of emission reductions. With the big efficiency wedge, even when all the positive-cost wedges are added, the total still does not exceed expenditure equivalent to 1% of GDP.
3.20.3 Costing a 2020 target of 15% renewable electricity

The problem was to assess (224) the national cost of South Africa achieving a target of 15% of electricity generated from renewable sources by 2020, in the following context. Most South African electricity is generated from coal (93.3% from coal, and 1.4% from renewables in 2009), but potential for renewables is high (solar and wind, and possibly wave).

We used a bottom-up, partial equilibrium MARKAL model of the South African energy system (originally developed for South Africa’s Long-Term Mitigation Scenarios) to model the electricity system, which allowed us to model supply options, as well the impact of demand-side options. We then applied a reliability check, to check that all the cases we modelled had adequate and comparable reliability (due to low resolution of MARKAL load curve, and the potentially high incidence of wind), and adjusted the MARKAL runs accordingly.

Scenarios

Reference Case – ‘business as usual’: assume current plans for new two new coal plants, and thereafter the least-cost option. All the scenarios are modelled with an energy efficiency programme (1A to 3A).

Renewables Cases:
- Lower wind resource assumptions: model chooses least-cost way of meeting target.
- Higher wind resource assumptions: model chooses least-cost way of meeting target.

Nuclear Case modelled for comparison: capacity after planned units is nuclear.

Results

The cost of electricity will not be significantly affected, but investment requirements are a very significant challenge (Figure 197). The impact of investment requirements will depend on ability to develop ‘partner programmes’, specifically: a) an energy efficiency programme, which will lower cost, and b) an industrial development strategy, which will help South Africa capture the development benefits of the programme – significant opportunities for solar thermal. Carbon finance will make a significant difference to the viability/attractiveness of the programme – price level is important.
3.21 South Korea

3.21.1 Impact assessment of CO₂ mitigation options

The Korea Electric Power Research Institute (KEPRI) has performed a study to analyze the deployment impact of CO₂ mitigation options in the power generation sector in Korea, with IEA Clean Coal Centre. The goal of this study (225) is the identification of the viable technology and legal options for CO₂ mitigation, and the impact assessment of the options for the Korean power generation sector. The MARKAL modeling package of IEA/ETSAP was used as an appropriate tool to make the database of Korean energy system in the model and assess the effects of the options.

Scenarios

Four scenarios, which were considered the most likely by KEPCO in Korea, were developed to study the effect of CO₂ emission reductions on the Korean electricity industry:

Base Scenario:
- Only technologies either current in 2004 or included in the National Electricity Plan were included.
- Current trend for renewables introduction was reflected in the model. Constraints for some technologies were set according to the resource limit and geographical limit.

New Technology Scenario
- Twenty likely and speculative new technologies using coal and gas, like IGCC, IGFC and CCS, were added to the Base Scenario for application within the lifetime considered in the model.
- CCS was included within these new technology variants.

Carbon Tax Scenario
- Various carbon taxes ($13, $25, $50, $75/tCO₂) were imposed for both the Base Scenario and the New Technology Scenario. Lower generation limit was set on coal-fired power plant.

Total Carbon Emission Cap Scenario
- Various total carbon emission caps (120%, 100%, 80%, 60% compared to the 2004 level) were imposed on the Base Scenario (CToT) and New Technology Scenario (NCToT). Lower generation limit was set on coal-fired power plant.
Results

The sensitivity of this approach was examined by setting the total carbon emission cap at 120%, 100%, 80%, 60%, and 40% of the emissions level in 2004. For scenarios CToT-120 to CToT-80, as the total carbon emission cap became tighter, gas power technology increasingly replaced coal power technology within the capacity mix while the annual load factor of competitive gas power technology increased, resulting in an increase in overall utilisation and a corresponding decrease in total capacity, Figure 198. However, to achieve even lower target levels of carbon emissions (CToT-60 and 40) was not possible just through a replacement of coal by gas fired technology as the coal fired plant had just about been eliminated from the grid.

The consequence of this approach was to massively increase the use of zero emission technologies (nuclear and renewables) as well as the (lower carbon) LNG technologies, at the expense of coal. As in the carbon tax scenarios, these total carbon emission cap scenarios indicated that gas power would replace coal power unless other alternative fuel technologies became available. Also, when the cap was particularly severe, then the capacity mix required appeared to be unrealistic and relatively expensive.

Figure 198. Capacity by fuel type in 2044, base scenario vs. CToT scenario

For the new technology + total carbon emission cap scenario analysis (NCToT), Figure 199 shows some change in overall capacity and fuel type as the total carbon emission cap became more severe. Thus the capacity of coal power technology facilities decreased by close to 40% when the cap was decreased from 120 to 100%. However, at the same time there was a strong driver for advanced technology with CCS to be introduced. That is, the stronger the emission cap, the earlier CCS technology was introduced and the more advanced the technology that was introduced.

In these NCToT scenarios, if only new power technologies with CCS were compared it appeared that coal power technology was adopted more rapidly, achieved higher capacity and had a higher load factor than gas power technology. It implies that as the total carbon emission cap was tightened, new coal power technologies with CCS, which have the capability of mitigating more carbon emission to produce same amount of electricity, are necessary to meet the cap.

Figure 199. Capacity by fuel type in 2044, base scenario vs. NCToT scenario

It is necessary to take into account security of supply concerns, which require a certain capacity (30%) of coal fired power plant to be maintained on the grid. In comparison to the NCToT scenarios, the LNCToT scenarios promoted the introduction of new coal power technology with CCS but delayed that of new gas power technology with CCS. Consequently there was a greater cost associated with the LNCToT scenarios compared to the NCToT scenarios to achieve the same carbon emission mitigation effect.
Under the base scenario based on the National Electricity Plan of Korea, the future power generation will be dominated by nuclear and coal power plants, with some of natural gas fired plant and a very small proportion of renewables. However, with increasing pressure to mitigate CO₂ emissions, the analysis results of all four scenarios and combination of the scenarios showed that Korea would have to adopt a little different approach.

3.22 Spain

3.22.1 Implementation of the EU renewable directive

Based on the European project RES2020, the analysis (226,227) evaluates the energy strategies to be implemented in Spain in order to satisfy the EU Renewable Directive. The modelling framework relies on the technico-economic model TIMES-Spain, part of the Pan-European TIMES model used in the project.

Scenarios

Four scenarios were defined in order to examine the achievement of the 2020 renewable targets.

- Reference Scenario (BaU): No enforcement of the targets for renewable energy sources in 2020. However, the existing support mechanisms for renewable energy per country are being considered (feed-in tariffs for example). The Kyoto or the post-Kyoto targets set by the 2007 European Spring Council are not imposed as a limit, but it is assumed that the current Emission Trade Scheme operates at a clearing price of 20€/ton of CO₂ in 2010, with a smooth increase up to 24€/ton of CO₂ in 2030.

- RES Reference Scenario (RES-Ref): Enforcement of the target for renewable energy sources and CO₂ targets in 2020. The 20% target for renewable energy sources in 2020 is allocated over the Member States, following the path as given in the Directive.

- RES Statistical Transfer Scenario (RES-Trade): Same as RES Reference, including a virtual trade of “RES rights” allowing the transfer to other countries of the surplus certificates (the latter account for the production of renewable energy) after the domestic target is reached in line with the statistical transfer mechanism proposed in the Directive.

- RES-30 Scenario (RES-30%): Same as RES Reference, but enforcing a 30% reduction target for CO₂ emissions over the whole European Union.

Results

The decrease in the total primary energy supply observed in RES scenarios compared to the BaU scenario (Figure 200) is the result of complementary factors characterizing the energy system: decrease in the final energy demands, shutdown of inefficient technologies such as the coal power plants, penetration of more efficient technologies (for example, more efficient lighting) and energies (partial substitution of coal by gas and renewable, whose use, when expressed in fossil energy equivalent as regards the renewable, is more efficient than the use of coal).

The most important result is that the absolute value of renewable-based electricity generation does not increase more in the RES scenarios (except under the stricter climate target where a slight increase is observed) than in the BaU, and the higher share of renewable observed in RES scenarios is due to the lower overall electricity production, given the implementation of conservation measures in industry. In other words, the penetration of renewables in the generation of electricity is mainly due to the incentives included in the BaU scenario (feed-in tariffs, carbon tax imposed on the ETS sectors) that result in the progressive reduction in electricity generation from coal while the imposed targets in the RES scenarios do not contribute to any additional installed capacity except when the emission target is stricter.
Figure 200. Primary energy consumption in Spain

Renewable electricity generation is based mainly on wind and hydropower (Figure 201). Solar PV does not belong to the solutions selected by the model, and wind power plants, including offshore technologies that penetrate when the onshore potential is fully used, are the preferred technologies, except in the case when a stricter GHG target is imposed, making CSP competitive.

Figure 201. Generation of electricity from renewable energy sources in Spain.

The emissions of the BaU increase by 15% from 2000 to 2020. The sectors with the higher increases in CO₂ emissions are industry (ETS) and transport (mainly road transportation). As a result, the contribution of the power sector to the total emissions decreases, representing 31% of the total emissions in 2000 but 20% in 2020 in the BaU. The additional discounted costs of the RES scenarios compared to the BaU, representing the costs of the renewable and climate policies, remain minor; the total discounted costs of the system increase 0.17% (RES-Ref), 0.18% (RES-Trade) and 0.35% (RES-30%) compared to the BaU discounted costs.

Among the results, it appears that the gap regarding the renewable deployment in Spain between the Business-as-Usual case (including the existing policies) and the EU Directive should be compensated mainly by the penetration of bioenergy in transport and industry, and by the implementation of conservation measures, which contribute to reduce the total energy demand and thus makes useless additional investments in renewable power plants compared to the Business-as-Usual case.

3.23 Sweden

3.23.1 Ancillary benefits of Climate Policy

In this paper (228), we build on the well-established literature suggesting that GHG reduction policies, which create incentives to reduce the use of fossil fuels, can have important local and regional
environmental impacts quite distinct from the global and longer-term benefits directly associated with avoided climate change. The paper addresses a number of health-related improvements (ancillary benefits) that could accompany the reduction in CO₂ under different climate policy designs in Sweden. These designs differ primarily in terms of how the country chooses to meet a specific target and where the necessary emission reductions take place. The reliance on a technology-rich energy system optimization model of the Swedish energy system (TIMES-Sweden) has permitted us to address the economic significance of these environmental side-effects as well as to provide a detailed assessment of the respective technology and fuel choices that underlie any net changes in the estimated ancillary benefits.

The analysis relies on simulations within the energy system optimization model TIMES-Sweden, and focuses on four non-GHG pollutants: Nitrogen Oxides (NOₓ), Non Methane Volatile Organic Compounds (NMVOC), inhalable particles (PM₂.₅), and Sulphur dioxide (SO₂). The simulations permit detailed assessments of the respective technology and fuel choices that underlie any net changes in the estimated ancillary effects.

TIMES-Sweden is a techno-economic and original developed as a part of the Pan-European TIMES model. TIMES-Sweden has been constantly improved with national data, especially regarding regional emissions. In present study, TIMES-Sweden generates the energy mix, the regional emissions, the CO₂-emissions for four different policy scenarios. The resulting emissions and system cost in year 2020 are used to calculate the ancillary benefits from different policy scenarios compared with a Baseline scenario. The ancillary benefits are estimated using three different measures: Annual reduced damage costs (Euro), Reduced annual damage costs per reduced tonne of CO₂ emissions (Euro/tonne reduced CO₂) and Reduced damage costs per increased annual total system costs (percentage share).

Scenarios

Three main climate policy scenarios, which all involve a stricter climate policy, are compared to the Baseline scenario. One of the climate policy scenarios are modelled with two different CO₂-constraints. In the baseline scenario no national emissions targets are defined and the EU emission trading system (EU ETS) is assumed to have a weak target resulting in emission permit prices of 11 EUR₂₀₀₀ per tonne of CO₂. For all three policy scenarios the cap in EU ETS is assumed to be tightened, resulting in increasing prices of tradable emissions permits. The assumed prices are 22 EUR2000 per tonne of CO₂ in the period 2010-2014 and 44 EUR2000 per tonne of CO₂ from the year 2015 and onwards. In addition, three scenarios each describing a specific climate policy target at the country level, are employed.

- The Country-Cap scenario represents a scenario in which the entire 40 percent reduction target must be achieved through domestic reductions. Thus, in this scenario we have a national cap on emissions, which in addition to the existing cost of emitting CO₂ (either through permit trading or a tax) creates a uniform shadow price on CO₂ emissions. The marginal cost of abatement is equalized across all sources. In this way we obtain a cost-effective reduction of emissions within the country, but it is not possible to utilize the benefits of emissions trading.

- The EU scenario is a scenario in which the domestic policies remain the same as in the Baseline scenario, and in which all sectors freely can trade permits at a pre-specified EU ETS price level (see above). The marginal abatement cost is thus equalized across all sources at the level of this exogenous price. In other words, in this scenario the climate policy target is achieved by including the permits traded, and total emissions may exceed the national target by permits bought as these emission reductions are accomplished in other countries.

- In two different Sector-Cap scenarios the trading sector can engage in permit trading within EU ETS but (unlike the EU scenario) the 40 percent target must be achieved exclusive of traded permits. Thus, an important implication of this national emission target is that if a firm in the trading sector chooses to buy permits, a corresponding reduction has
to be made in the non-trading sector (e.g., through adjustments in the carbon tax). In this way the EU ETS participants can “involuntarily” transfer emissions reductions to the non-trading sector. Given the present Swedish policy it is useful to also consider the case where only a fraction of the national target must be achieved domestically. The scenario is thus divided into two sub-scenarios: the Sector-CapA scenario allows for one third of the reductions abroad (through purchases of permits), while in Sector-CapB the entire reduction target must be achieved domestically.

Table 40 summarizes the modelled restrictions on CO₂ emissions in the respective scenarios, and outlines the respective national CO₂ targets (in million tonnes) for the years 2010 and 2020.

**Table 40. Modelled CO₂ Restrictions in Each Policy Scenario**

<table>
<thead>
<tr>
<th></th>
<th>Baseline</th>
<th>Country-Cap</th>
<th>Sector-Cap</th>
<th>EU</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trading sector</td>
<td>No</td>
<td>Not applicable</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Non-trading sector</td>
<td>No</td>
<td>Not applicable</td>
<td>Emitted CO₂ in the non-trading sector ≤ national target - emitted CO₂ in the trading sector</td>
<td>No</td>
</tr>
<tr>
<td>Total</td>
<td>No</td>
<td>Emitted CO₂ ≤ national target</td>
<td>Emitted CO₂ in the trading sector + emitted CO₂ in the non-trading sector ≤ national target</td>
<td>Emitted CO₂ in both sectors – net purchase of TEP ≤ national target</td>
</tr>
</tbody>
</table>

**National Targets for Each Policy Scenario, 2010 and 2020**

<table>
<thead>
<tr>
<th></th>
<th>Country-Cap</th>
<th>Sector-CapA</th>
<th>Sector-CapB</th>
<th>EU</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>-</td>
<td>49.2 (96%)</td>
<td>49.2 (96%)</td>
<td>49.2 (96%)</td>
</tr>
<tr>
<td>2020</td>
<td>-</td>
<td>30.8 (60%)</td>
<td>37.6 (73%)</td>
<td>30.8 (60%)</td>
</tr>
</tbody>
</table>

* National emissions presented in million tonnes of CO₂ and in the brackets the ratios (in percentage) of the resulting CO₂ emissions in the baseline scenario (equalling 48.5 million tonnes of CO₂ in the year 2000) and the emission level in the year 1990 are outlined.

**Results**

The results indicate that significant ancillary benefits accompany Swedish climate policy and they constitute a far from insignificant share of the increase in total system costs, thus reducing the overall cost of climate policy, Figure 202. Moreover, this share appears to be particularly significant in the scenarios that entail the largest emission reductions domestically. The latter results reflect the fact that since an increase in emissions reductions abroad also implies a lost opportunity of achieving important welfare gains from the reductions of a number of regional and local environmental pollutants. This shows, thus, that the notion of full flexibility in compliance measures (including geographical location) may not necessarily represent the most cost-effective strategy for an individual country.
The model simulations also illustrate that the estimated ancillary benefits of climate policy in Sweden appear to be a non-linear function of the reduced CO₂-emissions, both in terms of the ancillary benefits per reduced tonne of CO₂ and as a share of the total system cost. This is explained by differences in the technology choices following each of the policy scenarios. Overall our findings illustrate the usefulness of analyzing the ancillary benefits of climate policy with a bottom-up energy system model. In this paper we have, for instance, highlighted the allocation of biomass in the presence of the weight given to domestic emission reduction versus the use of permit trading, illustrated in Figure 203. We also find important differences across policy scenarios with respect to wind power and oil use, in part resulting in significantly higher ancillary benefits from NOₓ and SO₂ reductions in the scenarios involving a stronger focus on domestic emission reductions.

**Figure 203. Allocation of Biomass between sectors in year 2020**

The non-linearity was also identified in the sensitivity analysis where the ancillary benefit was shown to be sensitive to the assumed CO₂ reduction target (in the domestic reduction scenario) and to changes in the permit price (in the permit trading scenario), but appeared not to be heavily influenced by changes in the discount rate. In further tests looking at different years strengthening the non-linearity of ancillary benefits, the energy system changes between years and consequently the technology and/or the fuel switch that causes the CO₂ reduction differ resulting in very different ancillary benefits. To summarise then, ancillary benefit measures are system specific and can not be used as general numbers, but rather need to be calculated for each country and each time period.
Clearly additional research efforts are needed to shed more light on the issue of to what extent the ancillary benefits of climate policies could potentially offset a portion of the costs of these policies. For instance, in most studies the baseline issues probably deserve more attention. In our analysis we pay attention mainly to the impact of environmental policy and fuel taxes. Still, other baseline issues may be equally important to consider in more detail, including other policy issues (e.g., health policy) and non-policy issues such as technological change, transportation trends and demographic developments. In the Swedish context it is worth noting that a significant proportion of the estimated ancillary benefits appear in the transport sector, and limited diffusion of alternative fuels in the transport sector appears already in the baseline scenario. Clearly, however, the future evolution of vehicles and fuels is highly uncertain, not the least due to the competition for the biomass (in part illustrated in this paper), and the presence of significant network externalities in the fuel supply infrastructure.

### 3.23.2 Regional use of biomass and development of the bioenergy sector

In the context of mitigating climate change and increase energy security, the utilization of biomass in the energy sector is expected to play a major role. However, to estimate the future use of biomass sources in the energy sector, current energy system models need to be further developed to consider the inherent high spatial variances in supply and cost of biomass sources.

In this paper (229, 230, 158) we firstly present how highly spatial and temporal estimations of biomass potentials can be integrated into a sub-national TIMES model. The model specifically focuses on the bioenergy sector and as such only focuses on this section of the national energy system, Figure 204. Thus, only the bioenergy sector is represented in the model and the rest of the energy system is assumed to develop according to predefined scenarios. Secondly, we in the paper evaluate the possible extension of the bioenergy sector in Sweden and France based on the increased range of feedstocks available for bioenergy production and development of conversion technologies. The proposed model is evaluated for France and Sweden as both countries employ large amounts of forestry biomass in the energy sector. In this text, however, we will only focus on the model for Sweden. The proposed model is constructed to assess the bioenergy production potential based on biomass sources in excess to the production of food, feed, and woody products. A prime assumption of the proposed model is that it evaluates the development of the bioenergy sector based on unutilized and domestic biomass feedstocks. The considered country is assumed to maintain its current self-reliance level of food, feed, and woody products. The only biomass sources considered as available for bioenergy production are those that do not decrease national food and wood supply. Although in the future, food, feed, and energy crops may compete for agricultural land, and while pulp & paper producers, biofuel producers, and combined heat and electricity producers may compete for forestry biomass resources, the study aim to assess the bioenergy production potential without compromising food and feed production as well as forest industries’ wood requirements.

**Figure 204. Outline of the Energy system**
Scenarios

To evaluate the impact of the cost and supply of the biomass sources on the development of the energy sector, a number of scenarios were developed. The scenarios reflect different future developments as well as high volatility in the costs. Based on the available data for Sweden, the potential of agricultural crops for energy purposes was defined on an aggregated national level and in terms of each crop type: oil, sugar, starch, wood, and grass. The potential of forestry harvesting products for energy use was defined in terms of three wood assortments: forest residues, pulpwood, and refined wood products. While the potential of pulpwood and refined wood products was defined on aggregated national levels, the potential of forest residues was separately defined for each of Sweden’s 21 counties, using detailed cost-supply curves based on geographical estimations of the location of harvesting sites and conversion facilities (Figure 205).

Figure 205. The 21 counties in Sweden

The proposed model considers contribution of biomass sources to the heat, electricity, and biofuels sectors. An end-use demand was specified for each of these three sectors. To evaluate the effect of the end-use demands on the development of the energy sectors, three bioenergy demand scenarios were developed based on the 2008 long-term energy projection by the Swedish Energy Agency (Långsiktspregnos). The Swedish Energy Agency long-term forecast projects the development of the Swedish energy system and end-use energy demand up to 2030. The Business as usual (BAU) scenario developed by the SEA assumes gradual development in line with recent trends and was here used to formulate three demand scenarios for the bioenergy sector until 2050. The three demand scenarios were based on the BAU scenario until 2030, after which the scenarios differentiate in the development of the bioenergy sector to reflect the bandwidth within which the end-use demands of bioenergy may evolve. The demand scenarios were defined as follows:

- **D1**: The BAU scenario until 2030, after which bioenergy demands level out and no longer increase.
- **D2**: BAU scenario until 2030, after which each individual demand continues to grow in a linear fashion according to half the average growth rate between 2005 and 2030.
- **D3**: BAU scenario until 2030, after which each individual demand continues to grow in a linear fashion according to the average growth rate between 2005 and 2030.
Results

Our results show that national potentials are sufficient to fulfil the demand for biofuels in Sweden (Figure 206). First generation biofuels will continue to play an important role in biofuel production in Sweden and biodiesel production from oil crops shows to be an important source of biofuels. However, while the production of biodiesel increases by time, its share of the total production of biofuels decreases. Ethanol from cereals is a very important conversion technology for biofuel production in Sweden, consisting of a major part of the total production of biofuels. In terms of second generation biofuel production, only a small amount of second generation bioethanol will be produced and this from lignocellulosic woody material. However, the introduction year and production levels of second generation biofuel were found to vary between demand scenarios. For demand scenarios D3, the conversion technology is already utilized 2020, while for demand scenarios D1 and D2, the conversion technology is not utilized to a high degree until the 2050.

Figure 206. Conversion technologies utilized for production of biofuels in Sweden depending on the demand of bioenergy

As the potential of agricultural and woody biomass sources were defined individually for each county in Sweden, spatial differences in harvesting levels could be studied. Differences between counties in harvesting levels of forestry products were observed due to the differences in biomass potential and harvesting costs. Figure 207 shows the percentage harvest of the total potential of forest residue in the 21 counties. Some differences in counties’ harvest level of forestry residues could be observed, and generally, the difference between the counties increases as the marginal price of forest residues decreases. Furthermore, three counties stood out with a lower percentage outtake of forest residue: Norrbotten, Västerbotten, and Jämtland. When the national harvesting level of forest residues is low in comparison to the total potential (for example year 2040 and 2050), we observe a particularly high difference in the harvest level between the counties.

The difference in harvesting levels as well as the decrease in the counties Norrbotten, Västerbotten, and Jämtland is a result of the high harvesting cost of the most expensive harvesting sites in these three counties. The TIMES model assumes that forest residue is only harvested from areas with a harvesting cost lower than the marginal cost of forest residues. Thus, the portion of a county’s forestry residue cost-supply curve that is above the marginal cost will not be harvested. As the cost-supply curves for the counties Norrbotten, Västerbotten, and Jämtland have larger portions above the marginal cost of forestry residues, their percentage harvesting rate of forestry residues was lower than other counties. As seen in Figure 208, for the marginal price of forest residue year 2050, there is a large variance between the counties in the portion of their cost-supply curves that is above the marginal price and thus will not be harvested.
The proposed model shows how the development of the bioenergy sector can be assessed by linking highly detailed spatial data concerning biomass sources with the evolution of the energy system. The proposed methodology helps to identify biomass sources and conversion technologies crucial to developing the bioenergy sector, and provides a basis for assessing the location and cost-specific comparative advantages of specific biomass feedstocks. Our results indicate that domestic biomass sources could contribute significantly to the total energy supply without the expense of domestic food and forestry supply. Furthermore, the results suggest that high amounts of first generation biofuels may very well be produced in the future, and that a complete transition from first to second generation biofuel production may not occur within the next decades. Concerning forest residues, the results show that while there will be regional differences in the harvest levels, the overall national harvest levels of will still be high in the future. Our results are encouraging considering the bioenergy sector’s potential for growth. However, if full potential is to be achieved, it will involve successful and widespread willingness from farmers and forest owners to harvest and sell biomass sources for energy purposes.

3.24 Switzerland

3.24.1 Intermediate steps towards the 2000W society: An energy–economic scenario analysis

In the future, sustainable development under the umbrella of the 2000W society could be of major interest. Could the target of the 2000W society, i.e. a primary energy per capita (PEC) consumption of
2000 W, be realized until 2050? Various combinations of PEC and CO₂ targets are tested, and the additional costs to be paid by the society are estimated. The assessment (231) is carried out with the Swiss MARKAL model (231), a bottom-up energy-system model projecting future technology investments for Switzerland.

Scenarios
The baseline scenario portrayed here depicts future trends in the energy system of Switzerland without any radical political, technical or social change. In this sense, it represents a plausible middle-of-the-road development of the Swiss energy system.

Results
Figure 209 shows the primary energy consumption for two scenario sets without and with primary energy targets at an oil price of 75 US$2000/bbl. On the one hand, more stringent CO₂ reduction limits without imposing a primary energy consumption constraints reduces the amount of fossil energy carriers and increase renewable energy use. At the same time, nuclear energy remains a dominant source for the production of electricity. On the other hand, the implementation of a 3.5kW/cap society, without any CO₂ constraints, induces only a moderate decrease (12%) of fossil fuel use, from 2.63 to 2.35kW/cap. The energy system still largely depends on fossil fuels. Energy-efficiency improvements and the implementation of energy-saving measures play an important role. A positive consequence of reducing the PEC consumption to 3.5 kW/cap is the resulting reduction in CO₂ emissions, which corresponds to nearly 5% reduction.

Therefore, the scenario that combines 3.5 kW/cap and 5% CO₂ reduction targets, looks very similar. Only when implementing a combined 3.5kW/cap and 10% CO₂ reduction target, a significant reduction of fossil energy carriers is achieved, and the use of renewable energies is augmented. Nuclear energy becomes indispensable for reaching these goals.

Figure 209. Primary energy consumption per energy carriers in 2050 for various kW/cap and CO₂ targets*

* With an oil price of 75 US$2000/bbl.

The transformation of the energy system is not cost-free. Whereas less stringent PEC targets are still relatively cheap, strong targets are more expensive. At an oil price of 75 US$2000/bbl in 2050, the additional costs to reach a 3500W society amount to about 20 billion US$2000 (discounted at 3%/yr). The cost should be compared with a Kyoto-forever target (i.e. 5% CO2 reduction per decade), which has about the same CO2 emissions in 2050. The costs to reach this modest target are about 15 billion US$2000, or 5 billion US$2000 less than the above, see Figure 210.
The analysis reveals that the 2000W society should be seen as a long-term goal. For all contemplated scenarios, a PEC consumption of 3500W per capita (w/cap) is feasible in the year 2050. However, strong PEC consumption targets can reduce CO₂ emissions to an equivalent of 5% per decade at maximum. For stronger CO₂ emission reduction goals, corresponding targets must be formulated explicitly. At an oil price of 75 US$2000/bbl in 2050, the additional (cumulative, discounted) costs to reach a 10% CO₂ reduction per decade combined with a 3500W per capita target amount to about 40 billion US$2000. On the contrary, to reach pure CO₂ reduction targets is drastically cheaper, challenging the vision of the 2000W society.

3.24.2 Social MARKAL: Integrating behavioural changes in the residential and commercial sectors

3.24.2.1 Approach and methodology

The present study (232,233) aims at assessing the joint impact of awareness campaigns and technology choice, on end-use energy consumption behaviour. A new MARKAL framework, the Socio-MARKAL, was recently proposed by the authors. As opposed to the traditional MARKAL framework based on technical and economic considerations, the Socio-MARKAL concept integrates technological, economic and behavioural contributions to the environment. This study takes into consideration, technological improvements on the demand side by consumers as well as behavioural changes minimizing CO₂ emissions and encouraging rational use of energy. The study presented in this paper, “Lighting Consumptions Habits in Geneva Households”, was conducted from September to December 2009. Based on the statistical analysis of this survey, we have determined coefficients to feed the database of the Socio-MARKAL model.

Below, we present a method for collecting social data in the context of the Socio-MARKAL project: 1) Qualitative research to identify potentials of behavioural change regarding energy consumption, handled through qualitative methods; 2) Survey research to test and measure hypotheses; 3) Construction of long-term scenarios including behavioural change; 4) Transformation of the Socio-MARKAL data and scenarios to feed the MARKAL data base.

The main focus of this paper is on lighting technologies. The first observation indicates that 58.84% of the population can potentially switch technology (without light bulbs to incandescent) or change their consumption behaviour (through better use of incandescent bulbs). The corresponding maximum of incandescent light ranges from 25% to 75% of the bulbs. However, 20% of the respondents responded « I don’t know », which seems to indicate that they have no information about the technology (incandescent or not) they have been using for lighting.
Behavioural change in SOCIO-MARKAL requires introducing virtual technologies, whose purpose is to trigger behavioural change among energy consumers. For the bulb demand devices section of the Socio-MARKAL model, we ended up with the following representation (Figure 211).

**Figure 211. Bulb demand devices section of the Socio-MARKAL**

We’ve got four demand devices. Parameters RLD1 and RLD4 represent the real and tangible lighting technologies, receiving electric power as input, and generating residential lighting. Parameters RLD2 and RLD3 represent the virtual technologies. As opposed to the real technologies, virtual technologies receive inputs that are intangible, leading to energy savings or technology switch. These devices are presented below:

- RLD1, “existing incandescent bulbs”
- RLD4, “existing low consumption bulbs”
- RLD2, “moderate use of incandescent bulbs”, and
- RLD3, “switch to low consumption bulbs”
- MRKRP2 and MRKRP3 are marketing/awareness campaigns which have the effect of changing the behaviour of energy consumers. MRKRP2 and MRKRP3 are respectively supposed to trigger the “Moderate use of incandescent light bulbs”, and the behaviour towards low consumption bulbs, i.e. “Technology Switch towards low consumption bulbs”.

Then, we show how the statistics obtained from the survey research are transformed to feed the bulb demand devices section of the Socio-MARKAL model.

### 3.24.2.2 First modeling attempts in the Nyon residential and commercial sectors

Based on this new SOMARKAL formulation (234,235,236), we will simulate the possible contribution of awareness campaigns in triggering energy consumption behavioural changes and possibilities of technology switch, in the residential area of the city of Nyon (Switzerland), for the period 2005-2025, using ANSWER, the IEA’s platform. The main focus is on lighting technologies. Three fictitious scenarios were produced, referring to three possible penetration rates of low consumption lighting technologies.

**Scenarios**

A number of assumptions have been introduced, specifically regarding both the demand investments for residential lighting technologies. The overall demand for light bulbs is expected to grow by about 50% over the evaluation period. Residual capacity is split between RLD1 and RLD4, respectively for 80% and 20% (Table 41).
Table 41. Summary of the main assumptions made on demand devices and investment costs

<table>
<thead>
<tr>
<th>DM for light bulbs [x 100 units]</th>
<th>2005</th>
<th>2010</th>
<th>2015</th>
<th>2020</th>
<th>2025</th>
</tr>
</thead>
<tbody>
<tr>
<td>IC for RLD1 [CHF/bulb]</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>IC for RLD4 [CHF/bulb]</td>
<td>20</td>
<td>18</td>
<td>15</td>
<td>12</td>
<td>10</td>
</tr>
</tbody>
</table>

Notes:
DM represents the total demand for all types of bulbs (i.e., RLD1 to RLD4) IC: investment costs

We consider three fictitious scenarios.
- **Scenario 1**: the first scenario is based on an unconstrained MARKAL model.
- **Scenario 2**: the second scenario is based on the use of a modelling approach in which the modeller sets reasonable bounds. These bounds are more or less subjective, and therefore depend on the modeller’s appreciation and erudition.
- **Scenario 3**: The third scenario introduces the SOMARKAL approach.

**Results**
One can observe as outlined in Figure 212, that after 2005, there is no investment in incandescent bulbs (i.e., RLD1), while all investments go to low consumption bulbs (i.e., RLD4). Furthermore, the growing demand will be met in priority through low consumption bulbs (i.e. RLD4), because bounds are set for the minimum capacity of incandescent light bulbs (i.e., RLD1), so as to keep them in the optimal solution. Their penetration will be kept at the bound level.

**Figure 212. Outcome of scenario 1 and 2, without and with bounds**

This approach aims at introducing virtual process technologies as well as determining the values of bounds (Figure 213). Virtual process technologies represent awareness campaigns both for energy savings and technology switch. These process technologies act as enablers for demand devices RLD2 (i.e., moderate use of incandescent bulbs) and RLD3 (i.e. technology switch to low consumption bulbs). This approach allows us to keep the MARKAL formulation and introduce behavioural parameters.

**Figure 213. The third scenario introduces the SOMARKAL approach.**
3.24.2.3 Observing and analyzing operating modes of staff using IT appliances

This particular study (237) aimed at analyzing the electricity consumption of ICT equipment used by staff members of the Geneva School of business administration (HEG). Our main focus was on the fundamental aspects governing the operating modes, provided that the latter are a credible indicator of consumers’ behavior. First, the methodological approach used for information collection was presented. Second, a model designed to derive the subsequent electricity consumption has been presented. This information is intended to be fed into the Socio MARKAL model developed at the Service Science Laboratory of the HEG (Fragnière et al., 2010; Nguene et al., 2011). This model embeds both technological and behavioral contributions.

A number of conclusions have been drawn from this study: (1) technologies alone cannot be effective in reducing energy consumption; (2) a huge and untapped energy reduction potential exists in our behavior through an appropriate operating mode; (3) just as technology switch in an energy system, behavioral change can also contribute to energy supply security. In conclusion, behavioral change through operating modes should be integrated into Socio-MARKAL scenarios.

3.24.3 Coupling top-down and bottom-up models to study post-2012 climate policies

Two studies have been performed in the Research group on the Economics and Management of the Environment of EPFL to assess the Swiss post-Kyoto climate policy with a focus on the residential sector. We couple two existing top-down and residential bottom-up models in order to carry out a integrated assessment of various post-2012 climate policies for Switzerland.

3.24.3.1 Assessment of GHG mitigation policies after 2012 with focus on the residential sector

The objective of the first paper (238) is to assess some of the instruments envisaged for the the revision of the Swiss CO₂ Law. To attain our objective we devise a coupled model, combining a global economic model (GEMINI-E3) with a Swiss residential energy use model (MARKAL-CHRES). The benefit of coupling a top-down Computable General Equilibrium (CGE) with a bottom-up energy use models is twofold. On the one hand, it allows to estimate the consequences of global or national policies on the Swiss economy and more specifically on the Swiss residential sector. On the other hand, the coupled model allows to test policies targeting energy use in the Swiss residential sector with a very detailed representation of the energy technologies both used and available in that sector, and to asses the impact of those policies on the overall economy.

Scenarios

We test three scenarios.

- In the first scenario, we analyze two types of taxes, first a progressive tax that increases linearly up to the target year and, secondly, a uniform tax, which has a fixed value from 2008 till 2050. We also compare CO₂ taxes with a tax covering all GHG. In the second scenario, we consider the implementation of technical regulation which aims at restricting the investments in technologies considered inefficient.

- Then, as of 2015, we restrict households’ investments to those technologies having an energy efficiency superior or equal to the average. Technologies not using fossil fuels or electricity were not restricted, and in the case of residential heating, we do not consider heat pumps, neither in the calculation of the average efficiency nor in the list of restricted technologies. Examples of inefficient technologies falling in the restricted list are incandescent and halogen lamps.

- Finally, the third scenario considers the joint use of both instruments. The next section presents the integrated assessment of those policies.
Results

The bottom-up part of the coupled model shows, (Figure 214), that the residential sector reacts to the introduction of the taxes by a strong switch to electricity between 2020 and 2035. A uniform tax of 156.5 USD/tCO2eq would even have an earlier and stronger impact and would even trigger an almost CO2 free residential sector.

Figure 214. Residential fuel mix

Figure 215 presents the evolution of installed capacity of various room heating technologies following the implementation of a progressive GHG tax allowing to reach 50% abatement by 2050. It clearly indicates that, in all building types, heat pumps will have a rapidly growing share and, as of 2030, be the dominant technology used for room heating. This is due to the fact that heat pumps have a high energy efficiency and that they only consume electricity, which is, to a large extent in Switzerland, not produced from fossil fuels. Finally, the figure also shows that an important part of the final energy demand is met by installing energy saving technologies, in particular in new single family houses where almost a fourth of the energy is saved by using appropriate insulation and other energy efficiency standards.

Figure 215. Installed capacity of room heating technologies
We have studied the impacts of CO2 and GHG taxes as well as technical regulation applied to the residential sector and shown that the latter would not be sufficient to achieve major emissions reductions and loose their raison d’être when used in conjunction with emission taxes. This effect might be a little overestimated by the MARKAL-CHRES part of the coupled model, which assumes that consumers adopt perfectly optimizing behavior based on exact investment, maintenance and usage prices for all possible technologies. Furthermore, this study confirms that GHG taxes are more effective than CO2 taxes, without further jeopardizing the production of the economic sectors.

3.24.3.2 Sustainability, neutrality and beyond in the framework of Swiss post-2012 climate policy

In this paper (239) we use a coupled top-down bottom-up model to assess the impacts of a number of ambitious climate policies in Switzerland. We find that stringent policies with both domestic and total emission targets are affordable for a wealthy country like Switzerland.

Scenarios

In order to set a realistic international framework, we have defined 3 scenarios for international policies. Table 42 presents the different GHG emissions quotas in 2050 for all regions. We assume that each region receives annually emissions certificates at the level of its annual target and is then free to trade them within the region as well as with other regions. The “high” scenario is inspired by the recommendations of the Energy Modeling Forum 22 (EMF, 2008) and adapted to the specific regional aggregation that we use in the model. The “mid” and “low” scenarios consider alternatives where climate negotiations would lead to lower emission targets, in particular from the DCS.

Table 42. International emissions targets in 2050 relative to 2001 emissions

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Low</th>
<th>Mid</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>EUR</td>
<td>50</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>OEU</td>
<td>10</td>
<td>20</td>
<td>30</td>
</tr>
<tr>
<td>JAP</td>
<td>50</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>OEC</td>
<td>30</td>
<td>40</td>
<td>50</td>
</tr>
<tr>
<td>DCS</td>
<td>0</td>
<td>25</td>
<td></td>
</tr>
</tbody>
</table>

a % of 2030 emissions; b baseline emissions

For Swiss, we consider 4 scenarios with different objectives and therefore different total emissions targets.

- First, the “50%” scenario is in line with the targets of most European countries. It aims at achieving a 50% reduction of emissions by 2050 compared to the level of 2001.
- Secondly, the “sustainable” scenario aims at globally sustainable per-capita emissions of 1 tCO2/cap by 2100. We consider, as simplifying assumption and to be in line with the time horizon of the model, that this translates to a 2 tCO2/cap target by 2050. Considering that the population of Switzerland in 2050 is estimated at approximately 7 millions inhabitants, the emissions reduction should be of approximately 75% when compared to 2001 levels.
- Thirdly, the “neutral” scenario, which follows the climate neutrality idea, aims at a 100% reduction of GHG emissions in 2050, largely through compensation.
- Fourthly, the “zero footprint” scenario takes into account the net emissions embedded in Swiss foreign trade. Thus, this scenario aims at offsetting not only the domestic emissions but also those generated abroad to produce goods imported in Switzerland less the Swiss emissions resulting from the production of exported goods. With the simplifying hypothesis that the embedded emissions remain constant, we consider that the abatement should reach 180% of 2001 emissions in 2050.

In all four scenarios, we set the Swiss tax at a level such that its revenues are sufficient to purchase the emissions certificates required to offset the Swiss emissions up to the defined target.
In order to prepare the Swiss economy for future stringent emissions reductions, a minimum of domestic reductions should be ensured in the forthcoming commitment period. With that in mind, we consider four additional scenarios similar to those described above but with the additional requirement of having a minimum domestic abatement of 50% compared to the emissions of 2001. We name those scenarios “50%+”, “sustainable+”, “neutral+” and “zero footprint+”.

Results

Figure 216 shows to what extent the residential sector can contribute to the abatement, by presenting how the emissions of the residential sector and of the rest of the economy evolve over time, as well as what share of the abatement is undertaken by the residential sector. The MARKAL-CHRES, through its explicit modeling of technological options, shows that, without having to implement “backstop” technologies, a strong and natural switch to cleaner technologies takes place in case of high taxes. In order to avoid high costs in the future, households invest in cleaner technologies rapidly. The residential sector starts contributing significantly to the overall abatement when the GHG tax reaches around 30 USD/tCO2eq (Mid - Neutral), and does the major part of it when the tax gets close to 100 USD/tCO2eq (Low - 50%+). In the high scenarios, the residential sector stops emitting CO2 as early as 2030, switching to technologies using electricity instead of fossil fuels.

Figure 216. Contribution to the abatement of the residential sector (MtCO2eq)

All scenarios examined here project a reduction, or at least a stabilization in residential fuel consumption from levels in 2000 (Table 43). A similar trend is observed in the residential heating sub-sector, where even in the scenarios with the low emission reduction targets, energy consumption stabilizes around its year 2000 value of 165 PJ. Considering increases in residential floor area over the next 40 to 50 years, already this observation indicates that substantial improvements are likely to arise without stringent climate policy, even though further reductions in consumption are attainable when appropriate policy measures are implemented. However, these results also show that implementation of mild (low) world-wide emission targets does not achieve significant reductions in domestic fuel consumption when Switzerland is able to meet its emission reduction commitments through the
purchase of tradable certificates. In this case, technological change is moderate, with technologies similar to the existing ones and that have slightly higher efficiencies but still consume the same type of fuel. Examples of these technologies include oil and natural gas room heating or combined room and water heating systems.

When low world-wide emissions targets are combined with a requirement to achieve emission reductions with domestic measures, we observe a significant impact on the Swiss residential sector. In the residential sector this change is triggered by switching from fossil heating installations to heat pumps in single and multi-family houses. Although a minimum domestic abatement of 50% is required in Switzerland, the additional reductions required in the scenarios neutral+ and zero-footprint+ are achieved by purchasing emission certificates. Only when high (stringent) world-wide emission targets are combined with strong domestic emission targets (corresponding to the neutral and zero-footprint scenarios), does the Swiss residential sector shift completely away from fossil fuels.

**Table 43. Fuel consumption and energy savings for residential heating in PJ**

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>All fuelsa</th>
<th>Energy Savingsb</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>World</td>
<td></td>
<td></td>
<td>2020</td>
<td>2050</td>
<td>2020</td>
</tr>
<tr>
<td>Low</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50%</td>
<td>sustainable</td>
<td>164.7</td>
<td>168.6</td>
<td>9.5</td>
<td>15.9</td>
</tr>
<tr>
<td></td>
<td>neutral</td>
<td>164.7</td>
<td>168.4</td>
<td>9.5</td>
<td>16.1</td>
</tr>
<tr>
<td></td>
<td>zero‐footprint</td>
<td>164.4</td>
<td>165.2</td>
<td>9.8</td>
<td>17.1</td>
</tr>
<tr>
<td>50%+</td>
<td>sustainable+</td>
<td>146.6</td>
<td>76.8</td>
<td>10.9</td>
<td>19.9</td>
</tr>
<tr>
<td></td>
<td>neutral+</td>
<td>146.6</td>
<td>76.8</td>
<td>10.9</td>
<td>19.9</td>
</tr>
<tr>
<td></td>
<td>zero‐footprint+</td>
<td>146.6</td>
<td>78.1</td>
<td>10.9</td>
<td>19.9</td>
</tr>
<tr>
<td>Mid</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50%</td>
<td>sustainable</td>
<td>164.4</td>
<td>160.7</td>
<td>9.8</td>
<td>17.1</td>
</tr>
<tr>
<td></td>
<td>neutral</td>
<td>163.8</td>
<td>154.3</td>
<td>10.4</td>
<td>18.1</td>
</tr>
<tr>
<td></td>
<td>zero‐footprint</td>
<td>148.4</td>
<td>79.6</td>
<td>10.9</td>
<td>19.8</td>
</tr>
<tr>
<td>50%+</td>
<td>sustainable+</td>
<td>146.6</td>
<td>78.1</td>
<td>10.9</td>
<td>19.9</td>
</tr>
<tr>
<td></td>
<td>neutral+</td>
<td>146.6</td>
<td>78.1</td>
<td>10.9</td>
<td>19.9</td>
</tr>
<tr>
<td></td>
<td>zero‐footprint+</td>
<td>147.3</td>
<td>78.5</td>
<td>10.9</td>
<td>19.9</td>
</tr>
<tr>
<td>High</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50%</td>
<td>sustainable</td>
<td>158.1</td>
<td>96.2</td>
<td>10.6</td>
<td>19.0</td>
</tr>
<tr>
<td></td>
<td>neutral</td>
<td>137.0</td>
<td>67.3</td>
<td>11.1</td>
<td>20.2</td>
</tr>
<tr>
<td></td>
<td>zero‐footprint</td>
<td>95.7</td>
<td>57.9</td>
<td>13.4</td>
<td>23.5</td>
</tr>
<tr>
<td>50%+</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

a Total energy used; b Useful energy saved

### 3.24.3.3 Linking bottom-up models to the multi regional MERGE model

MARKAL-MACRO (M-M) and TIMES-MACRO (T-M) are general equilibrium models of a single region model. They aggregate all non energy sectors of the economy in a single sector and they represent it with a single CES production function. Is it possible to extend the general equilibrium version of MARKAL-TIMES models to more than a single region?

There are two versions of the MACRO stand-alone model developed by A. Manne; the first one corresponds to the macroeconomic module of MERGE while the second one corresponds to the M-M approach specially developed for the ETSAP tools. Activities (240) will start with the national T-M or M-M models trying to decompose them and link them either with a stand-alone macroeconomic sub-model or with MERGE directly (each effort covering different purposes) and will continue with extensions to multi-regional global models like e.g., TIAM or GMM. The new ETSAP tools will be completed with the active participation of the ETSAP team in charge of the GAMS codes and the users’ interfaces and the procedures to be developed will be made available to the ETSAP tools licensed users.
3.24.4 Experience from the development a new TIMES electricity model

Understanding how structural changes occur in energy supply requires approaches that are able to represent the structure of the energy system in detail and the main factors affecting structural change. To account for this range of factors, we propose (241,242) to develop a technology-rich, bottom-up energy-systems model using the advanced modelling framework TIMES. We will develop a Swiss TIMES Energy system Model (STEM) and validate its input variables through stakeholder engagement.

Scenarios

We proposed to analyse scenarios to look at the circumstances under which structural changes occur and the nature of those changes, with the aim of identifying the key factors influencing the pace and direction of change:

- BASE: Business as usual
- CO2_S: Stabilizing CO\textsubscript{2} at 2000 level (power sector only)
- NoNuc_S: The above scenario without any newly built nuclear
- CO2_Z: Zero carbon electricity by 2050
- NoNuc_Z: The above scenario without any newly built nuclear

Results

This model will be applied to examine robust energy technology and infrastructure options for the future development of the Swiss energy system (Figure 217).

![Figure 217. Comparison of electricity generation mix in 2050 *](image)

* Resource cost includes imported electricity

3.25 Taiwan

3.25.1 Long-term CO\textsubscript{2} emissions reduction target and scenarios of power sector

This study (243) analyses a series of CO\textsubscript{2} emissions abatement scenarios of the power sector in Taiwan according to the Sustainable Energy Policy Guidelines, which was released by Executive Yuan in June 2008. The MARKAL-MACRO energy model was adopted to evaluate economic impacts and optimal energy deployment for CO\textsubscript{2} emissions reduction scenarios. This study includes analyses of life extension of nuclear power plant, the construction of new nuclear power units, commercialized timing of fossil fuel power plants with CCS technology and two alternative flexible trajectories of CO\textsubscript{2} emissions constraints.
Scenarios
A series of analyses were performed to examine the electricity deployment and economic impacts in each scenario. Table 44 gives an overall picture of the main differences among the analyzed scenarios.

Table 44. List of scenarios.

<table>
<thead>
<tr>
<th>No.</th>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>BAU</td>
<td>Increase LNG usage: develop renewable energy; improvement of energy efficiency and intensity; Nuclear-Free Homeland Policy</td>
</tr>
<tr>
<td>2</td>
<td>Rf1</td>
<td>CO₂ emissions returns 2000 levels (219.5 Mton) by 2025, 70% of 2000 levels (153.7 Mton) by 2050; nuclear power plants will be constructed with maximum of eight new units, with one commercial operation from 2020 onwards and two new units every 5 years until 2040; 20 years life extension of nuclear power plants; CCS technology starts at 2030</td>
</tr>
<tr>
<td>3</td>
<td>Rnu5</td>
<td>Same as Rf1, except no new construction of nuclear power plants is assumed</td>
</tr>
<tr>
<td>4</td>
<td>Rnu6</td>
<td>Same as Rf1, except no new construction of nuclear power plants and no life extension is assumed</td>
</tr>
<tr>
<td>5</td>
<td>Rnu7</td>
<td>Same as Rf1, except 40 years life extension is assumed</td>
</tr>
<tr>
<td>6</td>
<td>Rnu8</td>
<td>Same as Rf1, except 6 nuclear power units will be commercially operated by 2025 and the other two units by 2030</td>
</tr>
<tr>
<td>7</td>
<td>RCCS2</td>
<td>Same as Rf1, except CCS emerges from 2035 onwards</td>
</tr>
<tr>
<td>8</td>
<td>RCCS3</td>
<td>Same as Rf1, except CCS emerges from 2025 onwards</td>
</tr>
<tr>
<td>9</td>
<td>Rt4</td>
<td>CO₂ emissions returns to 2005 levels (262.1 Mton) by 2025, 70% of 2005 levels by 2050</td>
</tr>
<tr>
<td>10</td>
<td>Rt5</td>
<td>CO₂ emissions returns to 2005 levels (262.1 Mton) by 2025, 80% of 2005 levels by 2050</td>
</tr>
</tbody>
</table>

Results
Electricity generation in 2050 for each individual scenario is illustrated in Figure 218. In the BAU scenario, PC/SCPC power plants will be the major generation in 2025 and 2050. In 2050, all the coal/gas-fired power plants will be integrated with CCS technology.

Generally, among fossil fuel power plants, the use of IGCC with CCS is the least expensive option while NGCC with CCS is the most expensive option in terms of calculating CO₂-related costs. However, NGCC with CCS has a superior share than IGCC with CCS in all the CO₂ emissions constraints runs since the CO₂ emissions constraint is strict, except in the Rt4 and Rt5 scenarios. In Rnu6, there is only one nuclear unit left in 2050, so fossil fuel power plants with CCS need to generate more electricity. In Rnu7, all the nuclear power plants will continue operating, including the old plants that were built in the 1980s. Fossil fuel power plants with CCS generate less electricity than other scenarios. The capacity of nuclear power plants is operated at full capacity at the upper bounds in each scenario. This means that the use of nuclear power plants is the least expensive option for all scenarios. Among all the scenarios in 2025 and 2050, except for the BAU scenario, the electricity generation from renewable is the same. The development of renewable in each reduction scenario has reached its upper limit.

Figure 218. Comparison of electricity generation by fuel technology in 2050
Three CO$_2$ emissions reduction scenarios, Rrf1, Rt4 and Rt5, were analyzed with MAC curves as shown in Figure 219. In other words, the price of CO$_2$ emissions reduction in the Rrf1 scenario is dramatically high and there is a serious extent of economic impacts. The highest costs observed in UK’s MARKAL-Macro model are found in the 80% reduction cases, relative to 2000 emissions, with a cost range of £208–395/t CO$_2$. In the case where there is no use of nuclear power plant and no use of CCS with biomass and wind constraints, the highest costs are observed primarily due to the lack of available low-carbon abatement technologies in the electricity generation sector. Comparing the marginal costs of the Rrf1 scenario with the UK’s MARKAL model, the CO$_2$ emissions constraint in the Rrf1 scenario is impossibly difficult to achieve for Taiwan. The marginal abatement costs in the Rt5 scenario in 2050 is 472 2001$US/ t CO$_2$ and the slope gradually increases. Therefore, the CO$_2$ emissions constraint in the Rt5 scenario is much more feasible and acceptable than in the Rrf1 scenario.

**Figure 219. Marginal abatement costs of Rrf1, Rt4 and Rt5 scenarios**

![Marginal cost graph]

The results show that nuclear power plants and CCS technology will further lower the marginal cost of CO$_2$ emissions reduction. GDP loss rate in reference reduction scenario is 16.9% in 2050, but 8.9% and 6.4% in Rt4 and Rt5, respectively. This study shows the economic impacts in achieving Taiwan’s CO$_2$ emissions mitigation targets and reveals feasible CO$_2$ emissions reduction strategies for the power sector.

### 3.25.2 Sensitivity study of energy prices for CO$_2$ abatement scenarios

Recent changing global energy prices have caused worldwide concern. The future role of the various energy carriers, energy conversion technologies as well as energy-saving measures in the energy system strongly depends on how energy prices develop. The purpose of this paper (244) is to discuss under the CO$_2$ emissions reduction targets, how the energy prices development affect the technology development and domestic economics. Different trajectories of energy prices (low, base, medium and high) are set and economic impacts are analyzed in CO$_2$ abatement scenarios.

### Scenarios

A series of analyses were performed to examine the effects of energy prices changing on energy and electricity deployments, GDP loss rate and the marginal abatement cost in CO$_2$ reduction scenarios:

- **BAU**: Increase LNG usage; develop renewable energy; improve energy efficiency and intensity; Nuclear-Free Homeland policy; CCS technology can be operated commercially since 2026.
- **N1**: 1. CO$_2$ emissions return 2000 levels by 2025, 50% of 2000 levels by 2050. 2. No new construction of nuclear power plants. 3. No life extension of existed nuclear power plants.
- **N2**: Same as N1, except 20 years of life extension and power uprate of existed nuclear power plants.
- **N3**: Same as N2, except new nuclear power units (2021-25=2.5; 2026-30=2.5; 2031-35=2; 2036-40=2; 2041-45=2; 2046-50=2).
⇒ Low energy prices: 30% decrease of baseline energy prices from 2010. 50% decrease of baseline energy prices after 2030.

⇒ Base energy prices: the projected energy prices, the baseline cases (BAU, N1, N2 and N3).

⇒ Middle energy prices: 30% increase of baseline energy prices from 2010. 50% increase of baseline energy prices after 2030.

⇒ High energy prices: 30% increase of baseline energy prices from 2010. 100% increase of baseline energy prices after 2030.

**Results**

Figure 220 shows the GDP loss rate of CO₂ reduction scenarios. BAU scenario with lower energy prices (BL) has minus GDP loss rate, which means lower energy prices are helpful for economic development.

**Figure 220. CDP loss rate compare to BAU scenario**

On the other hand, higher energy prices are harmful to the economic growth. No matter what the year is, what the energy prices are and what the nuclear policy is, the quantity of nuclear power is always reach the setting limit in all scenarios. Due to site limit and nuclear policy, there is upper limit setting but no any lower bound for nuclear power plant. N3 series scenarios have the lowest marginal cost and GDP loss rate compare to N1 and N2 scenarios. In the other words, building nuclear power generation is a robust strategy to confront either the energy prices changing or CO₂ reduction scenario.

The change of energy prices will affect the GDP loss rate and marginal abatement cost obviously. For the high energy prices cases (100% higher than base), the GDP loss rate is 6.5% in BH (BAU with high prices scenario), 2.95% in N1H (Nuclear Free Homeland) and 2.6% in N3H (new nuclear) scenario higher than the cases of base energy prices in 2050. Nuclear power generation is an indispensable and effective way to mitigate the economic impacts. The GDP loss rate in N3H with high energy prices scenario is lower than N1M and N2M scenarios with middle energy prices.

Higher energy prices will lead to use more electricity by coal instead of oil and gas in CO₂ abatement scenario. If CCS technology is not ready, higher energy prices may lead higher CO₂ emissions in energy sector. Higher energy prices will stimulate the investments into energy efficiency and renewable energy. When the energy prices are higher, it is tending to decrease the CO₂ emissions from industry and energy sectors after CCS and renewable energy are more mature. Other sectors, like transport and residential, will choose to use more electricity to reduce CO₂ emissions.

3.26 The Netherlands

3.26.1 Planning for an electricity sector with CCS

Before energy companies will invest in power plants with CCS, appropriate climate policy should be in place, a need for new power plants must exist, CCS technology should be cost-effective, and CO₂...
transport infrastructure and CO₂ sinks must be available. In order to get more grip on planning, we carried out a quantitative scenario study (245) for the electricity and cogeneration sector in the Netherlands using the energy bottom-up model generated with MARKAL.

**Scenarios**

We analysed strategies to realise a 15% and 50% reduction of CO₂ emissions in respectively, 2020 and 2050 compared to the 1990 level. We choose the scenario Strong Europe (SE) to investigate CCS trajectories. SE creates an environment in which it is likely that international agreements regarding climate change are made. We specify different variants of the SE scenario in order to explore the influence of two dynamic factors. First, since CCS is not a cost-effective technology without a climate policy being in place, we aim to study different emission reduction pathways in detail: a non-reduction variant, a DirectAction variant with CO₂ reduction targets from 2010 onwards, and a PostponedAction variant with targets from 2020 onwards.

**Results**

In this section, the results of the MARKAL-NL-UU runs are discussed. Figure 221 depicts the resulting capacities (in GW) of the different technologies over time for the BAU, DirectAction, and PostponedAction NV variants in which the power plants are decommissioned after 30 years.

The amount of CO₂ stored varies between 33 Mt (DirectAction NV) and 44 Mt (DirectAction EV) per year in 2020 and comes from 6 to 7 GW of power plants. This corresponds to on average 29 Mt CO₂ avoided. In the DirectAction EV variant, most CO₂ is stored and avoided due to the large scale retrofitting of existing PCs. In the DirectAction NV variant, the least CO₂ is stored, because retrofitting is not cost-effective and short-term mitigation strategy is based more on the use of NGCCs.

**Figure 221. Total installed capacity of different technologies for the ‘normal’ vintage variants**
We found that, if nuclear energy is excluded as a mitigation option, CCS can be sufficiently cost-effective in 2020 to avoid 29 Mt per year in 2020 in the Dutch electricity sector (which is half of the CO₂ emission abatement necessary in this year). We identified the following important factors for planning. In a postponement strategy in which CO₂ is reduced from 2020, CO₂ can be abated at less than 30 s/t up to 2020. A gradual reduction of 2.5% annually from 2010, asks for a climate policy that makes expenditures possible of 50 s/t CO₂ before 2015. Construction of coal-fired power plants without CCS are preferably not built or, in the postponement strategy, only to a limited extent. Finally, early planning is required to realise the construction of a transport infrastructure with a length of around 450 km before 2020.

3.26.2 The impacts of CO₂ capture on transboundary air pollution

The focus of this research (246) is to develop a first assessment of the impacts of the implementation of CO₂ capture technologies in the Dutch power sector on the transboundary air pollution (SO₂, NOₓ, NH₃, NMVOC, PM₁₀ and PM₂.₅) levels in 2020.

**Scenarios**

These scenarios are:

- The Business as usual (BAU) scenario represents the most economical configuration of the power sector without climate policy, i.e. no CO₂ reduction targets are defined for this sector.
- The Postponed Action (PA) scenario entailing a 15 % CO₂ reduction in 2020 in the power sector compared to 1990 levels. This scenario incorporates CO₂ reduction targets from 2020 onwards.
- The Direct Action (DA) scenario also assumes a 15 % CO₂ reduction in 2020 in the power sector compared to 1990 levels. The difference with the Postponed action scenario is that in this scenario CO₂ reduction targets are incorporated from 2010 onwards.
- The Direct Action - post-combustion gas variant (DA-PC) where all gas fired power plants are directly equipped or retrofitted with CO₂ capture in the year 2020 whereas the coal fired power plants remain unaltered.
- The Direct Action – oxyfuel variant (DA-Oxy) where all new built gas and coal fired power plants from 2010 onwards will be equipped with the oxyfuel combustion concept. Existing coal power plants are retrofitted with oxyfuel technology.

**Results**

Results show (Figure 223) that for the power sector SO₂ emissions will be very low for scenarios that include large scale implementation of CCS. The annual emissions of NOₓ are estimated to be lower in all scenarios with GHG reductions. However, applying the post-combustion technology on existing power plants may result in higher NOₓ emissions per kWh.
Both SO$_2$ and NO$_x$ emissions from the power sector are a substantial part of the current national total. Large scale implementation of the post-combustion CO$_2$ capture technology may result in more than 5 times higher NH$_3$ emissions compared to scenarios without CCS and to other capture options (i.e. pre-combustion and oxyfuel combustion). Particulate Matter (PM) emissions are lower in the scenarios with CO$_2$ reduction. A scenario with large scale implementation of the oxyfuel technology shows the lowest emissions of PM. In the scenarios with post-combustion capture Non Methane Volatile Organic Compounds emissions may increase due to the emission of solvents used in the capture process. The main conclusion is that climate policy and air quality policy are entwined and may result in synergies and trade-offs.

3.26.3 Designing a cost-effective CO$_2$ storage infrastructure using an integrated GIS-MARKAL toolbox

3.26.3.1 Approach and methodology

Large-scale implementation of CCS needs a whole new infrastructure to transport and store CO$_2$. Tools that can support planning and designing of such infrastructure require incorporation of both temporal and spatial aspects. Therefore, a toolbox that integrates ArcGIS, a geographical information system with elaborate spatial and routing functions, and MARKAL, an energy bottom-up model based on linear optimization, has been developed (247). Application of this toolbox for devising blueprints of a CO$_2$ infrastructure in the Netherlands, shows that early knowledge on the availability, potential, and suitability of sinks is of major importance for a cost-effective design of the infrastructure. The applied methodology in this research consists of four successive steps as depicted in Figure 224.
For CCS to play a major role in 2020, construction of CO$_2$ trunklines needs to start from 2012. Consequently, the design of a CO$_2$ infrastructure is urgently needed. Clarity on the required performance of sinks, realistic estimates of their potential, and an early decision on whether onshore storage is allowed are of importance for designing the infrastructure so that the CCS option is fully taken advantage of. With regard to the toolbox we make the following three observations.

- First, it provides insights into cost-effective locations of capture plants and CO$_2$ storage sites, and into the timing when capture units need to be built or when sinks will be used for CO$_2$ storage.
- Secondly, the toolbox may support the identification of sinks in the upper part of the techno-economic CO$_2$ storage pyramid, the "matched capacity". It takes into account cost-effectiveness of specific sinks and could also include performance requirements according to regulation with respect to CO$_2$ storage once that has been formalized. The combination of MARKAL and ArcGIS proofed valuable for the matching of sources and sinks since it can deal with both the temporal as well as the spatial aspects of connecting multiple sources to multiple sinks.
- Thirdly, because the toolbox allows for results to be visualized in maps making the development of a CO$_2$ infrastructure more imaginable, it could be used as communication tool among stakeholders.

### 3.26.3.2 Designing a cost-effective CO$_2$ storage infrastructure

Application of this toolbox (248,249) led to blueprints of a CO$_2$ infrastructure in the Netherlands. The research methodology applied in our study can be summarised into several steps, including extension of MARKAL-NL-UU model to incorporate spatial data from ArcGIS and unning of MARKAL-NL-UU for different variants.

### Scenarios

Variants of the base scenario are created to investigate the impact of the availability of storage capacity and various policy measures on the infrastructure development costs and role of CCS, and to explore the sensitivity of the results to parameters such as the terrain factor, and constant cost factors for pipelines. Besides the Base case in which all sinks can be used, two variants with limited storage capacity are explored.

- In the Only offshore variant, it is assumed that CO$_2$ is only allowed to be stored in offshore sinks (including Utsira) in order to diminish the risk of storage and public opposition to CCS.
- The Only offshore - No Utsira variant is similar to the Only offshore variant but excludes the option to store CO$_2$ in the Norwegian Utsira aquifer.

The impact of policy measures is further investigated in the following three variants.

- First, the Low renewables variant is the Base case without any renewable electricity targets.
• In the R_30/80 variant CO₂ emissions need to be reduced by 30% and 80% in 2020 and 2050, respectively, compared to the 1990 level.
• The R_20/80 is similar to the R_30/80 variant, but with a 20% target in 2020.
• Finally, the variants CF_1120 and C_2080 investigate the sensitivity towards a change in the constant cost factor for pipelines: 1120 V/m, and 2080 V/m, respectively, instead of 1600 V/m in the Base case.

Results

Figure 225 shows the annual amount of CO₂ captured at power plants and industry per region in the Netherlands. In the end of the analysis period the Eemsmond, Rijnmond and IJmond regions generate all three substantial amounts of CO₂ that needs to be stored (between 10 and 22 Mt per year).

**Figure 225. Annual amount of CO₂ captured at power plants and industry per period per region, Base case**

Due to a fairly steep increase of CCS deployment in the Netherlands, the amount of CO₂ stored will be around 23 Mt per year in 2020 (Figure 226). The cumulative amount of CO₂ captured, transported and stored in 2050 is 1.4 Gt, which is 44% of the Dutch storage capacity. The total investment costs in trunklines between 2010 and 2050 amounts to 1.4 billion euro. Until 2040 all CO₂ is stored in onshore reservoirs. Around 2040 the share in onshore storage declines, whilst the offshore storage becomes costeffective.

**Figure 226. Annual amount of CO₂ stored and investment costs for transport and storage, Base case**

In the Only Offshore variant the cumulative amount of CO₂ over the total analysis period is almost equal to the Base case. However, the majority of the CO₂ (700 Mt) is stored in the Utsira formation from 2033 onwards (Figure 227). The contribution of CCS to CO₂ reduction remains on average 26%, although the
transport costs are in some time steps almost three times higher. The low storage costs (being 1 V/t when 40 Mt per year is injected based on the assumptions in this study) in the Utsira formation ensure that CCS remains a competitive option. On the other hand, in the Only Offshore - No Utsira variant, the amount of CO₂ stored diminishes by 33% due to limited availability of storage locations. Instead an energy mix with more offshore wind energy is found to be more cost-effective to reach the CO₂ target. In this variant costs of transport plus storage increase substantially (with 72-121%).

Figure 227. The annual amount of CO₂ storage and investment costs for transport and storage

The results show that in a scenario with 20% and 50% CO₂ emissions reduction targets compared to their 1990 level in respectively 2020 and 2050, an infrastructure of around 600 km of CO₂ trunklines may need to be built before 2020. Investment costs for the pipeline construction and the storage site development amount to around 720 mV and 340 mV, respectively. Several conclusions which are of importance for stakeholders involved in CCS can be drawn.

- First, results show that the policy choice to allow the storage of CO₂ onshore or not, is of major importance for the design of the infrastructure. If allowed, a CO₂ transport pipeline from Rijnmond to the sinks in the NorthEast of the Netherlands seems a cost-effective option. If not, a trunkline to a mega structure abroad (e.g. the Utsira formation) from around 2030-2035 has to be considered in order to keep CCS costs competitive.

- Secondly, such a policy decision should be taken as soon as possible because already now preparations should be on the way for constructions of a few large trunklines (planning routes, acquiring permits and licenses) to facilitate the CO₂ storage in the future.

- Thirdly, the necessary investment decisions need to be underpinned by policy strategies, specific CO₂ reduction targets, and sink evaluations in order to reduce uncertainties with respect to future pipeline use.

- Fourthly, it should be studied how to take advantage of the early opportunities in Limburg and Zeeland, which are further away from potential sinks.

- Finally, although currently capture costs make up the major share in the total CCS costs, storage can become the restricting factor for the cost-effectiveness of CCS in the medium term (2035-2045) if cheap storage locations are filled or not available. It is recommended to seek ways to reduce these costs.
3.26.3.3 Feasibility of storing CO₂ in the Utsira formation

This study (250) provides insight into the feasibility of a CO₂ trunkline from the Netherlands to the Utsira formation in the Norwegian part of the North Sea, which is a large geological storage reservoir for CO₂. The feasibility is investigated in competition with CO₂ storage in onshore and near-offshore sinks in the Netherlands. Least-cost modelling with a MARKAL model in combination with ArcGIS was used to assess the cost-effectiveness of the trunkline as part of a Dutch GHG emission reduction strategy.

Scenarios

The following scenarios are studied:

1. Base case. This scenario is based on the base scenario assumptions above.
2. CO₂ storage offshore only. CO₂ can either be stored in the Dutch near-offshore sinks or in the Utsira formation offshore Norway.
3. CO₂ flows from Dutch sources only.
4. CO₂ flows from Dutch sources only and CO₂ storage offshore only. A combination of scenarios 2 and 3.
5. Low CO₂ permit price _ low electricity demand scenario. In this scenario, the electricity demand grows less (from 110 TWh in 2005 to 137 TWh in 2050) as in the Regional Communities scenario, the CO₂ permit price increases from 25 s/t CO₂ in 2010 to 45 s/t CO₂ in 2030, and remains at this level up to 2050. Germany and Belgium will pay only 5 s/ t CO₂ for transport and storage of their CO₂ from the collection point in the Netherlands.

Results

The annual amount of CO₂ captured per region in the Netherlands is presented in Figure 228. In 2015, only CO₂ from industrial units (5 MtCO₂) is captured and stored in Dutch onshore fields. In 2050, the Eemsmond, Rijnmond and IJmond regions all generate substantial amounts of CO₂ that need to be stored (21, 14, and 20 MtCO₂/yr, respectively). IJmond is a favoured location for CO₂ capture, because in this scenario it is also the location where the CO₂ is collected for transport to Utsira. Figure 229 presents the total amount of CO₂ stored per year including the CO₂ from Germany and Belgium, and shows that from 2030 onwards storage in the Utsira formation is considered a cost-effective option by the model (60 MtCO₂/yr is transported from the Netherlands to Utsira). From 2040, the CO₂ flow to Utsira increases to 120 MtCO₂/yr. The investment costs are distributed unevenly over the analysis period: in 2015–2020, the basis of the CO₂ infrastructure in the Netherlands is laid down, in 2030 one trunkline is built to the Utsira formation, and in 2040 a second one.

Figure 228. Annual amount of CO₂ captured at power plants and industrial units per region, base case

![Figure 228. Annual amount of CO₂ captured at power plants and industrial units per region, base case](image-url)
Figure 229. Total annual amount of CO₂ stored in onshore sinks and the Utsira formation (a) and upfront investment costs for transport and storage in the period 2010–2050 (b)

Table 45 summarizes the main results for all scenarios investigated. The results show that under the condition that a CO₂ permit price increases from $25 per t CO₂ in 2010 to $60 per t CO₂ in 2030, and remains at this level up to 2050, CO₂ emissions in the Netherlands could reduce with 67% in 2050 compared to 1990, and investment in the Utsira trunkline may be cost-effective from 2020–2030 provided that Belgian and German CO₂ is transported and stored via the Netherlands as well. In this case, by 2050 more than 2.1 Gt CO₂ would have been transported from the Netherlands to the Utsira formation. However, if the Utsira trunkline is not used for transportation of CO₂ from Belgium and Germany, it may become cost-effective 10 years later, and less than 1.3 Gt CO₂ from the Netherlands would have been stored in the Utsira formation by 2050. On the short term, CO₂ storage in Dutch fields appears more cost-effective than in the Utsira formation, but as yet there are major uncertainties related to the timing and effective exploitation of the Dutch offshore storage opportunities.

Table 45. Overview of results per scenario

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Average transport and storage costs (€/tCO₂)</th>
<th>Total amount of CO₂ stored (MtCO₂) until</th>
<th>Origin CO₂ (MtCO₂ stored until 2050)</th>
<th>Trunkline to Utsira</th>
<th>Total amount of CO₂ stored in Utsira formation (MtCO₂)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2010</td>
<td>2035</td>
<td>2050</td>
<td>2010</td>
<td>2035</td>
</tr>
<tr>
<td>1 Base case</td>
<td>3.5</td>
<td>7.0</td>
<td>8.5</td>
<td>202</td>
<td>1451</td>
</tr>
<tr>
<td>2 CO₂ storage offshore only</td>
<td>8.6</td>
<td>8.1</td>
<td>8.3</td>
<td>139</td>
<td>1164</td>
</tr>
<tr>
<td>3 CO₂ flows from Dutch sources only</td>
<td>4.1</td>
<td>4.2</td>
<td>8.8</td>
<td>121</td>
<td>868</td>
</tr>
<tr>
<td>4 CO₂ flows from Dutch sources only and CO₂ storage offshore only</td>
<td>8.3</td>
<td>10.6</td>
<td>9.2</td>
<td>89</td>
<td>697</td>
</tr>
<tr>
<td>5 Low CO₂ permit price – low electricity demand</td>
<td>4.2</td>
<td>5.3</td>
<td>10.8</td>
<td>126</td>
<td>738</td>
</tr>
</tbody>
</table>

3.27 Thailand

3.27.1 Co-benefits of CO₂ reduction in a developing country

In this paper (251,252), we examine the co-benefits of reducing CO₂ emissions in Thailand during 2005–2050 in terms of local pollutant emissions as well as the role of renewable-, biomass- and nuclear-energy. It also examines the implications of emission reduction policy on energy security of the country. The analyses are based on a long term energy system model of Thailand using the MARKAL framework.

Scenarios

Besides the base case, the three emission reduction target scenarios are considered:

- 10% Emission reduction target (hereafter called as “ERT10” Case)
- 20% Emission reduction target (hereafter called as “ERT20” Case)
• 30% Emission reduction target (hereafter called as “ERT30” Case)

The ERT10 case is the ‘what if’ scenario, in which a cumulative reduction of not less than 10% of the cumulative CO₂ emission during the planning horizon in the base case is desired, all other things remaining the same as in the base case. The ERT20 and ERT30 cases are defined similarly for cumulative reductions in CO₂ emissions of not less than 20% and 30%, respectively, from the base case emission.

Results

The energy system would be more carbon intensive over time during the planning horizon in the base case in that CO₂ emission per unit of total primary energy supply (hereafter “CO₂ intensity of energy use”) would increase from 51kg/GJ in 2005 to 75kg/GJ in 2050. Interestingly, significant reduction in CO₂ intensity of energy use begins around 2025 under ERT10 and ERT20, while it starts much earlier (i.e., before 2015) under ERT30 (Figure 230).

As can be seen from Figure 231, the difference between marginal costs of CO₂ reduction under ERT10 and ERT20 is relatively small, while the marginal cost of CO₂ reduction in ERT30 is significantly higher than that in ERT20. This analysis shows that it could be possible to cost effectively reduce cumulative CO₂ emission by up to 20% from that in the base case in a rapidly industrializing developing country like Thailand at the carbon price that grows exponentially from $1.4 to $102.4/tCO₂ during 2005–2050. The total discounted system cost would increase only nominally in the selected ERT cases as compared to that in the base case; i.e., by less than 0.01% in ERT10, 0.02% in ERT20 and 0.13%, in ERT30 (Figure 231).

Will CO₂ emission reduction targets have positive impacts on energy security of the country? This issue is analysed in terms of changes in net energy import dependency and diversification of energy resources resulting from least cost strategies to attain the selected CO₂ emission reduction targets. The results show that the diversification of total primary energy requirement (TPES) would increase during the planning horizon.
As can be seen from Figure 232 a, the value of the SWI in all the ERT cases would be higher than that in the base case. Moreover, the value of the index is found to increase with the emission reduction target except in ERT30 during 2005–2050. This is because the share of coal in the cumulative TPES during the period would further decrease and that of the natural gas would increase in ERT30 as compared to that in ERT20. The present study also shows that there would be a higher degree of diversification in net energy imports with ERT (Figure 232 b) like in the case of TPES.

### 3.27.2 CO₂ mitigation with CCS in the power sector

Thailand currently relies largely on natural gas, coal & lignite, fuel oil, and less portion in renewable energy for electricity production. Due to the cheap fuel costs, fossil fuels dominate in energy supply. However, utilization of more fossil fuels results in increasing CO₂ emissions. The introduction of CCS for the future thermal power plant in Thailand is modeled in the multi-period linear programming MARKAL (MARKet ALlocation) model (253).

#### Scenarios

The differences in marginal costs are analyses in terms of CO₂ mitigation in the business-as-usual (BAU), nuclear (NUC) and renewable (RE) cases up to 20% share: RE05, RE10, RE15 and RE20. These scenarios are used to develop alternative energy scenarios compared with the potential of CCS technology.

Seven scenarios are considered in this study. These studies consist of BAU and six alternative scenarios which consider different shares of renewable energy and nuclear power policy. In the BAU, it consists of 29 existing power plant, 2 purchasing from Lao PDR and Malaysia and 5 new power plants. As shown in Table 46, for CCS case, the 4 new power plants are installed with CCS technologies.
Table 46. Scenarios of selected technologies in the study

<table>
<thead>
<tr>
<th>Cases</th>
<th>Technologies</th>
<th>Fuels</th>
<th>Installed (MW)</th>
<th>Start</th>
</tr>
</thead>
<tbody>
<tr>
<td>NUC</td>
<td>BAU=Nuclear LWR</td>
<td>uranium</td>
<td>2,000</td>
<td>2021</td>
</tr>
<tr>
<td></td>
<td>BAU&gt;CCGT (CCS) #1</td>
<td>LNG</td>
<td>1,400</td>
<td>2014</td>
</tr>
<tr>
<td>CCS</td>
<td>BAU&gt;CCGT (CCS) #2</td>
<td>LNG</td>
<td>2,800</td>
<td>2020</td>
</tr>
<tr>
<td></td>
<td>BAU&gt;IGCC (CCS)</td>
<td>coal</td>
<td>2,100</td>
<td>2020</td>
</tr>
<tr>
<td></td>
<td>BAU&gt;Supercritical (CCS)</td>
<td>coal</td>
<td>700</td>
<td>2015</td>
</tr>
<tr>
<td></td>
<td>Conventional fossils, renewable and *new biomass power plants</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Results

When consider all scenarios, CO₂ mitigation is the highest case when applying CCS in 2014 (Figure 233). There will be 255.6 PJ (with the decreasing rate per year of 17.7%) of coal decreasing in 2020 to 2030.

Figure 233. CO₂ mitigation from the power sector in alternative cases

With decreasing in imported coal and natural gas in the RE05-RE20 cases and nuclear case, the electricity generation from fossil fuel decreases so that CCS can keep CO₂ in the fewer portions compared with the base case. When considering with the marginal cost, the marginal cost of CO₂ emission reduction has positive in the case of renewable energy and negative in NUC and CCS as shown in Figure 234. The marginal costs of CCS option are -132.08 US$/tCO₂ in 2014 and -346.51 in 2022. It means that in this period CCS technology is competitive. While in 2024 marginal cost up to 999.55 US$/tCO₂ so in this period to 2030 CCS technology is not competitive. The marginal reduction cost of CO₂ in the case of CCS is competitive only during the period of 2014-2022.

Figure 234. Marginal cost from CCS scenario

The results show options are better from the optimality side of CO₂ mitigation strategies, associated costs compared with utilizing Carbon Credit Mechanism (CDM) program and possible future technologies for investment in Thailand.
3.27.3 Optimization of energy supply and demand in the power sector

In the same context, the objective of this study (254,255,256) is to optimize the long-term energy supply and demand in Thailand with the potential of renewable energy on the low carbon fuels and technologies in the power sector. The increasing in renewable electricity production share at least 5-20% of the total electricity production can mitigate CO₂ emission around 0.62-6.88 % per year. The introduction of 1% (RE1) to 10% (RE10) renewable electricity generation share in 2020 obviously reduce emission compared with the BASE scenario as shown in Figure 235. The reduction of final energy demand leads to a reduction in the primary energy consumption and emission.

Figure 235. CO₂ emission in several increased renewable shares (RE)

Figure 236 shows the discounted total system cost for each renewable electricity generation shares compare with promote nuclear power plant case.

Figure 236. Total discount system cost

3.27.4 Comparison of the future power plants competitiveness

The paper (257) describes the application of MARKAL (MARKet Allocation) for comparing economic parameters of the future power plant Thailand. All calculations for demand technologies in this study cover a time frame of 25 years from 2006 to 2030. The method is applied to determine competitive specific investment costs of power plants which are planned to be built in the future. The main candidates are combined cycle gas fired plants and nuclear power plants, which the first nuclear power plant is planned to be built in 2020 with the starting electricity production capacity of 1,800 MW then the production capacity is planned to be increased to 3,600 MW in 2021.

Performed analysis shows that future competitive nuclear power plant is cost competitive with other forms of electricity generation except where there is direct access to low-cost fossil fuels. Comparing costs for nuclear power plants with other types of power plants, fuel cost only accounts for a minor portion of total generating cost; however, the capital costs for nuclear power plants are much greater than those for thermal plants. A discount rate of 10% is selected as most appropriate for analysis of the long-term technological choices. The Thai MARKAL energy systems model has been used to investigate long-term planning in the electricity generation options. The results of the MARKAL model are used to develop selected scenario in future developments of reference energy system.
3.28 Turkey

3.28.1 Determining optimum energy strategies

The TURKISH MARKAL model is available to analyze alternative scenarios in order to see their possible effects on our energy system (259,260,261,258). General structure of MARKAL model and the database architecture is overviewed by the group with an interdisciplinary approach.

Scenarios

Base Scenario serves as a reference which other scenarios would be analyzed and compared with. In this respect, determination of the country’s Base Scenario depends on the status of the calibration year, which is required to be equipped with optimal level of data.

Results

In analysis period, between the years 2005-2025, 3% of overall consumption and demand assumed an increase at a rate of 3.3%. Total primary energy resources going up from 4472 PJ to the level of 14849 PJ in Turkish Energy System, so the total energy supply would increase at a rate of 232% in period of 2005-2025 as illustrated in Figure 237.

Figure 237. Total primary energy in Turkey, Base scenario

Similarly, looking at the consumption level results of all sectors in Figure 238, 3067 PJ of final energy in 2005 goes up to 8000 PJ by the year 2025 and analysis period consumption increases at a rate of 160%. However, due to various losses in 2005, 2026 PJ of useful energy consumed, while 5141 PJ in 2025. The fact that serious differences observed between the amount of energy supply to meet demand because of both transmission and distribution losses occurred and present technical efficiencies of technologies used by the system. Energy savings can be achieved by new investments in the electricity transmission system with energy efficiency measurements in the current technologies in each sector which a number of power plants to generate the equivalent amount.

Figure 238. Total final energy in Turkey, Base scenario

For further and more detailed Turkish MARKAL studies, additional alternative scenarios may be applied and run on this Base Scenario in order to analyze the possible effects on the energy system as follows:
• Options for efficiency improvement of thermal power plant expansion plans or technologies used in end use sectors,
• Options of candidate power plant analyses to obtain the annual investment levels and electricity load percentages,
• Analyzing the possible effects of increasing the alternative potentials of hydraulic, wind, solar and wave energy resources to national energy system,
• Utilizing the cogeneration in all sectors,
• Analyzing the candidate nuclear power plants’ effects in the energy system,
• Analyzing the domestic renewable energy resources’ utilization on possible higher levels,
• Analyzing the CO₂ mitigation scenarios to estimate a road map of environmental aspects,
• Analyzing the effects of possible changes in natural gas import prices.

3.28.2 Establishing energy technologies selection and emissions mitigation strategies

Achieving the goal of sustainable development may be possible with the long-term strategic plans, which take into account and optimize the global and unique circumstances, economic and environmental constraints. Different decision support based approaches are also needed for planning in every country to optimize energy, economy and ecology aspects in the system. The main purpose of this study (262,263,264) is to bring up a model for our country that can be used for this purpose. MARKAL energy model, used by more than 40 countries around the world today, is established for our country based on the years 2000 and 2005. Analysis period contains the interval of years 2000-2025. Technical, economical and environmental effects were analyzed on the base scenario for the stated future cases by creating specific scenarios as CO₂ emission mitigation, utilization of renewable energy resources, demand side management in power generation and industry, increased cogeneration, technical efficiency improvement by the rates 1%, 2% and 3%, limited import of natural gas with higher prices and nuclear energy.

In addition, this study (264) has aimed at developing clear perception and mitigation options for energy-related emissions and the economic costs of the different measures that can be taken in all Turkish energy sectors and at handling Turkish side of the problem as well as integrating to the world solution efforts. Major priority for establishing GHG emission mitigation options is to use none polluting and relatively inexpensive energy types especially in producing electricity and grid connection of renewable energy sources. Electricity produced from renewable resources can be used especially in small-scale consumptions of immobile residential, commercial, industrial and alike sectors. In the first stage, 50% renewable energy in electricity production should be targeted with respect to results obtained by this study.

These presentations (262,263) show results of these applications.

Scenarios
• CO2M: CO₂ emission level will be decreased 5% below 2005 level till 2020, which is the same as countries with responsibility in this mitigation process.
• REN1: The target is to increase the renewable energy utilization up to the upper available levels until 2020 from the year 2005 and applying carbon tax on the whole system.

Results
The total final energy consumption (Figure 239) and the emissions (Figure 240) are presented for the three scenarios.
3.28.3  A Preliminary study for post-Kyoto period

With several input parameters of technology related, economic and environmental coefficients MARKAL calculates the alternatives for minimum possible cost. This article (265) reports the results of the Turkish energy model that has been developed by using MARKAL Model Generator.

Scenarios

Once the RES is introduced into MARKAL it is easy to develop scenarios for studying various possible alternatives to the BAU such as the cost implications for mitigations of the GGE. For this article two scenarios sustaining the economic growth have been developed:

- The first scenario is about keeping the emission level of CO₂ constant, i.e. 2005 value of 236.8 Mton, during the 2005-2025 period (CO₂STA).
- The second scenario is about mitigating the CO₂ emission by 11% during the period of the study, i.e. reducing the CO₂ emissions to 210.8 Mton by 2025 (CO₂MITG). The CO₂ MITG scenario is even more demanding than the CO₂STA scenario for the reason that it foresees to mitigate the CO₂ emissions rather than keeping them constant. This is indeed a difficult task for a country in the course of economic and social development.
Results
Table 47 compares the BAU and the CO₂MITG scenarios. The CO₂ MITG scenario has similarities with the CO₂ STA scenario. The target of emission mitigation is 56.0% in the former and it is 50.6% in the latter. “Total Imports of Fossil Energy Carriers” and “Total Domestic Supply of Fossil Energy Carriers” values are identical in both scenarios; there is only a slight difference in year 2025. The CO₂ MITG scenario foresees slightly more use of “Total Primary Energy” than the CO₂ STA scenario and this is mainly realized by the even wider usage of renewables. This results in the increased “Total System Cost.” It is also worth noting that the increase in “New Investment Cost” compared to “Total System Cost” in the CO₂ MITG scenario is higher than the corresponding values in the CO₂ STA scenario. This is plausible, because the former foresees comparably wider use of renewables which require immense new investments.

Table 47. Comparison of the BAU and the CO₂ MITG scenarios

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Units</th>
<th>2005</th>
<th>2010</th>
<th>2015</th>
<th>2020</th>
<th>2025</th>
</tr>
</thead>
<tbody>
<tr>
<td>BAU</td>
<td>Emission (Mton CO₂)</td>
<td>236.8</td>
<td>294.0</td>
<td>348.6</td>
<td>411.6</td>
<td>479.9</td>
</tr>
<tr>
<td>CO₂MITG</td>
<td>Emission (Mton CO₂)</td>
<td>236.8</td>
<td>230.4</td>
<td>223.8</td>
<td>217.3</td>
<td>210.8</td>
</tr>
<tr>
<td>Diff. BAU-CO₂MITG</td>
<td></td>
<td>0.0%</td>
<td>-22.0%</td>
<td>-35.0%</td>
<td>-47.0%</td>
<td>-50.0%</td>
</tr>
<tr>
<td>BAU</td>
<td>Total Primary Energy (PJ)</td>
<td>3850.7</td>
<td>4703.7</td>
<td>5542.1</td>
<td>6848.3</td>
<td>7841.4</td>
</tr>
<tr>
<td>CO₂MITG</td>
<td>Total Primary Energy (PJ)</td>
<td>3850.7</td>
<td>4793.6</td>
<td>5776.0</td>
<td>6742.8</td>
<td>7407.7</td>
</tr>
<tr>
<td>Diff. BAU-CO₂MITG</td>
<td></td>
<td>0.0%</td>
<td>2.0%</td>
<td>3.4%</td>
<td>-2.5%</td>
<td>-0.0%</td>
</tr>
<tr>
<td>BAU</td>
<td>Total Imports of Fossil Energy Carriers (PJ)</td>
<td>3011.0</td>
<td>3594.6</td>
<td>4212.6</td>
<td>5058.0</td>
<td>5864.5</td>
</tr>
<tr>
<td>CO₂MITG</td>
<td>Total Imports of Fossil Energy Carriers (PJ)</td>
<td>3011.0</td>
<td>2922.9</td>
<td>3196.7</td>
<td>3251.3</td>
<td>3022.6</td>
</tr>
<tr>
<td>Diff. BAU-CO₂MITG</td>
<td></td>
<td>0.0%</td>
<td>-19.0%</td>
<td>-24.0%</td>
<td>-36.0%</td>
<td>-48.0%</td>
</tr>
<tr>
<td>BAU</td>
<td>Total Domestic Supply of Fossil Energy Carriers (PJ)</td>
<td>3394.4</td>
<td>4188.6</td>
<td>4930.8</td>
<td>6087.6</td>
<td>6919.9</td>
</tr>
<tr>
<td>CO₂MITG</td>
<td>Total Domestic Supply of Fossil Energy Carriers (PJ)</td>
<td>3394.4</td>
<td>3907.8</td>
<td>4561.9</td>
<td>4746.1</td>
<td>4562.1</td>
</tr>
<tr>
<td>Diff. BAU-CO₂MITG</td>
<td></td>
<td>0.0%</td>
<td>-7.0%</td>
<td>-12.0%</td>
<td>-22.0%</td>
<td>-35.0%</td>
</tr>
<tr>
<td>BAU</td>
<td>Total Usage of Renewable Energy Carriers (PJ)</td>
<td>637.2</td>
<td>750.6</td>
<td>882.7</td>
<td>992.4</td>
<td>1223.6</td>
</tr>
<tr>
<td>CO₂MITG</td>
<td>Total Usage of Renewable Energy Carriers (PJ)</td>
<td>637.2</td>
<td>2294.6</td>
<td>3102.2</td>
<td>3798.0</td>
<td>4682.9</td>
</tr>
<tr>
<td>Diff. BAU-CO₂MITG</td>
<td></td>
<td>0.0%</td>
<td>205.7%</td>
<td>251.4%</td>
<td>282.7%</td>
<td>282.7%</td>
</tr>
<tr>
<td>BAU</td>
<td>Total System Cost (Million USD)</td>
<td>78890.4</td>
<td>95499.2</td>
<td>112422.9</td>
<td>128075</td>
<td>161095.6</td>
</tr>
<tr>
<td>CO₂MITG</td>
<td>Total System Cost (Million USD)</td>
<td>76947.4</td>
<td>125846.3</td>
<td>154670.4</td>
<td>183505.6</td>
<td>198871.5</td>
</tr>
<tr>
<td>Diff. BAU-CO₂MITG</td>
<td></td>
<td>-1%</td>
<td>32%</td>
<td>38%</td>
<td>44%</td>
<td>49%</td>
</tr>
<tr>
<td>BAU</td>
<td>New Investment Cost (Million USD)</td>
<td>58279.2</td>
<td>69273.7</td>
<td>81538.2</td>
<td>85822.7</td>
<td>114148.2</td>
</tr>
<tr>
<td>CO₂MITG</td>
<td>New Investment Cost (Million USD)</td>
<td>58276.5</td>
<td>101633.3</td>
<td>127985.0</td>
<td>154742.6</td>
<td>169817.3</td>
</tr>
<tr>
<td>Diff. BAU-CO₂MITG</td>
<td></td>
<td>0%</td>
<td>47%</td>
<td>57%</td>
<td>78%</td>
<td>49%</td>
</tr>
<tr>
<td>BAU</td>
<td>Total System Cost, Net of Taxes/Subsidies (Million USD)</td>
<td>1019028.0</td>
<td>1253161.0</td>
<td>1212479.0</td>
<td>1212479.0</td>
<td>1212479.0</td>
</tr>
<tr>
<td>CO₂MITG</td>
<td>Total System Cost, Net of Taxes/Subsidies (Million USD)</td>
<td>1253161.0</td>
<td>1212479.0</td>
<td>1212479.0</td>
<td>1212479.0</td>
<td>1212479.0</td>
</tr>
<tr>
<td>Diff. BAU-CO₂MITG</td>
<td></td>
<td>21%</td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

3.29 Ukraine

3.29.1 Achieving EU targets on renewable energy

Though “Energy Strategy of Ukraine till 2030” indicates RE development in the country, the document has been strictly criticized by energy experts, NGOs and renewable energy advocates for its “nuclear orientation”. Implementation of feed-in tariff is the very first step toward increased use of renewables for electricity production in country’s national energy balance. According to a Government Decree, IEF was assigned to create information-analytic system for strategic planning of energy sector and projection of the energy balance, where TIMES-Ukraine model was supposed to be taken for the basis. The work on TIMES-Ukraine model (266) started at IEF in 2006 in the framework of special research projects of Ukrainian National Academy of Sciences. In 2009 after joining SYNENERGY project and with contribution from IRG and CRES experts the initial TIMES-Ukraine model was finished, however, the model update is performed quarterly.

Scenarios

The energy system of Ukraine is represented as the single region. Although the base year is 2005, in order to reflect the impact of the world economic crisis the model has also been additionally calibrated with data for 2006 and 2009.
Results

Feed-in tariff for electricity producers introduced in 2009 turned out to be indeed effective instrument for attracting private investment in renewable energy (Figure 241). The number of applications to build the new power capacities and the progress rate of new installations just during the last year give us ground to say that Ukraine could be confident enough to achieve the targets of EU Directives (Figure 242).

However, to have enough of manoeuvrable capacities there will be a need for modernization or installing of new power plants on traditional fossil fuels. The most prospective seems to be the use of renewable energy for heating and water heating in the commercial and residential sectors and for cogeneration auto-production in industry. In the transport sector biodiesel promises to be the dominating type of biofuel.

Figure 241. Gross final consumption of energy, PJ

Figure 242. New power plants building by fuel type, GW

3.29.2 Dual problem of the coal sector development

This presentation (267) focuses on the coal sector development and starts by introducing the Agenda of the Ukrainian coal sector development. Naturally that in the Energy Strategy of Ukraine till 2030 the scenario of the extended coal consumption is considered as the most preferable (Expected level of coal consumption is 130 mln tones). In addition, consideration of Ukrainian coal resources as the biggest potential source of hydrogen for the Western Europe (REACCESS project). Finally, restructuring of the Ukrainian coal sector in the spirit of the EU reforms that were aimed at radical greening of economy and rehabilitation of regression coal regions (like in UK, Germany or Poland).

Scenarios

Scenario of expanded usage of coal (Reference): Reference Scenario provides for the state stimulating coal consumption mainly for electricity and heat production. The share of coal in the TPP fuel mix will increase from 70 to 93% that can be achieved owing to the better quality of coal concentrate. Modernization of existing and installation of new coal-fired power plants will have cost advantages over the other technologies for electricity production because of the state budget subventions. The increase of coking coal consumption will be determined by the world steel prices and will be limited to the existing capacities of the production of coke (20-30% more than in 2008). State subsidies to metallurgical sector (10% discount on electricity and gas prices) will be annulled in the mid-term period, as it is assumed that the production level of other sectors will ensure the surplus of trade balance.
Scenario of the coal sector development in the spirit of EU reforms: EU reform scenario envisages decommissioning of unprofitable mines, that must reduce pressure on the state budget, but it can also lead to a significant shortage of coal in the domestic market, especially for the steam coal. Lack of technological flexibility will not allow consumers to quickly switch to alternative fuels, while the growth of coal imports will be possible only after a much larger increase in capacity of Ukrainian sea harbors. Growing energy demand thus must be covered by the existing and new capacities (including renewable sources), and also by performing energy efficiency measures. Thus, while maintaining the existing macroeconomic proportions and technological structure, economic development with the focus on existing domestic energy resources may lead in the near future to the formal replacement of natural gas imports from Russia to import coal and coke, which in the absence of sufficient transport infrastructure can lead to significant additional cost.

Results

Energy System cost (Figure 243) under Renewable potential scenario decreases by 8.5% because of installation of the new technologies that use renewable energy and refusal from the old inefficient technologies. Under the scenario of Renewable plus Energy Efficiency the previous decreasing of System cost is supported by the higher penetration of new efficient technologies (higher building standards and modernization of the heating plants, direct iron techs in metallurgy and in transport). Under the third scenario renewable potential was supplemented with the specific targets – 13% of RE in final energy consumption, including 10% of biofuel in transport sector.

Figure 243. Change in total discounted system cost

In all alternative scenarios electricity generation is increasing by 10-15% comparing to the reference scenario because of the higher efficiency of electric end use devices (Figure 244). The structure of new electricity generation capacities mostly consists of Hydropower Plants, Renewable (mostly Wind Power plants), and also small oil-fired Cogeneration Plants. These new capacities totally cover the demand for electricity, that under the Base scenario was produced by new coal and gas Power Plants.

Figure 244. Impact on power generation system
Under the Reference (expanded coal usage) scenario till 2015 it is possible to cover the growing demand for coal with a help of existing mines. After 2015 new extracting capacities will be needed only for anthracite and steam coal. For the coking coal there would be even enough the capacities of the privatized and profitable state-owned mines.

Although under EU reforms scenario we expect for very moderate increasing of electricity and heat production from coal (from 26.8% to 27.9% and from 1.2% to 1.7%), economically grounded penetration of renewable resources and implementation of energy efficiency projects would not allow to refuse from the import of coal and non-profitable coal mines completely. We expect for reduction of demand for anthracite by 8%, 29% reduction for coking coal and 11% for steam coal. Overall reduction for coal thus will reduce on 16%.

3.29.3 Methodological challenges in model development

This presentation (268) deals with practical validity of input parameters. After protracted crisis of the nineties, relatively high rates of economic growth among European countries were maintained in Ukraine by virtue in large part of the availability of comparatively cheap energy resources from Russia and favorable conditions in the foreign markets of metal and chemical products. This recalls the fact that it is impossible to define universal dependencies and assessments of elasticity, but the modelers should always try to determine the direct action of price and income elasticity over the past period to justify elasticity projection in the model. The methodological trick: Energy consumption of the sector is the amount of energy, consumed by enterprises, that belong to this sector by NACE code of their main economic activity. Production output of the sector is the overall production of commodities, that belong to the commodity nomenclature of this sector by the first six characters of their CPA code (regardless of the NACE belonging of the manufacturer).

Manufactured non-core commodities are not necessarily intermediate products, they may also be final products and the level of productions may be predicated upon domestic demand, as well as favourable external market environment (Figure 245).

Figure 245. Non-core production by metallurgy in Ukraine, 2005

3.30 United Kingdom

3.30.1 The role of bioenergy in long-term energy scenarios

3.30.1.1 Approach and methodology

Bioenergy chains. We report the proposed bioenergy technologies to be considered in the UK MARKAL modules (269), to be consistent with: i) the main bioenergy trends and possible pathways; ii) the availability of input data for each technology; iii) other UK-MARKAL modules. Changes proposed cover: (1) the reformulation of the technology description, in which case the data review stage of the work will be particularly important, but at a first stage the values presently in UK-MARKAL could be kept; (2) the addition of technologies, in order to represent possible biomass sources and technologies in a balanced way (between themselves and when compared to other types of fuels); and (3) the suppression of some technologies, e.g. where it was felt some were over-detailed, or when some bioenergy pathways were not considered as promising as they used to. Most of the changes proposed in this report are for the
resources, process and infrastructure, and electricity (and heat) modules. Other changes for the demand side modules should be further developed as part of the TSEC-BIOSYS project, in particular to enhance the representation of the building sector (in the residential and service module).

Bioenergy data. This working paper (270) presents the detailed dataset used for the bioenergy chains of the BIOSYS-MARKAL model used for the TSEC-BIOSYS project modelling exercise. A key objective pursued in the revision of the bioenergy chains for the BIOSYS-MARKAL database was that each data input to the model needed to be referenced. This was done either based on current literature considered appropriate within the bioenergy community, either based on experts input coming from consultation within the TSECBIOSYS project, but also other projects such as UKERC Energy 2050, or REFUEL. The resulting dataset for the BIOSYS-MARKAL model is a key input to the modelling exercise undertaken in the TSEC-BIOSYS project. The formulation of long-term bioenergy scenarios are informed both by qualitative storylines, and by quantitative insights provided by MARKAL modelling. Model runs are defined based on the “reference dataset” presented in this paper, as well as additional “base-case” assumptions corresponding to some policy, environmental and/or social constraints which are described elsewhere.

3.30.1.2 Future formulation and modelling of long-term bioenergy scenarios

This paper (271) explores the prospects and policy implications for bioenergy to contribute to a long-term sustainable UK energy system. The UK MARKAL technology-focused energy systems dynamic cost optimisation model - which has been used to quantify the costs and benefits of alternative energy strategies in UK policy making - is enhanced with detailed representation of bio-energy chains and end-uses. This provides an important advance in linking bioenergy expert-knowledge with a whole system modelling approach, in order to better understand the potential role of bioenergy in an evolving energy system. This work is of interest as no UK energy systems model (and very few other countries’) undertook detailed analysis of the contribution of bioenergy pathways, in particular within integrated scenarios of low carbon and energy security policy objectives.

Scenarios

Therefore the BIOSYS modelling and scenario exercise are characterised by the following: (a) (environmental) sustainability ambition and (b) energy system in dependence (mostly related to energy security of supply— and linked to the balance of imported energy vs. domestic sources of energy). Hence, as with many other scenario exercises, these underlying policy objectives are set up in a 2*2 matrix of four BIOSYS scenarios (Figure 246).

- “World Markets” is the base case BIOSYS 1 scenario. In this scenario, little concern is paid to energy security, energy efficiency or sustainable energy production and climate change. Some renewable technologies are adopted because they are cost-effective.
- “Energy independence above all” is the BIOSYS 2 scenario, where a supply of cheap and secure energy is the main underlying (policy) objective. Domestic sources of energy are prioritised (both fossil and renewables). The concerns for environmental sustainability (and climate change) come only second to energy security ones.
- “Environmentally conscious energy autonomy” is the BIOSYS 3 scenario, in which energy systems are restructured around the use of domestic sources of energy but with a priority given to renewables and low carbon sources.
- Finally, “Global Sustainability” is scenario BIOSYS 4, which involves a drive for sustainability in energy supply, promoted in a globalised manner. This would imply a growth in imported energy sources that are certified as low carbon and/or “sustainable”.

229
Results

The results of the BIOSYS-MARKAL runs are analysed with a focus on the bioenergy technologies and pathways, notably biomass resources, the end-use sectoral breakdown of bioenergy, and the bioenergy pathways in each scenario. The overall (long-term) level of final (bio-) energy ranges between about 1200 PJ for BIOSYS 1 (Figure 247), 3 (Figure 249), and 4 (Figure 250) to about 1500 PJ in BIOSYS 2 (Figure 248).

Figure 247. Evolution of the use of bioenergy in different end-use sectors in BIOSYS 1, 2000–2050

Figure 248. Evolution of the use of bioenergy in different end-use sectors in BIOSYS 2, 2000–2050
From the practical point of view, our results suggest that a combination of existing bioenergy technologies, and those currently under development could contribute significantly to meeting current UK energy policy objectives. The UK could significantly increase its use of bioenergy in all three main end use sectors (heat, power, and transport), providing between 16% and 23% of final energy demand by 2050. Bio-heat seems a cost effective option even in the base scenario, suggesting that uptake is hindered by non-economic factors, such as securing feedstock quantity and quality (e.g. from farmers willing to grow energy crops), the availability of infrastructure required to support the growth in biomass use, or local and regional market dynamics.

### 3.30.1.3 Accelerated development of bioenergy in the future energy mix

This work (272) explores the potential contribution of bioenergy technologies to 60% and 80% carbon reductions in the UK energy system by 2050, by outlining the potential for accelerated technological development of bioenergy chains. Due to the number and complexity of bioenergy pathways and technologies in the model, three chains and two underpinning technologies were selected for detailed investigation: (1) lignocellulosic hydrolysis for the production of bioethanol, (2) gasification technologies for heat and power, (3) fast pyrolysis of biomass for bio-oil production, (4) biotechnological advances for second generation bioenergy crops, and (5) the development of agro-machinery for growing and harvesting bioenergy crops.

Detailed literature searches and expert consultations led to the development of an 'accelerated' dataset of modelling parameters for each of the selected bioenergy pathways, which were included in five different scenario runs with UK-MARKAL (MED).
Scenarios
These accelerated scenarios were built around the UKERC Energy 2050 project scenarios. Description of the five scenarios run as part of the accelerated technology development (ATD) scenarios:

- **ATD Bioenergy** All five bioenergy technologies were accelerated together. No acceleration of any other technologies
- **LC-Acctech (60%)** without fuel cells All technologies (wind, marine, bioenergy, solar PV, coal CCS, and nuclear) accelerated together to achieve a 60% reduction in carbon emissions by 2050
- **LC-Acctech (80%)** without fuel cells All technologies (wind, marine, bioenergy, solar PV, coal CCS, and nuclear) accelerated together to achieve an 80% reduction in carbon emissions by 2050
- **LC-Acctech (60%)** with fuel cells All technologies (wind, marine, bioenergy, solar PV, coal CCS, nuclear and fuel cells) accelerated together to achieve a 60% reduction in carbon emissions by 2050
- **LC-Acctech (80%)** with fuel cells All technologies (wind, marine, bioenergy, solar PV, coal CCS, nuclear and fuel cells) accelerated together to achieve an 80% reduction in carbon emissions by 2050

Results
Overall, there is a larger uptake of bioenergy in the ATD Bioenergy scenario than in the LC-Core scenario. The increased uptake of bioenergy in the ATD scenario appears to be due to the availability of cheaper resources (energy crops). Although energy crops are utilised in both scenarios in 2010, there is a much larger uptake of bioenergy crops across all vintages in the ATD scenario from 2010 to 2050 (Figure 251). The land available for energy crop production is not fully utilized in the LC-Core scenario and produces a maximum of 113 PJ of domestic energy crops. The production of energy crops in the ATD scenario, however, reaches a physical constraint when all available domestic land for energy crop production is utilized in 2030 (at 415 PJ).

**Figure 251. Energy crop production in UK**

When all the technologies are accelerated together in the LC Acctech (no fuel cells) scenario at 60% carbon reduction, there is less biomass for electricity after 2040 than there was in ATD Bioenergy (Figure 252). This is likely due to the abundance of other cheap alternatives for electricity production. In LC Acctech (no fuel cells) (80%) there is much less biomass deployed for electricity production (a peak of 150 PJ as opposed to 290 PJ in LC Acctech (no fuel cells) (60%). When all the technologies (including fuel cells) are accelerated for a 60% carbon reduction target then bioenergy is used more for electricity generation than in any other scenario (including the single technology acceleration-ATD Bioenergy). When all the technologies (including fuel cells) are accelerated with an 80% carbon reduction target then biomass is used less for electricity generation than in the other accelerated scenarios.
Bioenergy was deployed in larger quantities in the bioenergy accelerated technological development scenario compared with the LC-Core scenario. In the electricity sector, solid biomass was highly utilised for energy crop gasification, displacing some deployment of wind power, and nuclear and marine to a lesser extent. Solid biomass was also deployed for heat in the residential sector from 2040 in much higher quantities in the bioenergy accelerated technological development scenario compared with LC-Core. There is much potential for future deployment of bioenergy technologies to decarbonise the energy sector. All bioenergy technologies should become increasingly more economically competitive with fossil-based technologies as feedstock costs and flexibility are reduced in line with technological advances.

3.30.2 Soft-linking MARKAL to a GIS to investigate spatial aspects of new hydrogen infrastructures

This paper (273,274,275,276) describes an innovative modelling approach focusing on linking spatial (GIS) modelling of hydrogen (H₂) supply, demands and infrastructures, anchored within a economy-wide energy systems model (MARKAL). The UK government is legislating a groundbreaking climate change mitigation target for a 60% CO₂ reduction by 2050, and has identified H₂ infrastructures and technologies as potentially playing a major role, notably in the transport sector.

Scenarios

An exploratory scenario set focuses on reference and CO₂ constrained runs (60% reduction by 2050 applied across the entire model) to compare the updated nonspatial version of the UK MARKAL model, with this spatially disaggregated model (soft-linked via GIS). A sensitivity run carried out restricting on imported hydrogen (H₂) is discussed, as well as runs on alternate CO₂ emissions targets:

- REF: Reference case (non-spatial model)
- C60: CO₂ 60% reduction by 2050, implemented from 2010 (non-spatial model)
- GIS–REF: MARKAL–GIS H₂ model reference case (meta-pipeline GH₂, LH₂, small-scale GH₂)
- GIS–C60: MARKAL–GIS H₂ model CO₂ 60% reduction by 2050
- Sensitivity run
  - GIS–C60I: MARKAL–GIS H₂ model CO₂ 60% reduction by 2050, with no imported hydrogen
- Alternate constraints
Results

In an integrated energy systems model, changes in the H₂ and transport sector impact other parts of the system, and Figure 253 illustrates electricity generation in 2050. The reference cases for the non-spatial and spatial models are similar, however, the amount of decarbonised electricity and generation mix in the CO₂ cases is radically different. In the spatial model, overall (decarbonised) electricity generation is significantly less, partly as small-scale H₂ production from electrolysis is no longer cost optimal compared to geographically distinct large-scale H₂ infrastructures. With far less pressure for a large, decarbonised power sector the generation mix changes, with nuclear power no long invested in, and reduced requirements for marine and imported electricity. In addition, some coal CCS capacity is reallocated to more flexible gas CCS plant which combines with increased (geographically distributed) on- and offshore wind to complete the generation mix.

Focusing now on hydrogen, using conventional nonspatial energy systems modelling approach finds that H₂ use in transport modes and infrastructures is built up from 2030 and is heavily influenced by resource availability. In the nonspatial model reference case, all H₂ is produced from coal gasification (without CCS), with distribution for large-flow modes (HGVs, rail) made using pipelines, with lower-flow bus depots being serviced by road tube trailer, and with dispersed sources (cars, LGV) being serviced by liquid H₂ via road tanker. This changes under CO₂ constraints, where the power sector utilizes all available low cost UK CCS capacity and the H₂ network is sourced from liquid H₂ imports, which flow to bus, car, HGV and LGV modes, again supported by small-scale electrolysis distributed to the car refuelling network.

Figure 253. Electricity generation in 2050

The imposition of different levels of CO₂ reduction targets has a significant effect on the marginal price of CO₂, rising in 2050 from £55.2/tCO₂ for GIS–C40 to £217.9/tCO₂ for GIS–C60 and then to £504.8/tCO₂ for GIS–C80. As the CO₂ constraint tightens, the transport sector (and thus H₂) plays an increasing role in economy-wide decarbonisation (Table 48). Under less stringent constraints (GIS–C40), the power and industrial sectors combine with a decarbonisation of H₂ production to constitute the majority of reductions. Moving to GIS–C60 sees zero-carbon H₂ substituting for transportation fuels (combined with additional bio-fuels), while very stringent constraints (GIS–C80) see the electricity and residential sectors almost completely decarbonised.

Table 48. Sectoral CO₂ emissions in 2050 – alternate constraint cases
The spatial treatment gives nuanced findings on H2 deployment. In the reference case the spatial model focuses on lowest cost (and smaller) geographical infrastructures. In the CO2 constrained cases as competing costs of conventional fuels rise, H2 deployment is able to thrive by spatial matching of supply and demand. Crucially, clustering of demand centres to enable supply economies of scale. With both liquid H2 and large-scale gaseous H2 delivery infrastructures, the model seeks to cluster demands as far as possible in order to benefit from economies of scale in supply and distribution.

This modelling approach facilitates exploration of the wider energy systems impacts of spatial consideration of H2 networks, notably the size and changing generation mix of the electricity sector as it competes both for low-carbon resources and to meet a range of transport and buildings energy service demands.

3.30.3 Impacts of long term decarbonisation targets on the energy system (60% by 2050)

3.30.3.1 Uncertainties in key low carbon power technologies

The UK government’s economy-wide 60% CO2 reduction target by 2050 requires a paradigm shift in the whole energy system. Numerous analytical studies have concluded that the power sector is a critical contributor to a low carbon energy system, and electricity generation has dominated the policy discussion on UK decarbonisation scenarios. However, range of technical, social and market challenges, combined with alternate market investment strategies mean that large scale deployment of key classes of low carbon electricity technologies is fraught with uncertainty. The UK MARKAL energy systems model has been used (277) to investigate these long-term uncertainties in key electricity generation options.

Scenarios

This section describes two core scenarios via a business as usual (BS) and 60% CO2 reduction by 2050 (CS), and six variant scenarios.

- BS: A business as usual (Base) scenario includes legislated policy measures as of 2005 [1], including the projected uptake of conservation measures through 2020 [66], Climate Change Levy, electricity, and transport renewable obligations, EU-ETS and so on.
- CS: A low carbon energy system with 60% CO2 reduction by 2050 from the 1990 level. This CO2 constraint is applied across the entire energy system.

The low carbon scenario (CS) and other global modelling scenarios [40] identify the key power sector decarbonisation role for coal with CCS, nuclear generation and intermittent renewable technologies. Therefore, the following parametric sensitivities are performed to foresee the future energy system without these low carbon technologies.

- CS-T1: investments on CCS is restricted.
- CS-T2: investments on new build nuclear is restricted.
- CS-T3: investments on both CCS and new build nuclear are restricted.
- CS-T4: investments on CCS, new build nuclear and advanced renewable (e.g. off-shore wind, tidal and wave streams) are restricted.

Energy sector investments are undertaken with a range of risks including technology failure, volatile energy prices and regulatory barriers. One way to weight these risks and/or to represent transference of risks and barriers to the public sector, is with alternate discount factors. Therefore, the following two discount variants are also analysed in the CS scenario.

- CS-D3.5%: A low-risk (social rate) discount factor of 3.5% is implemented.
Results

Electricity generation mix in 2050 of the selected scenarios are compared in Figure 254. Figure 255 shows the sectoral share of CO₂ emissions in 2050. In the base case, total CO₂ emissions in 2050 are about 570 million t-CO₂ whereas they are only about 237 million t-CO₂ in the low carbon scenarios. Clearly from the base case to low carbon scenarios the power sector emissions significantly declines. The power sector accounts for 43% of the total emissions in the BS whereas it is only 7% in the CS scenario, both in terms of its percentage and absolute quantity. If hydrogen is not produced from electricity, which often occurs when CCS is unavailable or not cost effective (in CS-D15), transport sector emissions increase. In the absence of CCS emissions from the power sector declines (i.e. less residual emissions from CCS). This enables the transport sector to use conventional gasoline and diesel fuels, thereby leading to higher transport sector CO₂ emissions.

Figure 254. Electricity generation mix in 2050

With no major low-cost low carbon electricity generation technologies (CS-T3 and CS-T4) the decarbonisation pathways changes quite drastically. It transfers decarbonisation efforts to the buildings and transport sector. The latter is dominated by bio-fuels, including bio-kerosene for aviation. The service sector uses more heat (from gas-based CHP) for space heating thereby allowing gas to be used in power sector.

The role of the power sector is crucial in cost effective decarbonisation pathways which also enables decarbonisation of the transport sector. Both nuclear and CCS play a crucial role. If nuclear was to be dropped from the future electricity portfolio then 53 GW of CCS capacity should be in operation by 2050. On the other hand if CCS fails to reach market then the system requires 41 GW nuclear by 2050. However, uncertainties involved with assessing future costs of these two technologies are considerable and tipping point is very trivial.
3.30.3.2 Contribution of the residential sector in decarbonisation pathways

The UK residential sector accounts for around 30% of the total final energy use and more than one-quarter of CO₂ emissions. This paper (278) focuses on modelling of the residential sector in a system wide energy–economy models (UK MARKAL) and key UK sectoral housing stock models. The UK residential energy demand and CO₂ emission from the both approaches are compared. In an energy system with 60% economy-wide CO₂ reductions, the residential sector plays a commensurate role.

Scenarios

The scenarios and their variants are described below. For all these scenarios and its variants, sensitivity is performed without the residential conservation measures as they play a key role in CO₂ emission mitigation.

- **BASE**: A business as usual (BAU) case that assumes only UK legislated measures as of 2005, including the projected uptake of conservation measures through 2020 [42]. However no new future policies or measures would be enacted to reduce energy use or CO₂ emissions.
- **C-2030**: A low-carbon energy system with 60% CO₂ reduction by 2050 from the 2000 level. This constraint is applied across the entire energy system (not specific to the residential sector) with a 30% reduction in 2030 and linearly interpolated to 60% reduction in 2050.
- **C-SLT** is a straight line trajectory – a variant to C-2030, in which the 60% CO₂ constraint is implemented from 2010 and linearly extrapolated to 2050. Thus the difference between C-SLT and C-2030 is an early mitigation action and thus a higher cumulative emission in C-SLT.
- **C-2030R** is another variant focus on residential emissions. In C-2030R a second CO₂ 60% reduction constraint is imposed on residential sector direct emissions which is in addition to the economy wide CO₂ constraint in C-2030.
- **BASE-C, C-2030C, C-2030RC**: Sensitivities on the above runs, now without any residential conservation measures.

Results

Figure 256 shows share of sectoral final energy demand and CO₂ emissions for the BASE and C-2030 scenarios in 2050. For the residential and electricity sectors, their actual energy demand (in PJ) and CO₂
emissions (in Million tonnes (Mt-CO₂)) are also shown. The residential final energy use of 1962 PJ in the base year 2000 declines to 1848 PJ in C-2030 scenario. This is because of efficiency improvements including condensing boiler, uptake of conservation measures, etc. However, the share of residential energy in total final energy increase from 32% in 2000 to 34% in 2050. Figure 256 elucidates the sectoral tradeoffs in energy system models. For example, the share of residential energy in 2050 is increased to 34% compared to 32% in the base year 2000, while energy demand in transport sector declined due to use of hybrid cars. The residential sector direct emissions increase in the low carbon C-2030 scenario while the power sector is almost decarbonised.

Figure 256. Sectoral final energy demand and CO₂ emissions in 2050

The UK MARKAL scenario results are compared with residential building stock model scenarios. The results show the huge variations in energy demand projections which underpins the uncertainties in model assumptions. The stock models incorporate some behavioural aspects of energy demands but neither cost nor energy system tradeoffs are considered. On the other hand the whole system approach, e.g. model like MARKAL, addresses sectoral interactions more effectively, but is weaker in representing an individual housing stock. Therefore, a key challenge in energy system modelling is to find a balance between sectoral details versus depiction of entire energy system pathways.

3.30.4 Analysis with the UK MARKAL & MARKAL-Macro (M-M) energy systems model

3.30.4.1 Hybrid modeling for long-term CO₂ reduction scenarios: MARKAL-MACRO

This paper (279,280) summarizes the development of a new hybrid MARKAL– Macro (M–M) energy system model for the UK. This hybrid model maintains the technological and sectoral detail of a bottom-up optimisation approach with aggregated energy demand endogeneity and GDP impacts from a single sector neoclassical growth model. The UK M–M model was developed for underpinning analysis of the UK’s groundbreaking mandatory long-term ~60% CO₂ emissions reduction target.

Scenarios

An extensive set of 54 low-carbon scenarios were modelled with the UK M–M model for the UK Energy White Paper (DTI, 2007). Although these scenarios illustrate the breadth of drivers of long-term UK energy scenarios, they do not constitute a formal assessment of uncertainty. Instead this scenario set gives a systematic `what-if` analysis of long-term reductions in energy system CO₂ emissions; what the trade-offs are between different technology pathways, and what the costs might be.

Results

These concentrate firstly on the insights from the hybrid model. 60% reductions in CO₂ emissions entail radical changes in resource and infrastructure use, and investment in new technology portfolios. This is emphasized in Figure 257 which focuses on electricity generation in 2050 by major technology class. As these base-cases assume the absence of any future carbon price, electricity portfolios see an overall
growth dominated by next generation base-load coal plants, together with a limited expansion in renewable technologies due to falling costs and the policy driver of the Renewables Obligation (RO). Due to favourable natural gas economics in the low price gas, CCGT generation also plays a role in meeting intermediate electric capacity demands. Under CO₂ constrained scenarios, the less flexible MARKAL runs have the greatest expansion of zero-carbon electricity, which enables CO₂ reductions in the residential and service sectors. This is as end-use buildings sectors cannot reduce energy service demands through behavioural change, cannot meet a tight emissions constraint with direct (albeit high efficiency) use of natural gas, and cannot utilize biomass in direct applications (limited biomass capacity is utilized in the transport sector). Hence the additional flexibility of the M–M demand endogeneity has important energy systems consequences for reducing decarbonisation costs.

Focusing on the M–M sensitivity runs, the portfolio is dominated by coal CCS plants (limited by available UK cost-effective storage capacity) and new generation nuclear plants. Uncertainties in the future costs and characteristics of both new and nuclear technologies mean that it is impossible to robustly project that one technology is dominant. That the technology pathway evolution is inherently uncertain and path dependent is also illustrated in the SLT case, where the earlier CO₂ constraint results in far less nuclear capacity, with earlier emission reductions coming from more mature wind technologies and second generation bio-fuels in transport. When major zero-carbon electricity technologies are restricted, electricity generation declines, and without either nuclear or CCS the electricity portfolio transforms again to be dominated by offshore wind, supplemented by natural gas and bio-gas CCGT plants.

Figure 257. Electricity generation: 2050 comparison.

Figure 258 details GDP impacts for the six M–M CO₂ constraint scenarios, together with two additional scenarios that limit innovation across all technologies to 2020 or 2010 levels respectively. The central CO₂ constraint case gives an annual GDP reduction of 0.72% by 2050 (or £20.3 bn reduction from a projected UK GDP of £2807 bn). The full range of macroeconomic losses varies between 0.3% and 1.5% of GDP in 2050. The higher cost estimates are strongly influenced by more pessimistic assessments of future low-carbon technologies.

For UK policy makers an important message from this modelling exercise is that deep long-term CO₂ emission reductions are feasible. However, there are endemic uncertainties, notably a trade-off between behavioural and technological decarbonisation options with resultant energy system impacts in the requirements for zero-carbon electricity. However cost impacts from the UK M–M model are
likely to be in the lower range for stringent CO₂ reduction pathways as the simplicity of the reduced form macro-linkage omits competitiveness and transitional impacts on the UK economy.

Figure 258. UK M–M model — % change in GDP

3.30.4.2 Scenarios and sensitivities on long-term carbon reductions

This UKERC Research Report (281) encapsulates the final report for the DTI and DEFRA on the development of a new UK MARKAL & MARKAL-Macro (M-M) energy systems model. The focus of this final report is on the extensive range of UK 60% CO₂ abatement scenarios and sensitivity analysis run for analytical insights to underpin the 2007 Energy White Paper. Model development (enabled through the energy systems modelling theme of the UK Energy Research Centre (UKERC)) is summarised, notably the range of enhancements to improve UK MARKAL’s functionality and analytical sophistication. A major component of the development work was the integration of MARKAL with a neoclassical growth model (MARKAL-Macro), to facilitate direct calculation of macro-economic impacts from changes in the energy sector as well as endogenous behavioural change in energy service demands.

Scenarios

Results focus on a selected set of MARKAL-Macro (M-M) model scenarios, utilizing an integrated set of UKERC assumptions and data:

- Base-case, CO₂ emissions in 2050 constrained to 60% of 2000 levels (C-60), and alternate CO₂ emission trajectory (SLT) implemented linearly from 2010;
- Resource import (high and low) price scenarios, from DTI projections;
- Technology scenarios: restricted innovation (limited to either 2020 or further to 2010 levels of improvement), no-nuclear, no-CCS or no-nuclear / CCS scenarios.

In all, over 50 full scenarios sets were run for this project. Results from additional scenario runs (including standard model runs) are used to further discuss key tradeoffs between mitigation pathways.

Results

In general for the CO₂ constrained scenarios, all upstream and end-use sectors contribute to the stringent 60% reduction target (from a 2050 base-case projection of 596 MtCO₂ to 218 MtCO₂). As illustrated in Figure 259 for the core CO₂ constrained case, the electricity sector is a major source of carbon reductions, complimented by fuel switching, efficiency conservation measures and demand reductions in the end-use sectors. The small increase in 2020 is a reflection of the model utilising existing carbon intensive capital before the constraint is implemented.
One of the main strengths of UK M-M is a detailed depiction of the technologies used to deliver the energy requirements of different sectors. A 60% reduction in UK CO₂ emissions entails radical changes in resource and infrastructure use, and investment in new technology portfolios. When innovation is limited or major zero-carbon electricity technologies are restricted from the solution (e.g. nuclear and CCS) electricity generation declines (Figure 260). Without either nuclear or CCS the electricity portfolio transforms again to be dominated by offshore wind, supplemented by higher costs renewables (including marine) with base-load requirements met using natural gas and bio-gas CCGT plants. Note that large shares (up to 61% in the no-CCS no nuclear cases) of UK electricity generation by (intermittent) wind necessitates a very large expansion of offshore wind capacity and remote electricity infrastructure.

The central undiscounted abatement cost (C-60) in 2050 is £B8.8 with a low estimate of £B2.1 if all optimistic technological assumptions are employed and a high estimate of £B19.8 if innovation is restricted to 2010 levels. Similar to average CO₂ prices, negative costs in 2025-2035 are a reflection of cost effective conservation options in the residential, services and industrial sectors, enabled through additional policies to address information barriers and other market barriers.

As noted earlier, there is a relatively low energy system growth vs. growth rates of the rest of economy. Figure 261 illustrates base-case GDP growth (on the right hand axis) and energy system cost growth (on
the left hand axis) for the resource case sensitivities (which show the most base-case variation). Base case GDP rises (in £2000) from around £1 trillion in 2000 to £2.8 trillion in 2050 with a much more modest growth in energy systems costs (with differences due to the diverging price of imported energy resources). This faster economic growth combined with improved energy intensity/efficiency leads to the energy sector’s contribution to GDP falling from around 9% in 2000 to 5.5% in 2050.

Figure 261. Base-case GDP and energy system cost trends – resource scenarios

![Base GDP and Energy costs - Resource price sensitivities](image)

The higher cost estimates are strongly influenced by more pessimistic assessments of future low carbon technologies. Energy system trade-offs are pervasive under alternate assumption sets. These trade-offs illustrate endemic uncertainties in future resources, infrastructures, technologies and behaviour.

### 3.30.4.3 The iterative contribution and relevance of modelling to energy policy

This paper (282) discusses the iterative provision of modelling insights on long-term decarbonisation scenarios for UK energy policymakers. A multi-year model construction process of the UK MARKAL-Macro-hybrid energy-economic model, and four subsequent major policy analyses illustrates the scope of this interaction. This paper analyses the large number of long-term UK CO2 reduction scenarios through a clustering approach on target stringency and barriers to implementation.

#### Scenarios

To better assess the insights (notably on the robustness of main findings and on key uncertainties) that the range of M-M model runs provided policymakers. This paper clusters the model runs based on two axes: Axis X focuses on the stringency of the 2050 CO2 reduction target (60% vs. 80%). Axis Y reflects the barriers to uptake of abatement options (fewer vs. increasing). Figure 262 provides an indication of the main sensitivity run assumptions and the clusters in which they belong.

Figure 262. Clustering approach to UK M-Mmodel runs.

<table>
<thead>
<tr>
<th>Cluster 1 (60%, &lt; barriers)</th>
<th>Cluster 2 (80%, &lt; barriers)</th>
</tr>
</thead>
<tbody>
<tr>
<td>60% reduction, fewer barriers</td>
<td>80% reduction, fewer barriers</td>
</tr>
<tr>
<td>Central case, Alternative trajectory, DTI assumptions, Low / high energy prices, Lower ESI costs</td>
<td>Central case, Alternative trajectory, BER assumptions, Low / high energy prices, Overseas credits available</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cluster 3 (60%, &gt; barriers)</th>
<th>Cluster 4 (80%, &gt; barriers)</th>
</tr>
</thead>
<tbody>
<tr>
<td>60% reduction, increasing barriers</td>
<td>80% reduction, increasing barriers</td>
</tr>
<tr>
<td>No new nuclear, No new nuclear / CCS, Restricted innovation to 2010 / 2020 levels, Higher ESI costs</td>
<td>No nuclear, no nuclear / CCS, Restricted innovation to 2010 / 2020 levels, Biomass constraints, International aviation included</td>
</tr>
</tbody>
</table>
Results

Figure 263 illustrates the breakdown of CO₂ emissions by sector in 2050 under various 80% reduction target runs (with increasing barriers). An interesting observation is that electricity emissions remain low irrespective of which low carbon options are restricted. This reflects an optimistic view of the substitutability of generation from nuclear, CCS or large scale renewables (particularly wind). However, the ability to scale up the production of low-carbon electricity under increased barrier cases, impacts the scope of reduction available in other sectors (e.g., transport) and required additional end-use effort (e.g., residential sector switch from gas to electricity). The resource constraint cases typically results in a higher level of emissions from the transport sector and/or increased hydrogen use, primarily through restrictions on bio-fuels and more expensive electricity for transport. In the restricted innovation cases, restrictions on all advanced technologies or energy chains (e.g., hydrogen) result in a very different energy mix including increased residual industrial CO₂ emissions.

Figure 263. Average % CO₂ emissions by sector for selected 80% reduction cases, 2050.

The M-M model, as a general equilibrium formulation of MARKAL, provides impacts of increasing energy system costs on GDP (Figure 264). Under the 60% reduction clusters, the impact on GDP is 0.7–1.1% reductions in 2050, whilst higher reduction target clusters lead to between 1.5% and 2.0% reductions in 2050.

Figure 264. Average % annual change in GDP (2000–2050) by cluster

This clustering approach illustrates that as the stringency of the decarbonisation target increases (from a 60% to a 80% reduction by 2050), decarbonisation efforts and hence emissions and GDP costs rise sharply. Additionally, as averaged cost levels increase, the uncertainties in the type and impact of new energy system configuration are also much greater. When increasing barriers are put in place to the
optimal development of a low carbon energy system, a nuanced description emerges on the interplay between different sectors, resources, infrastructures and technology vs. behavioural responses.

Within the scenarios, the key robust insights are firstly that all sectors contribute to mitigation efforts, underscoring the value of an energy systems approach to investigate trade-offs between resources and infrastructures and between technology vs. behavioural responses. However, this modelling suggests that overall economic impacts by 2050 may not be cost prohibitive even for an 80% CO2 reduction at between 1.5% and 2.0% of GDP, although again with the possibility of higher impacts (up to 3.2%).

3.30.5 Long-term scenarios for low carbon societies

Under the Japan-UK research project ‘Low-Carbon Society (LCS) Scenarios Towards 2050’, an international modelling comparison (283,284) was undertaken by nine national teams, with a strong developing-country focus. Core model runs were a Base case, a Carbon price case (rising to 100/tCO2 by 2050) and a Carbon-plus case to investigate an LCS scenario with a 50% reduction in global CO2 emissions by 2050. The comparison emphasis was to focus on individual model strengths (notably technological change, international emissions trading, non-price (sustainable development) mechanisms and behavioural change) rather than a common integrated assumption set. A complex picture of long-term LCS scenarios comes from the range of model types and geographical scale (global vs. national); however, common themes for policy makers do emerge.

A core finding is that LCS scenarios are technologically feasible. However, preferred pathways require clear and early target setting and incorporation of emissions targets across all economic activities. This will probably entail significant socio-economic changes. To realize major LCS transitions requires sustained progress in R&D and deployment of a broad range of technologies, with CCS a key technology in most low-carbon portfolios. Developing countries, in particular, face an immense challenge to achieve LCS in light of their economic growth requirements. As such, international cooperation is required in iterative and flexible burden sharing under international emissions trading regimes.

In the same context, an integrated set of low-carbon society (LCS) scenarios for the UK were analysed using the UK MARKAL Macro (M-M) model (285). A $100/tCO2 carbon price scenario was compared with long-term LCS scenarios with a domestic 80% CO2 reduction target. As M-M is a national-level model, a set of international drivers were investigated, and grouped under Annex 1 consensus and Global consensus assumption sets. For economy-wide results the inclusion of international aviation and potential large-scale purchases of CO2 permits (when available) are most important. For sectoral implications, all international drivers considered here are important; for example in divergent overall size and configuration of the UK electricity sector. The carbon price scenario and set of 80% targets scenarios dive GDP losses rising from 0.36% to a range of 1.64%-2.21% in 2050. This steep cost convexity in deep CO2 reductions represents increasing efforts to decarbonize the UK energy system, and the further impact of key international drivers. This illustrative analysis demonstrates that UK policy makers should be cognisant of, and flexible with respect to, international strategies on LCS and emission reduction targets.

3.30.6 Impacts of long term decarbonisation targets on the energy system (80% by 2050)

The UK set itself a groundbreaking climate change mitigation policy with the publication of a long-term national CO2 reduction target (initially set at -60% by 2050) (286). Over the last decade, achieving this landmark target has generated intense discussion on alternate technology pathways, behavioural implications and sectoral and economy-wide costs. However, new evidence strengthening the science of global climate change, a high profile review of the costs and benefits of mitigation and progress under the G8 Gleneagles Dialogue on the goal of achieving at least 50% reductions in global emissions by 2050, has reinforced policy resolve to decarbonise the UK economy. The UK CO2 reduction target has been strengthened to an 80% reduction (relative to 1990 levels), has become legally binding through the Climate Change Bill, and a series of carbon budgets to guide iterative decision making has been established through the creation of the independent Committee on Climate Change (CCC).
3.30.6.1 Building a low carbon economy

Ensuring action will require strong leadership from government and a concerted response from individuals and businesses. It will require policy commitment to cutting emissions steadily over time, sticking on the path to an 80% reduction, and reacting to any diversion with new policies to get back on track. The UK’s Climate Change Act makes that commitment, establishing a system of five year “carbon budgets”. The Committee on Climate Change is charged with recommending the level of those budgets. In this our first report (287,288), we begin by explaining why the UK should aim for an 80% reduction by 2050 and how that is attainable, and we then recommend the first three budgets that will define the path to 2022.

Scenarios

We have therefore used MARKAL to model the feasibility and the costs of scenarios for both 80% and 90% cuts in UK energy and industrial process CO₂ emissions. The 80% scenario represents a situation in which non-CO₂ and International Aviation and Shipping are able to contribute their full share to achieving the 80% overall target, while the 90% scenario represents a situation in which less can be achieved in these other sectors.

Results

Both the 80% reduction case (Figure 265) and the 90% alternative illustrate the pattern which might be implied by the technology options available. In both scenarios the most dramatic early reduction occurs via the decarbonisation of electricity generation, which needs to be close to complete by 2030, with g/kWh below 70 by 2030 in the 80% scenario and below 40 in the 90% scenario, falling further to 35 and 20 respectively by 2050. Important early progress is also made in the residential sector via improvements in home insulation and improved efficiency of electrical appliances, lighting and ICT, and in the transport sector via the rapid improvements in the fuel efficiency of petrol and diesel vehicles.

From the 2020s onwards, decarbonised electricity is increasingly used to drive further significant abatement in the car and light van subsectors of transport (via plug-in hybrid and battery electric vehicles) and in residential heat-related emissions.

Figure 265. UK sectoral CO₂ emissions to 2050 on an 80% emissions reduction path

The model also enables us to consider what might happen if key technologies were not available or if society chose not to deploy them. CCS is currently not a proven technology at full commercial scale. If it were unavailable at reasonable cost, the MARKAL model suggests that a huge expansion of nuclear power would be the least-cost option, but that renewables would also need to expand to 30% of supply by 2025 (Figure 266). If nuclear as well as CCS were not available, the model suggests that 80% or even
90% reductions would still be attainable, but at substantial additional cost, and with greater energy demand reduction (either price-induced or via life-style change).

**Figure 266. Proportion of electricity generation coming from renewable sources under different scenarios**

MARKAL modelling suggests that a reduction of 80% or more in domestic CO₂ emissions is feasible at manageable economic cost, even if no international emissions trading is possible. The analysis suggests that a reduction of 80% to 90% in domestic CO₂ emissions by 2050 might reduce 2050 GDP by between 1% and 1.5% versus the MARKAL reference case. These estimated costs do not increase significantly if CCS is not available, with the model assuming that cost-competitive nuclear power can expand instead. But the costs do increase significantly if neither CCS or nuclear are available, reaching 2% of GDP in the 80% target case, but 3% in the 90% case.

### 3.30.6.2 Implications of renewable and climate change policy on energy scenarios

A second key UK energy policy is to increase the share of final energy consumption from renewables sources to 15% by 2020, as part of the wider EU Renewable Directive. The UK’s principle mechanisms to meet this renewable target are the Renewable Obligation (RO) in the electricity sector, the Renewable Transport Fuel Obligation (RTFO), and most recently the Renewable Heat Programme (RHP) for buildings. This study (289,290) quantifies a range of policies, energy pathways, and sectoral trade-offs when combining mid- and long-term UK renewables and CO₂ reduction policies.

**Scenarios**

This paper undertakes exploratory analysis of the interactions of intermediate renewable policy (RO, RTFO, and RHP) on long-term carbon reduction targets for the UK. Specifically four core scenarios are discussed:

- **Reference Scenario (RS):** No CO₂ constraint. RO and RTFO are kept at current policy levels of 15 and 5% of electricity generation or transport final energy from 2015.

- **Low Carbon Scenario (LCS):** Relative to 1990 levels, CO₂ emissions are reduced by 26% in 2020, and linearly tightened to 80% in 2050. All other conditions are the same as the RS.

- **Renewable Policy Scenarios (RPS):** By 2020, the RO has been increased (in steps of 5%)—from 15% (the RS value) up to a 50% share. (Note the RO of 45 and 50% are applied from 2035). By 2020, the RTFO has been increased (in steps of 5%)—from 5% (the RS share) up to a 20% share. Renewable Heat Programme (RHP) is set at 12% from 2020. All other conditions are the same as the RS.
a. RO only cases are included;
b. RO and RTFO only cases are included; and
c. RO, RTFO, and RHP cases are included

- Low Carbon Renewable Scenarios (LCRS): combinations of LCS and RPS.
  a. RO only cases are included;
b. RO and RTFO only cases are included; and
c. RO, RTFO, and RHP cases are included

Results

Under the low carbon scenario (LCS), decarbonisation is foremost in the power sector till the middle or end of the projection period (Figure 267). Then major efforts switch to the residential/ transport/service sectors. In 2020, the early decarbonisation requirements of the electricity sector are achieved by replacing coal plants with coal-CCS plants, supplemented by nuclear by 2050. Renewable electricity is again limited, and is not invested in beyond the minimum RO-15% share.

As a significant share of end-use sector decarbonisation is achieved by shifting to electricity (plug-in hybrid vehicles and electric boilers/heat pumps in buildings), demand for electricity by 2050 is higher in the LCS (2071 PJ) than that in the RS (1583 PJ). Beside technology switching and efficiency improvements, uptake of energy saving conservation measures in the near-term (especially through 2020) and price driven demand responses in the long terms and major contributors to decarbonisation under LCS. Demand reduction levels are dependent on elasticities and the availability of technical substitutes, and in 2050 vary from 5% for car demands to 30% for industry and residential sector energy services demands. Long-term climate change policy does not meet the intermediate EU target of 15% renewable energy in UK final consumption.

Figure 267. Sectoral CO₂ emissions in LCS during 2000–2050

A better metric is societal welfare losses to meet the climate change targets and renewable policies. Figure 268 presents the CO₂ emissions versus annual welfare cost in the RS, LCS ,RPS, and LCRS in 2020. CO₂ emissions in 2020 in the RS case are 495 MtCO₂. A 26% reduction from 1990 levels gives a value of 432 MtCO₂ in the LCS, and this binding constraint is seen in the vertical line of LCRS runs that do not meet renewable targets.

The shaded area shows the scenarios that meet both the EU renewable directive and climate change target in 2020. In the LCRS, among the scenarios that meet the EU directive, the welfare cost is lowest (£B5.3) at RO-40, RTFO-5, and RHP-12 followed by RO-25, RTFO-15, and RHP-12 (£B5.7); and RO-35, RTFO-10, and RHP-12 (£B5.8). More generally there is a linear relationship between falling CO₂ emissions and increasing welfare costs, with differences driven by interactions between renewable policies. In 2050, much higher annual costs are required to meet the binding constraint of 80% reductions in CO₂ emissions, which for LCS is £B 44.0 (in 2000 prices).
Combining both policies in the LCRS, if the 15% UK renewable target is met, this is the binding constraint in 2020. The lowest requirement to meet both the EU renewable directive and climate change target is an RO of 20%, an RTFO of 20%, and an RHP of 12%. Welfare costs in 2020 are generally linearly increasing with decreasing CO₂ emissions. However, interactions between renewable policies and CO₂ policies can drive costs much higher in the mid-term. Looking further out to 2050, the CO₂ reduction constraint is the binding driver for all scenarios, and entails much higher welfare costs (around £B44.0). A similar pattern of power-transport and electricity–biofuel–natural gas trade-offs occur as in the RPS scenarios.

### 3.30.6.3 Failure to meet long-term UK carbon reduction targets

The UK was the first G20 country to legislate a GHG reduction targets (of at least -34% by 2020 and -80% by 2050, relative to a 1990 baseline). This paper (291) investigates this dichotomy between the UK policy priority in reducing energy-related CO₂ emissions, and concerns over the feasibility, costs and achievability in meeting this unprecedented change in energy production and use. To systematically investigate failure to achieve long-term CO₂ targets, this paper utilises the UK MARKAL model.

#### Scenarios

In the discussion on failure scenarios, the following definitions of a “failed scenario” are utilised:

- Does not meet CO₂ reduction targets (in practice the model backstop emissions reductions option (£5,000/tCO₂) is triggered in order that the model still solves).
- Meets CO₂ target but still at excessive costs (marginal price and welfare loss).
- Meets CO₂ target but with reliance on uncertain model elements with little empirical basis.

The initial results and discussion focus on the first two elements – build rates and resource imports.

#### Results

In an initial set of results, the focus is on a CO₂ reduction of 90% in 2050, reflecting the additional role of CO₂ emissions outside the UK energy system (e.g. bunker fuels) and the retention of non-CO₂ GHGs in agriculture and other sectors. It is important to note there is a generic capacity for scenario failure in all models, through potentially unrealistic outputs generated by that model. For example, Figure 269 illustrates the annual investments in the UK power sector (current size 84GW) in an optimal UK MARKAL run with no build rate constraints. As new vintages of plants become available (via global R&D, global learning rates and international supply chains), and as CO₂ targets tighten (leading to an expansion of zero emission power production.)
Figure 269. Unconstrained annual build rates (GW) in the power sector under a CO2-90% case

Focusing on the cross cutting modes for failure scenarios, the remaining outputs are for combinations of imposed build rates and imported fuel restrictions. Build rates on large capital investments – coal, gas, CCS plants, wind (on- off-shore), nuclear, marine (tidal & wave), distributed generation. Build rates per technology class are (until 2030) 1GW pa, and (from 2030) 2GW pa. Comparing to a reference case with no carbon constraint, the model runs are given in Table 49.

Table 49. Build rate and import constraint combination scenarios

<table>
<thead>
<tr>
<th>Scenario name</th>
<th>CO2 constraint by 2050</th>
<th>Build rates imposed</th>
<th>Fossil fuel prices</th>
<th>Biomass imports</th>
<th>Hydrogen imports</th>
</tr>
</thead>
<tbody>
<tr>
<td>REF</td>
<td>No</td>
<td>Yes</td>
<td>Central</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>C90</td>
<td>Yes</td>
<td>Yes</td>
<td>Central</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>C90-LF</td>
<td>Yes</td>
<td>Yes</td>
<td>Low</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>C90-LFB</td>
<td>Yes</td>
<td>Yes</td>
<td>Low</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>C90-LFBH</td>
<td>Yes</td>
<td>Yes</td>
<td>Low</td>
<td>No</td>
<td>No</td>
</tr>
</tbody>
</table>

It is unsurprising that meeting a 90% reduction in UK CO2 emission produces a radically different portfolio of technologies, infrastructure and behaviour change, as seen in comparing the REF to C90 scenario’s primary energy. A major component of this change is the C90 scenario is the deployment of cofiring CCS and biomass CCS. In terms of costs, the most restrictive scenarios (C90-LFB, C90-LFBH) essentially fail, and would not solve without the existence of a placeholder backstop technology at the very high price of £5000/tCO2. This suggest that the role of imported sustainable biomass for the UK is critical if it is to meet stringent CO2 targets.

Some scenario assumptions can benefit the UK, such as lowered global fossil fuel prices (due to declining global demand) that in the medium term at least outweigh the welfare costs of decarbonisation (Figure 270). However this effect is short-lived and by 2050 UK welfare losses range from £23.8 billion to £58.7 billion. Although these annual amounts should be taken in context of an overall UK economy that should be three times larger than its current size (to around £3 trillion), this is still a very significant cost and could cause this scenario to fail due to societal and business opposition.

Figure 270. Annual welfare costs (£ billion)
By focusing on common mode failures and modelling the long-term impacts, it is relatively easy to trigger the failure criteria: that there is no viable solution, that the solution is deemed too expensive, or that the solution is based on one or more embryonic supply options or fundamental changes in energy service demands.

3.30.6.4 Uncertainty under stringent UK decarbonisation targets (80% by 2050)

This paper (292) describes ongoing energy-economic modelling that seeks to better characterize uncertainties in long term UK decarbonisation transition pathways, specifically recognizing the iterative characterisation of UK decision making and the inherent nature of uncertainties in key UK and global assumptions that may only be resolved through time. A major 2009 update for this paper has been the establishment of a global region to facilitate analysis of uncertainties not being able to be impacted by UK decision makers. These include international resources prices (fossil, uranium, biomass), rates on innovation and learning on key low carbon energy technologies, CO₂ emission markets, and inclusion of emission from international aviation and shipping.

The legally binding UK GHG emissions targets were in part derived using deterministic variants of UK MARKAL. UCL, under UKERC, has developed a new two-stage stochastic variant, which provides additional near-term insights for policy makers under future uncertainties. In this paper (292,293,294), the use of cumulative CO₂ targets, equivalent to 80% and 90% reductions by 2050 allow comparison between current UK policy and the modelled results.

Scenarios

The analysis extrapolated two GHG reduction strategies for the UK, modelled in this study. It is therefore unlikely that the UK CO₂ emissions reduction target can be less than 80%, especially given the legal weight of the target. However, it may be necessary to increase the ambition of the GHG emission target to 90% or more by 2050. The uncertainties that contribute to whether a further reduction will be necessary are as follows:

- i. Considerable uncertainty surrounding the quantity of abatement possible in non-CO₂ gases beyond 2020, especially in the agricultural sector;
- ii. Considerable uncertainties in the measurement of non-CO₂ gases;
- iii. Global near-term emissions are more than expected;
- iv. Sectors not yet covered by policy e.g. international aviation grow, above forecast levels.

Results

Figure 271 shows the CO₂ emissions from 2 deterministic cumulative emission scenarios equivalent to 29/80 and 29/90 scenarios. The blue lines represent the stochastic scenario, while green lines the deterministic scenarios. Prior to 2020, the single blue line represents the stochastic hedging strategy, while there are two least-cost trajectories for the deterministic scenarios. The model takes significant early action to address the more stringent 29/90 equivalent target. Note that despite the equal probability weighting assigned to each of the future scenarios, the hedging strategy lies significantly lower than the average, only slightly above the deterministic 29/90 trajectory. This indicates the dominance of the extra cost of increasing the stringency of the cumulative emissions target.

The stochastic scenario also demonstrates the trade off between periods resulting from the hedging strategy. For example, if in 2020, uncertainty over emissions reveals that a move to the more stringent scenario is not necessary, the model leads to an increase in CO₂ emissions in the recourse strategy over the 29/80CUM deterministic scenario due. In contrast, if the move to the more stringent scenario is necessary, the hedge means that only minor extra effort is necessary.
Figure 271. A stochastic and deterministic scenario with cumulative emissions equivalent to 29/80 and 29/90

By varying the probability weightings assigned to the future states of the world, it is possible to view the response of the model under different levels of uncertainty. For example, when the modeller assigns a 90% weighting in favour of the 29/80 scenario, the model makes a smaller hedge towards the 29/90 scenario. If this assessment is incorrect and the 29/90 scenario is instead required, the energy system must then decarbonise more steeply in the recourse strategy. Figure 272 shows the inter-temporal trade-offs made across the full range of weightings.

Figure 272 Results over a range of weightings applied to the future states of the world

The model showed that, under equal weighting of the outcomes, an optimum near-term investment strategy (i.e. one that minimises expected cost of the scenario and assumes a risk neutral investor) lies very close to the severe 29/90 equivalent decarbonisation pathway. This is equivalent to a 40% reduction in CO2 on 1990 levels by 2020. The cost of this hedging strategy (EVPI) is around £1.3B.

Under uncertain future cumulative CO2 emission targets, the cost of the hedging strategy is related asymmetrically to the weighting of future scenarios. When the cumulative CO2 targets are equally weighted, the near-term investment strategy lies close to that of the deterministic 90% CO2 target. This indicates that steep near-term decarbonisation is important given exponentially rising cumulative welfare costs with increasingly stringent cumulative emission targets.

3.30.7 Analysis with the UK MARKAL elastic demand (MED) model

3.30.7.1 Pathways to a low carbon economy

This report (295,296,297,298,299) is the first in the UKERC Energy 2050 project series. It focuses on a range of low carbon scenarios underpinned by energy systems analysis using the newly developed and updated UK MARKAL elastic demand (MED) model. Subsequent UKERC Energy 2050 reports focus on a broad scope of sensitivity analysis to investigate alternative scenarios of energy system evolution.
**Scenarios**

A first set of scenarios (CFH, CLC, CAM, CSAM), focus on carbon ambition levels of CO₂ reductions (in 2050) ranging from 40% to 90% reductions. These runs also have intermediate (2020) targets of 15% to 32% reductions by 2020 (from the 1990 base year). These scenarios investigate increasingly stringent targets and the ordering of technologies, behavioural change and policy measures to meet these targets. A second set of scenarios (CEA, CCP, CCSP) undertake sensitivities around 80% CO₂ reductions with cumulative CO₂ emission targets, notably focusing on early action and different discount rates. Together with a base reference case, all seven decarbonisation scenarios are detailed below in Table 50.

**Table 50. Carbon pathway scenarios**

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Scenario name</th>
<th>Annual targets (reduction)</th>
<th>Cumulative targets</th>
<th>Cum. emissions GTCO₂ (2000-2050)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>Base reference</td>
<td>-</td>
<td>-</td>
<td>30.03</td>
</tr>
<tr>
<td>CFH</td>
<td>Faint-heart</td>
<td>15% by 2020</td>
<td>-</td>
<td>25.67</td>
</tr>
<tr>
<td>CLC</td>
<td>Low carbon</td>
<td>26% by 2020</td>
<td>-</td>
<td>22.46</td>
</tr>
<tr>
<td>CAM</td>
<td>Ambition</td>
<td>26% by 2020</td>
<td>-</td>
<td>20.39</td>
</tr>
<tr>
<td>CSAM</td>
<td>Super Ambition</td>
<td>32% by 2020</td>
<td>-</td>
<td>17.98</td>
</tr>
<tr>
<td>CEA</td>
<td>Early action</td>
<td>32% by 2020</td>
<td>-</td>
<td>19.24</td>
</tr>
<tr>
<td>CCP</td>
<td>Least cost</td>
<td>80% post 2050</td>
<td>Budget (2010-2050) similar to CEA</td>
<td>19.24</td>
</tr>
<tr>
<td>CCSP</td>
<td>Socially optimal least cost</td>
<td>80% post 2050</td>
<td>Budget (2010-2050) similar to CEA</td>
<td>19.24</td>
</tr>
</tbody>
</table>

**Results**

If no new policies/measures are enacted, energy related CO₂ emissions (in the Base Reference Scenario, B) in 2050 would be 584 MtCO₂, which is 6% higher than the 2000 emission level and only 1% lower than the 1990 emission level. Existing policies and technologies would bring down the emissions in 2020 to about 500 MtCO₂ achieving over 15% reductions, which falls well short of the minimum government target of a 26% reduction.

For the CO₂ mitigation scenarios where annual emissions constraints are not imposed (CCP and CCSP), these two scenarios choose the optimal emissions path with the cumulative emissions level as CEA (Figure 273). As expected, UK MARKAL MED results shows later action for the CCP run as the model tries to delay reductions as far as possible (owing to the 10% discount rate and hence lower costs assigned to reductions in later periods). For the CCSP run (at 3.5% discounting), the model undertakes earlier decarbonisation as the overall objective function now gives more weight to costs imposed later in the time horizon. As CCSP focuses on earlier emission reductions it requires a reduction of only 70% in 2050. On the other hand, the CCP run suggests that the UK can go beyond an 80% target in 2050 as its later action cuts UK emissions by 89% in 2050. The flexibility offered by the cumulative constraint rather than imposed annual reductions is reflected by a slightly lower discounted system cost in CCP, about £700 million lower than in CEA (with the same cumulative emissions).

In the Base B, electricity generation increases by 24% during 2000-2050 to meet continuously increasing electricity demand in the end-use sectors. Over two thirds of total electricity generation comes from fossil fuels (coal and gas) in the base reference case in 2020. Electricity generation mixes under B, CFH, CLC, CAM and CSAM are shown in Figure 274 for selected years 2035 and 2050. As decarbonisation efforts tighten through 2050, end-use sectors shifting to electricity leads to relatively high demand for electricity, which has to be generated from low carbon sources. Hence there is a trade off between the decarbonisation of end-use sectors by shifting to electricity, and both efficiency improvements and demand reductions affect the overall demand for electricity.
The marginal emission prices rise as the annual CO₂ constraint tightens across scenarios and through time. In 2035 marginal CO₂ prices rise from £13/tCO₂ in CFH to £133/tCO₂ in CSAM, and by 2050 this range is £20/tCO₂ to £300/tCO₂. This convexity illustrates the difficulty of achieving very deep CO₂ reductions.

Demand reduction is one of the preferred options to reduce CO₂ emissions, notwithstanding the societal loss in utility due to the demand reduction. Demand reduction levels for selected sectors and transport energy service demands under different scenarios in 2050 are shown in For dynamic path dependence in decarbonisation pathways, we focus next on the range of sensitivity runs with the same cumulative CO₂ emissions. Under a cumulative constraint (CCP) the model chooses to delay mitigation options, with this later action resulting in CO₂ reductions of 32% in 2020 and up to 89% in 2050. This results in very high marginal CO₂ costs in 2050, at £360/tCO₂ higher even than the constrained 90% reduction case. Conversely, a cumulative constraint with a lowered (social) discount rate (CCSP) gives more weight to later costs and hence decarbonises earlier - with CO₂ reductions of 39% in 2020 and only 70% in 2050. Similar to the early action case (CEA), this CCSP focus on early action gives radically different technology and behavioural solutions. In particular, effort is placed on different sectors (transport instead of power), different resources (wind as early nuclear technologies are less cost competitive), and increased near-term demand reductions.
Figure 275 (full demand reduction tables are in Appendices A1 and A2). Demand reduction levels are relatively higher in 2050 than in 2035 as the CO2 reduction constraint is tighter. Agriculture, industry, residential and international shipping have higher demand reductions than the air, car and HGV (heavy good vehicles) transport sectors.

Welfare costs (sum of producer and consumer surplus) in 2050 range from £5 - £52 billion. In particular moving from a 60% to an 80% reduction scenario almost doubles welfare costs (from £20 - £39 billion).

For dynamic path dependence in decarbonisation pathways, we focus next on the range of sensitivity runs with the same cumulative CO2 emissions. Under a cumulative constraint (CCP) the model chooses to delay mitigation options, with this later action resulting in CO2 reductions of 32% in 2020 and up to 89% in 2050. This results in very high marginal CO2 costs in 2050, at £360/tCO2 higher even than the constrained 90% reduction case. Conversely, a cumulative constraint with a lowered (social) discount rate (CCSP) gives more weight to later costs and hence decarbonises earlier - with CO2 reductions of 39% in 2020 and only 70% in 2050. Similar to the early action case (CEA), this CCSP focus on early action gives radically different technology and behavioural solutions. In particular, effort is placed on different sectors (transport instead of power), different resources (wind as early nuclear technologies are less cost competitive), and increased near-term demand reductions.

Figure 275. Selected demand reduction level in 2050 under different scenarios

3.30.7.2 Developing transition pathways for a low carbon electricity system in the UK

This paper (300) describes the approach to developing transition pathways for a low carbon electricity system in the UK, being pursued in a major new inter-disciplinary research project. The project aims (a) to learn from past transitions to help explore future transitions and what might enable or avoid them; (b) to design and evaluate transition pathways towards alternative socio-technical energy systems and infrastructures for a low carbon future; and (c) to understand and, where appropriate, model the changing roles, influences and opportunities of large and small ‘actors’ in the dynamics of transitions.

The paper describes the approach, which builds on the work of Dutch researchers on transitions and transition management using a multi-level framework of niches, socio-technical regime and landscape, as well as on other parts of the innovation systems literature. It also describes its application to several outline transition pathways to a low carbon energy system in the UK.

3.30.7.3 Modelling a resilient energy scenario in the Elastic Demand (MED) version

Climate change and energy security have come to dominate the energy policy agenda. Concerns about energy security in the UK have been driven by the loss of self-sufficiency in oil and natural gas and a growing dependency on imports. This report (301) explores ways of enhancing the “resilience” of the UK energy system to withstand external shocks and examines how such measures interact with those designed to reduce CO2 emissions. The concept of resilience explored and a set of “indicators” is developed to define quantitatively the characteristics of a resilient energy system. In the report we systematically test the response of the UK energy system under different scenarios to hypothetical shocks. We have used three energy models to conduct this analysis.
• The first is the MARKALMED model, a linear optimisation model which covers the entire UK energy system and can address interactions between different parts of the energy system.

• The second is the WASP electricity generation planning model originally developed by the International Atomic Energy Agency (IAEA). The WASP model is fed electricity demand assumptions from MARKAL-MED.

• The third model is the geographically explicit Combined Gas and Electricity Networks (CGEN) model which is used to assess where electricity generation capacity should be located and how much gas and electricity infrastructure should be constructed. It is fed results from both MARKAL-MED and WASP.

A Reference scenario which assumes no policy measures other than those contained in the 2007 Energy White Paper is the starting point. Under the Low Carbon scenario, CO₂ emissions are constrained so that they fall 36% below 1990 levels by 2025 and 80% by 2050. Our Resilient scenario embodies a number of constraints that enhance the ability of the energy system to withstand shocks, but has no CO₂ constraints.

3.30.7.4 Approaches in modelling a resilient energy scenario

Under the UK Energy Research Centre (UKERC) Energy 2050 project, four core scenario analyses have been undertaken to explore the pathways to a low carbon and resilient energy system. A resilience energy system is defined as the set of technologies, physical infrastructure, institutions, policies and practices located in and associated with the UK which enable energy services to be delivered to UK consumers. Within the analytical framework of the UK MARKAL elastic demand (MED) model (302), the resilient energy system has been characterised through diversity in energy supply and reducing the final energy demand. A set of user-defined constraints have been chosen to model the resilient scenario in MED.

Scenarios

The list of parametric constraints used in the MED analyses is given in Table 51. The constraints are systematically applied to a reference scenario (REF) which includes legislated policy measures as of 2005, including the projected uptake of conservation measures through 2020, climate change levy, electricity and transport renewable obligations, EU-ETS and so on. However, no new future policies or measures would be enacted to reduce energy use or CO₂ emissions.

Table 51. List of constraints used for the parametric analyses

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Rationale</th>
<th>Name and description of constraints</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diversity in primary energy supply</td>
<td>This criterion is intended to promote supply diversity in overall energy system.</td>
<td>R_PE: A maximum market share of 40% is applied to each fuel type. Import and domestic fuels are aggregated as a single category. Uranium for nuclear power generation is excluded in this constraint but nuclear generation is constraint through diversity in power supply.</td>
</tr>
<tr>
<td>Diversity in power sector</td>
<td>This criterion is intended to promote supply diversity specifically for the electricity sector.</td>
<td>R_P (PJ): Diversity in electricity generation mix A maximum market share of 40% is applied to electricity generation from each fuel source. In general, fuel sources are aggregated as coal, gas, nuclear and renewable.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>R_P (GW): Diversity in installed capacity Similar to the diversity of electricity generation mix constraint R_P (PJ), but applied to installed capacity.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>R_POW: Diversity in both installed capacity and generation mix Combination of the above two constraints, R_P (PJ) and R_P (GW)</td>
</tr>
<tr>
<td>Reduction of final energy demand</td>
<td>This criterion is intended as proxy for expenditure on final energy that would reduce the UK’s economic exposure to volatility or enduring rises in global energy prices.</td>
<td>R_FE-A: 2.4% per annum</td>
</tr>
<tr>
<td></td>
<td></td>
<td>R_FE-B: 2.8% per annum</td>
</tr>
<tr>
<td></td>
<td></td>
<td>R_FE-C: 3.2% per annum</td>
</tr>
<tr>
<td></td>
<td></td>
<td>R_FE-D: 3.6% per annum</td>
</tr>
</tbody>
</table>

1 The 40% threshold is derived from an equivalent Herfindahl-Hirschman Index (HHI) of 30%. HHI is used by the Office of Fair Trading to measure excessive concentration when considering mergers and acquisitions.
Due to the existing capital stocks and near term policy constraints, all the above constraints are implemented from 2015.

Coal/gas with and without CCS is aggregated only to new build nuclear plants.

Offshore wind, tides, marine and wave.

In the reference scenario [REF], energy intensity reduces between 1.79% and 2.74% per annum during 2010-2050 (Anandarajah et al., 2008).

The objective of the EU Energy Efficiency Action Plan (EC, 2006) is “to control and reduce energy demand and to take targeted action on consumption and supply in order to save 20% of annual consumption of primary energy by 2020 (compared to the energy consumption forecasts for 2020). This objective corresponds to achieving approximately a 1.5% saving per year up to 2020.” It is difficult to compare this with the energy intensity that has been imposed in the Resilient scenario, but, with an assumed economic growth rate of around 2%, a 3.2% reduction in energy intensity is at least comparable to a 1.5% p.a. reduction in energy use. It is likely therefore that the Resilient scenario achieves or comes close to achieving the EU energy efficiency objective, whereas the Reference scenario does not.

Results

In the reference scenario, diversity of primary energy (just) meets the resilience criteria but the generation mix does not. In the low carbon scenario, diversity of primary energy fails to meet the resilience constraint but electricity generation mix is most diverse because of the uptake of nuclear power. Compared to the supply diversity, reducing the final energy demand is the hardest. All the end use sectors responses to the final energy constraint through a combination of energy efficiency improvement, fuel switch and demand side response. However, the demand side response is the most significant. For example, the residential heating demand is reduced up to 25% in 2025 and 47% in 2050.

Figure 276 shows the final energy demand. In general, constraining the final energy supply promotes the use of electricity due to high efficiency at end use technology. For example, gas based heating in the residential sector switch to efficient heat pumps. This fuel switch should have increased the electricity demand, but total electricity demand is decreased due to the demand side response. The demand reduction is very high when the final energy constraint becomes more stringent. The reduction in final energy reduces the primary energy supply, and the CO₂ emission up to 40% from the 1990 level. However, the high level of demand reduction results in high welfare cost, that varies between £ 10 and 45 billion in 2050.

Figure 276. Final energy demand in parametric analyses

From the parametric analyses, it is clear that none of the single constraints fulfils all the criteria for the resilient energy system. Therefore, for the core resilient scenario three constraints namely, diversity in primary energy supply [R_PE], diversity in electricity generation mix [R_P (PJ)] and a reduction in final energy intensity of 3.2% per annum [R_FE-C] have been combined. These resilient constraints are
applied to the reference and the 80% low carbon scenarios to produce a Resilient and low carbon resilient (LCR) scenarios. Table 52 summarises the key indicator from the core scenarios.

The resilient energy system reduces CO2 emissions but does not go far enough to stay on the pathway to the 2050 80% reduction goal. There is remarkably little progress in electricity decarbonisation in the resilient scenario, and progress is slower if resilient constraints are added to the low carbon scenario. The diversity of power sector plays key role to diversity of primary energy supply. Cheap alternatives allow either diverse or low carbon generation mixes to make big contributions to overall goals.

Deduced energy demand, and thereby imports dependence, is the key to achieve a low carbon and resilient scenario. The low-carbon scenario contributes to reduced energy demands but it does not go far enough to meet the criteria for the resilient energy system. The demand reduction through behaviours changes is very important and the residential sector is critical in this regard. The resilient scenario requires a substantial change from demand side that incurs huge welfare cost.

Table 52. Key indicators of core scenario in 2050 (from 2000 level)

<table>
<thead>
<tr>
<th>2050</th>
<th>Reference</th>
<th>Resilient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary energy supply:</td>
<td>-4%</td>
<td>-44%</td>
</tr>
<tr>
<td>Max share of primary energy:</td>
<td>36% (Coal)</td>
<td>20% (Gas)</td>
</tr>
<tr>
<td>Electricity demand:</td>
<td>+26%</td>
<td>+2%</td>
</tr>
<tr>
<td>Max share of electricity generation:</td>
<td>81% (Coal)</td>
<td>40% (Coal)</td>
</tr>
<tr>
<td>Max share of capacity:</td>
<td>51% (Coal)</td>
<td>27% (Coal)</td>
</tr>
<tr>
<td>CO2 intensity of electricity (g/kWh):</td>
<td>591</td>
<td>352</td>
</tr>
<tr>
<td>Final energy demand:</td>
<td>+4%</td>
<td>-31%</td>
</tr>
<tr>
<td>Residential energy demand:</td>
<td>-2%</td>
<td>-50%</td>
</tr>
<tr>
<td>CO2 emission (from 1990 level):</td>
<td>-2%</td>
<td>-52%</td>
</tr>
<tr>
<td>Welfare cost:</td>
<td>0 EB</td>
<td>49 EB</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>2050</th>
<th>Low carbon</th>
<th>Resilient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary energy supply:</td>
<td>-32%</td>
<td>-49%</td>
</tr>
<tr>
<td>Max share of primary energy:</td>
<td>29% (Nuclear)</td>
<td>30% (Nuclear)</td>
</tr>
<tr>
<td>Electricity demand:</td>
<td>+30%</td>
<td>+16%</td>
</tr>
<tr>
<td>Max share of electricity generation:</td>
<td>41% (Coal CCS)</td>
<td>40% (Nuclear)</td>
</tr>
<tr>
<td>Max share of capacity:</td>
<td>25% (Coal CCS)</td>
<td>25% (Wind)</td>
</tr>
<tr>
<td>CO2 intensity of electricity (g/kWh):</td>
<td>31</td>
<td>15</td>
</tr>
<tr>
<td>Final energy demand:</td>
<td>-29%</td>
<td>-40%</td>
</tr>
<tr>
<td>Residential energy demand:</td>
<td>-55%</td>
<td>-50%</td>
</tr>
<tr>
<td>CO2 emission (from 1990 level):</td>
<td>-60%</td>
<td>-50%</td>
</tr>
<tr>
<td>Welfare cost:</td>
<td>38 EB</td>
<td>59 EB</td>
</tr>
</tbody>
</table>

3.30.7.5 Modelling transport energy demand in the Elastic Demand (MED) version

Despite an emerging consensus that societal energy consumption and related emissions are not only influenced by technical efficiency but also by lifestyles and socio-cultural factors, few attempts have been made to operationalise these insights in models of energy demand. This paper (303) addresses that gap by presenting a scenario exercise using an integrated suite of sectoral and whole systems models to explore potential energy pathways in the UK transport sector. Techno-economic driven scenarios are contrasted with one in which social change is strongly influenced by concerns about energy use, the environment and well-being.

Scenarios

UKTCM outputs (fuel consumption, vehicle fleet evolution by vehicle technology) were translated into MED inputs (technical energy efficiency, technology deployment constraints and bounds). MED was then run to produce four contrasting scenarios - two core Energy 2050 scenarios and two Lifestyle ‘variants’. In each case, they were distinguished by whether they were unconstrained (REF) or constrained (LC) to guarantee the achievement of an 80% fall in UK carbon emissions relative to 1990 levels by 2050. Thus, four scenarios resulted as follows:

• LC: constrained low carbon core Energy 2050 Scenario.
• LS REF: unconstrained Lifestyle variant.
• LS LC: constrained low carbon Lifestyle variant.

Results
The higher uptake of lower and zero carbon vehicles combined with efficiency gains, downsizing of cars, mode shifts and significant alterations to work, shopping and leisure travel patterns result in final energy demand being halved from this sector in the unconstrained Lifestyle variant (LS REF) by 2050 compared to the unconstrained reference case (REF) (Figure 277). The demand for conventional fuels (petrol+diesel) decreases by 57% by the year 2050 in the unconstrained Lifestyle variant (LS REF) and by 87% when constrained (LS LC). However, in all scenarios, conventional fuel still dominates use in 2020, never falling below 89% of total demand.

By comparison, electricity demand grows steeply, particularly in the second half of the period, accounting for 18% of total fuel demand in the unconstrained Lifestyle variants by 2050. This demand is 67% higher than in the unconstrained reference case (REF) where HEVs and BEVs have zero market share, even by 2050, although there is some increase in electricity use later in the period from rail, some battery operated buses and plug-in electric vans. Altogether, taking car (PHEV), vans (PHEV and BEV) and bus (BEV), a third of road transport energy demand is met by plug-in electric vehicle technology in 2050. Use of electrified rail also increases by over 200% over present use by 2050.

Figure 277. Transport fuel demand (PJ) by transport fuel in each scenario

![Graph showing transport fuel demand](image)

Bio-fuels only play a major role in the carbon constrained cases (LC & LS LC). This is a result of the availability of unconstrained blending of second generation biodiesel and the assumption within MED than bio-fuels have zero net carbon emissions (much liked by a scenario modelling an 80% caponemissions), while in the reference cases (REF and LSREF) demands decrease in line with petrol and diesel demands. Hydrogen also only plays a major role in the constrained cases (LC & LS LC) in the long term (2050), which sees three quarter of the truck fleet switching from diesel/biodiesel ICE to hydrogen fuel cell power trains. There is a minor role for hydrogen fuel cell trains from 2030 in the unconstrained cases, where hydrogen powers a third of rail energy demand by 2050.

Overall, the unconstrained Lifestyle variant (LSREF) resulted in a 26% and 58% reduction in transport CO2 emissions at source (or direct, tailpipe) by 2020 and 2050 compared to the core reference scenario (REF) levels (Figure 278). In the core constrained reference case(LC) the transport sector only starts to pull its weight from around 2030, mainly as a result of the wide spread use of second generation biofuels. In contrast, the constrained Lifestyle case (LSLC) follows the same carbon emissions trajectory...
as the unconstrained Lifestyle case (LSREF) up to about 2040, after which transport CO2 fall sharply to levels that are even 37% lower than in the core carbon constrained (LC) scenario. Modelling of radical changes in lifestyle led to a 74% reduction in distance travelled by car by 2050. The reduction in car travel comes about as a result of significant mode shifts, particularly to bus travel towards the latter half of the period (184% increase in vehicle kilometres) and cycling and walking.

The ‘what if’ Lifestyle scenario reveals a future in which distance travelled by car is reduced by 74% by 2050 and final energy demand from transport is halved compared to the reference case. Despite the more rapid uptake of electric vehicles and the larger share of electricity in final energy demand, it shows a future where electricity decarbonisation could be delayed. The paper illustrates the key trade-off between the more aggressive pursuit of purely technological fixes and demand reduction in the transport sector and concludes there are strong arguments for pursuing both demand and supply side solutions in the pursuit of emissions reduction and energy security.

Figure 278. Projections of CO2 emissions (Mt) at source from domestic transport in each scenario

3.30.8 Analysis with the MARKAL-UK and TIAM-UCL energy systems model

UK energy policy makers must reconcile the persuasive impact of external international drivers with the national level implementation of CO2 reduction legislation (-80% by 2050). This methodological ambiguity requires modelling at alternate scales: modelling at a national scale allows retention of detail on imposed policies, taxes, sectoral detail, and demand side changes; modelling at a global scale provides the capability for assessing the impact of global energy system drivers on the UK region. This paper (304) presents continuing work on combined modelling using partial equilibrium technology rich optimisation models; via UK MARKAL and via a new global model with a dedicated UK region (TIAM-UCL). The analysis focuses on the critical role of fossil fuel resources and prices, and on the availability and costs of international CO2 emissions credits.

Scenarios

Therefore, for this study we have assumed that only 12.5% of required emission reductions from the 1990 baseline, can be met via emissions credits. This ratio is kept in place from 2015-2050, and in 2050 this represents 59 MtCO2. Considering this ceiling in terms of total CO2 emissions, the UK could emit up to 177 MtCO2 in 2050 but have 1/3 of these as purchased credits to meet its -80% target (i.e., 118MtCO2).

The global mitigation outlook is based on a long term 450 ppm stabilisation scenario, focusing on energy sector emissions only (similar to the IEA ETP’s Blue map scenario). All regions are under targets, as presented in Table 53.
A key variable then considered is the operation of the global trading market, focusing on three variants: i) full trade permitted, ii) 12.5% of target permitted to be met through credit purchases and iii) no trade. The key question is how the marginal cost of carbon is impacted under a full or partial trading scheme, and where trade is not available. We are therefore using the following scenarios:

- Reference case (REF)
- 450 ppm carbon reduction case with full trading (450)
- 450 ppm carbon reduction case with limited trading (450_125)
- 450 ppm carbon reduction case with no trading (450_00)

**Results**

Table 54 details primary energy for the 3 scenarios in 2050 (along with the base year of 2000). By 2050 coal use recovers as subsequent generation CCS is still cost effective, and non fossil sources (notably renewable electricity) are also boosted. One surprise is that nuclear does not play a bigger overall role in higher fossil price scenarios. This is largely due to that fact that nuclear is not cost competitive until later vintages (especially 2030) but the fossil cost penalty on competing fossil based technologies is greatest in intermediate years. The impact of emissions credit purchases under these assumptions is modest as is only seen in later years where the price of CO₂ emissions credits is slightly lower than the marginal costs of domestic reduction options, and allows a fuel switch from biomass to natural gas and oil.

**Table 54. UK MARKAL primary energy (PJ)**

<table>
<thead>
<tr>
<th>Energy Source</th>
<th>2000</th>
<th>LC</th>
<th>2050</th>
<th>LC-FF</th>
<th>LC-CC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Renewable electricity</td>
<td>20</td>
<td>283</td>
<td>470</td>
<td>470</td>
<td>282</td>
</tr>
<tr>
<td>Biomass and waste</td>
<td>121</td>
<td>1142</td>
<td>1144</td>
<td>1078</td>
<td></td>
</tr>
<tr>
<td>Natural Gas</td>
<td>3907</td>
<td>1173</td>
<td>1114</td>
<td>1262</td>
<td></td>
</tr>
<tr>
<td>Oil</td>
<td>3043</td>
<td>385</td>
<td>405</td>
<td>439</td>
<td></td>
</tr>
<tr>
<td>Refined oil</td>
<td>-298</td>
<td>128</td>
<td>119</td>
<td>101</td>
<td></td>
</tr>
<tr>
<td>Coal</td>
<td>1500</td>
<td>1876</td>
<td>1797</td>
<td>1854</td>
<td></td>
</tr>
<tr>
<td>Nuclear electricity</td>
<td>282</td>
<td>769</td>
<td>641</td>
<td>776</td>
<td></td>
</tr>
<tr>
<td>Imported electricity</td>
<td>52</td>
<td>103</td>
<td>103</td>
<td>103</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>8628</td>
<td>5859</td>
<td>5794</td>
<td>5896</td>
<td></td>
</tr>
</tbody>
</table>

With TIAM-UCL, an initial comparison between a reference case (REF) and a 450 ppm carbon reduction case with full trading (450), illustrates the criticality of global assumptions. In terms of primary energy (Figure 279), REF in the long term continues to be fossil-dominated, with increasing use of coal meeting much of the increase in demand for energy services. The UK primary energy level in 2100 is approximately four times that observed in 2005. UK consumption levels of oil and gas also continue to grow, albeit at a much more gradual rate, as does the use of nuclear energy for electricity generation. Under the 450 (CO₂ constrained) case, fossil intensity of the energy mix reduces significantly over time, with increased use of renewables, biomass and nuclear. Coal is still an important part of the primary energy supply but for use in CCS plant.

In an initial comparative analysis, both models point to electricity as a key low carbon energy vector. However a range of difference include the use of nuclear as a dominant low carbon generation source and the electrification of various transport modes. This divergence was due to the detailed
implementation of policy (including renewables policy), and characterisation of the structure of the electricity supply network in the national model.

**Figure 279. REF case primary energy consumption in the UK region, 2005-2100 (PJ)**

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Preliminary analysis where these drivers are endogenous to the global model, illustrates both convergence but also considerable uncertainty in exogenously assumed values in a national model. This includes firstly critical thinking into the linked movement in costs and requirements for similar levels of UK purchases of international emissions credits. Secondly, underpinning model assumptions of fossil fuel resources need further critical examination. Future work will focus on an iterative soft-link between national and global scale model to fully harness the insights of each model scale.

### 3.3.0.9 Preliminary results with the TIMES-UK model

This presentation (305) introduces first results from the TIMES-UK model. The UK’s contribution to the EU GHG and renewables targets (as for other EU countries) can be evaluated in the PET model.

**Scenarios**

Reference – BaU : Discussion with DGTREN concluded that the BaU scenario should use the same background assumptions as the Baseline Scenario in the “European energy and transport: Trends to 2030 – Update 2007” as published by DGTREN. No bound on CO2, but ETS scheme operates at a clearing price of 20€(2005)/ton CO2 in 2010. For the post-Kyoto period carbon prices increase smoothly to 24€(2005)/ton CO2 in 2030 and this price applies to the current ETS sectors.

RES Reference : The target for renewable energy sources in 2020 is imposed per country, following the path as given in the directive proposal:

- Only CO2 emissions.
- The total CO2 both from the ETS and non-ETS sectors, has the upper bound of 3591 Mtons in EU27 for 2020. This value comes from GAINS, where the 20% reduction of the GHG emissions from the 1990 level, by 2020 is translated into a 18% reduction of CO2 only in the same year.
- ETS Sectors: Full trade of CO2 from the ETS sectors with in EU27.
- Non-ETS Sectors: An upper bound in the emissions of CO2 from the non-ETS sectors is imposed for 2020.

RES Trade : All the other assumptions hold as in the Scenario RES Reference. A Green Certificate is allocated for each unit of Renewable Electricity that is being generated and each unit of a renewable energy carrier that is being used in the final energy consumption. This Certificate can be used either for fulfilling the country’s obligation for the 2020 target or it can be used for trading with the other countries. So there is physical trade of electricity, bioenergy and at the same time there is trading of green certificates.
Results (preliminary)

Bioenergy use is preferred in the final energy consumption because of the way the target is imposed (Figure 280). The cost of the CO₂ constraint relative to the Renewables constraint shows that it is the GHG reduction target, that seems to “pull” the Renewable target. In the case of GC trading, physical trade of bioenergy is reduced.

Figure 280. Final Energy Consumption – Renewable Energy – UK

3.31 United States

3.31.1 Analysis of multi-pollutant policies for the power sector under uncertainty

We analyze (306) how three uncertainties - electricity demand growth, natural gas prices, and power sector GHG regulations could affect electric power sector investment decisions and costs in the U.S. over the next four decades. The effect of multi-pollutant regulations such as the Clean Air Interstate Rule (CAIR) upon these decisions and costs is also considered. We use decision trees to structure the problem, defining multiple futures for each uncertainty and then simulating how the U.S. energy market responds to them. A two-stage stochastic version of the energy-economy model MARKAL simulates the market. Relative importance of the uncertainties is assessed using two indices: expected cost of ignoring uncertainty (ECIU) and expected value of perfect information (EVPI). We also calculate the value of policy coordination (VPC), the cost saved by avoiding surprise changes in policy. The analysis shows that the possibility of GHG regulation is the most important uncertainty by these measures. The basis of the below analyses is the USEPA National MARKAL database (version EPANMD07).

Scenarios

The NOₓ and SO₂ caps in Table 55 are applied in the cases where we assume continuation of the existing Title IV and SIP call policies that the USEPA Clean Air Interstate Rule would supersede. The table also shows the assumed caps for those criterion pollutants under the assumption that some variant of the CAIR or Congressional three pollutant (NOₓ, SO₂, mercury) legislative proposals will be passed.

Table 55. Assumed emission limits, thousand tonnes

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-CAIR caps</td>
<td>NOₓ</td>
<td>4750</td>
<td>4000</td>
<td>3500</td>
<td>3,600*</td>
</tr>
<tr>
<td></td>
<td>SO₂</td>
<td>10,630</td>
<td>10,540</td>
<td>9900</td>
<td>8950</td>
</tr>
<tr>
<td>CAIR-Like Caps</td>
<td>NOₓ</td>
<td>4750</td>
<td>4000</td>
<td>1510</td>
<td>1510</td>
</tr>
<tr>
<td></td>
<td>SO₂</td>
<td>10,630</td>
<td>10,540</td>
<td>2250</td>
<td>2250</td>
</tr>
<tr>
<td>Possible CO₂ Cap</td>
<td></td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>560,000</td>
</tr>
</tbody>
</table>

a Slight increases allowed in later years.
**Results**

Figure 281 is a decision tree representation of the MARKAL market simulation in the face of uncertainty as to whether a tight CO₂ cap would be imposed on U.S. electric sector emissions starting in the year 2015. First, it is assumed that pre-CAIR caps on SO₂ and NOx emissions remain in place. The figure portrays the range of feasible decisions for 2000-2010 as the first decision node, and 2015-2050 decisions as the second set of decision nodes. Each decision node represents a continuous range of possible decision variable values considered in the stochastic version of MARKAL. However, we highlight two particular first stage solutions in the first stage, shown as separate branches: 1) the naïve solution developed assuming that the future is known, and there is no CO₂ cap; and 2) the optimal stochastic solution, in which market parties anticipate a 50:50 chance of a tight cap being imposed.

**Figure 281. Naïve and optimal stochastic solutions under CO₂ policy uncertainty (1995 U.S. Billion dollars).**

**pre- CAIR limits on SO₂ and NO.**

**CAIR-like limits**

The values above each of their chance nodes give the expected cost of each of those two strategies compared to the naïve solution under the “No CO₂ Cap” scenario, expressed in billions of dollars ($B, present worth, in 1995 dollars).

The naïve solution’s greater emphasis on pulverized coal steam generation (about 66 GW more added in 2000-2010, as indicated in (a)) results in lower overall costs by $35.8B (relative to the optimal stochastic solution), if there is no cap. With imposition of tighter CAIR-like caps upon SO₂ and NOx emissions starting in 2010, the U.S. generation mix shifts. The analysis of the optimal stochastic strategy and ECIU is repeated in (b), but for the case of the tighter CAIR caps upon conventional pollutants. ECIU is $77.8B (¼ $428.5B _ $350.8B) here, a slightly smaller amount because the CAIR caps slightly discourage the pulverized coal investment in the naïve solution that would be so heavily penalized if CO₂ caps are imposed.

The carbon cap uncertainty is the economically most important uncertainty compared to the electric demand and natural gas uncertainties. The optimal strategy in the face of the carbon cap uncertainty involves more investment in more efficient IGCC and cleaner natural gas-fired power generation capacity compared to the naïve solution, which results in the most significant ECIU.

**3.31.2 Impacts of the objectives of the American clean energy and security act**

**3.31.2.1 Optimal strategies for achieving the objectives of the American clean energy and security act**

IRG investigated cost-effective strategies to achieve the bills objectives for the Natural Resources Defense Council (NRDC) as part of its Cap 2.0 initiative. This paper (307,308) presents detailed results
from that effort. We used the US National MARKAL model (USNM-50) to identify least-cost technology and policy pathways for attaining these emissions reduction goals.

**Scenarios**

The American Clean Energy and Security Act (ACES), also referred to as the Waxman-Markey bill, calls for an 80% reduction in US GHG emissions by 2050 and includes a variety of incentives to help achieve this ambitious objective.

**Results**

Primary energy use will decrease under ACES due to energy efficiency improvements in the vehicle fleets in residential and commercial buildings and in industry (Figure 282). Endogenous technology learning for renewables and other advanced technologies such as coal with CCS drive their investment costs down, making them more attractive economically over time.

**Figure 282. Primary energy use under ACES**

Cost-effectively achieving the ACES targets will require the adoption of non-traditional light-duty vehicle (LDV) technologies starting with hybrids then plug-ins and after 2030 electric vehicles displacing gasoline vehicles. We implemented aggressive CAFE standards going to 80 mpg in 2050, which help to lower allowance costs, and we assumed that transportation system policies incentivized in the bill will reduce vehicle miles traveled (VMT) by 12% in 2050 relative to the business-as-usual (BAU) scenario.

**Figure 283. Oil imports**

ACES can improve energy security and reduce dependence on foreign oil through its incentives for CCS technology because its cost-effective to use the captured CO₂ for enhanced oil recovery (EOR) (Figure 283). The model results indicate that CO₂-stimulated EOR opportunities could produce up 4.8 mbd in 2050.
The model results indicate that ACES could lead to ~$850 billion in total discounted savings to society between 2012 and 2050 relative to the BAU – with increased expenditures in new, more efficient appliances and equipment and low-carbon technologies more than offset by savings from decreased expenditures on fuel and electricity.

### 3.31.2.2 US Technology Choices, Costs and Opportunities under the Climate Security Act

In the same context, this presentation (309) shows US technology choices, costs and opportunities under the Lieberman-Warner Climate Security Act, using the US National MARKAL model (USNM-50), a Comprehensive Energy System Planning Model.

#### Scenarios

US legislative policy scenarios examined:

- **Reference (BAU) Scenario** - in line with EIA projections.
- **Energy Efficiency & Renewable Energy (EE&RE),** with energy efficiency incentives and expanded renewable energy resources.
- **Lieberman-Warner (L-W) cap & trade bill**
  
  ⇒ Modeled as cumulative limit on 2000-2050 CO₂ emissions (67 billion tonnes carbon)
  
  ⇒ 15% limits on domestic (e.g., methane, forestry) and international offsets (e.g., EUA, CERs) each
  
  ⇒ 13 billion tons of CCS incentives
- **Two scenarios of energy system evolution under L-W**
  
  ⇒ Case A: Least-cost given assumed technology learning rates
  
  ⇒ Case B: Case A with enhanced role for CCS allowing greater coal use

#### Results

Policies to improve energy efficiency and promote renewable energy resources will achieve significant CO₂ emission reductions and reduce the total energy system cost, but they will not produce the necessary deep reductions called for in Lieberman-Warner (Table 56). In Case A, most CO₂ reductions come from the electric sector through a combination of end-use efficiency improvements, renewable energy use and CCS. Demand sector direct emissions are flat – with reductions offsetting growth (more than doubling over the modeling horizon). CCS grows to about 460 Mt/yr. CO₂ offsets average almost 1.2 Bt/yr.

In Case B intensive use of CCS technologies limits annual decline in coal power generation to 1%. Most CO₂ reductions continue to come from the electric sector and CCS increases to over 1.2 Bt/yr. Electric demand reduction, renewable energy and CO₂ offset use decline slightly compared to Case A.

#### Table 56. Scenarios to improve energy efficiency and promote renewable energy resources

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Change in System Cost</th>
<th>Change in Cumulative Emissions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Business as Usual (BAU)</td>
<td>0.0%</td>
<td>0.0%</td>
</tr>
<tr>
<td>Enhanced Efficiency</td>
<td>-1.3%</td>
<td>-7.5%</td>
</tr>
<tr>
<td>Expanded Renewables</td>
<td>-0.9%</td>
<td>-6.1%</td>
</tr>
<tr>
<td>Combined Efficiency &amp; Renewables (EE&amp;RE)</td>
<td>-1.9%</td>
<td>-11.9%</td>
</tr>
</tbody>
</table>

Primary energy use (Figure 284) is 12% lower under Lieberman-Warner than in the BAU. Coal use grows to about 27 quads in 2025 and then declines to between 7 and 16 quads by 2050. Oil and natural gas use
are reduced from the BAU case. Nuclear use remains constant, and renewable energy use increases to 26 quads in 2030 and to between 50 and 56 quads by 2050.

Electricity generation increases (Figure 285), but demand is 16% and 9% below the BAU case—with more generation in Case B to supply plug-in hybrids. Power plant fuel mix shows the transition from coal combustion to coal with CCS starting in 2020; Natural gas is replaced with renewables, except for peaking considerations, and nuclear power grows slightly due to upgrades at existing plants only. Renewables grow to between 50 and 60% of supply. Renewables are a mix of biomass, geothermal, concentrating solar power, solar photovoltaic (PV) and wind technologies and grow to between 800 and 1000 GW of installed capacity. Electric output from new renewables comes mostly from large remote wind farms with dedicated transmission to load centers, and concentrating solar power with integrated energy storage.

Figure 284. Primary energy use

![Primary Energy Use](image)

Oil imports drop to about 35% of total oil supply in the 2030 and 2035 periods due to both the lower demand and the use of CCS for Enhanced Oil Recovery (EOR), then rise after this resource (50 billion barrels) begins to deplete, although staying under 60% of total oil supply compared to over 80% in the BAU. Incentives in Lieberman-Warner help to stimulate the implementation of CCS technology early and result in a deployment of CCS above the level that can be used for EOR.

Figure 285. Electricity supply by type

![Electricity Supply by Plant Type](image)
Fleet efficiency for new Light Duty Vehicle (LDV) improves to about 35 mpg in the BAU case, but increases to 52 and 60 mpg in the two Lieberman-Warner cases (Figure 286). The LDV fleet converts to hybrids and plug-ins running flexibly on ethanol and gasoline. CCS-intensive case produces more electricity to fuel more plug-ins. Gasoline use decreases to about 40% of all LDV fuel in Case A and 25% of all LDV fuel in Case B. Ethanol fuel share is 25% to 30%, and the electricity fuel share is between 24% and 34% for Cases A and B, respectively.

**Figure 286. Light-duty vehicle market shares**

![Light-duty vehicle market shares](image)

The CO₂ emission reductions in Lieberman-Warner increase the energy system cost, but the net cost increase relative to the BAU case is only 0.45% in Case A. Case B has a 0.65% increase in the total system cost, given the lower learning rate assumed for CCS relative to renewable energy systems. In both cases CO₂ allowance prices are $12/ton in 2020, increasing to $20/ton in 2030 and almost $50 per ton in 2050. To achieve deep CO₂ emission reductions, increased investment in demand technologies is needed. Supply investments are similar to those required in the BAU case because reduced electricity demand offsets the cost of the more expensive generation technologies. Overall cost impacts are mitigated by savings in fuel expenditures. System cost impacts of limiting offsets are small, but the increase in CO₂ marginal costs is significant. Additional offsets beyond 15% are of little benefit.

**3.31.3 Energy efficiency and the benefits for CO₂ reduction**

The EPA currently has two MARKAL databases representing the U.S. energy system available for public use: a 9 region representation based on the U.S. census divisions, the EPAUS9r, and an aggregate national representation, the EPANMD. In this presentation (310,311) we will give an update on the status of the two databases and show a sample of the number of ways the databases have been utilized at the EPA for in-house research and for modeling in support of regulatory impact assessments. Using the EPA MARKAL Model, this presentation (312,313) deals with energy efficiency and the benefits for CO₂ reduction in the United States.

**Scenarios**

The scenarios:

- **Energy Efficiency Scenario (EE):** Increased usage of higher efficiency technologies, voluntary conservation, and shell improvements for new buildings.
- **Carbon Neutral Scenario (CN):** All demands for new buildings starting in 2030 are met by some combination of energy efficiency, building shell improvements, and on-site electricity.
generation with renewables all leading to zero emissions. In our model application these are “dummy” technologies which currently have no cost.

**Results**

How we got there – Energy Efficiency options (Figure 287):

- Shell improvements in new buildings reduces residential and commercial heating and cooling demands and water heating demands starting in 2010.
- Residential lighting largely compact fluorescents and LEDs by 2020.
- Commercial lighting largely efficient fluorescent and LEDs by 2020.
- Energy conservation efforts begin in 2010, for example: Programmable thermostats, Energy management systems, Low flow shower heads, Home weatherization.
- Starting in 2015, only highest efficiency technology choices are available for both new buildings and for replacement of retired technologies in old buildings.
- Ground source heat pumps penetrate the market reaching 2% of demand for space heating by 2015, increasing to 5% by 2030.

EE achieves 21% of Policy Induced Carbon Trajectory, while CN achieves 30% of Policy Induced Carbon Trajectory.

**Figure 287. Reduction in electricity use in the reference case in 2030 compared with other sources**

AEO High Tech (High Technology Case, AEO2009): Assumes earlier availability, lower costs, and higher efficiency for more advanced equipment and building shell efficiency improvements.

EPRI RAP (Realistic Achievement Potential, “Assessment of Achievable Potential from Energy Efficiency and Demand Response Programs in the U.S.”): Represents a forecast of likely consumer behavior, taking into account existing market, financial, political, and regulatory barriers.

EPRI MAP (Maximum Achievable Potential, “Assessment of Achievable Potential from Energy Efficiency and Demand Response Programs in the U.S.”): Represents a forecast under an ideal set of conditions, taking into account barriers that limit customer participation under a scenario of perfect information and utility programs.

AEO BAT (Best Available Technology, AEO2009): Assumes consumers will install only the most efficient technology regardless of cost, at normal replacement intervals, and that new buildings will meet the most energy efficient specifications available.

LBNL EE Potential (Lawrence Berkeley National Laboratory, “U.S. Building-Sector Energy Efficiency Potential”): Applies annual percentage savings estimates by end use drawn from several prior efficiency potential studies, including the U.S. Department of Energy’s Scenarios for a Clean Energy Future.

**3.31.4 Energy demand analytics using coupled technological and economic models**

This presentation (314) looks at the impacts of a range of policy scenarios on end-use energy demand using a coupling of MARKAL, an energy system model with extensive supply and end-use technological
detail, with Inforum LIFT, a large-scale model of the U.S. economy with inter-industry, government, and consumer behavioral dynamics.

The work was done as part of the Energy Modeling Forum (EMF) 25, ‘Efficiency and Shape of Future Energy Demand” This research study focuses on the key drivers and trends for energy demand and how energy efficiency opportunities can influence these trends. EMF developed a number of scenarios and brought together different modeling teams to run those scenarios. Collaborators on this modeling team: MITRE, EPA Office of Research and Development, University of Maryland. Carbon emissions reductions attributed to end-use demand response are analyzed and compared to carbon emissions reductions attributed to changes in the electric sector.

**Scenarios**

EMF 25 Prescribed Scenario Descriptions

- **Carbon Tax** – Beginning 2010, CO\(_2\) taxed at $30/ton, tax rate increased 5%, inflation adjusted, each year
- **General Energy Sales Tax** – Beginning 2010, 15% tax applied to all forms of delivered energy, tax level increased 5%, inflation adjusted, each year
- **Standards for Residential, Commercial, and Transportation Sector** – building efficiency standards in line with Waxman-Markey, CAFÉ standards in line with Obama’s proposal
- **Reduced Costs for New Equipment** – Cost for new equipment reduced by 50% of cost premium over cheapest equipment
- **Standards + Carbon Tax**
- **Reduced Costs for Equipment + Carbon Tax**
- **7% Solution** – Consumers select energy equipment based solely on costs using a 7% discount rate

**Results**

Scenarios with the greatest impacts are a carbon tax case (Figure 288), resulting in a shift away from coal generation in the electric sector, and a normative case using a 7% discount rate for end-use technology investment decisions, resulting in increased adoption of energy efficient technology.

**Figure 288. Overall CO\(_2\) emissions reductions across all scenarios**

In the carbon tax case, emission reductions are found primarily in the electric sector. In the 7% solution case, emissions reductions are spread across the commercial, residential, and electric sector. The commercial and residential sector emissions come through efficiency improvements mainly in space heating, space cooling, and water heating.
The carbon tax cases have the largest impact on income (Figure 289), amounting to less than 1 percent by 2025. There is significant volatility in the carbon tax and sales tax cases. The LIFT model, like the actual economy, follows a long-run potential growth path. After an economy-wide price shock, GDP growth is reduced, but there are economy stabilizers (such as changes in interest rates and tax rates) tend to bring GDP back to the long-run growth path.

3.31.5 Highlights of recent US climate policy analysis at Brookhaven National Lab

A series of scenario based analysis (315) sponsored by the Office of Policy and International Affairs using the BNL’s 10-region US MARKAL model focused on current climate energy bills:

- The climate bills: Waxman-Markey and Kerry-Boxer
- Renewable Electricity Standard: Requires retail electricity suppliers to meet a certain percentage of their load with electricity generated from renewable resources, like wind, biomass, solar, and geothermal. The requirement begins at 6% in 2012 and gradually rises to 25% in 2025.
- Low carbon fuel standard: A market-based program for regulating the carbon content of transport fuels. The target is 5% reduction relative to 2005 baseline by 2025 and 10% reduction by 2030. The aim is to encourage biofuels production, electric and plug-in hybrid electric vehicles, improvements in refinery efficiency, the use of lower carbon refinery feedstocks.

3.31.5.1 The cap-and-trade program of the Climate Security Act

For example, this presentation (316) introduces an analysis of Climate Security Act (S. 2191) that establishes a cap on GHG emissions through a emission allowance program. Overall, close to 90% of GHG emissions are covered by the legislation (small emitters not covered). Initially 26.5% of allowances are auctioned while the remainder is distributed for free, but over time an increasing share of allowances will be auctioned (69.5% in 2050). Allowances are tradable, bankable and can be borrowed. The offsets may be purchased 1) from non-covered entities who reduce their emissions or CCS (15% max); from an international GHG emission trading market (15% max). The penalty for non-compliance is the higher of $200 per tonne of CO₂.

Scenarios

- Reference case (AEO 2007 data set – also includes the major provisions of EISA 2007)
- Climate Security Act (CSA) Base
- Climate Security Act with no allowance banking
- Climate Security Act with no international offsets
- Climate Security Act no nuclear or CCS
• Climate Security Act with advanced technology set

Results

The Climate Security Act leads to a clear departure from the reference case emission path and significantly lowers emission levels (Figure 290). Allowance prices increase over time as they become more scarce (Figure 291). This is accompanied by an increase in energy prices.

The power sector is the least costly to de-carbonize and accounts for the majority of emission reductions. The transport sector is the most costly to de-carbonize and emission reductions from this sector are small compared to other sectors. Deep carbon reductions require more severe cutbacks in transport and industrial sector emission, which are difficult to achieve with the base technology set.

Figure 290. Carbon emissions CSA base case

As another example, this presentation (317) introduces an analysis of current US Energy and Environmental Policy proposals related to Cap-and-trade and Renewable Portfolio Standards. Cap-and-trade is a market-based program for reducing GHG emissions in which covered entities must obtain tradable permits (allowances) for each ton of GHGs emitted. Allowances are auctioned by the federal government. In addition the program reduces the number of available allowances issued each year so that emissions are 3% below 2005 levels in 2012, 20% below in 2020, 42% below in 2030, and 83% below in 2050.

The analysis shows that national RES will have minor impact on electricity prices, but still leads to significant wealth transfer between regions. We estimate wealth transfer from renewable resource poor regions and to other regions and the federal government to be in the neighborhood of $7.5 billion in 2025. The national cap and trade program will lead to a significant departure from current trends, but
the provisions for offsets means that the cut in energy sector emissions are much lower than the 83% target stated in the bill. The power sector is the only sector that achieves major reductions from 2005 levels.

3.31.5.2 Role of biomass-to-hydrogen in deep CO₂ emission reduction scenarios

The goal of this analysis (318) is to explore the role that hydrogen technologies could play in meeting deep carbon emission reduction goals using the BNL’s 10-region US MARKAL model. We are examining the role of hydrogen fuel cell vehicles in reducing direct emissions of light duty vehicles (LDVs), the impact of using biomass to produce hydrogen with CCS in generating “negative” CO₂ emissions and the competition for biomass feedstocks between hydrogen, other biofuels and electric generation.

We focused on CO₂ caps from Waxman-Markey bill. For this analysis, we only modeled provisions directly related to the CO₂ cap and trade provisions. Renewable portfolio and appliance standards were not modeled. The reference case is calibrated to AEO 2009.

Scenarios

For this analysis we modeled the following scenarios:

- Reference Case: Ref. Case
  - Reference with Carbon Cap: Ref. w/CC
  - Reference with Carbon Cap Without International Offsets: Ref. w/CC w/o IO
  - Reference with Carbon Cap Without Any Offsets: Ref. w/CC w/o AO

- Fuel Cell Technology (FCT) Program: FCTP Case
  - FCT Program with Carbon Cap: FCTP w/CC
  - FCT Program with Carbon Cap Without International Offsets: FCTP w/CC w/o IO
  - FCT Program with Carbon Cap Without Any Offsets : FCTP w/CC w/o AO

Results

With the FCTP goal assumptions, fuel cell vehicles begin to penetrate and rapidly capture market share (Figure 292)

Figure 292. The fuel cell technology program

![Figure 292. The fuel cell technology program](image)

The FCT Program results in a 37% reduction in direct CO₂ emissions in the transportation sector (Figure 293). However, this is partially offset by a increase in industrial sector CO₂ emissions and the total emission reduction is about 10%.

With the FCT Program technology assumptions, we see a shift in carbon mitigation and show significant reductions in industrial and transportation sector emission relative to the reference case due to fuel cell vehicles and biomass to hydrogen with CCS (Figure 294).
The use of biomass-to-hydrogen with CCS can greatly reduce the cost of meeting deep carbon emission reduction goals. BTL with CCS also generates “negative” CO₂ emissions; the hydrogen pathway generates deeper reductions. However, under the strictest CO₂ cap, both BTL with CCS and hydrogen with CCS are needed. While the transport sector may be a more difficult sector to achieve deep CO₂ emission reductions, with a successful R&D program, deep CO₂ emission reductions can be achieved with a significant reduction in costs of meeting the CO₂ cap.

3.31.5.3 The role of technology R&D in mitigating carbon emissions

This analysis (319) utilizes parametric analysis to examine the potential for energy technology R&D to mitigate carbon emissions in the power generation sector. We are using a new 10-region U.S. MARKAL model of the U.S. energy system that solves for sector specific, fuel and technology choice from 2005 to 2050 in 5-year intervals. Model is calibrated to the AEO2007. Technology assumptions are based on U.S. DOE R&D goals used in the FY2009 Government Performance and Reporting Act (GPRA) Benefits Estimates. This analysis is a preliminary look at the effect of technology R&D on carbon mitigation on a regional level.

Scenarios

We tested 7 sets of technology assumptions:

- Base “business-as-usual” technology set
DOE R&D Goal technology sets for: Wind, Solar (PV and CSP), Geothermal, IGCC and carbon sequestration, Nuclear technology and acceptance, Combined set of DOE electric generation technology goals.

16 different carbon prices ranging from $0 to $100 per ton of CO₂. Carbon prices begin at half value in 2015, ramp up to full value in 2020 and remain flat thereafter.

Results (preliminary)

Substantial carbon savings in the power sector can be achieved with the base technology set. Energy technology R&D results in larger carbon savings at lower carbon prices (Figure 295). However, at higher carbon prices the incremental carbon savings decline relative to the base technology set. Regional representation of differences in renewable and sequestration potential affects carbon mitigation options, as well as, business-as-usual investment choice. Future analysis will incorporate enhanced electric load curves and adjustments to generation technology capital costs to reflect recent cost increases.

Figure 295. Effect of technology R&D on carbon abatement curves

3.31.6 Other studies

3.31.6.1 Rethinking demand technology representation

A key challenge with building a MARKAL database is determining the appropriate level of detail associated with demand technology representation across the commercial, industrial, residential, and transportation sectors. A database containing hundreds or thousands of demand technologies is at best difficult to maintain and cumbersome to run, and at worst may provide too much detail given the underlying uncertainty. In our view (320), the level of technology detail should be justified in light of uncertainty considerations. We think that identifying the key model outputs—and how the level of technology detail affects those outputs—should drive MARKAL demand technology representation. The resultant representation should be as simple as possible while still maintaining accuracy in key model outputs. The objective of our presentation is to initiate a discussion regarding different approaches to demand technology representation. To this end, we will review the residential and commercial sectors in the EPANMD and present alternative, simplified approaches for consideration.

3.31.6.2 Implications of unilateral United States carbon policy

The administration of President Barack Obama has announced targets for US GHG emission reductions, of 80% lower than the present. In addition, a renewable portfolio standard (RPS) of 25% of generation and a low carbon fuel standard (LCFS) of at least 20% relative GHG reduction, both by 2030, have been announced. A simple calculation shows (321) that these targets imply that the United States’ rate of per capita emissions would approach that of Europe, as defined by the IEA. Combined with the doctrine of
per capita emissions convergence, as developed by China and India, attaining these rates in the context of RPS and LCFS standards in the US implies dramatic changes in the structure of U.S. electricity generation, but with no impact upon global climate stabilization. MARKAL was used to model the implications of these policy actions.

### 3.31.6.3 Applications to economic impact analyses

EPA’s Office of Air Quality Planning and Standards (OAQPS) and Office of Research and Development (ORD) are exploring the application of MARKAL to EPA’s regulatory economic impact assessments. This presentation (322) will include an overview of a selection of these efforts and their future direction being conducted in the Air Benefits and Cost Group of the Health and Environmental Impacts Division of OAQPS. MARKAL provides a powerful and unique analysis tool, given its high level of technological detail, its representation of large sources of criteria and GHG emissions, and its ability to capture sectoral and cross-sector interactions. Of particular interest in such applications is the ability to conduct multipollutant analyses with MARKAL. Both current and future applications involve the use of MARKAL on its own and MARKAL in conjunction with other models in OAQPS’s toolkit. Stand alone applications include using MARKAL scenarios to bound the economic impacts in Regulatory Impact Analyses (RIA) and using MARKAL as a screening tool to identify key influential parameters and assumptions. Further, MARKAL can be used in a complementary fashion with other models. For example, economic outputs of EPA's computable general equilibrium models, Applied Dynamic Analysis of the Global Economy (ADAGE) and the Response Surface Model (RSM) were used with MARKAL for carbon cap scenario representation. Also, there is a potential opportunity to use the MARKAL emissions inventory with the Control Strategy Tool (CoST) and the Economic Model for Environmental Policy Analysis (EMPAX) computable general equilibrium model.

### 3.31.6.4 Macroeconomic policy analysis

This paper (323) describes the conceptual framework of REMI-E3 using the application of the REMI PI+ macroeconomic model conjoined with the MARKAL/TIMES energy system model. The REMI-E3 model framework has a two-way linkage between REMI PI+ and MARKAL/TIMES. In the REMI-to-MARKAL linkage the REMI model provides economic forecast parameters for the MARKAL/TIMES reference scenario. Users then simulate policy scenarios with MARKAL/TIMES, generating microeconomic data such as demand changes by industry, changes in fuel use, and costs of fuel operations, maintenance and investments. In the MARKAL-to-REMI linkage the relevant MARKAL/TIMES outputs are converted into policy variable inputs in REMI PI+. Using these policy variable inputs, the user runs REMI PI+ to show employment, output, and other macroeconomic changes that result from the scenario. The REMI PI model is a structural macroeconomic policy analysis model that has been calibrated for hundreds of economies at the national, state, regional and local level. MARKAL/TIMES is an energy system model. Due to the differing model frameworks, output variables from MARKAL/TIMES need to be mapped and/or translated into economic variables to simulate policy changes in PI+, and outputs from REMI PI+ need to be mapped to MARKAL demands. We present the REMI PI+ to MARKAL/TIMES mapping approach and the MARKAL/TIMES results to REMI PI+ mapping framework.

### 3.31.6.5 Demand driven computational model of the US energy grid

There is a growing need for a hierarchical integration of the entire energy supply and demand network as populations increase and new technologies are integrated into the energy system. New models need to focus on providing more realism in the simulation of the demand market to address new technology and policy issues, which focus on making the energy system more efficient, reliable, and resilient.

A MArket ALlocation (MARKAL) model (324) is constructed using a bottom-up demand model from preexisting New York City Best Practice Model house hold data to simulate travel demand and energy consumption at a micro level. This approach creates a fine resolution dynamic demand market to drive a supply chain model which co-optimizes supply resources and load-reducing demand resources to maximize reliability and minimize costs in real-time. This allows for an accurate assessment of market penetrating “smart” technologies, advanced electric storage, and peak-shaving technologies, which includes: plug-in hybrid electric vehicles (PHEVs), electric vehicles (EVs), distributed resources and
generation, and variable-output renewable resources. As well this model provides insight to key policy issues such as the effectiveness of free competitive retail markets, incentives to provide customers with real-time rates, pollution impacts and strategies, energy efficiency and reliability standards, and incentives for the development and deployment of “smart” technologies.

3.31.7 Georgia (United States): State-scale evaluation of renewable electricity policy

3.31.7.1 Development of a model of State electricity generation

We present (325) a least-cost linear-optimization model of electricity generation using MARKAL that can be applied at the level of an individual state. Our methodology is applied to a case study of the state of Georgia and used to analyze the evolution of its electricity generation portfolio under different efficiency scenarios.

Scenarios

We have modeled several scenarios to analyze potential policy implementations and parameter variations.

- Business as Usual (BASE) Our business as usual scenario assumes the potential for and cost of efficiency gains presented by Brown et al. This is the most optimistic scenario addressed.

- High Cost Efficiency Gains (HCEFF) Efficiency programs have not historically been adopted at a level that would be generally be expected under traditional cost/benefit analysis. Therefore, we consider a scenario where costs of efficiency gains are doubled to partially account for this effect.

- No Efficiency Gains (NOEFF) We consider a scenario where no efficiency gains are made and demand grows according to business as usual projections.

Results

In the absence of efficiency gains the technology mix trends remain largely the same as the base scenario, except more new capacity is required account for the increased demand (Figure 296). Much of this added demand is made up for through additional coal generating capacity, which experiences steady growth beginning in 2025. We also find that assuming higher costs of efficiency gains results in slightly more natural gas development than the base scenario in early years, and an eventual addition of about half as much coal generating capacity as is added under the no efficiency scenario starting in 2040.

These preliminary results suggest that under business as usual demand growth and in the absence of any efficiency gains or policy implementation, additional demand can be met most cost effectively through natural gas generation technologies. However, efficiency gains can significantly reduce the required new capacity. Realizing the full estimated potential for efficiency gains in Georgia leads to only a 10% increase in total generation by 2050 as opposed to a 40% increase experienced in the no efficiency scenario. Most of these reductions come from a diminished demand for new coal plants.
We develop (326) a linear optimization model at the state level, and use this model to investigate how policy constraints on GHG emissions may affect the lowest-cost choices for electricity generation over the next twenty years. The state-level model provides local and regional decision-makers with a basis for understanding the potential impacts of policy changes, and provides a basis for planning and policy analysis.

**Scenarios**

We present three scenarios that encompass a range of potential emissions prices. The low cost, base and high cost scenarios assume emissions prices of $10/ton, $20/ton and $25/ton respectively in 2015, with a 5%, 5% and 8% respective annual real cost escalations through 2040.

- Low Cost Emissions 10 21
- Mid Cost Emissions 20 42
- High Cost Emissions 25 80

**Results**

Results show MARKAL’s projected lowest cost electricity generation portfolio of the base scenario through 2030. Additional nuclear generation appears in 2020, with the planned capacity addition at plant Vogtle that is expected to come online in 2016 or 2017. The large majority of other new demand is met through NGCC generation and only very small increases in hydroelectric, biomass and wind generation are evident.

Results depict the generation portfolio evolution of the three priced emissions scenarios, as compared with the base scenario. The high cost scenario shows significant growth in nuclear generation and by 2030 almost all existing coal capacity has been retired and replaced by either nuclear or natural gas based generation technologies (Figure 297). Biomass co-firing and other renewable generation reach their respective technical upper bounds by 2030 in all three scenarios; however, wind capacity develops more quickly in the high cost scenario.
Figure 297. Generating capacity in the high cost cap-and-trade scenario

These preliminary results suggest that in an unconstrained electricity future, NGCC is the lowest cost solution for meeting growing demand in Georgia. If an emissions pricing scheme is implemented, biomass co-firing capacity is developed at an emissions price of approximately $20/ton. However, its technical capacity is quickly met and co-firing is only able to provide about 9% of the state’s electricity. At an emissions price of around $80/ton, nuclear generation becomes a less expensive alternative to NGCC and is developed in large quantities in our high cost scenario.

3.31.7.3 The role of renewable electricity credits and carbon taxes

We have developed (327) a state-scale version of the MARKAL energy optimization model, commonly used to model energy policy at the US national scale and internationally. We apply the model to address state- scale impacts of a renewable electricity standard (RES) and a carbon tax in one southeastern state, Georgia.

Scenarios
We model scenarios in which the entire Georgia RES must be met through internal generation and examine the effect of REC prices in scenarios that allow for RECs to be freely purchased for use in Georgia across state lines.

Results
Results comparing the base scenario and the RES scenario are shown in Figure 298. In the RES scenario there are no RECs and the entire renewable requirement must be met through internal generation. It can be seen that a RES would be primarily be met through biomass generation in Georgia, which largely replaces the natural gas additions seen in the base scenario. The majority of this is provided through co-firing additions at current coal burning facilities; another significant amount is met through new dedicated biomass facilities; and a final small piece is met through increased biomass generation efficiency at industrial sites. Hydroelectric additions are consistent with the base scenario. There is a small amount of additional other renewable generation as compared to the base scenario, almost all of which is from wind.
Figure 299 shows that investment in new renewable generation capacity is most effectively encouraged through a RES without RECs, which leads to over three times greater renewable investment than if RECs are allowed and almost four times the renewable investment experienced under a $50/tCO2 carbon tax.

Figure 299. Total undiscounted investment in new capacity made between 2010 and 2030*

*Even under a RES with no RECs, total renewable investment is just over half the investment in the new nuclear reactors at plant Vogtle.

Biomass is the lowest cost option for large-scale renewable generation in Georgia; we find that electricity can be generated from biomass co-firing at existing coal plants for a marginal cost above baseline of 0.2–2.2 cents/kWh and from dedicated biomass facilities for 3.0–5.5 cents/kWh above baseline. We evaluate the cost and amount of renewable electricity that would be produced in-state and the amount of out-of-state renewable electricity credits (RECs) that would be purchased as a function of the REC price. We find that in Georgia, a constant carbon tax to 2030 primarily promotes a shift from coal to natural gas and does not result in substantial renewable electricity generation. We also find that the option to offset a RES with renewable electricity credits would push renewable investment out-of-state. The tradeoff for keeping renewable investment in-state by not offering RECs is an approximately 1% additional increase in the levelized cost of electricity.

3.31.8 Pennsylvania (United States): Effectiveness of carbon mitigation strategies at the municipal level

Realizing the value of quantitative modeling as a decision-aid at the municipal level, we focus our attention on modeling the energy (and material) systems so elected officials and administrators can better understand the behavior and responsiveness of the whole system to different policy scenarios. In this paper (328,329), we describe our efforts to develop and apply MARKAL-family of models at two
municipalities in Western Pennsylvania, and examine the responsiveness of the two energy and material systems to different policy instruments enacted at the state level and implemented at the municipal level. The legal framework at the state level, specifically, PA Act 129 and Act 213, provided the ex ante basis for modeling different scenarios, and the model outcomes provided clues on the effectiveness of existing measures to mitigate GHG emissions.

**Scenarios**

- Act 129: 1% reduction of demand each year due to demand-sidetechnology and behavioral changes (DEM_129 ), 1% improvement in efficiency of heating and cooling appliances (EFFAPPL), Phasing out low efficiency appliances in cooling, heating and lighting (PHASEOUT)
- Act213: Renewable Portfolio Standard -8% by 2020(REN_STD)

**Results**

Our results show clear limits to GHG reductions at the local level without changing the source of energy (mostly coal-fired power plants in PA) (Figure 300). Responsiveness of the two municipalities greatly depended on the asset-stock characteristics (both buildings and appliances), confirming our a priori expectation that the same policy instrument may have different effects in different regions/localities due to the nature (and quality) of existing stock. Our results also suggest that the easiest and cheapest way to reduce emissions is to change behavior – reducing demand for energy had almost the same effect as phasing out older appliances and replacing them with newer ones, and with no associated costs. Policy options that promote and incent such behavioral changes are likely to be more effective than options that attempt to change the characteristic of the energy system.

**Figure 300. CO₂ emission reductions in Pennsylvania**

3.31.9 California (United States): Modeling Optimal Transition Pathways to a Low Carbon Economy

Our project goal (330,331) is to develop an integrated system model that will identify optimized scenarios for meeting 2050 climate policy goals and evaluate the resource and economic impacts to the state of California (Figure 301). We hope to provide insights on how economic drivers, such as cost considerations and a cap-and-trade program, will affect future decisions on the investment of future energy technologies and utilization of resources under various scenarios. In particular, we will
investigate how the adoption of advanced vehicles for meeting statewide GHG emission goals could impact the structure and operation of the energy system and resource use. We focus on assessing low-carbon transportation energy futures for California to: 1) understand the potential interactions between the future transport and electricity sectors, 2) identify optimal (i.e. cost-effective) technology strategies for reducing GHG emission targets in 2020 and in 2050, and 3) understand the impacts of energy and GHG policies on the evolution of the transport and electricity sectors.

Figure 301. TIMES-CA model development and status

3.31.10 Colorado (United States): Renewable energy development infrastructure project

A state-specific MARKAL model is developed to assess the state’s renewable energy development potential for the Renewable Energy Development Infrastructure (REDI) project. The objective of the REDI project, funded by the DOE’s Office of Electricity Delivery and Energy Reliability, is to investigate and produce a report with recommendations that will lead to the expansion of a minimum of 1 GW of new renewable energy in Colorado.

The study (332) concentrates on the electric power system of Colorado and presents the development of an energy system incorporating Renewable Energy Standards, Demand-Side Management and Energy Efficiency (DSM/EE) measures. The focus of the study is to demonstrate the current status of power sector in Colorado and quantify the pathways for sustainable future energy system development meeting Colorado Climate Action Plan (CAP) goals by 2020. The model integrates existing installed generation capacity; future advanced technologies; power grid constraints for power import, DSM/EE programs under various policy scenarios, and provides total system cost of carbon policy scenarios as well as emissions profile. Natural gas price volatility and load forecast sensitivities are explicitly addressed. The study show 1 GW of Concentrated Solar Power and about 3.9 GW of additional wind generation is needed by 2020 to meet the CAP goals. The study also show higher DSM/EE measures by Investor Owned Utilities and Non-IOUs could reduce the renewable needs therefore, less costs and lower rates and more savings to the ratepayers.

3.32 Vietnam

3.32.1 Internalizing externalities into capacity expansion planning: The case of electricity

This paper (333) examines the impacts of including external costs such as environmental and health damages from power production on power generation expansion planning in Vietnam. Using the MARKAL model and covering a 20-year period to 2025, the study shows that there are substantial changes in the generation structure in favor of renewable energy technologies and other low emitting technologies.
Scenarios
To facilitate assessment of the impacts, two cases are analysed: the base case (BC) and the externality case (EC). The BC investigates the power system assuming that the current trend in the energy supply system is maintained into the future. That is, there is no consideration of externalities. In the EC, a policy scenario is developed which considers the externalities produced from power generation. In the EC, advanced lower emission technologies, conventional technologies with emission scrubbers and renewable energy technologies are introduced in addition to those available in the base scenario.

Results
Including external costs in the total production cost of electricity changes the generation mix. Even though coal continues to dominate, its share is reduced by 2025 by 21.6% compared with the BC. Specifically, by 2025, 11.08 GW of coal power plants in the BC is replaced by 3.29 GW of gas turbine and 14.63 GW of renewable energy technologies of geothermal, wind, and biomass. Moreover, selected coal-based technologies are those with low emission and/or emission control such as conventional coal power plant with DeSuf/DeNox and CO₂ scrubber and coal IGCC with CO₂ scrubber.

Relative to the BC, this change in generation mix delays the need for coal importation by five years and also reduces CO₂, NOₓ, SO₂, and PM emissions. However, this does not bring about a significant reduction in fossil fuel consumption given that coal-powered plants remain economic if emission controls are used.

The reduction in emissions reduces the external costs imposed on society and the environment. By 2025, the external costs in the EC are 2868 million USD or 1.1% of the projected GDP for the same year compared to 19,656 million USD or 7.5% of projected GDP in the BC. Representing in US cent/kWh, the avoided external costs would be equivalent to 4.4US cent/kWh. These gains are, however, not free as the average generation cost of electricity would be around 7.3US cent/kWh or about 2.6US cent/kWh higher under this case than the BC (Table 57).

Table 57. Major emissions and the average generation cost of electricity of both cases

<table>
<thead>
<tr>
<th>Case study</th>
<th>2010</th>
<th>2015</th>
<th>2020</th>
<th>2025</th>
</tr>
</thead>
<tbody>
<tr>
<td>The base case</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO₂ (thousand ton per year)</td>
<td>54,838</td>
<td>102,971</td>
<td>184,146</td>
<td>307,260</td>
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<tr>
<td>SO₂ (thousand ton per year)</td>
<td>424</td>
<td>892</td>
<td>1682</td>
<td>2880</td>
</tr>
<tr>
<td>NOₓ (thousand ton per year)</td>
<td>159</td>
<td>309</td>
<td>563</td>
<td>947</td>
</tr>
<tr>
<td>PM (thousand ton per year)</td>
<td>11</td>
<td>22</td>
<td>42</td>
<td>73</td>
</tr>
<tr>
<td>External cost per kWh ($ cent/kWh)</td>
<td>3.49</td>
<td>3.93</td>
<td>4.56</td>
<td>5.16</td>
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<tr>
<td>The average generation cost of electricity ($ cent/kWh)</td>
<td>4.57</td>
<td>4.62</td>
<td>4.68</td>
<td>4.79</td>
</tr>
<tr>
<td>The externality case</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO₂ (thousand ton per year)</td>
<td>30,460</td>
<td>29,111</td>
<td>38,462</td>
<td>53,468</td>
</tr>
<tr>
<td>SO₂ (thousand ton per year)</td>
<td>114</td>
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<td>65</td>
<td>91</td>
</tr>
<tr>
<td>NOₓ (thousand ton per year)</td>
<td>91</td>
<td>75</td>
<td>89</td>
<td>110</td>
</tr>
<tr>
<td>PM (thousand ton per year)</td>
<td>5</td>
<td>3</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>External cost per kWh ($ cent/kWh)</td>
<td>1.79</td>
<td>0.95</td>
<td>0.81</td>
<td>0.75</td>
</tr>
<tr>
<td>The average generation cost of electricity ($ cent/kWh)</td>
<td>9.03</td>
<td>7.26</td>
<td>7.30</td>
<td>7.43</td>
</tr>
</tbody>
</table>

These changes lead to a reduction in fossil fuel requirements, and consequently, a reduction of CO₂, NOₓ, SO₂, and PM emissions which could be expected to also reduce the associated environmental and human health impacts. The avoided external costs would be equivalent to 4.4US cent/kWh. However, these gains are not free as the additional electricity production cost would be around 2.6US cent/kWh higher if the switch to more expensive, but lower emitting technologies were made. The net benefit of internalizing these externalities is thus around 1.8US cent/kWh.
4. **Studies and Projects using Sub-National MARKAL and TIMES Models**

4.1 **Western Region (China)**

4.1.1 **Energy development and west to east energy transfer**

China is striving for coordinated regional economic development and to solve the energy shortage in eastern China through a western China development plan with one focus being energy development and west to east energy transfer. This paper (334) describes Western China Sustainable Energy Development Model (WSED) to evaluate various energy development scenarios for western China. The model includes a Western China MARKAL model, a Computable General Equilibrium Model for Western China (WCGE), and an Energy Service Demand Projection Model (ESDP). The ESDP provides energy service demand projections for the Western China MARKAL model, while the WCGE provides macroeconomic inputs for the ESDP and analyzes the impact of different energy development scenarios on western China economy.

**Scenarios**

A reference scenario and several different west to east energy transfer scenarios with and without consideration of the water constraints and the endogenous technology learning are presented.

To further consider endogenous technological learning, three other scenarios, C1-WC-ETL, E1-WC-ETL, and O1-WC-ETL, are designed. The technological progress rate (PR) for the IGCC and poly-generation systems is set to 0.94, the PR for the GTCC (Gas Turbine Combined Cycle) and poly-generation systems is set to 0.89, that of PV is 0.8 and that of wind power generation is 0.89. Each learning curve has 6 segments, except for PV, which has 8 segments with a higher starting point and a faster learning rate. The maximum cumulative wind and solar power generation scales are 300 and 600 GW at the end of the learning curve, with for the other technologies, the maximum is set to 200 GW.

**Results**

Figure 302 compares the changes of the installed power capacity for the various scenarios in 2050 against the reference scenario. Thus, the expected technological progress and water resources constraints on the large-scale west to east electricity transmissions will profoundly change the power structure of the western region.

With the increased use of renewable energy, the carbon emissions in 2050 are expected to be 15% to 20% less than in the scenarios with water constraints and endogenous technology learning in 2050 than in the E1 or O1 scenario, as shown in Figure 303. CCS technologies are needed for the coal- fired power plants and coal liquefaction plants to further cut carbon emissions in the west to east energy transfer scenarios. The investment costs for the energy conversion and processing sector increase when the water constraints are introduced into the analysis, but with much small change if endogenous technologies learning are considered.

The modeling results on the technology mix for the power sector during the planning period under the scenarios considering both pollution and water constraints as well as endogenous technology learning show that the roadmap for large scale energy development in western China should include:

- **Short-term**: development of ultra-supercritical air-cooled power generation units with FGD, hydropower, wind power and other renewable power generation technologies; research and demonstration of IGCC and poly-generation systems; and research on CCS including storage potential assessments in western China.

- **Medium-term**: deployment of IGCC and poly-generation systems; demonstration of CCS systems; development of large scale renewable energy in particular wind power and solar power.
• Long-term: deployment of advanced CCS systems.

Figure 302. Changes of installed power capacity in different scenarios compared to the reference in 2050

<table>
<thead>
<tr>
<th>Year</th>
<th>SC1</th>
<th>SC1-ETL</th>
<th>SC1-E1</th>
<th>SC1-E1-ETL</th>
<th>SC1-WC</th>
<th>SC1-WC-ETL</th>
<th>SC1-WC-E1</th>
<th>SC1-WC-E1-ETL</th>
</tr>
</thead>
<tbody>
<tr>
<td>2020</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2030</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2040</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2050</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 303. Comparisons of carbon emissions in O1 scenarios with/without water constraints and endogenous technology learning

The modeling results on the changes in investment costs for the energy conversion and processing sector for all the scenarios relative to the reference scenario shown in Table 3 tell us what an important role of technology learning could be in order to develop sustainable energy systems at lower costs.

4.2 Reunion Island (France)

4.2.1 Flexibility and reliability of the electricity sector in long-term planning

4.2.1.1 Approach and methodology

A series of presentations and papers focuses on the electricity sector and on problems of flexibility and reliability in power systems in order to improve results provided by long-term planning exercises (335,336,337,338,339,340). In (335,339), flexibility needs are integrated as an additional criterion for new investment decisions in a MARKAL model dedicated to the French electricity sector, while reliability of supply in future power systems is dealt with a focus on the Reunion Island. This series of papers enables the following understandings:

- Flexibility features are necessary to provide electric systems with enough installed capacities to satisfy the electric demand and follow the load curve. Using an augmented version of the MARKAL model of the French electricity sector, flexibility is proven to be a key parameter for reaching a better representation of the electricity generation system, where the level of installed capacities is well-anticipated.
- Reliability of power supply is crucial for operating power systems but is largely ignored in long-term planning exercises, consequently providing unrealistic options for power systems’ long-term development. However, thanks to a thermodynamic approach applied to power systems, reliability requirements can be taken into account when designing future power systems with TIMES model. A TIMES model dedicated to the electricity sector of the Reunion Island is built in order to implement reliability requirements in long-term planning.
4.2.1.2 Application to the Reunion island

In (336,337,338,340), we present a TIMES model dedicated to the electricity sector of the Reunion Island. The small power system of the Reunion Island, weakly meshed and without interconnection, along with the upcoming shares of renewable energy sources exacerbate reliability constraints in the future. Consequently, we seek to implement reliability requirements in the long-term planning exercises of the Reunion Island. The papers present the first results provided by the study of the Reunion Island. The work is still under progress and further results will be presented in a more detailed publication.

Scenarios

The Reunion Island aims to have in 2030 an energy consumption based to 100% on renewable energy sources. This paper (324) focuses on the target applied to the electricity sector, where the current use of renewable energy sources is 36%. Different scenarios have been built around three main assumptions concerning levels of fossil fuels imports, electricity demand, and sugarcane bagasse potential:

- An upper limit for the fossil fuels imports is set in 2008 and linearly decreased to 0 in 2030. The objective is to study the evolution of the electricity production in order to achieve an electricity system without fossil fuels. An alternative scenario limiting only coal imports is designed to soften the previous constraint. The two scenarios are compared to a business-as-usual scenario where no limits are set on the level of importations.

- Two scenarios for electricity demand are considered: a business-as-usual scenario and a scenario with a lower electricity consumption.

- The potential for the renewable energy sources are set at their maximum rates, except for sugarcane bagasse for which two options are considered. One scenario assumes standard improvements of the current potential of sugarcane, and an alternative scenario assumes a higher potential, where the sugarcane industry gives up sugar production and is only dedicated to energy production.

The scenarios are presented in Table 58).

Table 58. Scenarios specification

<table>
<thead>
<tr>
<th>Demand</th>
<th>Limit on imports</th>
<th>Limit on coal</th>
<th>Limit on all fuels</th>
<th>Sugarcane Bagasse</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard Low</td>
<td>MedDEM</td>
<td>MedDEM_NoCOA</td>
<td>MedDEM_NoFOS</td>
<td>MedDEM_NoFOS_UpBAG</td>
</tr>
<tr>
<td></td>
<td>LowDEM</td>
<td>LowDEM_NoCOA</td>
<td>LowDEM_NoFOS</td>
<td>LowDEM_NoFOS_UpBAG</td>
</tr>
</tbody>
</table>

The scenarios are built around three main assumptions concerning electricity demand, fossil fuel imports and sugarcane bagasse potential. The scenario MedDEM corresponds to the business-as-usual scenario.

Height scenarios are built around three main assumptions concerning electricity demand, fossil fuel imports and sugarcane bagasse potential.

Results (Preliminary)

The Figure 304 exhibits the shares of electricity generation for two different scenarios:

- In the business-as-usual scenario (MedDEM), the actual shares of production roughly follow the increase in the demand. In this scenario, there is no development of renewable energy sources despite high potentials.

- In the other scenario (LowDEM_NoFOS_UpBAG), there is a large room for the development of renewable energy sources when a constraint is set on coal or on all fossil fuels import. New renewable energy sources appear such as geothermy, ocean thermal energy, or wave energy. Besides, hydroelectricity increases sharply.
In order to provide plausible options for future power systems that consider reliability of power supply, generation mixes provided by the TIMES model must be assessed in the light of reliability requirements. We propose to assess the reliability of supply when evaluating power systems’ long-term development with the use of two reliability indicators. Further results about reliability of supply of electricity generation in the Reunion Island will be presented in a coming publication.

4.3 Lombardy (Italy)

4.3.1 Regional energy planning

How does it possible to support the energy planning process taking into account environmental, technological, political and economic issues? An useful approach (not the unique) is the development of an energy model (341) that is a mathematical simplified description of energy flows of the regional system, able to investigate different energy paths and the interrelations among all included sectors.

Scenarios

The goal is to to compare different evolutions of the local energy system subject to different environmental policies (Table 59):

- Scenario Alt1: manteins the same assumptions of reference case but includes a constraint on the CO₂ emission according to TheCommissions "2020 by 2020" policy target.
Scenario Alt2: describes the same structure and the same assumptions of BaU but includes a different constraint on the CO₂ emission (wider than the previous one).

Table 59. Scenarios analysed for regional energy planning

<table>
<thead>
<tr>
<th>Target Scenario Alt1</th>
<th>47000 (kt)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Target Scenario Alt2</strong></td>
<td><strong>ETS</strong></td>
</tr>
<tr>
<td>CO₂ Emissions (2005)</td>
<td>24628</td>
</tr>
<tr>
<td>Average European Target / National Target</td>
<td>-21.5%</td>
</tr>
<tr>
<td>Target by 2020</td>
<td>19333</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>59500 (kt)</strong></td>
</tr>
</tbody>
</table>

Results

The environmental target forces the system to use renewable energy sources, as the only way to reduce the CO₂ emissions (Figure 305). Inspite of the modelling of the most optimistic developments for demand sectors, system saturates all the new technologies (new options for each energy service) and also needs important changes in the electricity supply. (import/export+ 50PJ in comparison to the Reference scenario)

Figure 305. Biomass consumption in residential sector

Next steps: Merging of two mono-regional models (Piedmont and Lombardy) in order to create as all multiregional model (2) for testing some specific targets in a cooperative approach in comparison to the single regional models. The development of an Italian multiregional model is starting from the existing TIMES-MATISSE (electricity system) model in collaboration with CESI Ricerca Spa

4.4 Pavia (Italy)

4.4.1 The role of energy efficiency, renewables and cogeneration from biomass

The authors (342) will report the results of an energy planning case study (for an Italian province of half a million people) focused on the impact of the partial achievement of two of the EU commitment for the year 2020: 20% of the electricity (non-industrial use) from renewables and the reduction of 20% of residential electricity consumptions. The study is based on the assessment of feasible use of local biomass, related with the energy modeling of the territory, by focusing on non industrial energy. The residential sector has been analyzed in terms of costs and energy saving potential putting the attention on the impact of White Certificates and on the free riders effect. Methodology applied is ALEP (Advanced Local Energy Planning) developed by IEA whose aim is to develop consistent local energy plans. The used tool is Standard MARKAL, a dynamic energy model generator based on linear programming, written in GAMS.
Scenarios

The BASE scenario includes also two different kinds of subsidies, available at the current situation: (i) the green certificates (GC) for palm-tree oil technologies (12.1 M€/PJ on palm oil consumption); (ii) the short chain supply biomass subsidy (SC), affecting both biogas and rapeseed oil use (28.9 M€/PJ).

In the alternative scenario (S2T20) the aim is to (partially) fulfill two of the EU commitments for the year 2020: (i) deliver the 20% of the electricity (non-industrial use) from renewables (ii) reduction of 20% of residential electricity consumptions.

In order to reach the first goal the economic conditions have been evaluated, allowing new biomass technologies to become competitive by applying an additional subsidy. For reaching the reduction of 20% in residential electricity consumption we change the market hypothesis letting MMPP invest much more in efficient technologies.

Results

The comparison analysis between BASE and S2T20 scenario shows a growing difference of fossil fuel consumptions. The share of CO₂ reduction in S2T20 by comparison with BASE scenario reaches 7% in 2020: this means that the S2T20 configuration is not enough to reach the third UE commitment and a fundamental role is played by the improvement of the efficiency of electricity utilization in tertiary and industrial sectors.

Focusing the attention on the electricity use in residential sector the most considerable result is that the system cost is nearly the same in the two scenarios (Table 60). This means that most efficient technologies are still competitive and a low subsidy is needed in order to make them penetrate the market overcoming the larger initial investment. The gap between the cumulated cost (from 2003 to 2020) of the residential sector in BASE and S2T20 scenario, that could represent the total amount of an hypothetical subsidy, is 1 M€ (mean annual value is 0.06M€). The cumulated value of white certificates (100€/saved tep for a 5 year period) from 2003 to 2020 that derive from the 20% reduction of electricity consumption in residential sector can be estimated in 15M€ (mean annual value is 0.83M€) so the “free riders” total profit reaches 14M€ (mean annual value is 0.78M€) (Table 60).

<table>
<thead>
<tr>
<th>[€/household</th>
<th>2010</th>
<th>2020</th>
<th>2030</th>
</tr>
</thead>
<tbody>
<tr>
<td>BASE</td>
<td>416</td>
<td>494</td>
<td>521</td>
</tr>
<tr>
<td>S2T20</td>
<td>414</td>
<td>502</td>
<td>521</td>
</tr>
</tbody>
</table>

4.4.2 The impact of tightening the EPB directive requirements vs. the promotion of renewable

The aim of this work (343), a case study for the Province of Pavia, Northern Italy (190 municipalities and half a million people), is to analyze and compare different energy development scenarios in order to provide a strategic assessment of measures for the local energy planners, through a bottom up approach with an optimization model (MARKAL Standard). The study focuses on the thermal use of energy in the residential sector, being it the main target of the EPB Directive (2002/91/EC), whose impact is investigated: the rating system (A-rated, B-rated, ...) is considered as an exogenous driver in the assessment of the energy demand and three scenarios have been evaluated and analytically compared in terms of costs and environmental impacts.

Scenarios

- BASE SCENARIO no improvements in the buildings efficiency: the heating demand distribution is kept constant all over the considered period
• 311 SCENARIO the new and renovated buildings are more efficient than in the base year and the most of them are going to be C-rated (according to the taking in of the EBP Directive - 311/06 Italian law)

• CA SCENARIO the most of the new and renovated building fall in the A-rated consumption range and the heating demand drops off

Results

The results focus on the impact of alternative technologies and the role of the public commitment is highlighted in terms of effective policy that could drive both the technological competition and the real estate market to achieve the optimal configuration of the energy system by means of subsidies for renewables technologies (solar thermal, solid biomass boilers and district heating from biofuels) and/or for best rated buildings (Figure 306).

Figure 306. Energy consumption in the three scenario for Pavia

4.5 Southwest region (Sweden)

4.5.1 Biomass gasification in cost-optimized district heating systems

In this study (344), different applications of biomass gasification in connection to district heating (DH) are analysed and contrasted to conventional technology options. An application of the cost-optimizing energy system model MARKAL with a detailed description of the DH sector in a southwestern region of Sweden was developed within the study and used in the analysis. Policy measures for CO₂ reduction and for promotion of “green” electricity are assumed, and required subsidy levels for large-scale production of transport biofuels are calculated. The model also operates with different supplies of biomass: a local supply at a lower cost and an international supply of refined biomass at a slightly higher cost.

Scenarios

Except for a reference case (“REF”) with base assumptions, several additional cases with alternative assumptions are included in the analysis. In each alternative case, one parameter value is altered while all other parameter values are kept the same, with the exception for parameters directly affected by the change according to assumed relationships. For all model cases, the subsidy levels required in order to obtain different numbers of investments in biorefineries, and thereby to reach certain amounts of transport biofuel production, are assessed.

Results

Figure 307 shows the DH production in the reference case, classified according to technologies for different levels of the subsidy for transport biofuels (SNG and DME) and, thereby, different numbers of biorefineries included in the system: (a) no biorefineries, (b) one biorefinery, (c) two biorefineries and (d) three biorefineries.
Figure 307. Production of DH in the reference case for different levels of the biofuel subsidy

Figure 308 illustrates the negative CO\textsubscript{2} emissions, or the CO\textsubscript{2} emission savings, together with the total biomass use of the system for all analysed cases for model year 2019. For all tested cases, it is clear that the CO\textsubscript{2} emission savings outside the system (positive bars) by far exceed the CO\textsubscript{2} emissions from the system’s use of fossil fuels (negative bars).

Figure 308. System’s negative CO\textsubscript{2} emissions and total use of biomass for all analysed cases in 2019*

Scenarios: REF, reference; NG Lo, low natural gas price; GE Lo, low subsidy for green electricity; CO2 Hi, high CO\textsubscript{2} tax, INV Hi, high investment cost for biomass gasification-based plants.

* The electricity production is assumed to replace (fossil) electricity production at the margin and the biofuels are assumed to replace petrol or diesel. Within each model case, different levels of the biofuel subsidy give rise to different numbers of biorefineries in the system: (a) no biorefineries, (b) one biorefinery, (c) two biorefineries and (d) three biorefineries. For the same number of biorefineries, the same amount of biofuel is produced.
In the model-generated results, CHP generation in BIGCC plants is often included in cost-optimized DH systems and shows thus potential of being a cost-competitive future technology alternative. The most favourable conditions for the BIGCC CHP technology is found in the biggest DH system in the studied region, Göteborg, since the heat demand in this system is high enough to allow a BIGCC CHP plant of larger size, which is advantageous due to economies of scale. In the present study, synthetic natural gas (SNG) and dimethyl ether (DME) are included transport biofuel options. For the introduction of large-scale biofuel production in cost-optimized DH systems, a required biofuel subsidy level of 30–40 EUR/MWh was calculated under assumptions of an oil price of 50 USD/barrel, a CO$_2$ tax level increasing from 20 to 40 EUR/ton CO$_2$ from 2009 to 2029 and with base assumptions regarding plant investment costs.

With a limited amount of resources, prioritizing between available options is essential. In the model results, it is observed that when a large part of the available lower cost biomass resources is allocated to production of transport biofuels through high biofuel subsidy levels, conventional biomass ST CHP with higher heat efficiency but with lower electricity output than BIGCC CHP satisfies the heat demand to a lower total system cost than the BIGCC CHP technology. The best conditions for BIGCC CHP plants are, therefore, found in situations with low ambitions regarding transport biofuel production, i.e. with low biofuel subsidy levels. As a consequence, higher levels of transport biofuel production are linked to lower levels of electricity generation in the district heating sector, and this has implications for the CO$_2$ benefits of transport biofuels (Figure 308).

4.6 Kathmandu Valley (Nepal)

4.6.1 Energy and environmental implications of carbon emission targets

This paper (345) analyzes the sectoral energy consumption pattern and emissions of CO$_2$ and local air pollutants in the Kathmandu Valley, Nepal. It also discusses the evolution of energy service demands, structure of energy supply system and emissions from various sectors under the base case scenario during 2005–2050. A long term energy system planning model of the Kathmandu Valley based on the MARKet ALlocation (MARKAL) framework is used for the analyses.

Scenarios

In this study four scenarios are considered: the base case and three alternative scenarios. The base case is defined as the “business as usual” (BAU) scenario. Besides the base case, the following three CO$_2$ mission reduction target (ERT) scenarios are considered in this study:

- Cumulative CO$_2$ emission reduction target of 10% during 2005–2050 as compared to the cumulative emission in the base case, all other things remaining the same as in the base case (hereafter known as “ER10” case).
- Similarly, cumulative CO$_2$ emission reduction target of 20%, (hereafter known as “ER20” case), and
- Cumulative CO$_2$ emission reduction target of 30%, (hereafter known as “ER30” case).

Results

The cumulative final energy consumption (FEC) during 2005–2050 would experience a decrease of 1.0%, 2.8% and 4.6% in ER10, ER20 and ER30 cases, respectively, as compared to the base case.

As a result of CO$_2$ emission limits, the share of the petroleum products in the cumulative FEC would decrease from 28% in the base case to 27% in ER30 case, while coal and lignite use shows a 49% reduction and LPG and CNG would decrease by only about 1% under ER30 (Table 61). On the contrary, the share of biomass would increase from 11% in the base case to 12% under ER30 while electricity use is estimated to increase by almost 1.38 fold under ER30 (i.e., 38% higher than that in the base case). It is interesting to observe that hydrogen fuel vehicles would be adopted from 2045 under ER20 while they would be introduced earlier (from 2035 onwards) under ER30. The share of hydrogen fuel in the
cumulative energy consumption during the entire study period is estimated to be 0.2% under ER20 and 1% under ER30.

**Table 61. Total cumulative energy mix during 2005–2050, PJ**

<table>
<thead>
<tr>
<th>Energy type</th>
<th>Base case</th>
<th>ER10</th>
<th>ER20</th>
<th>ER30</th>
</tr>
</thead>
<tbody>
<tr>
<td>Petroleum products</td>
<td>770</td>
<td>754</td>
<td>729</td>
<td>724</td>
</tr>
<tr>
<td>LPG and CNG</td>
<td>240</td>
<td>240</td>
<td>240</td>
<td>238</td>
</tr>
<tr>
<td>Coal and lignite</td>
<td>574</td>
<td>466</td>
<td>394</td>
<td>291</td>
</tr>
<tr>
<td>Electricity</td>
<td>777</td>
<td>889</td>
<td>991</td>
<td>1073</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>0</td>
<td>0</td>
<td>7</td>
<td>26</td>
</tr>
<tr>
<td>Biomass</td>
<td>300</td>
<td>308</td>
<td>314</td>
<td>317</td>
</tr>
<tr>
<td>Other renewables</td>
<td>41</td>
<td>41</td>
<td>41</td>
<td>41</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>2703</td>
<td>2698</td>
<td>2715</td>
<td>2710</td>
</tr>
</tbody>
</table>

The cumulative CO₂ emissions during 2005–2050 in the base case are estimated to be 124,322 kt CO₂. Figure 309 shows the yearly CO₂ emissions under the base case and different CO₂ emission reduction cases. As can be seen, a substantial reduction in CO₂ emission would take place only after 2040 under ER10, whereas a significant reduction in CO₂ emission would have to start much earlier i.e., after 2030 and 2020 under ER20 and ER30, respectively.

The total system cost would increase by 68 million US$, 256 million US$ and 798 million US$ under ER10, ER20 and ER30, respectively, as compared to the base case i.e., an increase of 0.5%, 1.9% and 6.0% in ER10, ER20 and ER30 cases, respectively.

**Figure 309. Yearly CO₂ emissions under base case and different CO₂ ERTs**

The paper shows that a major switch in energy use pattern from oil and gas to electricity would be needed in the Valley to achieve the cumulative CO₂ emission reduction target of 30% (ER30). Further, the share of electricity in the cumulative energy consumption of the transport sector would increase from 12% in the base case to 24% in the ER30 case.
5. Studies and Projects using Local MARKAL and TIMES Models

5.1 Urban planning in Salzburg (Austria)

5.1.1 Developing a Roadmap for the Future Energy Infrastructure in Salzburg

The main objective of the project presented in this paper (346,347) is to develop a roadmap for the future energy infrastructure in the city of Salzburg with focus on optimising heat supply chains using mathematical energy models. The paper describes a new methodology, which is able to give the required answers and which will help municipalities to keep or better increase the value of their assets in future. The work focuses on the district heating system, while the methodology could well be extended to other fields.

To this end a family of loosely coupled software tools is developed: (a) an energy system model of Salzburg having two major parts: a first part describing the complete housing stock and the possible refurbishment options and a second part describing in detail the possible heat supply options including a refined representation of the district heating system; (b) the asset management tool FAST (Fichtner Asset Services and Technologies) which proposes best maintenance strategies and offers estimates of the long term operational costs of the systems (c) the programme SisHyd which is used to make rather technical evaluations of the possible network extension or reduction programmes.

Scenarios

Two different heat demand scenarios - for high and low energy prices - were calculated for the residential sector (space heating and hot water). The heat price scenarios are illustrated in Figure 310. The energy price scenarios have been defined based on in-house data from the energy trading department (short term development) and data from EU DG TREN “European Energy and Transport” studies; long term scenarios) with support by experts from the Energy Economics Group (EEG) of TU Vienna.

Figure 310. Assumed heat price developments for high and low energy price scenario, full costs of heat

Results (Preliminary)

Figure 311 gives an impression about the development of the heat demand as it shows the heat demand in the year 2030 based on the same building stock according to a high price scenario. The results are still preliminary because the first user constraint mentioned above is not set and consequently the model just implements the least cost intensive refurbishment measures. This in turn leads to a slight overestimation of the long term heat demand.

A first rough estimation: setting the border for supplying a cell economically with a district heating infrastructure at a value of 1,000 MWh, one can see which cells would have enough heat demand for that energy source in the future. This indicates that district heating systems might have the potential to play a central role in heat supply of urban areas in the next decades and to contribute significantly in
reaching political goals by an efficient and cost effective path. Actually the best way of supplying the calculated heat demand is analysed in more detail applying the heat supply model.

Figure 311. Heat demand of the residential sector in Salzburg in 2030, high price scenario

A special model was created to define district heating expansion projects automatically in more detail. The goal of this model was to find which street segments in a defined region should be connected to the district heating system and which should be better left out by pure economic reasoning (matching required length of pipeline and connectable heat load / heat demand). This model can also be used to analyse the connection densification potential in areas which are already supplied with DH and to determine the maximum DH connection density in an area under certain economic conditions (e.g. amount of connection fees to be paid from the consumers).

Figure 312. Heat generation units and heat flow into the raster cells (regions) for 2005
As an example how results of the heat supply model can look like Figure 312 shows the calculated district heating flows into the regions (raster cells) in the year 2005. One can see the major lines of heat supply starting from the heat sources (combined heat and power plants and heating stations). The major result of the project will be a consistent bundle of measures concerning re-design of pipeline-bound energy infrastructure in Salzburg. The main focus is the optimisation of the district heating (DH) and natural gas grid infrastructure in the city of Salzburg. The resulting “energy infrastructure roadmap” will also serve as a basis for improving middle and long-term coordination between planned construction, re-construction and maintenance projects for the energy infrastructure of the multi utility company Salzburg AG with projects regarding infrastructure owned by the city of Salzburg like sewage water system and road works.

5.2 Rural Areas (Germany)

5.2.1 Spatial optimization of rural energy systems with focus on biomass

Facing the characteristics of rural energy systems and the competition of food versus energy an optimization model of rural energy systems is developed. In order to achieve transferability the model is based on public spatial data. The high spatial resolution enables a better representation of interdependencies of local structures and local energy systems. To offer small communities a decision support tool, a computer based optimization model for regional energy systems is developed (348).

Using the data derived from the GIS models and the assumptions on harvesting and on energy conversion processes, including investment costs and maintenance costs, and assumptions on commodities the input data for the TIMES model are developed. In order to develop scenarios assumptions on general conditions and future developments (e.g. oil and milk prices) are elaborated. The model is implemented as a case study for the municipality St. Roman in Austria and the results allow diverse analysis.

Results

The scenarios in the case study demonstrate the high potential of rural areas regarding a sustainable energy supply. The change from oil heating to heating systems based on wood chips, split logs and biogas brings an intense reduction of CO₂ emissions in the heating sector (Figure 313).

Figure 313. Energy mix

For the testing municipality an expansion of district heating can be recommended, what can be supported by strategic municipal energy planning. Moreover measures to mobilize unused forest stand are obvious, in order to supply the high biomass demand within the own municipality (Figure 314).
The model results provide an instrument of communication for municipal stakeholder, which shows interrelations within the energy system and between energy system and agriculture as well as forestry. In addition the results serve as basis for the derivation of strategies and measures. An expansion of the model with further processes and commodities may lead to differing results and the presented model is subject to further evaluation and application in testing regions. Moreover further investigation on energy demand estimations are carried out and include approaches based on information about effective building areas.

Figure 314. Land use

5.3 Rural and Urban Areas (Austria and Germany)

5.3.1 Energy models for urban planning

5.3.1.1 Approach and methodology

The energy and system analysis group at the IPP has applied TIMES to model the energy systems of urban and rural areas. Three kinds of models were designed (249):

- 1. Models covering all sectors in the city. The first kind of model was applied in Greifswald and Oldenburg to define GHG emission targets.
  - ⇒ Models focusing on the heat demand
  - ⇒ Models of land use and energy demand of rural areas
- The second model was applied in Salzburg to define a strategy to enlarge the district heating system. The central features of the model were a very high spatial granularity and the option to decide by a binary variable if or not a special enlargement project was applied. By the later feature it was possible to model real project plans of the local heat supplier.
- The last kind of model is mainly used to understand the possibility of rural areas to become self-sufficient in regard of energy. The energy model is coupled with a simple land-use model which is also implemented in TIMES.

5.3.1.2 Economic effects of GHG emissions reduction on a local level

This presentation (350) focuses on the applications of a model for a middle-sized city. The investigation area is Greifswald in the northeast of Germany, situated in the federal state Mecklenburg- Western Pomerania and which is famous for tourism and intensive agriculture and having a low population density (55,000 inhabitants). The City has a very small industrial sector and the main economic sectors are a university, the university clinic centre and a lot of administration. More than 90% of the electricity supply and the heat supply are provided by the local municipal utility. The energy production is characterized by using of combined heat and power plants. The approach involves the development of an energy model and a simplified model of the local economy, using the TIMES framework.
Scenarios

The approach uses a quantitative analysis of different measurements, which are changing energy supply and demand (Table 62), and the analysis of the reactions of the economic system in order to valuating the different measurements in reference to their economic consequences.

Table 62. Scenarios analyzed with a middle-sized city model

<table>
<thead>
<tr>
<th></th>
<th>Basis</th>
<th>Growth</th>
<th>CO2-Cap</th>
<th>Biogas</th>
<th>Reconstruction</th>
<th>SolarCity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Population/ households</td>
<td>constant/ constant</td>
<td>low increasing/ increasing</td>
<td>constant/ constant</td>
<td>constant/ constant</td>
<td>constant/ constant</td>
<td>constant/ constant</td>
</tr>
<tr>
<td>Jobs/ sector allocation</td>
<td>constant/ constant</td>
<td>increasing/ tertiary sector increase</td>
<td>constant/ constant</td>
<td>constant/ constant</td>
<td>constant/ constant</td>
<td>constant/ constant</td>
</tr>
<tr>
<td>University size</td>
<td>constant</td>
<td>increasing</td>
<td>constant</td>
<td>constant</td>
<td>constant</td>
<td>constant</td>
</tr>
<tr>
<td>Reconstruction rate</td>
<td>low</td>
<td>mid</td>
<td>mid</td>
<td>low</td>
<td>high</td>
<td>low</td>
</tr>
<tr>
<td>Energy prices</td>
<td>increasing</td>
<td>increasing</td>
<td>high increasing</td>
<td>increasing</td>
<td>increasing</td>
<td>increasing</td>
</tr>
<tr>
<td>CO2-prices</td>
<td>increasing</td>
<td>increasing</td>
<td>high increasing</td>
<td>increasing</td>
<td>increasing</td>
<td>increasing</td>
</tr>
<tr>
<td>District heating grid</td>
<td>constant</td>
<td>enlargement possible</td>
<td>enlargement possible</td>
<td>enlargement possible</td>
<td>enlargement possible</td>
<td>enlargement possible</td>
</tr>
<tr>
<td>Electricity appliances</td>
<td>constant</td>
<td>increasing</td>
<td>increasing</td>
<td>increasing</td>
<td>increasing</td>
<td>constant</td>
</tr>
<tr>
<td>Scenario specific parameter</td>
<td>-</td>
<td>-</td>
<td>CO2-emission cap</td>
<td>biogas in the grid and biogas cfp</td>
<td>Subsidies for reconstruction</td>
<td>Minimum level for photovoltaic and solar thermal systems</td>
</tr>
</tbody>
</table>

Results

There is a huge potential for reducing CO2-emission on the local level (Figure 315). Reconstruction is one of the most efficient ways to reduce energy consumption. The use of biomass in stationary systems is an efficient way to reduce CO2-emissions. It’s very important to consider the specific possibilities but the specific problems of local energy systems.

Figure 315. Electricity consumption of households

5.3.1.3 Different model sizes for different questions

Models of different sizes deals with different types of questions. Three different sized examples are presented in this presentation (351).

- Small sized, for which the central question is: to which extend can biomass and agricultural residues be used to substitute commercial energy carriers without challenging food production? Consequently, the model needs to cover land use and agricultural product flows.
• Medium sized, for which the central question are: what is the optimal space heat supply technology? How can a good balance between refurbishment and sustainable supply technologies be found?

• Large sized, for which the central question is: Can European legislations be fulfilled?

Scenarios

An example of framework for medium sized cities was presented and consists in two part:

• TIMES-Buildings: The city is subdivided in 250*250 m² raster and each building is classified following a more or less self made building typology. Each type is a process in the model so there are refurbishment options. Building construction and demolishment is done “by hand”. Limits on refurbishment rates are major constraints. The development of the heat price is give exogenously. Finally, the existing district heating network is described by the exchange power between adjacent networks and power plants are individually modelled.

• TIMES-Networks: The city is subdivided in 250*250 m² raster and in each raster the heat demand is taken from TIMES building. Local heating technologies are described individually in each raster. The district heating network is described by the exchange power between Raster and the individual power plants. Constraints are put on CO₂ emissions and local air emissions like NOx and dust. Renewable heat needs to supply certain fractions. Finally, new networks are described by “projects”, which can be constructed or rejected by the optimisation.

Results

The district heating network for medium sized city as modelled by TIMES is illustrated in Figure 316. But what is still missing? Better models of “end users” and their behaviour, new approaches in quantititative urban development (like cellular automata - multi agent model) and ways to combine these models with energy models, tools need to be supplied to introduce energy in the daily city planning processes.

Figure 316. TIMES networks, medium sized city

5.4 Val d’Agri (Italy)

5.4.1 Integrated evaluation of the environmental impact of anthropogenic activities

The implementation of resource management strategies aimed at reducing the impacts of the anthropogenic activities system requires a comprehensive approach to evaluate on the whole the environmental burdens of productive processes and to identify the best recovery strategies from both an environmental and an economic point of view. In this framework, an analytical methodology based on the integration of Life Cycle Assessment (LCA), ExternE and Comprehensive Analysis was developed to perform an in-depth investigation of energy systems. This paper (352) presents an integrated application of these three methodologies to a local scale case study (the Val D’Agri area in Basilicata,
Southern Italy), aimed to better characterise the environmental impacts of the energy system, with particular reference to extraction activities.

**Scenarios**

The Reference scenario (Business As Usual—BAU case) implements the PER hypotheses as concerns the contribution of renewable sources (PV, wind, biomass and mini-hydroelectric). Efficiency increase due to technology turnover as well as energy conservation measures in residential (double glazed windows and thermal insulation of roofs, ceilings and external walls) were taken into account.

Two additional scenarios were defined to examine and compare the effects on the energy system’s configuration, costs of constraints on environmental impacts and eco-taxes on the main pollutants. As shown in Table 63, the Impacts scenario, includes four cases that analyse the effects of exogenous constraints on aggregated impacts indicators, whereas the Ecotaxes scenario, includes six cases in which the external costs were introduced as taxes on local air pollutants (NOx, SO2, TSP and VOC) as well as on CO2, to evaluate their influence on the system configuration and to assess their synergies.

**Table 63. Main scenarios assumptions**

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Cases</th>
<th>Main features</th>
<th>Constraints</th>
<th>External costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference</td>
<td>BAU</td>
<td>Do nothing</td>
<td>No</td>
<td>All pollutants, ex post</td>
</tr>
<tr>
<td>Impacts</td>
<td>Greenhouse</td>
<td>Constraint on Greenhouse Effect</td>
<td>–1.1% Greenhouse Effect</td>
<td>All pollutants, ex post</td>
</tr>
<tr>
<td></td>
<td>Acidification</td>
<td>Constraint on Acidification</td>
<td>–0.6% Acidification</td>
<td>All pollutants, ex post</td>
</tr>
<tr>
<td></td>
<td>Smog</td>
<td>Constraint on dusts level</td>
<td>–1.5% Smog</td>
<td>All pollutants, ex post</td>
</tr>
<tr>
<td></td>
<td>Mix</td>
<td>Combined constraint on environmental impacts: Greenhouse Effect + Acidification + Smog</td>
<td>–1.1% Greenhouse Effect; –0.96% Acidification; –0.02% Smog</td>
<td>All pollutants, ex post</td>
</tr>
<tr>
<td>Eco-taxes</td>
<td>TAX-CO2</td>
<td>19 Euro/ton on CO2</td>
<td>No</td>
<td>CO2, ex ante</td>
</tr>
<tr>
<td></td>
<td>TAX-NOX</td>
<td>7100 Euro/ton on NO2</td>
<td>No</td>
<td>NO2, ex ante</td>
</tr>
<tr>
<td></td>
<td>TAX-SO2</td>
<td>5000 Euro/ton on SO2</td>
<td>No</td>
<td>SO2, ex ante</td>
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<tr>
<td></td>
<td>TAX-TSP</td>
<td>12000 Euro/ton on TSP</td>
<td>No</td>
<td>TSP, ex ante</td>
</tr>
<tr>
<td></td>
<td>TAX-VOC</td>
<td>2800 Euro/ton on VOC</td>
<td>No</td>
<td>VOC, ex ante</td>
</tr>
<tr>
<td></td>
<td>TAX-TOT</td>
<td>Taxes on all the analysed emissions (CO2, NOx, SO2, TSP, VOC)</td>
<td>No</td>
<td>All pollutants, ex ante</td>
</tr>
</tbody>
</table>

**Results**

It can be seen that the lowest values for NOx and SO2 are obtained in the Mix case (respectively +0.05% and +1.19% respect to the BAU case), for TSP and VOC in Acidification and Smog (respectively +0.12% and +0.01%). As concerns CO2, the minimum is achieved obviously in the Greenhouse case (+7.27% respect to the BAU case) but a noticeable reduction is observed also in the Mix case (+5.70% respect to the BAU case). These data highlight the effectiveness of the constraints on the aggregated impacts that allow reducing single pollutants emissions emphasising at the same time the cause–effects relationships. The introduction of exogenous environmental constraints causes an obvious increase of the total system cost (Figure 317), the highest value being achieved in the Greenhouse case (1207 MEuro) and the smallest in the Smog case (1039 MEuro).

**Figure 317. Total system costs of impact scenario’s cases**

The scenario analysis shows once more that efficiency increase and energy saving are privileged tools for driving a steady reduction of energy consumption, whereas renewable energy sources have a key role in the supply system but need an in depth characterisation of the construction and dismantling
phases, that may contribute heavily to environmental damage. As concerns the integration of externalities, eco-taxes are important to estimate fair prices of resources and to promote the use of eco-compatible technologies and resources. In fact, including the environmental component in the costs of goods and services, it is possible to reduce the cost gap among traditional and innovative technologies.

5.4.2 Comprehensive energy systems analysis support tools for decision making

This work (353) was aimed to support the definition of sustainable energy-environment strategies focused on the reduction of the whole environmental burdens related to the Val D’Agri (Basilicata region, Southern Italy) energy system. The case study considered is a place of naturalistic interest that has been interested, in the last decades, by a huge development of oil mining activities, representing the largest oilfield of Italy. An innovative approach was applied, based on the integration of MARKAL models generator with Life Cycle Assessment (LCA) and ExternE results.

Scenarios

A reference scenario (BAU) was implemented to calibrate the MARKAL Val’d’Agri model and to point out the unconstrained optimized development of the energy system with reference to the standard commodities and to the additional environmental parameters (aggregated impacts indicators) provided by LCA.

Beside the reference scenario, three environmental scenarios were analyzed: CO₂, Impacts and Ecotaxes.

- The CO₂ scenario includes three cases with increasing constraints on CO₂ emissions (from 1% to 5% of the whole time horizon BAU levels);
- the Impacts scenario, is made up of four cases that analyze the effects of exogenous constraints on aggregated impacts indicators (respectively, Greenhouse effect, Acidification, Smog, and a combination of these three indicators-Mix), whereas in
- the Eco-taxes sce and then all together (Tax-TOT case), to evaluate the economic impact of environmental pollution and the effectiveness of environmental taxes in mitigation strategies.

Results

The observed energy reduction increases about 1% in the environmental constrained scenarios, in which some changes in resource use can be observed, with particular regard to electricity production.

Figure 318. Electric energy production by fuel in the four impacts scenarios
The reduction of anthropogenic environmental impacts is in fact obtained by increasing the endogenous production of electricity by renewable (+17%), in particular wind energy and mini-hydro, which substitute the thermal plants and the imports from neighbour regions (Figure 318).

The environmental constraints determine obviously an increase of the total discounted energy system cost which ranges from 2 to 15% (in detail, Smog: +1.5%, Acidification: +1.8%, Mix: +8.7%, Greenhouse effect: +15.2%). Taking into account the total emission levels achieved in the three CO₂ scenario cases (Figure 319) the average cost of CO₂ reduction is about 167 Euro/ton.

Figure 319. Total system cost increase vs. CO₂ abatement percentages

A comparison of the results obtained in the different scenarios allows deriving some general considerations:

- the reduction of energy consumption is a privileged tool for defining sustainable energy-environmental policies and can be obtained by an increase of efficiency and energy saving interventions;
- an increasing use of renewable energy sources is a key issue for improving air quality, allowing a reduction of atmospheric pollution due to combustion processes and reducing energy dependence, which represents one of the main objectives of the European Commission;
- the evaluation of environmental impacts should be based on the overall life cycle of goods and services, taking into account also construction and disposal phases, in order to avoid wrong conclusions related only to the use phase;
- the cost increase due to the necessity to reduce pollutant emissions and the cost gap among traditional and innovative technologies should be evaluated also with reference to external costs, in order to take into account environmental benefits related to avoided emissions;
- Eco-taxes can be an effective tool in environmental and economic terms to reorient consumers and enterprises towards eco-compatible products, processes and services.

5.5 Madrid (Spain)

5.5.1 Market penetration analysis of the use of hydrogen in the road transport sector

Nobody can doubt today that hydrogen will, in the not-too-distant future, represent a very significant percentage of the total energy used by the transport sector. This study (354) therefore consists of the modelling and simulation of energy consumption, by type of vehicle and fuel or energetic vector, in the road transport sector of the Madrid Region, during the period 2010–2050, using the MARKAL model. It
has been necessary to complete this model by adding numerous specifications in order to determine the features of the Madrid Region, the richest Region in Spain.

**Scenarios**

We proposed two scenarios: the Base scenario, which would occur if the current growth trends for energy consumption continued, and the Energy Efficiency scenario, which considers efficient measures taken to reduce such growth.

**Results**

Figure 320 shows the results of the Base simulation of the energy demand in the transport sector, expressed in PJ, by year and type of fuel and energy vector used.

**Figure 320. Evolution over time of the total demand for energy for all vehicles**

As for the other two simulations, Minimum and Maximum, the results are shown in Figure 321, in order to be able to appreciate the differences with the Base simulation model.

In the three scenarios simulated in this study, the consumption levels of road transport in the Madrid Region in 2050 will be divided as follows:

- In the so-called Minimum scenario, slightly more than half the consumption will be covered by alternative fuels and energy vectors, mainly hydrogen, but almost half will still be covered by conventional fuels.
- In the Base scenario, slightly more than half this consumption will be covered by hydrogen, almost a quarter by conventional fuels and almost another quarter by alternative fuels and electricity.
- In the Maximum scenario, almost all the road transport demand will be met by alternative fuels and energy vectors, with hydrogen representing over two-thirds of the total.

The results show a profound change in the current situation as there is a significant decrease in the consumption of fossil fuels and an increase in that of alternative non-fossil fuels and hydrogen. The latter, in particular, will rise from 0.1% in the year 2010, to around 50% in the year 2050, which will mean a drastic drop in the sector’s CO₂ and atmospheric pollutant emissions.
5.6 Beijing, Guangdong and Shanghai (China)

5.6.1 The future of natural gas consumption

Natural gas could possibly become a significant portion of the future fuel mix in China. However, there is still great uncertainty surrounding the size of this potential market and therefore its impact on the global gas trade. In order to identify some of the important factors that might drive natural gas consumption in key demand areas in China, we focus (355) on three regions: Beijing, Guangdong, and Shanghai. Using the economic optimization model MARKAL, we initially assume that the drivers are government mandates of emissions standards, reform of the Chinese financial structure, the price and available supply of natural gas, and the rate of penetration of advanced power generating and end-use.

Scenarios

To examine the influence of SO$_2$ constraints, we developed three “core” scenarios. In the base case reference scenario (R), we assume no changes are made to the status quo. The reference case scenario only includes policies that are currently implemented, as well as highly likely extensions of those policies. From this starting point, there are two main scenario developments. We also combined the factors with each other in ways shown in Table 64. In all, we looked at 12 scenarios. These scenarios allow us to explore four broad hypotheses:

- A. Policies which constrain total SO$_2$ emissions from the entire system lead to increased natural gas consumption.
- B. The rate of technological diffusion significantly influences the amount of natural gas consumed within the system.
- C. Varying the cost of capital for different sectors has an effect on energy consumption patterns.
- D. Gas prices and the availability of gas are important factors in determining which sector consumes what volume of natural gas.
Table 64. Summary of scenarios in this study

<table>
<thead>
<tr>
<th>Primary runs</th>
<th>Primary assumptions</th>
<th>Secondary runs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference (&quot;R&quot;)</td>
<td>Status quo emissions control</td>
<td>1.5% annual market share growth of new demand technology 10% discount rate for all sectors No gas supply from Russia (LNG availability unconstrained)</td>
</tr>
<tr>
<td>Plausible (&quot;P&quot; scenarios)</td>
<td>40% SO₂ reduction</td>
<td>P: Reference secondary assumptions Same as reference P,Fast: faster penetration of demand technologies 3%, 5% annual market share growth of new demand technology P,Diffcost: different costs of capital 5.8% for power sector 10% for industrial 25% for residential and commercial Gas supply from Russia available (LNG availability unconstrained)</td>
</tr>
<tr>
<td>Aggressive (&quot;Ag&quot; scenarios)</td>
<td>75% SO₂ reduction</td>
<td>P,Moregas: high availability of cheap gas Same as reference Ag,Fast: Faster penetration of demand technologies 3%, 5% annual market share growth of new demand technology Ag,Diffcost: different costs of capital 5.8% for power sector 10% for industrial 25% for residential and commercial Gas supply from Russia available (LNG availability unconstrained)</td>
</tr>
<tr>
<td>Plausible w/ more gas availability (&quot;C&quot; scenarios)</td>
<td>40% SO₂ reduction</td>
<td>M,Moregas: high availability of cheap gas M,Diffcost: Different costs of capital 3%, 5% annual market share growth of new demand technology gas supply from Russia available (LNG availability unconstrained) M,Exp: More expensive oil and gas 5.8% for power sector 10% for industrial 25% for residential and commercial Gas supply from Russia available (LNG availability unconstrained) at a more expensive price</td>
</tr>
</tbody>
</table>

Results

Figure 322 shows projections of natural gas consumption for the reference (R), plausible (P, 40% reduction in emissions), and aggressive (Ag, 75% reduction) scenarios from 2000 to 2020 in all three areas. The estimates for consumption vary widely depending on which SO₂ constraint is implemented in the system. These results suggest that a tighter SO₂ constraint leads to more gas demand. While these results shed some light on the sensitivity of the model to SO₂ policies, a deeper understanding of the system comes from looking at the projections within each of the three city regions.

In summary, as a supply-constrained market, Guangdong is the only region that is sensitive to the availability of new supplies of gas. In particular, we explore the hypothesis that limits on SO₂ could yield, incidentally, some reduction in CO₂ due to greater use of natural gas. CO₂ emissions reductions in response to SO₂ limits are most apparent in Guangdong. If we take the case of the aggressive scenario, about 99 million tons less of coal would be used in 2020 compared with the reference case. Figure 323 explains the carbon consequences of this fuel switch for Guangdong. About 57 million tons of CO₂ emissions can be averted by imposing a 75% emissions cap on SO₂ emissions.

Figure 322. Natural gas consumption for all study areas in reference and SO₂ constrained scenarios
5.7 New York City (United States)

5.7.1 A tool for integrated energy, waste, water and GHG emission analysis

The results from the model show that the level of natural gas consumption is most sensitive to policy scenarios, which strictly limit SO2 emissions from power plants. The model also revealed that the low cost of capital for power plants in China boosts the economic viability of capital-intensive coal-fired plants. This suggests that reform within the financial sector could be a lever for encouraging increased natural gas use.

The study suggests five key findings on the competitiveness of natural gas in China over the next two decades.

- First, China is a supply-constrained environment for natural gas.
- Second, gas demand is highly dependent on financial policies.
- Third, the industrial sector can in some cases be more attractive for fuel switching than the power sector.
- Fourth, the fuel mix for electricity generation is unlikely to change dramatically.
- Fifth, non-climate policies could have a large impact on carbon emissions. For example, in the case of China, a cap on SO2 emissions could have a significant effect on CO2 emissions by promoting the use of cleaner burning fuels and more advanced technology.
environmental regulatory regime, including multi-media aspects of carbon control, at the Regional or National level. The stakeholder collaboration using the Urban MARKAL framework will help cast studies that meet all future validation criteria for GHG under regional Protocols, such as the Regional Greenhouse Gas Initiative, Energy Star, Landfill Methane Outreach Program (LMOP), Transportation and Air Quality Program, Green Power Partnerships and a possible federal cap and trade regime.
6. References

**Type of reference**

0 = Online information  
1 = Presentations  
2 = Research papers/reports (or long abstract)  
3 = Peer-review articles  
4 = Books or book chapters  
5 = Ph.D. Thesis

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**Global - ETP**

**ETSAP - TIAM**

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**ETSAP-TIAM-IER**


**Global - EFDA**

| 70 | Han W.E. Ward D.J. (2009). Revised assessments of the economics of fusion power. Fusion Engineering and Design 84: 895–898. | 3 | TIMES | Global: EFDA |

**Global – Others**

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### Regional: Other Europe

| 120 | Reiter U. (2010). Assessment of the European energy conversion sector under climate change scenarios. Ph.D. Thesis. ETH Zurich, Switzerland and Germany, 204 p. | 5 | MARKAL | Regional: EU | |

### Regional: Other Asia

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### National

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### Belgium

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<th>Journal</th>
<th>Keywords</th>
</tr>
</thead>
<tbody>
<tr>
<td>141</td>
<td>Renders N.</td>
<td>ECM Households: How to deal with no-regret measures? VITO, Flemish Institute for Technological Research, Belgium. Proceedings of the ETSAP workshop, Venice (Italy), June 16, 2009.</td>
<td>2009</td>
<td>MARKAL</td>
<td>National: Belgium (Flanders)</td>
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</tbody>
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### China

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<th>Journal</th>
<th>Keywords</th>
</tr>
</thead>
<tbody>
<tr>
<td>142</td>
<td>Wenyong C.</td>
<td>Recent MARKAL related modelling activities. Tsinghua University, China. Proceedings of the ETSAP workshop, Nice (France), December 15-17, 2008.</td>
<td>2008</td>
<td>MARKAL</td>
<td>Nation: China Local: Beijing</td>
</tr>
<tr>
<td>143</td>
<td>Wenyong C.</td>
<td>China’s energy and carbon options. Tsinghua University, China. Proceedings of the ETSAP workshop, Nice (France), December 15-17, 2008.</td>
<td>2008</td>
<td>MARKAL</td>
<td>National: China</td>
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<tr>
<td></td>
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<tr>
<td>149</td>
<td>The impacts of EU CO2 emissions trading on electricity markets and electricity consumers in Finland. Energy Economics 30 : 193–211.</td>
<td>Shukla S.</td>
<td></td>
<td>3</td>
<td>TIMES</td>
</tr>
</tbody>
</table>
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<th>Title</th>
<th>Publication Details</th>
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<tbody>
<tr>
<td>179</td>
<td>Gargiulo M. De Miglio R. Lanati F. Gelmini A.</td>
<td>A power generation scenario with the MATISSE model for Italy and how to move from MATISSE to MONET. E4SMA S.r.l. RSE S.p.A. Proceedings of the ETSAP workshop, Cork (Ireland), November 24, 2010.</td>
<td>1</td>
</tr>
<tr>
<td>180</td>
<td>Santi F. Gargiulo M. Gusmerotti M. Camporeale C. Carcasi G.</td>
<td>Electricity storage in Italy: a long term cost-benefit analysis conducted with a markal-times model of the italian electrical system. Proceedings of the 11\textsuperscript{th} IAE European Conference, Vilnius (Lithuania), August 25-28, 2010.</td>
<td>2</td>
</tr>
<tr>
<td>181</td>
<td>Gracceva F. Ciorba U. Tosato G.C. Gargiulo M.</td>
<td>The path towards the calibration of the extracted region: the example of Italy. Italian Agency for Energy, New technology and Environment, Italy. Proceedings of the ETSAP workshop, Paris (France), July 3-4, 2008.</td>
<td>1</td>
</tr>
<tr>
<td>184</td>
<td>Gracceva F.</td>
<td>Cost estimations of mitigation policies for 20-20 and beyond experiences (and ongoing research) in supporting Italian policymakers. Italian Agency for Energy, New technology and Environment, Italy. Proceedings of the ETSAP workshop, Nice (France), December 15-17, 2008.</td>
<td>1</td>
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<td>Page</td>
<td>Author(s)</td>
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</tr>
<tr>
<td>208</td>
<td>Fidje A.</td>
<td>Towards a Norwegian regional TIMES model. Institute for Energy Technology (IFE), Norway. Proceedings of the ETSAP workshop, Nice (France), December 15-17, 2008.</td>
<td>2008</td>
</tr>
<tr>
<td>209</td>
<td>Cleto J. Simões S. Fortes P. Seixas J.</td>
<td>The role of cost-effective measures in Portugal for compliance with the EU climate-energy targets. New University of Lisbon, Portugal. Proceedings of the ETSAP workshop, Paris (France), July 3-4, 2008.</td>
<td>2008</td>
</tr>
<tr>
<td>ID</td>
<td>Title</td>
<td>Authors</td>
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<tr>
<td>212</td>
<td>The impact of climate change mitigation options on air pollutants emissions in Portugal. Center for environmental and sustainable research (CENSE), New University of Lisbon, Portugal. Proceedings of the ETSAP workshop, Stockholm (Sweden), June 24, 2010.</td>
<td>Dias L., Gouveia J., Mauricio B., Fortes P., Seixas J.</td>
<td>1,2 TIMES</td>
</tr>
<tr>
<td>213</td>
<td>Quantifying the contribution of different exogenous assumptions on the uncertainty of GHG emission scenarios: case-study of the 2020 estimates for Portugal. Center for environmental and sustainable research (CENSE), New University of Lisbon, Portugal. Proceedings of the ETSAP workshop, Stockholm (Sweden), June 24, 2010.</td>
<td>Simões S., Seixas J., Fortes P.</td>
<td>1,2 TIMES</td>
</tr>
<tr>
<td>214</td>
<td>Forecasting of residential energy services demand: The Portuguese case for 2030. Center for environmental and sustainable research (CENSE), New University of Lisbon, Portugal.</td>
<td>Gouveia J., Fortes P., Seixas J.</td>
<td>3 TIMES</td>
</tr>
<tr>
<td>220</td>
<td>A representation of the Slovenian energy system using the NEEDS times model. Fresenius Environmental Bulletin 17 (9b): 1403-1411.</td>
<td>Loperte S., Cosmi C., Di Leo S., Macchiato M., Pietrapertosa F., Salvia M., Cuomo V.</td>
<td>3 TIMES</td>
</tr>
<tr>
<td>221</td>
<td>Technology learning for renewable energy: Implications for South Africa’s long-term mitigation scenarios.</td>
<td>Winkler H., Hughes A., Hawb M.</td>
<td>3 TIMES</td>
</tr>
<tr>
<td>222</td>
<td>Long Term Mitigation Scenarios For South Africa. Prepared for: Department of Environment Affairs and Tourism South Africa. Technical Summary,19 p.</td>
<td>ERC - Energy Research Centre</td>
<td>2 TIMES</td>
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Spain
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<td>249</td>
<td>Van den Broek M. Ramirez Ramirez A. Brederode E. Kramers L. Van der Kuip M. Wildenborg T.</td>
<td>Combining MARKAL and ArcGis for the design of a CO2 infrastructure tuned to the development of the energy system Case of the Netherlands. Utrecht University, Copernicus Institute, The Netherlands. Proceedings of the ETSAP workshop, Paris (France), July 3-4, 2008.</td>
<td>MARKAL of the Netherlands</td>
<td>National: The Netherlands</td>
<td>MARKAL</td>
<td>The Netherlands</td>
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<tr>
<td>318</td>
<td>Role of Biomass-to-Hydrogen in Deep CO2 Emission Reduction Scenarios</td>
<td>Friley P. Allståd T. Politis S.</td>
<td>Proceedings of the ETSA Symposium, Stockholm (Sweden)</td>
<td>2010</td>
<td>MARKAL, National: USA</td>
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<tr>
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<td>Title</td>
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<td></td>
</tr>
<tr>
<td>347</td>
<td>Botzhart F. Mühlich P. Hamacher T. Reiter D. (2010). Modelling the heat supply system of a city in TIMES, High local resolution and the integration of boundary conditions from a building database. Max-Planck-Institut für Plasmaphysik, Germany. Submitted to the International Energy Workshop (IEW), Stockholm (Sweden), June 21-23, 2010.</td>
<td>1 TIMES</td>
<td>Local: Cities in Germany</td>
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<tr>
<td>Van Regemorter D. (2010). Economic Cost of Climate Change in Europe: Outcome of the PESETA Project.</td>
<td>CES KU-Leuven.</td>
<td>1</td>
<td>GEM-E3 s.o.</td>
<td></td>
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