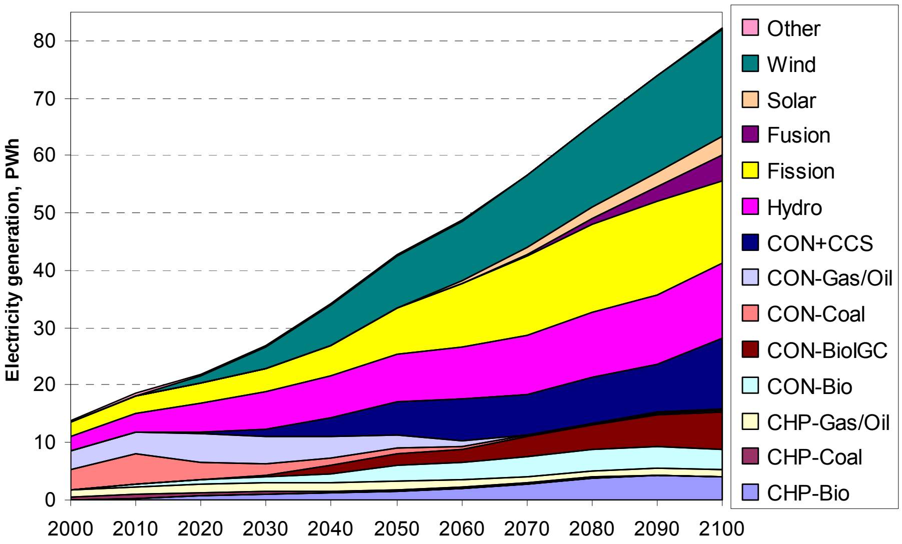
Global energy and emissions scenarios for effective climate change mitigation

- Modelling study with the ETSAP/TIAM model



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Preface

This report describes a scenario study on global climate policy and greenhouse gas mitigation scenarios prepared by VTT for the Finnish Ministry of Environment to support the international climate negotiations during the Finnish EU presidency in 2006. The modelling work concentrated on modelling the achivement of the 2 ºC stabilization target of the EU.

The global energy and greenhouse gas emissions scenarios studied in this work have been compiled with the global TIAM (Times Integrated Assessment Model) energy system model developed under the IEA/ETSAP Programme. The scenario studies compiled here have been presented to representatives of various Finnish ministries and EU experts in different phases of the work for getting comments and feedback.

The scenario modelling work described in this report has been compiled by Technology Manager Sanna Syri, Senior Research Scientist Antti Lehtilä and Research Trainee Tommi Ekholm. Research Professor Ilkka Savolainen has contributed especially in defining the scenarios and developing the atmospheric modelling approach in the VTT version of TIAM. The global and regional estimates of wind energy potentials and wind energy technologies as well as the estimates of network system requirements in connection with large amounts of wind power used in this work are compiled by Team leader Esa Peltola and Senior Research Scientist Hannele Holttinen from the Wind Energy team of VTT Energy Systems.

This report describes the status of the VTT modelling work in December 2006 - February 2007. The authors are alone responsible for the views expressed here. The authors wish to express their gratitude for all guidance and fruitful comments received in the meetings and discussions during this work.

Espoo, March 30th, 2007

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1. Introduction

The UN Framework Convention on Climate Change (UNFCCC) states as its ultimate objective the stabilisation of the atmospheric greenhouse gas concentrations at a safe level, which requires very deep emission reductions in the long term. The European Union has proposed that the global average temperature rise compared with the average temperature of the preindustrial era has to be limited to two degrees of Celcius. This would require stabilisation of carbon dioxide equivalent concentrations at the 450 ppm (CO_2e) level if the assumed climate sensitivity is about three degrees of Celcius. The CO_2 concentration in 2005 was 380 ppm and the growth rate was about 2 ppm per year between 1998 and 2005 (NOAA 2006). The contribution of other Kyoto Protocöl gases is about 50 ppm in carbon dioxide equivalents. The targeted stabilisation level of CO_2 concentrations might require that global green¬house gas emissions should be reduced roughly by 50% from today's emission levels by mid of the century. Challenges for the reduction of the emissions are posed by the growth of the world population and economy. The world population is expected to reach 8 billion in 2030 and 9 billion in 2050. The global economy is expected to grow, especially in the rapidly industrialising economies of China, India and other Asian countries.

In the year 2000 the global emissions of Kyoto Protocol gases were about 40 billion tonnes in CO_2 equivalents (Pg CO_2e). The CO_2 emissions from fossil fuels were 24 billion tonnes and from deforestation about 8 billion tonnes, the rest of emissions were mainly methane and nitrous oxide emissions from predominantly from agriculture and forestry sectors (de la Chesnaye et al. 2006).

The above deep emission reductions would change the world's energy systems and influence significantly the world economy. However, without stabilisation of greenhouse gas concentrations, the impacts of damages due to changing climate on the economy of the world could be much more serious, e.g., as assessed in the recently published Stern report (2006).

The impacts of deep emission reductions on energy systems are very difficult to analyse without integrated energy system models and the systematic quantitative picture they produce. This work assessed the long-term changes in energy economy and in other greenhouse gas emitting sectors as scenario results from the Global TIAM system model.

2. Global scenario models of greenhouse gas emissions and reduction possibilities

This section describes the VTT version of TIAM model used in this study. In addition, the main properties of other often used techno-economic scenario models used in the assessment of greenhouse gas emission scenarios and mitigation studies are described and their properties are compared with the model used in this study.

2.1. VTT version of ETSAP/TIAM model

2.1.1. General

The scenarios in this study were formed using the ETSAP/TIAM (TIMES Integrated Assesment Model, TIAM), an energy system model developed under the IEA Energy Technology Systems Analysis Programme (ETSAP). The underlying modelling system, TIMES (The Integrated MARKAL EFOM System), has also been fully developed under the ETSAP Programme, with VTT's active participation (Loulou et al. 2005). Several enhancements and improvements to the original model have been made at VTT. These include the accounting of all non-energy sources of greenhouse gases and a module calculating the concentrations and radiative forcing from each of the main gases, leading to changes in average global temperature, as well as a full review of the database for all power and heat generation technologies.

The global ETSAP/TIAM model used in this study a partial equilibrium bottom-up energy system model with a detailed description of different energy forms, resources, processing technologies and end-uses, while taking projections for the rest of the economic system as external projections. Commodity prices and consumption are calculated through demand-price elasticises throughout the energy chain, providing a market equilibrium solution for the energy sector. The model is thus very suitable for assessing the effect of the energy system alone on for example greenhouse gas emissions or industry development, holding other factors constant.

Given the input data on technological development, resource availability and different end-use demand projections, the model calculates the resulting scenario as a minimum of global system cost, including plant investment, commodity and process activity costs, but also the cost of lost demand due to price hikes of commodities. This can also be interpreted as representing the maximization of consumer and producer surplus under the efficient market hypothesis. The model also assumes centralized decision making and unlimited foresight throughout the time horizon. Thus the model does not account game theoretic setups such as competition or conflicts of interests. In this respect the scenarios might not be necessarily sound and reliable predictions for reality, but rather optimal trajectories how decisions should be made in order to acquire the least cost solution while satisfying all the demand projections and other constraints.

A policy scenario study is initiated by forming a baseline scenario, which describes a business-as-usual trajectory with appropriate projections for drivers and energy demands. Then an alternative policy scenario, in which, for example, the amount of emissions or usage of certain technologies, are constrained in a desired way, is calculated. The solution of the policy scenario is based on the baseline scenario with respect to the final demands so that a demand in the policy scenario is deviated from the baseline scenario demand through price elasticity using the deviation of the commodity price between the baseline and policy scenario. Therefore the baseline scenario provides a reference price and demand quantity, from which the equilibrium solution is deviated in the policy scenario through price elasticity mechanisms.

2.1.2. Model resolution and the Reference Energy System (RES)

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. International trade of crude oil, natural gas and LNG is included. 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.

The global TIMES model provides a very technology-detailed basis for estimating the global energy dynamics over a long-term, multi-period time horizon. Figure 1 illustrates the basic structure of the so-called reference energy system (RES) for each region within the model. The commodity flows are indicated by the links in the diagram. The RES describes all the relevant energy, material and emission flows in the energy system, from primary production to the demand of energy services. On a more detailed level, each of the sectoral blocks in the RES includes characterizations of various energy and process technologies relevant to the sector. In total, each region includes the description of about 1500 different existing and new technologies. Depending on region, energy services have been grouped into 42–60 distinct categories, each of which has its own baseline demand scenario. The maintenance and updating of such a large technology database is a demanding task.

The primary supply of energy is described in the form of supply cost curves and trade links. Indigenous supply is further divided into the production of fossil and nuclear fuels (MIN) and renewable energy sources (RNW). While the fossil and nuclear fuel resources are usually described as in terms of cumulative potentials, resources of renewable energy are described as annual production potentials. The primary energy sources for combustible renewables include solid biomass, energy crops, industrial and municipal wastes, landfill gas, as well as liquids from biomass. Other renewables include potentials for hydro, wind and tidal power, geothermal energy and solar energy.

Table 1. Original world regions in the Global TIMES model.

Code	**Region**
AFR	Africa
AUS	Australia-New Zealand
CAN	Canada
CHI	China (includes Hong Kong, excludes Chinese Taipei)
CSA	Central and South America
EEU	Eastern Europe
FSU	Former Soviet Union (includes the Baltic states)
IND	India
JPN	Japan
MEX	Mexico
MEA	Middle-East (includes Turkey)
ODA	Other Developing Asia (includes Chinese Taipei and Pacific islands)
SKO	South Korea
USA	United States
WEU	Western Europe (EU-15, Iceland, Malta, Norway, Switzerland)

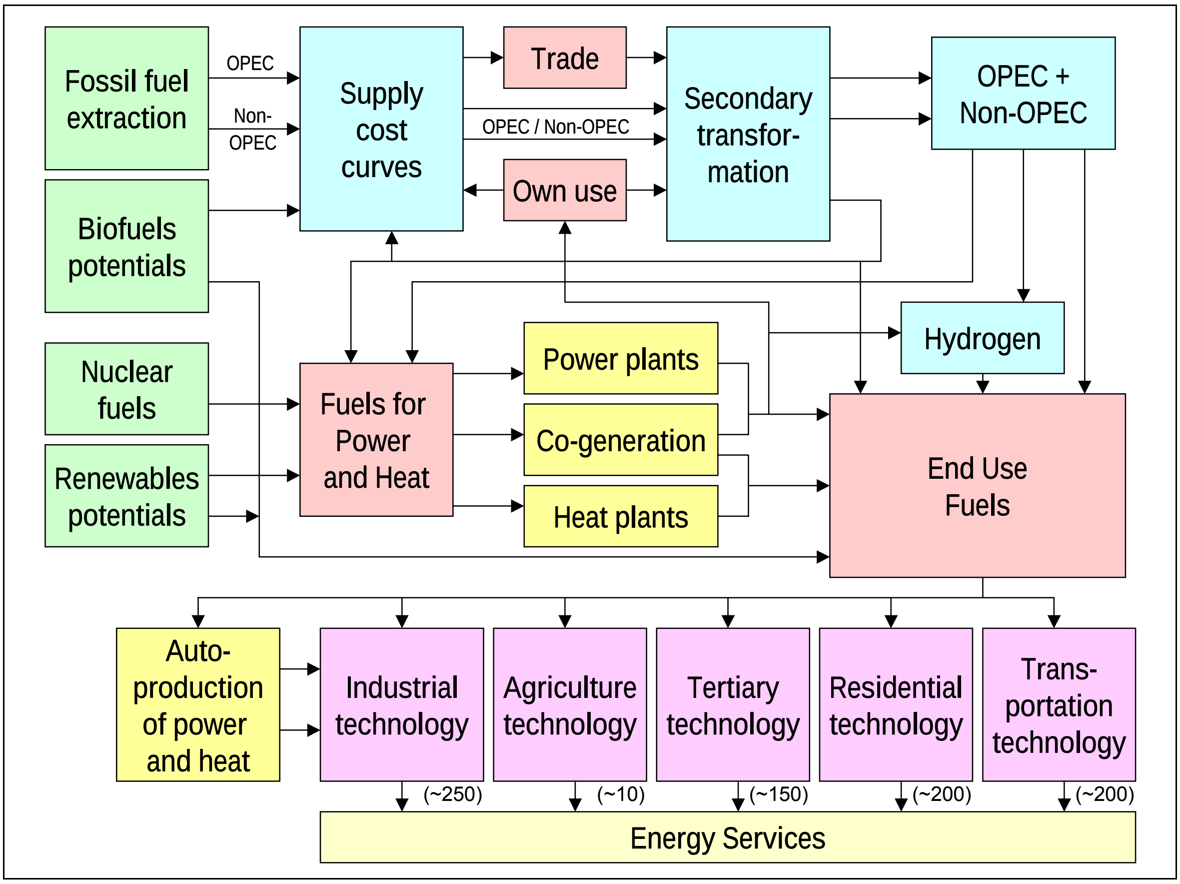

Figure 1. Simplified structure of the Reference Energy System (RES) in each region.

The secondary transformation module converts the primary energy commodities into fuels that are distributed and consumed in the electricity and heat generation sector and end-use sectors. The main processes involved include e.g. oil-refining processes, coking plants, blast furnaces and recovery of fuels from petrochemical industry. This sector also includes e.g. the production of methanol from natural gas or energy crops.

The electricity and heat generation sector includes various technologies for public power and heat generation. These technologies cover all main energy sources and a large variety of existing and new technology categories. In addition, the sector includes so-called fuel technologies, which distribute the fuels and other energy sources from the primary production or secondary transformation sectors for electricity and heat generation. The main electricity and district heat grids could also be modeled in this sector, but currently these have not been explicitly modeled. No trading of electricity (or heat) is currently included in the model, as their trade between the 15 regions is usually not significant.

The end-use sectors (industrial, residential, commercial, agriculture and transportation) are characterized by a number of categories for the demand of energy services. In addition, non-energy use of fuels has been described in the industrial and transport sectors. The number of energy services categories is 9 in the industrial sector, 11–23 in the residential sector, 8–14 in the commercial sector, and 15 in the transport sector. The variation in the number of residential and commercial energy services is explained by an optional sub-regional disaggregation of these sectors. In the current model, four geographic sub-regions have been included for USA and Canada, and two sub-regions for Africa, China, India, Middle East and Mexico. This additional resolution applies only to the residential and commercial sectors. Each energy service can be produced by a number of technologies. The approximate amount of such technologies in each sector has been indicated in Figure 1. Moreover, each end-use sector includes fuel technologies for the distribution of final energy to the sectors.

At the sub-annual level, the model includes three seasons (winter, intermediate, and summer season), and all seasons are further divided into daytime and night-time hours in order to take into account the day-night variations in the demand for electricity and heat. Consequently, in total there are six so-called timeslices within each model year.

2.1.3. Greenhouse gases and climate module

VTT has completed some enhancements to the TIAM model, in particular related to the modelling of greenhouse gas emissions and theirs climate change impacts. As of end-2006, the VTT version of the model includes a complete modelling of all anthropogenic methane (CH_4) and nitrous oxide (N_2O) emissions. In addition, the emissions of all F-gases of the Kyoto protocol are included in the model in early 2007. In this report, results of the joint modelling of carbon dioxide, methane and nitrous oxide emissions are presented.

CO_2 accumulation in the atmosphere is represented by a linear three-reservoir model: the atmosphere, the quickly mixing upper ocean + biosphere, and the deep ocean. CO_2 flows in both directions between adjacent reservoirs. The approach has been adapted from Nordhaus & Boyer (1999), who calibrated their model to the Bern carbon cycle model with a neutral biosphere. The 3-reservoir model can be mathematically described by the following 3 equations when the step of the recursion is equal to one year (Loulou et al. 2005):

$$M_{atm}(y) = E(y-1) + (1 - \varphi_{atm\text{-}up})\, M_{atm}(y-1) + \varphi_{up\text{-}atm}\, M_{up}(y-1) \tag{1}$$

$$M_{up}(y) = (1 - \varphi_{up\text{-}atm} - \varphi_{up\text{-}lo})\, M_{up}(y-1) + \varphi_{atm\text{-}up}\, M_{atm}(y-1) + \varphi_{lo\text{-}up}\, M_{lo}(y-1) \tag{2}$$

$$M_{lo}(y) = (1 - \varphi_{lo\text{-}up})\, M_{lo}(y-1) + \varphi_{up\text{-}lo}\, M_{up}(y-1) \tag{3}$$

with

- $M_{atm}(y)$, $M_{up}(y)$, $M_{lo}(y)$: masses of CO_2 in atmosphere, in a quickly mixing reservoir representing the upper level of the ocean and the biosphere, and in deep oceans (GtC), respectively, at period t (GtC)
- $E(y-1)$ = CO_2 emissions in previous year (GtC)
- φ_{ij}, transport rate from reservoir i to reservoir j ($i, j = atm, up, lo$) from year y-1 to y

The accumulation of the concentration of the other two important greenhouse gases, CH_4 and N_2O, can be reasonably well estimated using first order linear models of decay (so-called box models). This approach has been used in e.g. the REFUGE model (Monni & al. 2003) and the MERGE Model (Manne and Richels, 2004). For both CH_4 and N_2O, a constant concentration level caused by natural emissions is assumed, and the additional anthropogenic concentration is modeled using a single box model based on an average lifetime of 9.5 years for CH_4, and 119 years for N_2O (Monni & al. 2003).

The relationship between CO_2 accumulations and increased radiative forcing, $\Delta F(t)$, is derived from empirical measurements and climate models. The unit for radiative forcing is W/m^2. The formulas expressing the globally averaged radiative forcing due to greenhouse gas concentrations have been adopted from IPCC (2001), and are shown below in Equations 4–7.

$$\Delta F_{CO2}(t) = \gamma * \frac{\ln\left(C_{atm}(t)/C_0\right)}{\ln 2} \tag{4}$$

$$\Delta F_{CH4}(t) = \beta(M^{\frac{1}{2}} - M_0^{\frac{1}{2}}) - [f(M,N_0) - f(M_0,N_0)] \tag{5}$$

$$\Delta F_{N2O}(t) = \varepsilon(N^{\frac{1}{2}} - N_0^{\frac{1}{2}}) - [f(M_0,N) - f(M_0,N_0)] \tag{6}$$

$$\Delta F_{TOT}(t) = \Delta F_{CO2}(t) + \Delta F_{CO2}(t) + \Delta F_{CO2}(t) + O(t) \tag{7}$$

where:

- C_{atm} is the atmospheric CO_2 concentration and C_0 is the pre-industrial (circa 1750) reference atmospheric concentration of CO_2 = 596.4 GtC
- γ is the radiative forcing sensitivity to atmospheric CO_2 concentration doubling = 3.53 · ln(2) W/m^2
- M is the atmospheric CH_4 concentration and M_0 is the natural reference concentration of CH_4
- β is the radiative forcing sensitivity to CH_4 concentration, $\beta = 0.036$
- N is the atmospheric N_2O concentration and N_0 is the natural reference concentration of N_2O
- ε is the radiative forcing sensitivity to N_2O concentration, $\varepsilon = 0.12$

- The function $f(M,N)$ takes into account the overlap of nitrous oxide and methane; $f(M,N) = 0.47 \cdot \ln[1 + 2.01 \cdot 10^{-5} \cdot (M \cdot N)^{0.75} + 5.31 \cdot 10^{-15} \cdot M(M \cdot N)^{1.52}]$
- $O(t)$ is the increase in total radiative forcing at period t relative to pre-industrial level due to anthropogenic GHG's not otherwise accounted for in the model. In TIMES, only some non-Kyoto gases are not accounted for (e.g. CFC's, aerosols, ozone).

For simplicity, the emissions of F-gases are converted into CO_2 equivalent emissions in the model, and are treated in the same way as CO_2 emissions. The radiative forcing from F-gas concentrations is therefore included in the equation 4 above.

In the TIMES Climate Module as in many other integrated models, climate change is represented by the global mean surface temperature. In addition, the deep ocean represents a second temperature reservoir. The idea behind the two-reservoir model is that a higher radiative forcing warms the atmospheric layer, which then quickly warms the upper ocean. In this model, the atmosphere and upper ocean form a single layer, which slowly warms the second layer consisting of the deep ocean.

$$\Delta T_{up}(y) = \Delta T_{up}(y-1) + \sigma_1 \{ F(y) - \lambda \, \Delta T_{up}(y-1) - \sigma_2 \, [\Delta T_{up}(y-1) - \Delta T_{low}(y-1)] \} \qquad (8)$$

$$\Delta T_{low}(y) = \Delta T_{low}(y-1) + \sigma_3 \, [\Delta T_{up}(y-1) - \Delta T_{low}(y-1)] \qquad (9)$$

with

- ΔT_{up} = globally averaged surface temperature increase above pre-industrial level,
- ΔT_{low} = deep-ocean temperature increase above pre-industrial level,
- σ_1 = 1-year speed of adjustment parameter for atmospheric temperature,
- σ_2 = coefficient of heat loss from atmosphere to deep oceans,
- σ_3 = 1-year coefficient of heat gain by deep oceans,
- λ = feedback parameter (climatic retroaction). It is customary to write λ as $\lambda = \gamma / C_s$, C_s being the *climate sensitivity* parameter, defined as the change in equilibrium atmospheric temperature induced by a doubling of CO_2 concentration.

Remark: in contrast with most other parameters, the value of C_s is highly uncertain, with a possible range of values from 1°C to 10°C. This parameter is therefore a prime candidate for sensitivity analysis, or for treatment by probablilistic methods.

In the model, the non-linear forcing functions can be replaced by the linear approximations, in order to preserve the linearity of the TIMES equations. Such an approximation for CO_2 is illustrated below in Figure 3. In previous versions of TIMES the non-linear functions were directly used, and, consequently, the forcing and temperature equations could not be treated as bona fide TIMES equations, but rather as reporting devices. When using linearized functions, all the forcing and temperature equations can be made regular TIMES equations, allowing the user to put bounds on these quantities. Assuming that the linearizations are done carefully, focusing on the possible ranges of concentrations under foreseeable climate policy scenario alternatives, the errors caused by the linearization can be made quite small, as depicted in Figure 3.

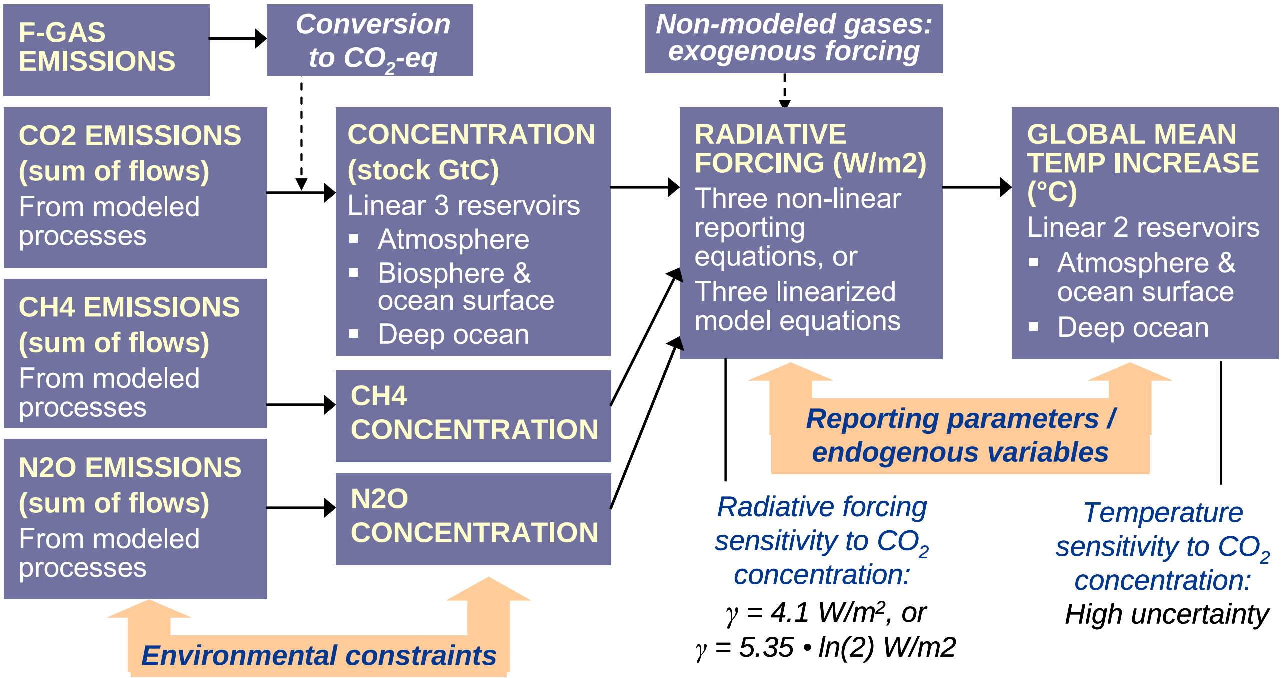

Figure 2. Components of the TIMES Climate Module.

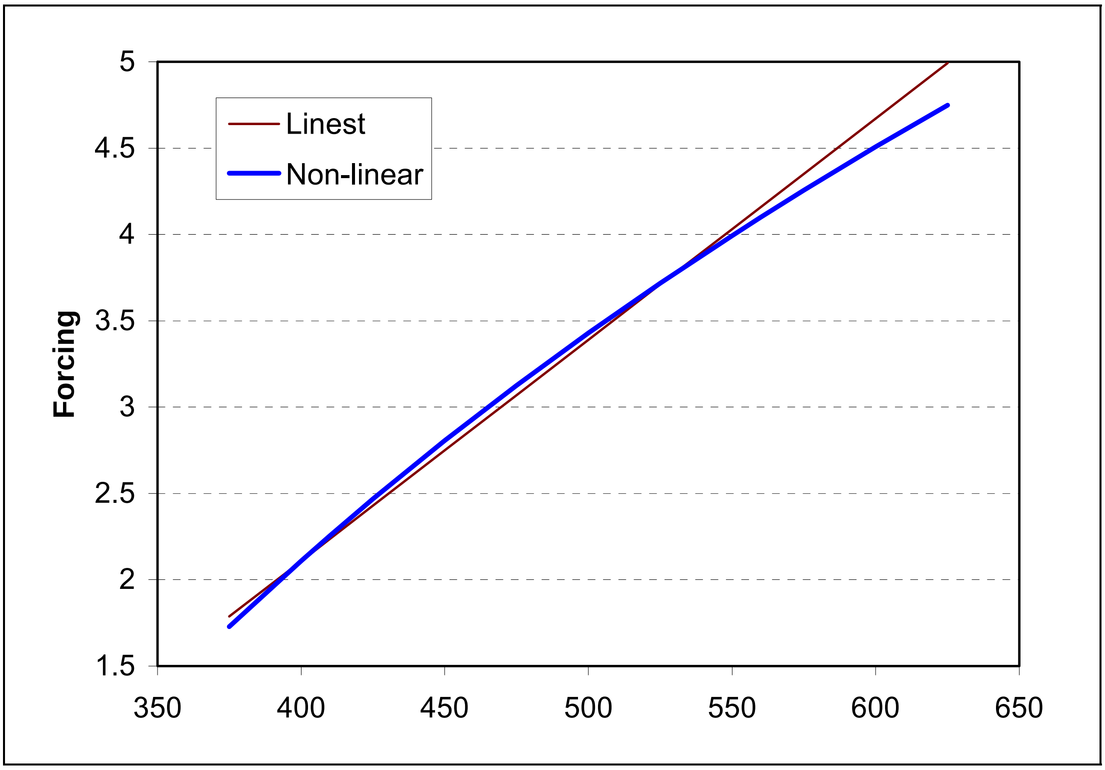

Figure 3. Impact of the linearization of the radiative forcing function for CO_2.

2.2. Models used in IPCC Special Report on Emissions Scenarios

The Intergovernmental Panel on Climate Change (IPCC) has developed a set of GHG-emission scenarios to 2100, reported in the Special Report on Emissions Scenarios (Nakicenovic 2000). In the SRES work, four distinctly different "storylines", i.e. views of world future development, were created. The work was done with six modelling approaches:

- Asian Pacific Integrated Model (AIM): a large scale climate change simulation model for Asian-Pacific region that couples both top-down and bottom-up approaches; linked to a global model in order to produce global estimates. The National Institute of Environmental Studies, Japan (Morita et al., 1994)

- Atmospheric Stabilization Framework Model (ASF): using regional population and economic drivers forms demand for energy which is matched with the supply through a market model; agricultural and deforestation emissions are projected through estimates for the production of major agricultural products.

- Integrated Model to Assess the Greenhouse Effect (IMAGE) (Alcamo et al., 1998; de Vries et al., 1994, 1999, 2000): a set of three integrated models for energy and industry, terrestial environment and ocean-atmospheric interaction; the energy system dynamics are bottom-up modeled with investment decisions in generation and efficiency and supply based on anticipated demand, costs and institutional delays.

- Multiregional Approach for Resource and Industry Allocation (MARIA): a compact regional integrated assessment model using constant elasticity of substitution production functions; energy market prices are endogenously generated from extraction and utilization costs, and demand levels are estimated for industry, transportation, and other public uses (Mori 2000).

- Model for Energy Supply Strategy Alternatives and their General Environmental Impact MESSAGE) (Messner & Strubegger 1994, Nakicenovic & Riahi 2000, Rao & Riahi 2006): a part of an integrated modelling framework; exogenous population and economic projections are used to produce estimates for energy supply, which are fed to top-down (MACRO) and bottom-up (MESSAGE) optimization models with resource availability and technology palettes as constraints; non-energy emissions are taken from the AIM model 2ICF Consulting (Lashof and Tirpak, 1990; Pepper et al., 1992, 1998; Sankovski et al., 2000).

- Mini Climate Assessment Model (MiniCAM): a small rapidly running integrated assessment model for GHG emissions and climate change effects; energy sector emissions are calculated using labour force levels and labour productivity with a GNP/energy elasticity in a partial equilibrium model.

Since the SRES work, many of these models have been developed further. For instance, the MESSAGE model presently includes also full modelling of non-energy emissions (Rao & Riahi 2006).

2.3. IEA modelling approach

The international Energy Agency (IEA) publishes its view on the future of the enegy system, the World Energy Outlook, on a yearly basis. The 2006 edition depicts two scenarios, the Reference Scenario and the Alternative Policy Scenario, which describe two different futures with respect to whether new policy measures are introduced or not (IEA 2006). The Reference Scenario serves as a baseline, but not a preferable or even a likely scenario, and the Alternative Policy Scenario as an explorative scenario, with a variety of different policy measures that might be adopted due to economic or environmental reasons.

The scenarios are produced by using the IEAWorld Energy Model (WEM) (IEA 2006), a large scale mathematical partial equilibrium model. The model is divided into six main modules: final energy demand, power generation, refinery and other transformation, fossil fuel supply, CO_2 emissions, and investment. External assumptions are given for the development of economic growth, demographics, international fossil fuel prices and technological developments, which drive the demand, refinery and fossile fuel supply modules. These three modules are defined for 21 geographic regions and in turn the regional energy balance, and finally drive the emission and investment modules.

The parameters for demand side modules were estimated using econometric models with data ranging from 1971 to 2004. The demand module distinguishes several sub-sectors within industry, residential, service and transport sectors, within each the demand is derived from usually GDP driven activity variables, prices and other variables, such as technological changes. The module provides the demand for the refinery model, and the two form a supply-demand equilibrium through an optimization process in the refinery module. The demand from the refinery model is further fed as an input for fossil fuel supply module.

The same macroeconomic and population assumptions are used in the Reference and Alternative Policy scenarios. A policy and measure database of over 1400 policies aimed at energy security and climatic concerns were divided on the basis of whether the policies were already been adopted or not. The Reference Scenario carries on the policies already under implementation, whereas the Alternative Policy Scenario assumes that all of the policies are eventually adopted.

2.4. IPTS POLES model

The Institute of Prospective Technological Studies (IPTS) of the EU Joint Reseach Centre, located in Sevilla, develops and maintains the POLES model for energy policy analysis (http://energy.jrc.es). The POLES model is a world simulation model for the energy sector. It works in a year-by-year recursive simulation and partial equilibrium framework, with endogenous international energy prices and lagged adjustments of supply and demand by world region. Developed under EU research programs at the Institute of Energy Policy and Economics (IEPE) and currently also operated, expanded and maintained by the IPTS, the model is fully operational since 1997. It has been used for policy analyses by EU-DGs Research, Environment, and Transport and Energy, and by the French Ministry of Environment. POLES contains 18 world regions and 32 countries. The model enables to produce detailed long-term (2030 / 2050) world energy outlooks with demand, supply and price projections by main region. It produces CO_2 emission marginal abatement cost curves by region, and emission trading systems analyses under different market configurations and trading rules. In addition, the model can be used to analyse technology improvement scenarios, with exogenous or endogenous technological change and the value of technological progress in the context of CO_2 abatement policies.

IPTS is developing a series of modules for energy intensive industries (iron and steel, cement, aluminium, refineries and petrochemicals, and pulp and paper) as well as a detailed transportation model to be integrated in the POLES model. The pulp and paper sector module has been developed as collaboration between IPTS and VTT.

2.5. Summary of main properties of the models

The following table summarises the main properties of the global climate change mitigation assessment models presented in this section.

The level of technical detail, the inclusion of all emission sources (also non-energy sources) and the inclusion of all greenhouse gases mainly determine the comprehesiveness of the modelling approach. A larger number of geographical regions increases the political applicability of the model results (e.g. with how many regions Europe is represented, as there are different groups of countries: OECD countries, economies in transition, FSU etc.). On the other hand, the level of detail in the modelling always makes the model updating and development work more tedious and increases the model calculation time.

Model	ETSAP / VTT TIAM	POLES	IEA WEM	AIM	ASF	IMAGE	MARIA	MESSAGE	MiniCAM
Level of detail in energy system description	High	Medium	High	High	Medium	Medium	Low	High	Low
Gases	CO_2, CH_4, N_2O	CO_2	CO_2	CO_2, CH_4, N_2O	CO_2, CH_4, N_2O	All Kyoto gases	CO_2	All Kyoto gases	All Kyoto gases
Non-energy emissions included	Yes	No	No	Yes	Agriculture, deforestation	Yes	Land use change	Industry	Yes
No. of geographical regions	15	18, 32 countries	21	9	9	13	8	10	9
Atmospheric modeling	Rad.forcing, Temp. change	No	No		Rad.forcing, Temp. change	Rad.forcing, Temp. change, simplified circulation model	Temp. change	Rad.forcing, Temp. change	Rad.forcing, Temp. change
Endogenous technology development	No	Yes	Yes	No	No	Yes (TIMER -sub model)	Yes	Yes	No
Possibility for stochastic calculations	Yes	No	No	No	No	Yes	No	Yes	No

3. Scenarios compiled in this study

3.1. Scenario GDP assumptions

A key driver in the future development of the energy system is the development of energy demand, which in turn depends on the GDP development and the assumed decrease in the energy intensity of GDP. Regional and global GDP development scenarios were calibrated to the assumptions used in the IPTS POLES modelling. The global economic growth scenario used in this work assumed a rather modest economic growth (Figure 4, Table 2) compared to some other often used scenarios (e.g. IEA 2006a,b).

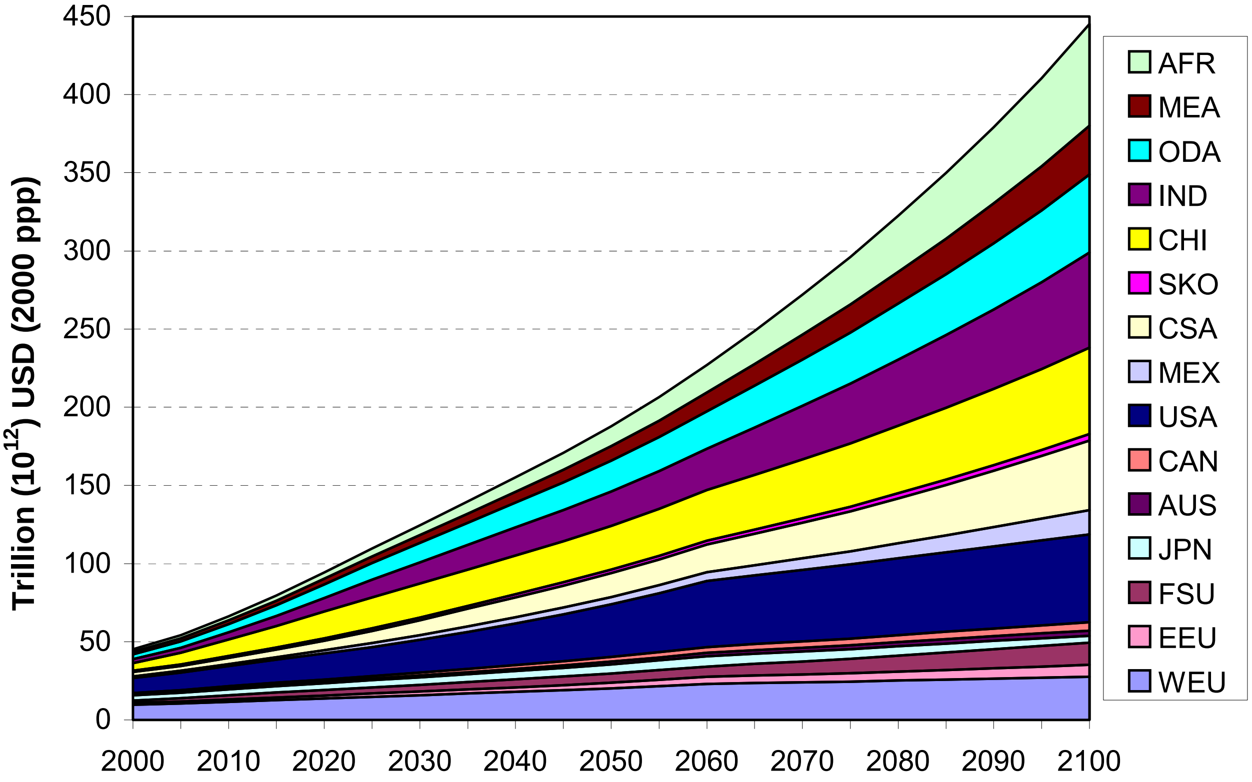

Figure 4. Development of regional GDP in the Baseline scenario.

Table 2. Average growth in GDP by region in the Baseline scenario.

Region	2000–2020	2020–2050	2050–2100
WEU	1.7%	1.3%	0.6%
EEU	2.9%	2.2%	1.6%
FSU	4.3%	1.6%	1.8%
JPN	1.3%	1.1%	-0.5%
AUS	2.4%	2.1%	1.2%
CAN	2.7%	2.4%	1.2%
USA	2.7%	2.4%	1.0%
MEX	4.1%	2.9%	2.4%
CSA	4.0%	3.0%	2.2%
SKO	3.4%	1.3%	1.3%
CHI	6.3%	1.7%	1.4%
IND	6.6%	3.1%	2.1%
ODA	5.2%	2.8%	1.9%
MEA	4.4%	3.2%	2.5%
AFR	4.5%	3.9%	3.3%
World	3.8%	2.3%	1.7%

3.2. Scenario assuptions on deforestation

Assumptions on future deforestation development used in the study were mainly derived from (Sathaye et al, 2001) (Figure 5). This represents an additional emission source in the modelling, which declines over time. The future deforestation development used in this study is more conservative than what was stated in the context of the EU Commision's recent energy and climate strategy (EU Commission 2007). The EU Commission states that the role of emissions from deforestation will be key to meet the 2°C objective. The application of a financial incentive per ton of CO_2 modelled by Dynamic Integrated Model of Forestry and Alternative Land Use (DIMA) resulted in a reversal from net source to net sink by 2020 in the EU Commission's background work. This is a very challenging target.

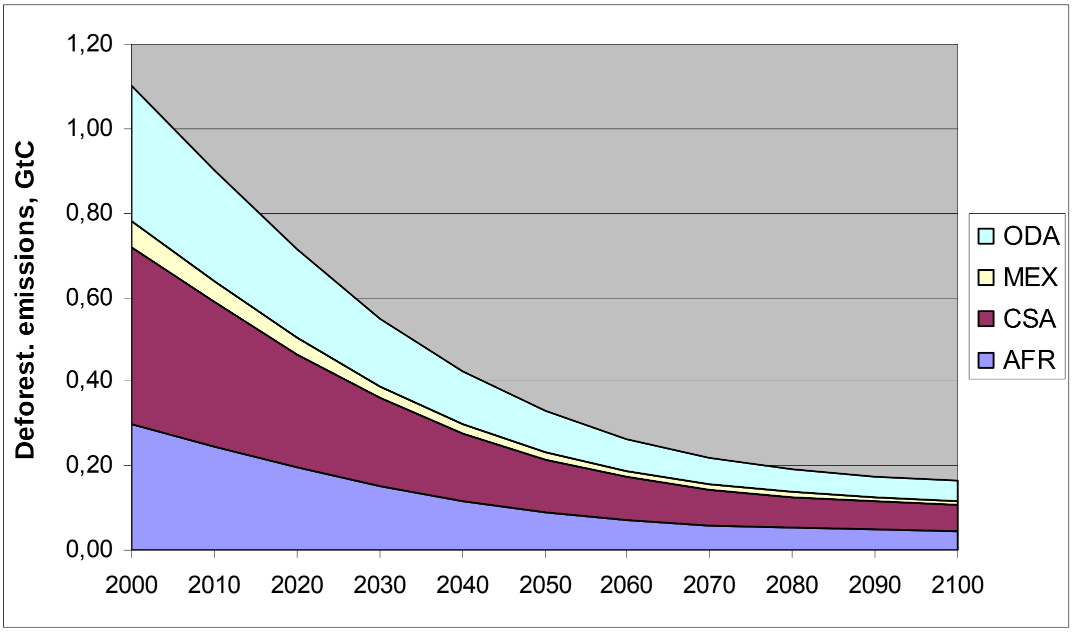

Figure 5. Future development of deforestation assumed in the scenarios studied.

3.3. Transportation demand

In the model, the demand for most transportation modes is derived mainly from the GDP growth. The transport modes driven by economic growth include passenger cars, light, medium and heavy trucks, freight transport by rail, inland and international shipping, and domestic and international aviation. Population growth has been as the main driver for bus transport as well as two- and three wheelers.

The transport volumes are not assumed to increase directly proportionally with the demand drivers. As for all other demands, the so-called driver elasticities determine the strength of the link between the drivers and the demand. In the case of passenger car transport, the elasticities are assumed to be greater than 1 in developing regions until 2020, but they are assumed to decrease considerably below 1 thereafter. Consequently, the transport volumes increase quite rapidly until 2020, but much more slowly thereafter. Figure 6 illustrates the increses in the passenger car volumes in the Baseline scenario.

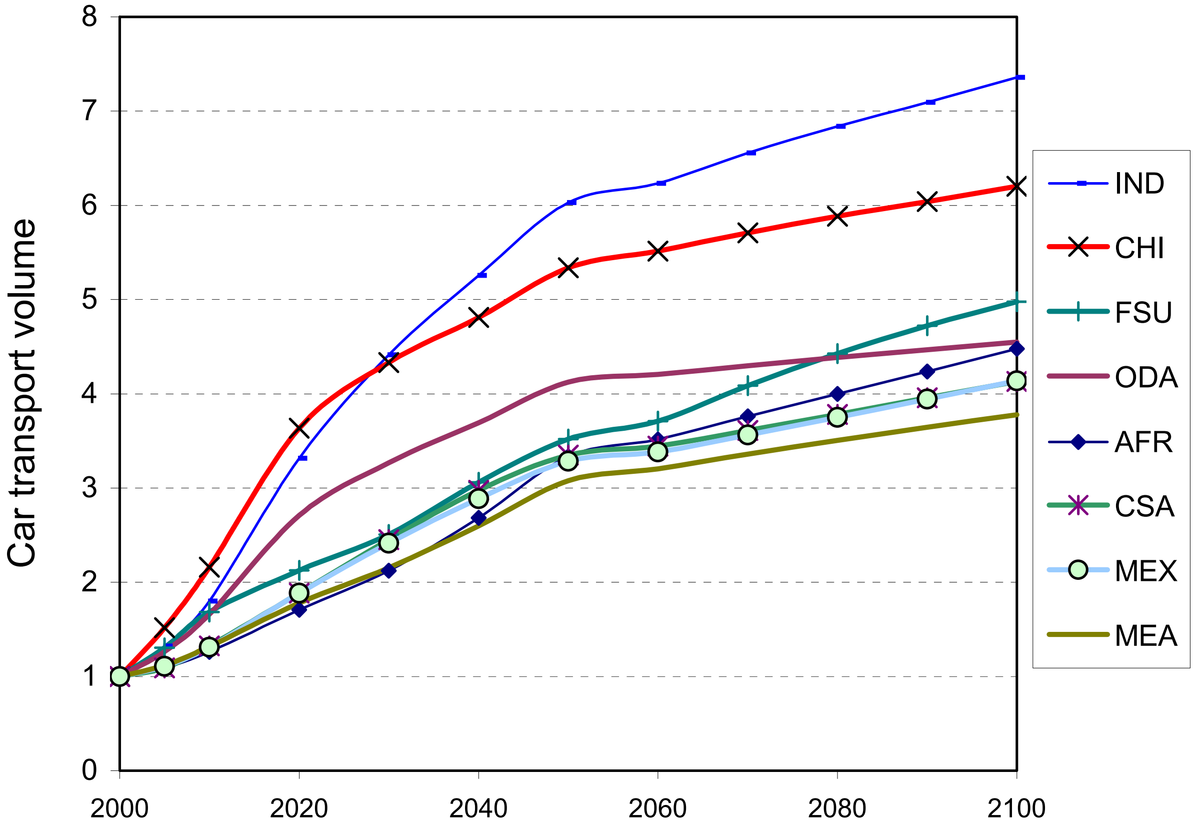

Figure 6. Development of the volume for passenger car transport in developing regions.

3.4. Resource estimates used

In long-term future scenario studies, the estimates of primary energy sources used can have a large influence on the scenario outcome. In demanding mitigation scenarios, many of the currently known energy resources may be used to their presently known resource limits.

3.4.1. Bioenergy

Estimates of future bioenergy potentials available globally and regionally for energy production in the long-term future are scarce and contain considerable uncertainties. The recent estimates cited by the IPCC are mainly based on (Hoogwijk 2004). Especially the higher end estimates reported by the IPCC, however, can be overly optimistic. Bioenergy production competes in land-use with e.g. food production. In the estimates, the scenarios in principle take into account the future population growth, the land area needed for food production and the future availability of land for energy crops.

However, a major expansion of food crops for energy uses (e.g. transport biofuel production) may in practise cause severe price shocks of food crops. This would have large adverse impacts especially on poor countries' ability to feed their population.

VTT has estimated potentials of the main energy crops (mainly based on FAO statistical databases). These estimates sum up to about 80 EJ, which is considerably lower than the range given by the IPCC.

3.4.2. Wind energy

Concerning regional wind power potentials, recent VTT estimates have been used. These are somewhat higher than some earlier used assumptions. This is partly due to the recent developments in wind power technology, as the unit power and unit height have increased considerably. Based on a country-by-country analysis of population density, wind resources and main geographical features, it was estimated that almost 300 GW of wind generation capacity could be built in an acceptable way in Western Europe: using only windy areas and in those areas not exceeding the present density of wind turbines in Denmark, northern Germany or the Netherlands.

As a rule of thumb, 10 km^2 of land area can have up to 80 – 100 MW of wind generation capacity. It is probable that in 2030 also the onshore turbines will have an average size of at least 3 MW. With a rotor diameter of about 100 m these turbines in a wind farm would be located about 600 – 1000 m apart from each other leaving most of the land area free for other use. Offshore turbines may well have an average rated power of 6 – 8 MW in 2030. With a rotor diameter of about 150 m and average turbine spacing of 1,0 – 1,5 km in large offshore wind farms, a 1000 MW offshore wind farm would occupy an area of about 150 km^2 (roughly 12 x 12 km).

In North America (USA, Canada) the bulk of the wind resources are located in Central plains but there is already now a tendency to develop wind generation in areas closer to load centres in Eastern coast and Western coast to reduce cost of grid connection and management. The offshore development in the eastern coast of USA is driven also by this.

3.4.3. Carbon capture and storage (CCS) estimates

The regional data on geological and ocean carbon storage potentials and costs used in the modelling work have been collected from many different sources of (IEA-ETP project, EMF-22, US-EPA, IPCC, other literature). Of course, there are many significant uncertainties related to these data (e.g. reservoir inventories and biological processes, risk of leakage, permanence). Summary of the assumed total potentials is presented in Table 3. The global total potentials have been calibrated according to literature estimates (Kauppi and Sedjo, 2001; Herzog et al., 1997). Note that the category with by far the largest potential is deep saline aquifers, for which the uncertainties are particularly large. Therefore, the costs for this option have been assumed so high that it represents basically only a backstop option. Table 4 shows the assumed potentials by main geographical regions.

Table 3. Assumed carbon storage potentials by main category.

Category	GtC
Enhanced Oil Recovery	42
Depleted oil fields (onshore)	62
Depleted gas fields (onshore)	224
Depleted oil fields (offshore)	14
Depleted gas fields (offshore)	57
Enhanced Coalbed Methane <1000 m	98
Enhanced Coalbed Methane >1000 m	98
Deep saline aquifers	3449
Storage in the deep ocean	114
Total	4157

Table 4. Assumed carbon storage potentials by main category and by main geographical regions.

Category	Africa	Asia	America	Europe	FSU	Oceania	Total
Enhanced Oil Recovery	1	21	10	1	8	0	42
Depleted oil fields (onshore)	1	35	12	1	12	0	62
Depleted gas fields (onshore)	6	94	26	6	92	0	224
Depleted oil fields (offshore)	1	5	6	2	0	0	14
Depleted gas fields (offshore)	2	29	11	12	0	3	57
Enhanced Coalbed Methane <1000 m	1	33	23	10	20	10	98
Enhanced Coalbed Methane >1000 m	1	33	23	10	20	10	98
Storage in the deep ocean	0	37	36	20	0	20	114
Deep saline aquifers	409	1029	1193	205	409	205	3449
Total	423	1315	1340	268	562	250	4157

3.4.4. Hydropower resources

Hydropower estimates used in this study are based on WEC estimates (WEC 2004). In the first stage, all of the estimated technical potentials and 25% of the additional theoretical potential were included for each region. However, during the work it became apparent that the resulting potentials for additional hydro power expansion were too optimistic, as they resulted in a many-fold increase in the hydro power capacity, particularly in developing countries. Therefore, the potentials were subsequently cut by about 30% in each region. These more conservative estimates thus correspond roughly to the total technical potentials as estimated by WEC.

3.4.5. Uranium reserves and nuclear energy technologies considered

Uranium reserves are primarily based on estimates made by OECD Nuclear Energy Agency (the so-called Red Book, OECD 2005). However, concerning unconventional resources, somewhat more conservative estimates have been adopted. The unconventional resources are mainly associated with uranium in phosphates, seawater and black shale, in which uranium exists at very low grades or can only be recovered as a minor and very expensive by-product. The total conventional resources were assumed to be about 15 million tonnes, but the unconventional resources only about 3 million tonnes.

For future fission reactors three models were defined: 3rd generation Light Water Reactor (LWR), a 4th generation Supercritical LWR (SCWR) and a Pebble-Bed Modular Reactor (PBMR). Assumed technical specifications, costs and introductory years were taken from literature, and cost projections were formed using the learning curve -model with new capacity estimates from IAEA (US DoE 2002, Koster et al 2003, Wallace et al 2006). SCWR was chosen as representative 4th generation reactor due to that numerous fossil fuel boilers already use supercritical technology. All of the chosen reactor designs use conventional nuclear fuel, and breeder reactors were deemed too speculative to be included in the model. This assumption causes that the known uranium reserves may start to exhaust in the end of the modelling period.

3.5. Key assumptions related to non-fossil power generation

As the electricity generation sector represents perhaps the most important sector with respect to CO_2 emission reductions, the assumptions concerning non-fossil energy resources relevant for power generation and the assumed market constraints for new electricity generation technologies are of significant importance to the overall results. Table 5 summarizes the main assumptions concerning the resources and market constraints.

Table 5. Key assumptions related to power generation from non-fossil energy sources.

Energy source	**Assumed resource base limitations**			**Constraints on capacity**	**Constraints on market penetration**
	Category	1000 t	EJ		
Uranium (fission power)	RAR	3300	1450	Regional limits (global total ≈ 3500 GW)	Endogenous within capacity limits
	EAR-1	1500	660		
	EAR-2	2500	1100		
	Speculative	7500	3300		
	Unconventional	3200	1400		
	Total	18000	7900		
Lithium (fusion power)	Translated to annual capacity expansion constraints			Global and regional limits on annual new installations	Endogenous within annual growth limits
Wind power	None assumed			Large regional potentials (global total ≈ 12,000 GW)	Max. 35% of market by season (Canada: 50%)

Solar power	None assumed	Large regional potentials	Max. 20–30% of market by season
Biofuels (all energy)	Regional max. annual yields Global total potentials: Crops ~200 EJ/a Residues ~60 EJ/a Total ~260 EJ/a	No definite constraints	Endogenous

3.6. Scenario specifications

The following scenarios were studied in this work:

Achivement of the 2 ºC stabilization target:

- Annex I reduction target –30 % from 2000 level by 2030 (–34% by 2020 from 1990)
- Additionally, Annex I reduction target –50 % from 2000 level by 2050 (–53% by 2050 from 1990)
- From 2050, global emissions trading is allowed. Before that, only trading within Annex I countries is allowed.
- VTT estimates of technology development and penetration
- Optimisation of CO_2, CH_4 and N_2O emissions
- The 2 ºC warming target was set to be achieved in 2100. In practise this target setting means that the temperature would continue to slowly increase up to about 2,5 ºC after 2100 before reaching equilibrium.

In addition, the following sensitivity runs were made:

- The global resources of wind power, CCS, hydropower, crops and uranium were reduced one at a time:
  - The available crop reserves were reduced by 50%.
  - The other resources were reduced by 20%, except for uranium.
  - For uranium, the unconventional reserves were assumed not to be available.

4. Results

4.1. Cost-minimisation of greenhouse gas reduction pathways

The TIAM model was used to find the global minimum pathways for the scenarios described above. The following figures present the results for the regional development of CO_2, CH_4 and N_2O emissions in the Baseline and 2 ºC scenarios (Figure 7, Figure 8, Figure 9, Figure 10, Figure 11, Figure 12).

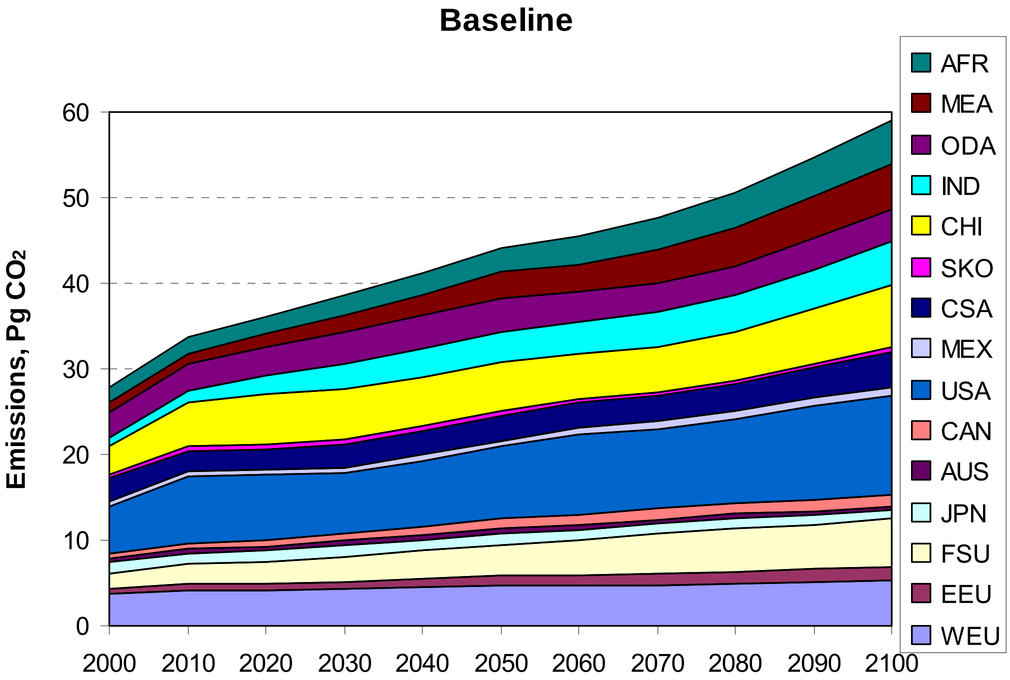

Figure 7. Development of global CO_2 emissions in the Baseline scenario.

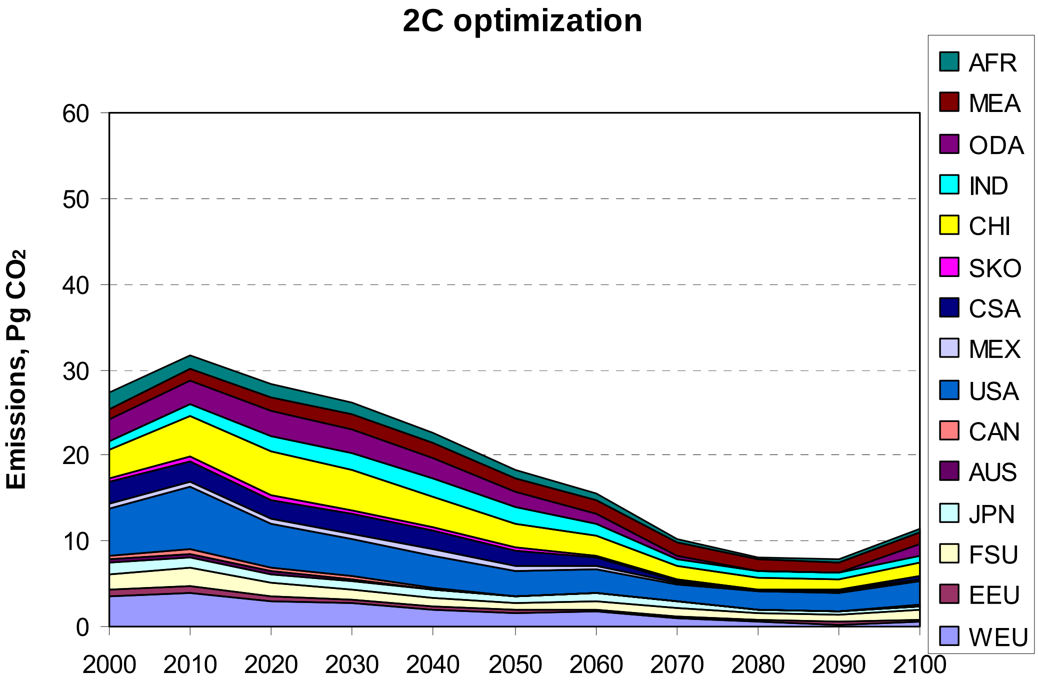

Figure 8. Development of global CO_2 emissions in the 2 ºC scenario.

The global CO_2 emissions would peak already in 2010 due to the imposed additional reductions for Annex I countries in this work. This global peak takes place earlier than in the EU Commission's background work, where global GHG emissions peak by 2020 and then decrease by 25 % by 2050 compared to 1990.

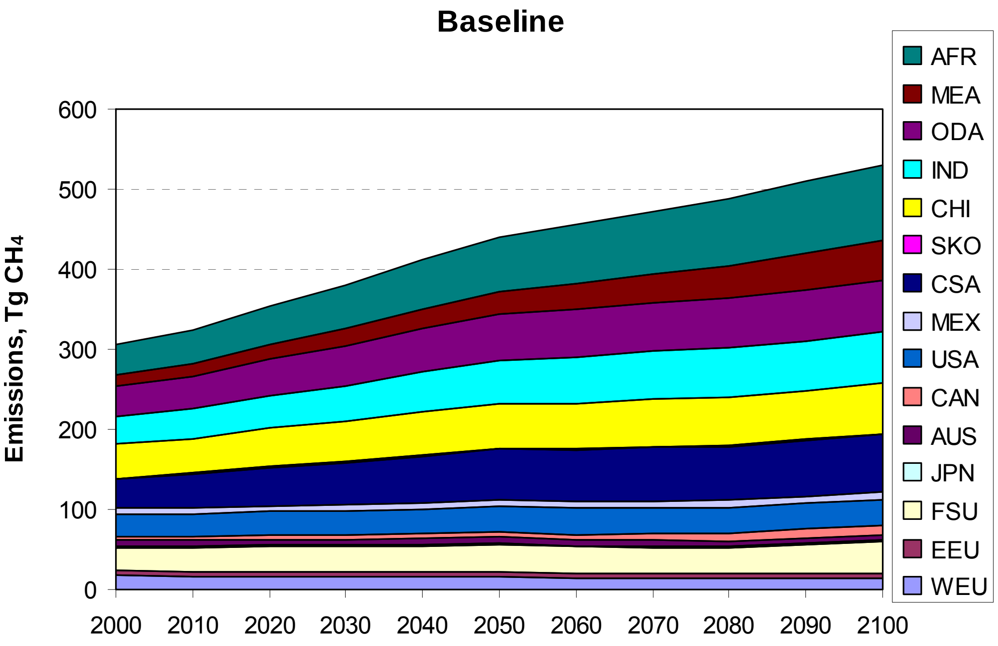

Figure 9. Development of global CH_4 emissions in the Baseline scenario.

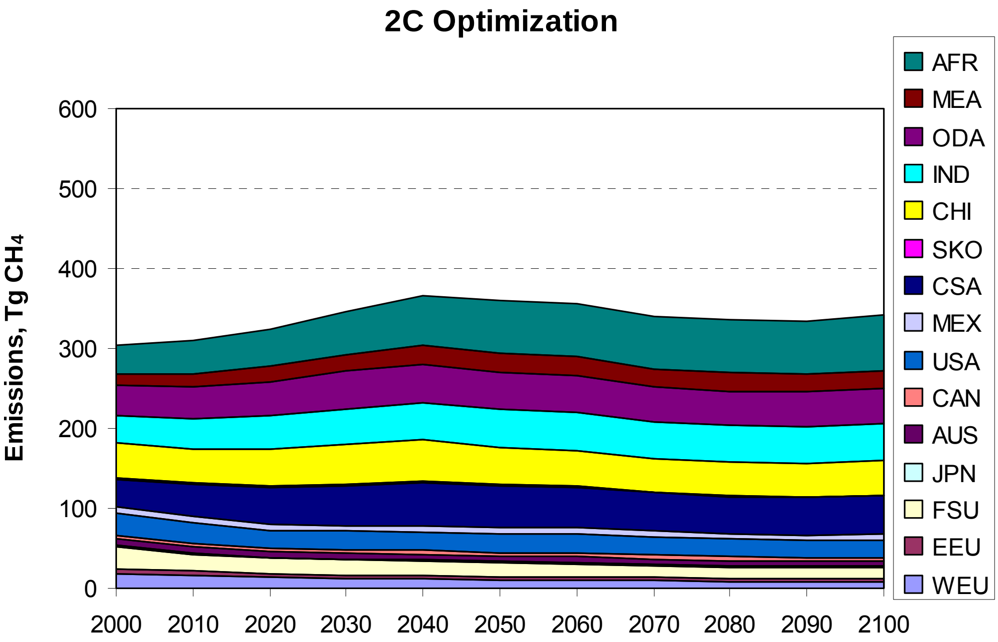

Figure 10. Development of global CH_4 emissions in the 2 ºC scenario.

Cost-efficient reduction measures of methane emissions taken at use in the mitigation scenario include waste-to-energy concepts, e.g. electricity generation and heat production technologies, collection and use or flaring of methane, degasification, catalytic oxidation etc. in coal mines, oil and gas fields and reduction of leakages in pipelines and losses in energy transmission.

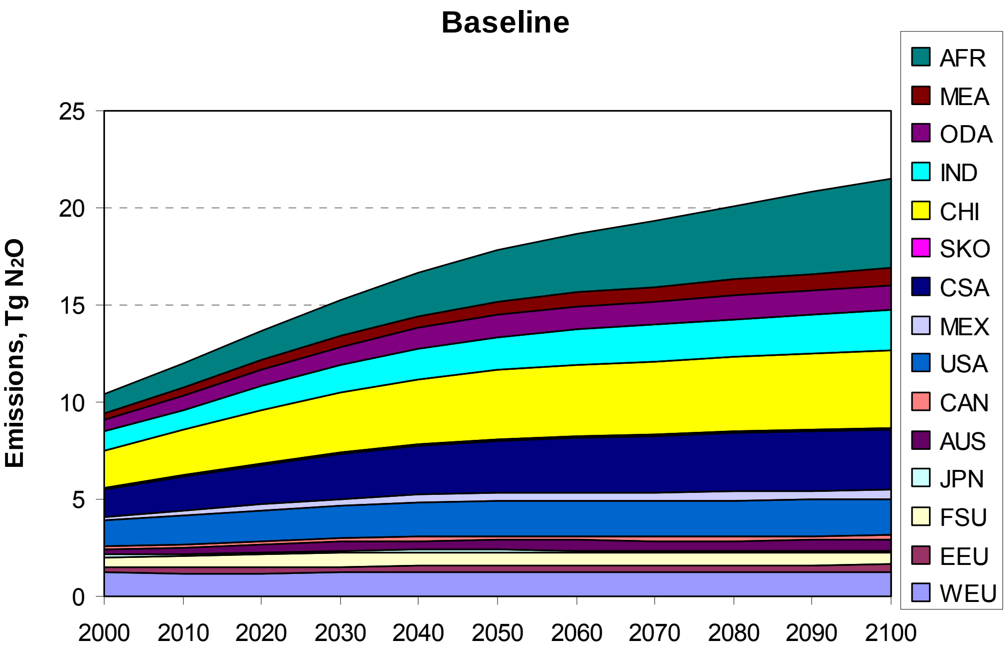

Figure 11. Development of global N_2O *emissions in the Baseline scenario.*

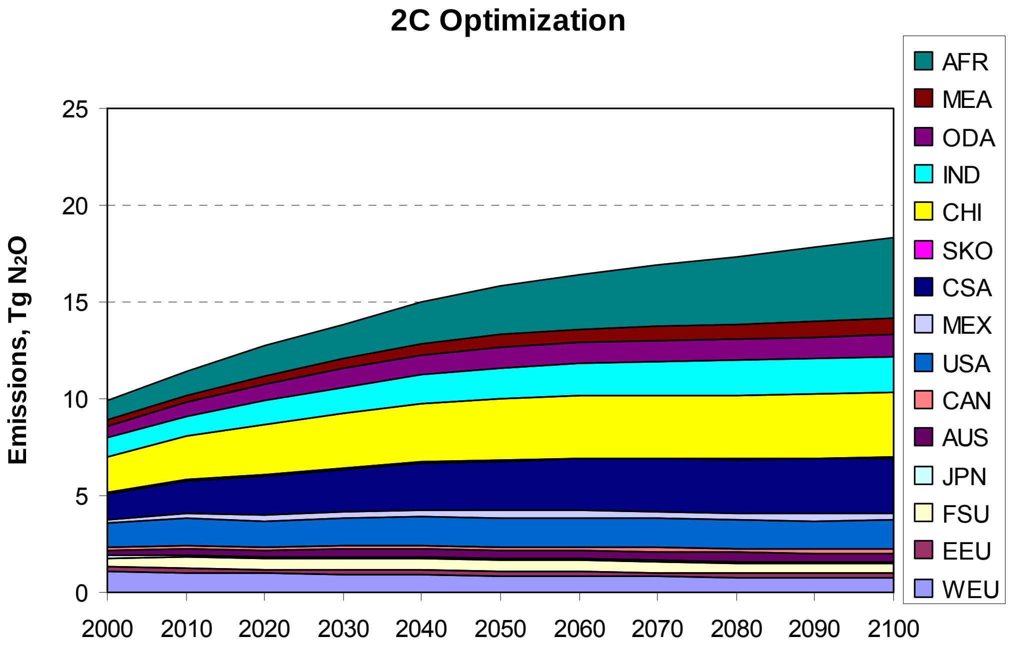

Figure 12. Development of global N_2O *emissions in the 2 ºC scenario.*

Cost-efficient reduction measures of nitrous oxide emissions taken at use in the mitigation scenario are mostly those in chemical industry, e.g., N_2O thermal destruction in adipic acid production and N_2O catalytic and non-catalytic reduction in nitric acid production. Especially the available measures in agriculture are mostly rather inefficient and expensive.

Figure 13 summarises globally the main technology groups concerning CO_2 mitigation. The largest single technologies in the scenarios are Carbon Capture and Storage (CCS) and large-scale afforestation measures. The largest wedge (between red and bluse lines) includes all other individual measures in the energy system, e.g. fuel switch, efficiency improvements, renewable energy, nuclear power, etc. These results are shown in more detail in the following sections.

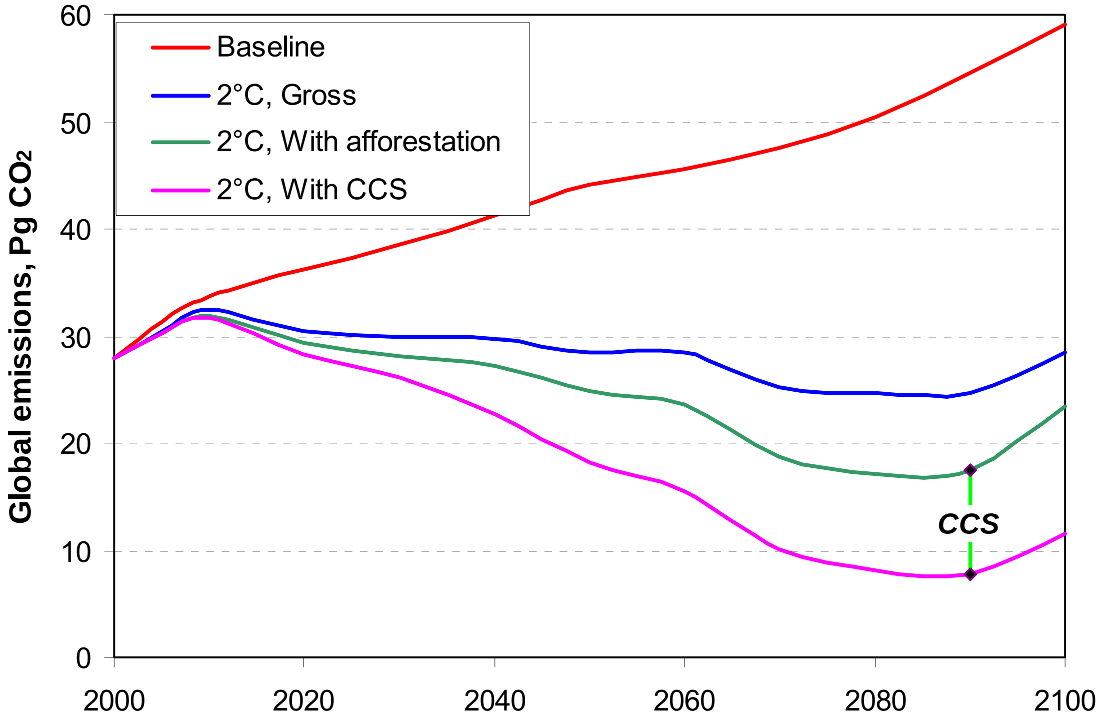

Figure 13. Main technology groups in CO_2 mitigation. (This shows the results for CO_2. The optimisation run includes also CH_4 and N_2O emissions.)

4.2. Development of GHG concentrations in the scenarios

The atmospheric concentrations of the main greenhouse gases, CO_2, CH_4 and N_2O, respond quite differently to the imposed emission reduction measures. This is due to their different atmospheric lifetimes. Figure 14 shows the development of CO_2 and N_2O concentrations in the atmosphere in the scenario runs. It can be seen that CO_2 concentrations peak in 2050-2060 at about 430-435 ppmv.

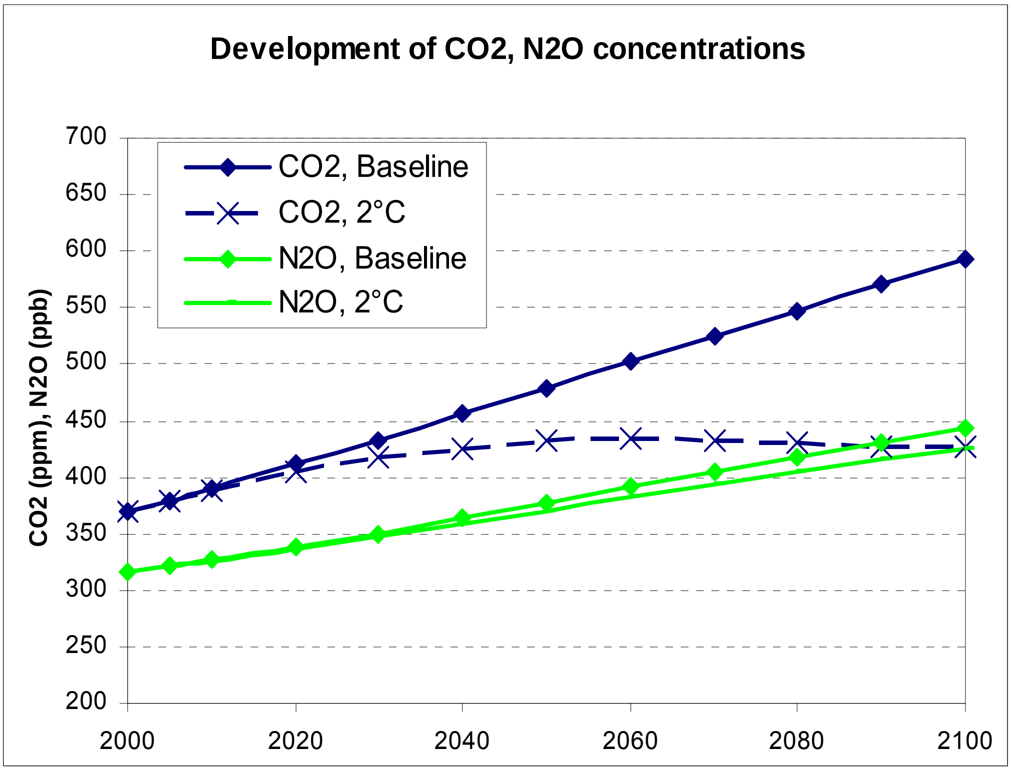

Figure 14. Development of atmospheric CO_2 and N_2O concentrations in the Baseline and 2 ºC mitigation scenarios. It can be seen that CO_2 concentrations peak in 2050-2060 at about 430 ppm.

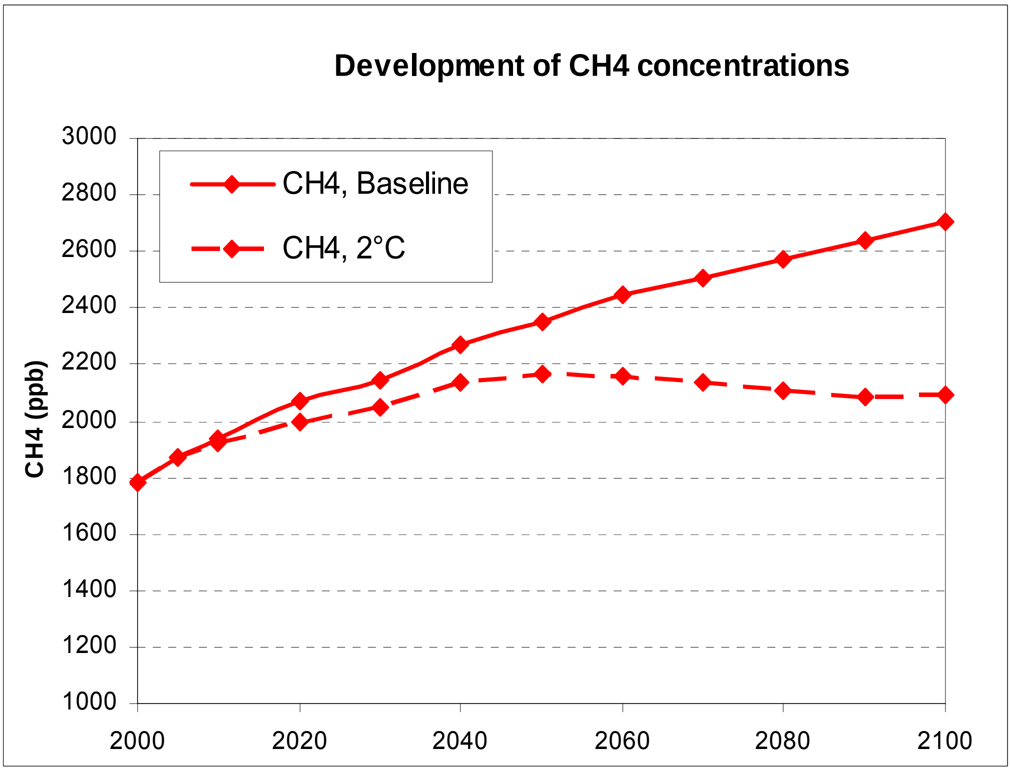

Figure 15. Development of atmospheric methane concentrations in the Baseline and 2 ºC mitigation scenarios.

Figure *15* shows the development of atmospheric methane concentration in the scenarios. It can be seen that due to its shorter atmospheric lifetime, methane concentrations respond rather rapidly to the control measures. Due the the availability on cost-efficient emission reduction possibilities, methane concentration in the 2 ºC mitigation scenario develops considerably lower than in the Baseline scenario.

4.3. Results for the electricity generation system

In the mitigation scenarios, the global energy system will need to transform very significantly towards the utilisation of low-carbon technologies. The development of the electricity generation by generation type illustrates rather well the necessary changes in the energy supply mix. In Figure 16, the development of the global electricity supply in the 2 ºC mitigation scenario is shown. It can be seen that in the 2 ºC mitigation scenario, the largest electricity generation types in this Century become wind energy, nuclear fission, hydropower and condensing power with CCS. The suffix "–Bio" refers to co-generation of various biomasses and recycled fuels (REF). Also co-firing using partly fossil fuels can be included in this category. Bioenergy and REF are best used in advanced technology concepts (Combined Heat & Power, gasification etc.) The large share of wind power requires power system operation with wind forecasts to manage grid interconnections and reserves. Flexible generation (gas turbines modelled here), DSM and storage can be increased to meet these requirements.

In the global electricity palette, also the introduction of fusion power can be feasible after 2050, as shown in Figure 16. The term "Solar" refers to solar photovoltaic technology. It should be borne in mind that solar heating systems gain market penetration to a much larger extent in the scenarios calculated here.

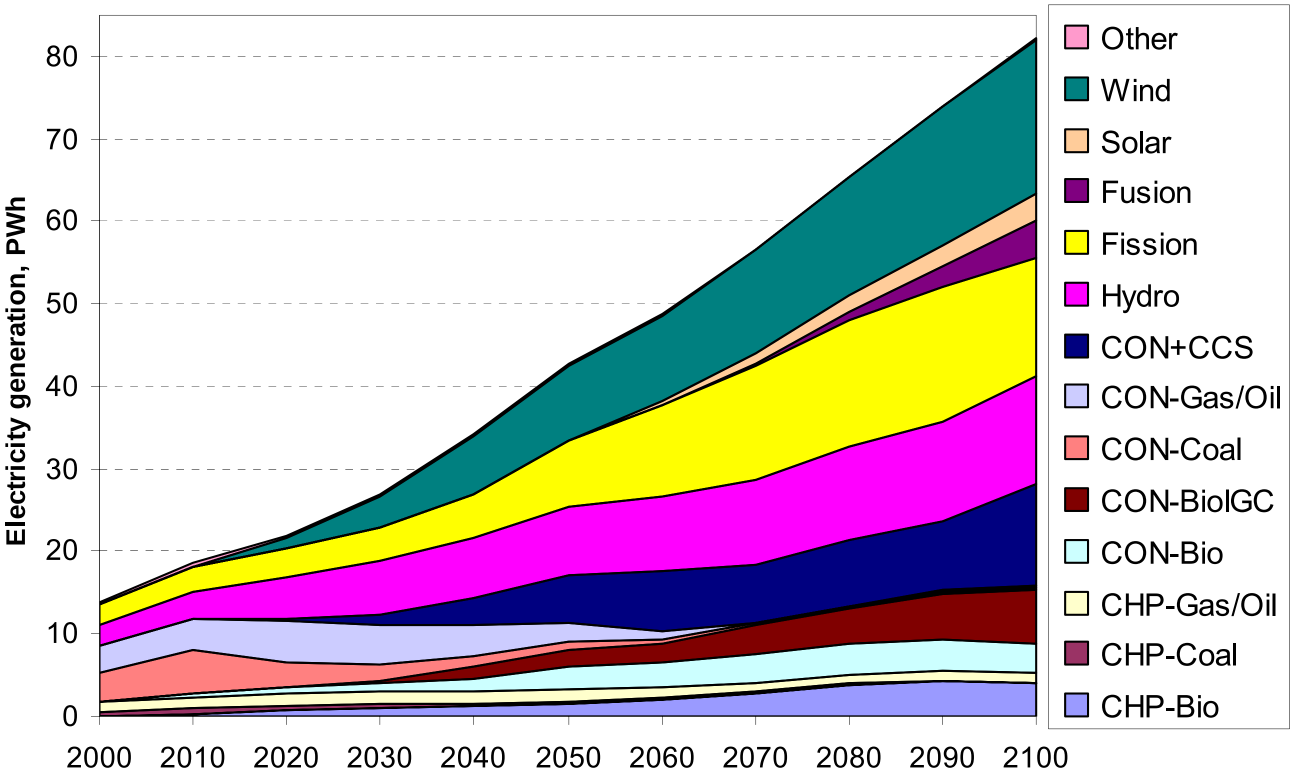

Figure 16. Global electricity generation by type in 2 ºC mitigation scenario.

Figure 17 and Figure 18 show the electricity generation development in Western Europe and in Eastern Europe in the 2 ºC mitigation scenario.

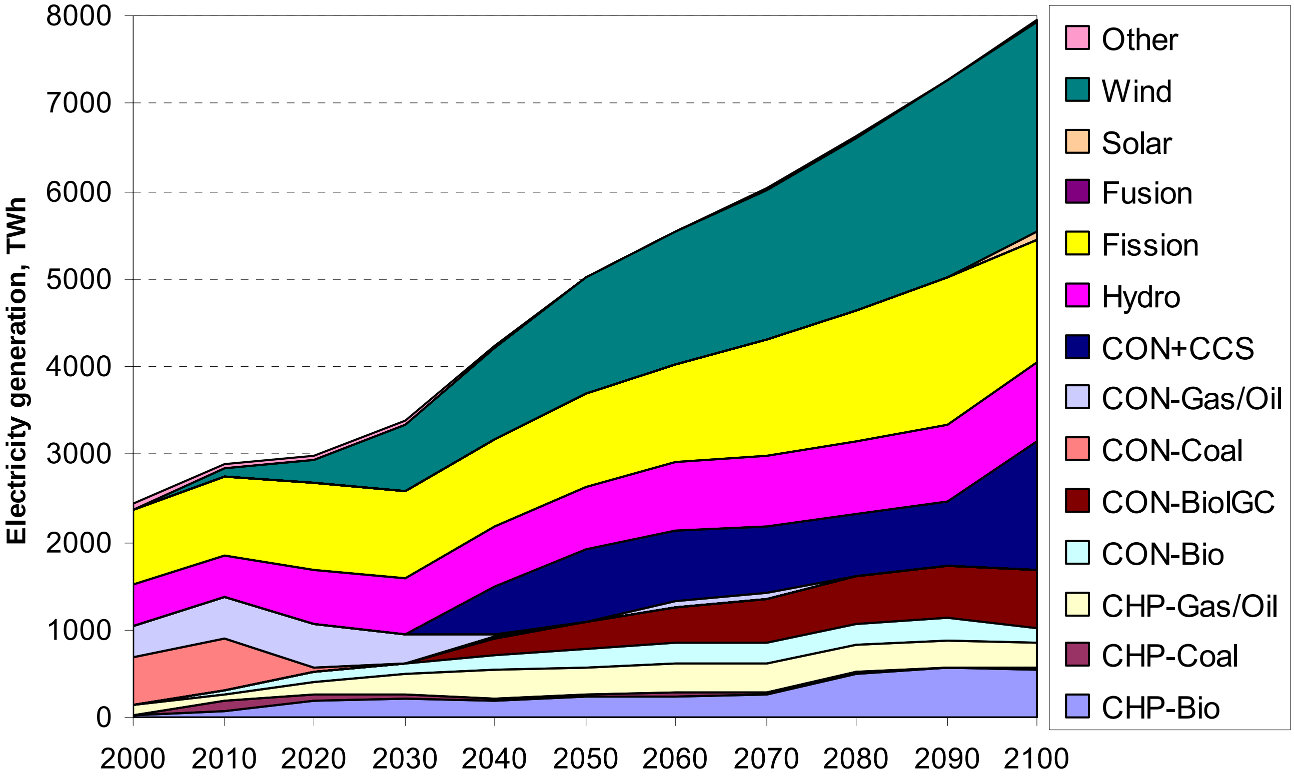

Figure 17. Electricity generation in Western Europe (EU-15, Norway, Switzerland) by type in 2 ºC mitigation scenario.

In the 2 ºC mitigation scenario for Western Europe (Figure 17), the largest electricity generation types in this Century become wind energy, nuclear fission, hydropower and condensing power with CCS. The suffix "–Bio" again refers to co-generation of various biomasses and recycled fuels (REF). Also co-firing using partly fossil fuels can be included in this category. Advanced technology concepts (Combined Heat & Power, gasification etc.) for the utilisation of bioenergy and REF gain considerable market share. The share of wind power in the total regional electricity generation becomes large, partly due to the abundant reserves of both coastal and off-shore wind in the regions. This requires power system operation with wind forecasts to manage grid interconnections and reserves. Flexible generation (gas turbines modelled here), DSM and storage can be increased to meet these requirements.

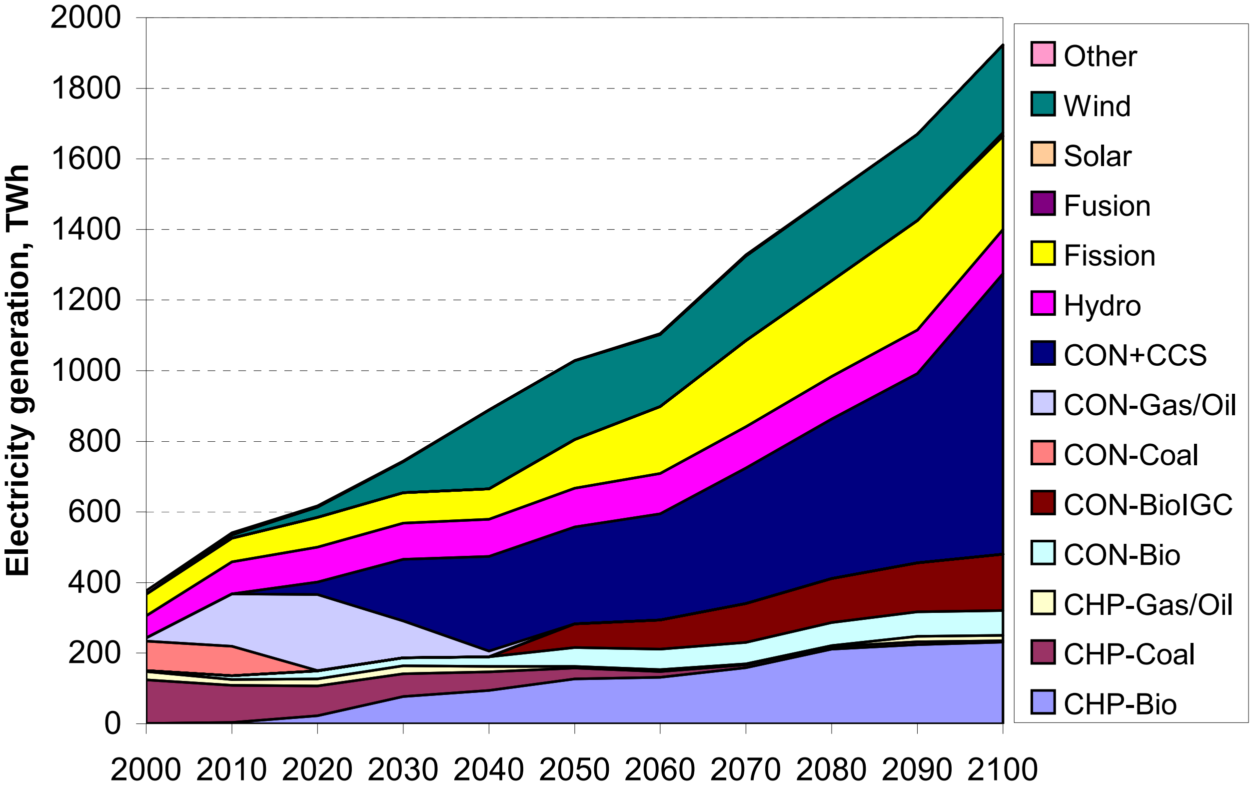

Figure 18. Electricity generation in Eastern Europe by type in the 2 ºC mitigation scenario.

In Eastern Europe, a remarkably large share of CCS emerges in the 2 ºC mitigation scenario. Reasons for this include the large and relatively cheap lignite reserves in Eastern European countries and abundant gas reserves in Russia and nearby regions. Large share of CCS in Eastern Europe is in the first decades mainly in conjunction with natural gas combined-cycle plants, later increasingly in coal and lignite power plants. Large CCS utilisation is explained by close proximity to Russian gas networks and later the substantial coal and lignite reserves in Eastern Europe. Therefore, it remains cost-efficient to rely the regional electricity generation on these reserves and to apply CCS technology. However, the transportation costs for captured CO_2 may need to be reviewed.

CHP using biomass and REF penetrates to a relatively large extent. This is due to the large forest and crops reserves available in the region. Additional land becomes available in the future due to the slowly decreasing population in the region. Especially coastal and off-shore wind power resources are smaller than in Western Europe, which in also reflected in the smaller relative share of wind power in the scenario.

4.4. Final energy and the impacts of demand reponse to prices

The global primary energy use in 2050 is about 700 EJ in the Baseline scenario shown here. This can be compared with the recent IEA Energy Technology Perspectives 2050 (ETP2050) Baseline scenario, where the total global primary energy use was about 920 EJ in 2050 (IEA 2006b). The difference is mainly due to the different background assumptions of economic growth and the related energy need.

The development on final energy demand in relation to the primary energy demand reflects the efficiency of the energy conversion and utilisation system. A major part of energy efficiency measures will be utilised already in the Baseline scenario of this study. This includes, e.g., vehicle efficiency improvements and hybrid vehicles, as well as hydrogen-based fuel cell vehicles, which start to penetrate in some regions already after 2020. Other technology options leading to significant efficiency improvements already in the Baseline include:

- replacement of conventional light bulbs by e.g. fluorescent lamps
- solar heating
- heat pumps

In the Baseline scenario calculated here, the final energy/GDP improves by 1,6% per year and 1,8% per year in 2 ºC mitigation scenario. This can be compared with the IEA ETP2050 optimistic scenario, where the final energy/GDP improves by 1,7% per year. Figure 19 and Figure 20 show the development of the final energy demand by region in the Baseline and 2 ºC mitigation scenarios.

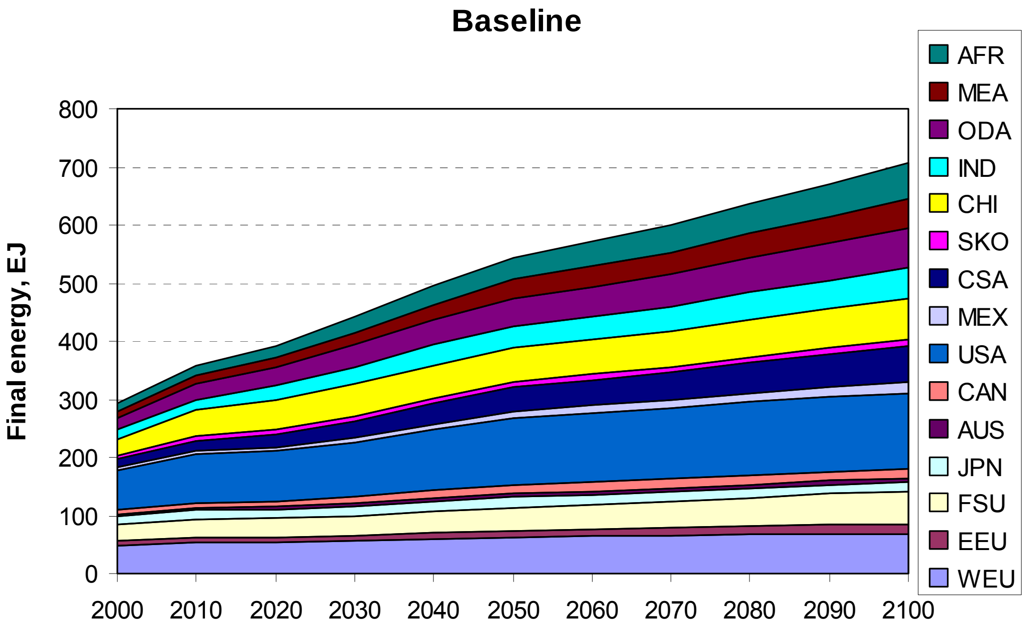

Figure 19 Final energy demand in Baseline scenario.

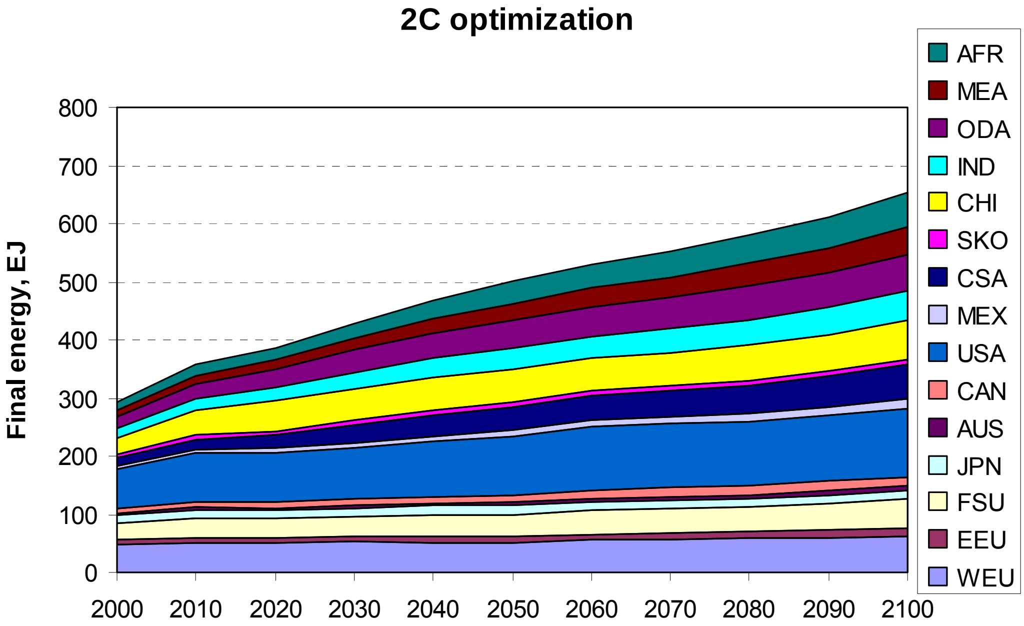

Figure 20. Final energy demand in 2 ºC mitigation scenario.

The global final energy demand in reduced by about 10% in the 2 ºC mitigation scenario compared to Baseline.

4.5. Reduction costs

The global emission reduction costs are 0.1 … 0.4 % of GDP in the scenarios calculated here, with costs increasing after 2050. For Annex 1 countries, the reduction costs are 0.3 … 0.8 % of Annex I GDP, with costs increasing after 2050.

Table 6. Annualized emission reduction costs as a percentage of GDP in Annex 1 countries by region. Note: Costs of traded commodities are allocated to the producers.

	2030	**2050**	**2080**	**2100**
AUS	0.2%	1.2%	0.7%	0.2%
CAN	0.8%	0.0%	0.0%	0.0%
EEU	0.5%	0.7%	0.9%	0.7%
FSU	0.8%	0.8%	0.5%	2.2%
JPN	0.1%	0.4%	0.9%	1.2%
USA	0.1%	0.7%	0.8%	0.3%
WEU	0.3%	0.8%	1.0%	0.5%

The development of the marginal emission reduction costs is shown in Figure 21. The constraints on the emissions of Annex I countries between 2020 and 2050 increase the marginal costs in these countries up to the level of 120 €/tCO2eq by the year 2050. However, the global emission trade assumed after 2050 reduces the marginal abatement costs temporarily back to about 60 €/tCO2eq. The highest marginal costs occur around 2090, when the global price of emission permits reaches 150 €/tCO2eq.

The emission abatement costs estimated in this study are comparable to the results in the recent work by the EU Commission (EU Commission 2007). In the POLES projections for the EU Commission, the global carbon price per tonne of CO_2 reached € 37 by 2020 and € 64 by 2030. Costs, as a result of investments in low carbon technologies, were estimated at less than 0.5 % of global annual GDP up to 2030. These figures, however, are not directly comparable due to the different assumptions on emission trading between Annex I and developing regions and the somewhat different emission reduction targets. The global carbon price estimates (with global emissions trading) are very similar in both studies.

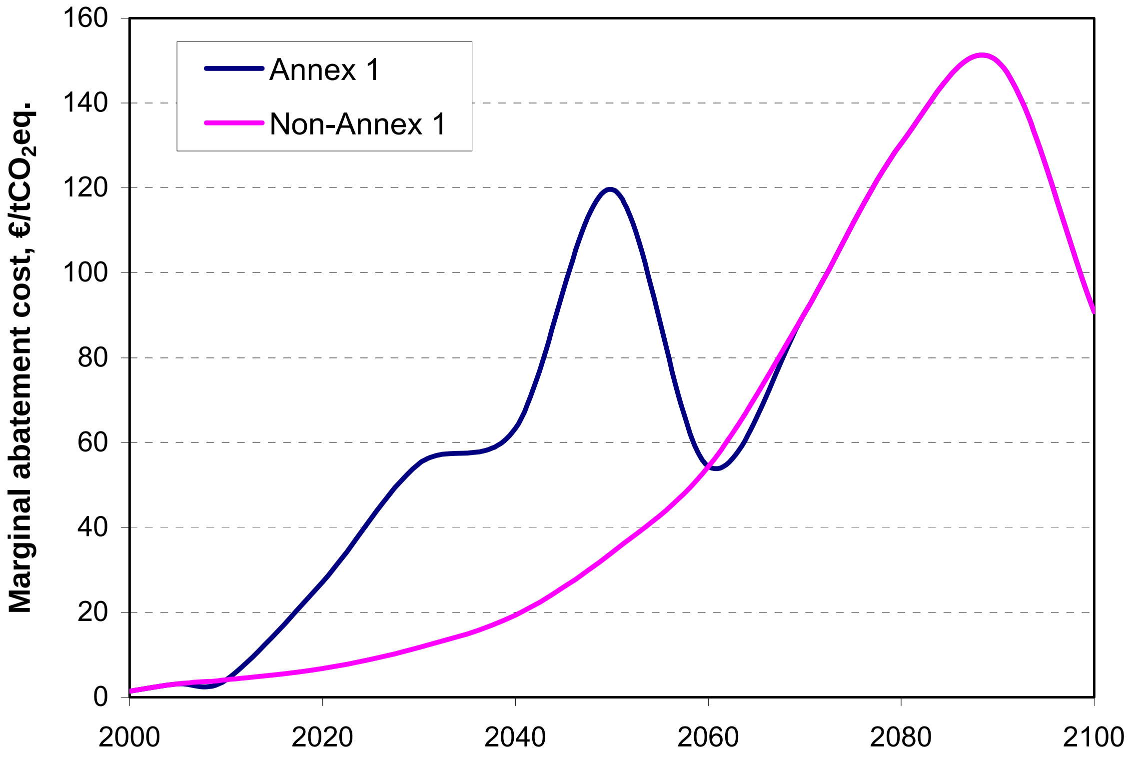

Figure 21. Development of marginal emission abatement costs in the 2 ºC mitigation scenario. The shape of Annex I marginal costs is due to the emissions trading limitations and emissions reductions imposed until 2050.

4.6. Sensitivity analysis concerning energy resources

The assumptions concerning energy resources were considered one major source of uncertainties in the results. Therefore, sensitivity analysis runs were performed on five different groups of resource assumptions: wind power potentials, hydro power potentials, CCS storage potentials, uranium reserves, and energy crop potentials.

The results from these sensitivity runs indicate that the overall results from using the TIAM model for analyzing climate change mitigation policies are quite robust with respect to uncertainties in the resource assumptions. No significant changes in the development of emissions were identified. Lower resource base assumptions obviously lead to somewhat higher mitigation costs:

- Lower wind power potentials resulted in 4% higher total mitigation costs, on an average;
- Lower hydro power expansion potentials and energy crop potentials resulted both about 3% higher average mitigation costs;
- Lower uranium reserves did not result in cost changes before 2080, but caused up to 5% increase in global mitigation costs by the end of the century;
- Lower CCS storage potentials did not cause notable cost increases before 2070, and even thereafter the cost increase remained below 2%; this is partly explained by the unlimited (but expensive) potential for CO_2 mineralization.

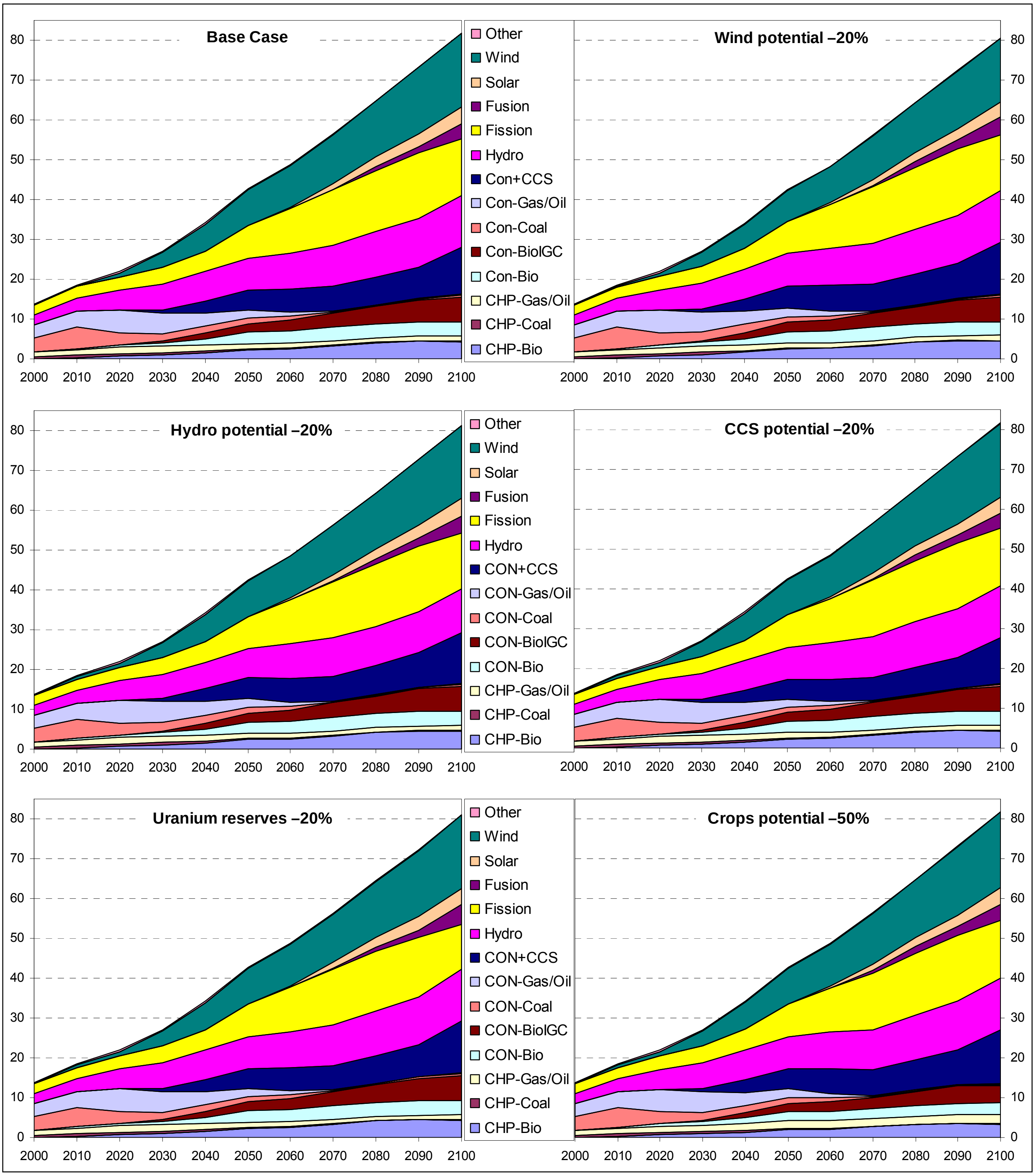

Figure 22. Comparison of the global electricity supply by generation type in the 2 ºC mitigation scenario under Base assumptions and in the sensitivity runs.

4.7. Remarks concerning wind power

The most cost efficient scenarios to reduce greenhouse gas emissions according to GlobalTimes-simulations include more than 3 000 TWh/a wind energy production globally and about 700-800 TWh/a in western Europe. The amount of wind generation capacity in 2005 and a scenario of the development of the capacity to reach these production figures are shown in Table 7. An estimate of both onshore and offshore wind capacity is included.

Table 7. The amount of wind generation capacity to reach production of 3000 TWh/a globally and 800 TWh/a in western Europe in 2030.

	Global wind capacity (MW) to reach annual production of 3000 TWh in 2030			Wind capacity in western Europe (MW) to reach annual production of 800 TWh in 2030			
End of year	Onshore	Offshore	Total	End of year	Onshore	Offshore	Total
2005	51 590	940	52 530	2005	36 890	940	37 830
2010	140 000	8 000	148 000	2010	78 000	6 500	84 500
2015	310 000	30 000	340 000	2015	120 000	18 000	138 000
2020	600 000	80 000	680 000	2020	160 000	37 000	197 000
2030	840 000	130 000	970 000	2030	200 000	56 000	256 000

Total wind capacity of almost 1000 GW would be required to reach global wind generation of 3000 TWh in 2030. Almost 40 % of this capacity would be built in North America, 25 % in Western Europe and about 10 % in China. About 13 % of the global capacity would be built offshore. In Western Europe about 22 % of the capacity would be offshore. These estimates are quite well in line with the outcome from the TIAM model. However, after 2030 the contribution of offshore wind power will increase rapidly in the 2 ºC mitigation scenario, and in Western Europe offshore wind power exceeds onshore wind power production (in energy terms) around 2050.

Despite the large amounts of wind capacity indicated, there are enough wind and land resources for the development of this capacity. Based on a country-by-country analysis of population density, wind resources and main geographical features, it was estimated that almost 300 GW of wind generation capacity could be built in an acceptable way in Western Europe: using only windy areas and in those areas not exceeding the present density of wind turbines in Denmark, northern Germany or the Netherlands.

There is a need to develop the present industrial capacity and infrastructure to support this kind of development. In 2006, about 15 000 MW of new wind generation capacity was built worldwide. The yearly installation rate has almost doubled in two years. The maximum annual installation rate indicated in these long-term scenarios is about four times larger than in 2006, i.e. around 60 GW per year.

The variability of wind power poses challenges to power system operation when more than 10 % of electricity is produced by wind power. Power system operation requires wind forecasts to manage grid interconnections and reserves. The wind penetration levels in this scenario exceed 10 % penetration in 2025 in Europe and globally in 2050. In 2100 the wind penetration levels reach 30 % in Europe and 25 % globally. Technically it is feasible to work with even higher penetration levels, however, high penetrations mean increased costs: increasing flexible generation (gas turbines modeled here), also demand-side-management (DSM) and storage may be needed in some areas.

The penetration rate of wind power depends much on the development of costs of wind power and the development of costs of other technologies and CO_2-prices. For wind power the investment cost level in 2005 was assumed to 1100-1200 €/kW onshore and 1500-1600 €/kW offshore. The development of the investment cost depends on the development of wind capacity. These costs were assumed to drop by 20-30 % onshore by 2030 based on the decrease of specific investment cost by 5 % by doubling of the installed capacity.

In all regions, the availablity of wind power capacity has been assumed 20% at the times of peak load, which ensures a reasonable reserve capacity.

4.8. Stochastic analysis experiment

4.8.1. Introduction

In the context of this work, also some stochastic scenario analysis concerning the climate sensitivity was committed. The climate sensitivity to strongly increased CO_2 conentrations is not yet very well known and the generally used parameters still contain considerable uncertainties. Therefore, stochastic sensitivity analysis can be consireded justified.

The stochastic scenario experiment was based on the following assumptions on the uncertainty of climate sensitivity to the doubling of CO_2 concentration compared to pre-industrial levels:

Table 8. Assumptions on the uncertainty of climate sensitivity to the doubling of atmospheric CO_2 concentration.

Climate sensitivity	Probability	Temperature adjustment lag (years)
1.5°C	0.2	15
3.0°C	0.4	40
4.5°C	0.2	67
6°C	0.2	80

4.8.2. Results

The results illustrate quite well the significance of the uncertainties in climate sensitivity with respect to the necessary climate change mitigation efforts (Figure 23). In the scenario experiment it was assumed that the uncertainties in the sensitivity of climate to greenhouse gas 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 CO_2 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°C. However, in this case it might actually be worth to strive at stricter targets with respect to global warming.

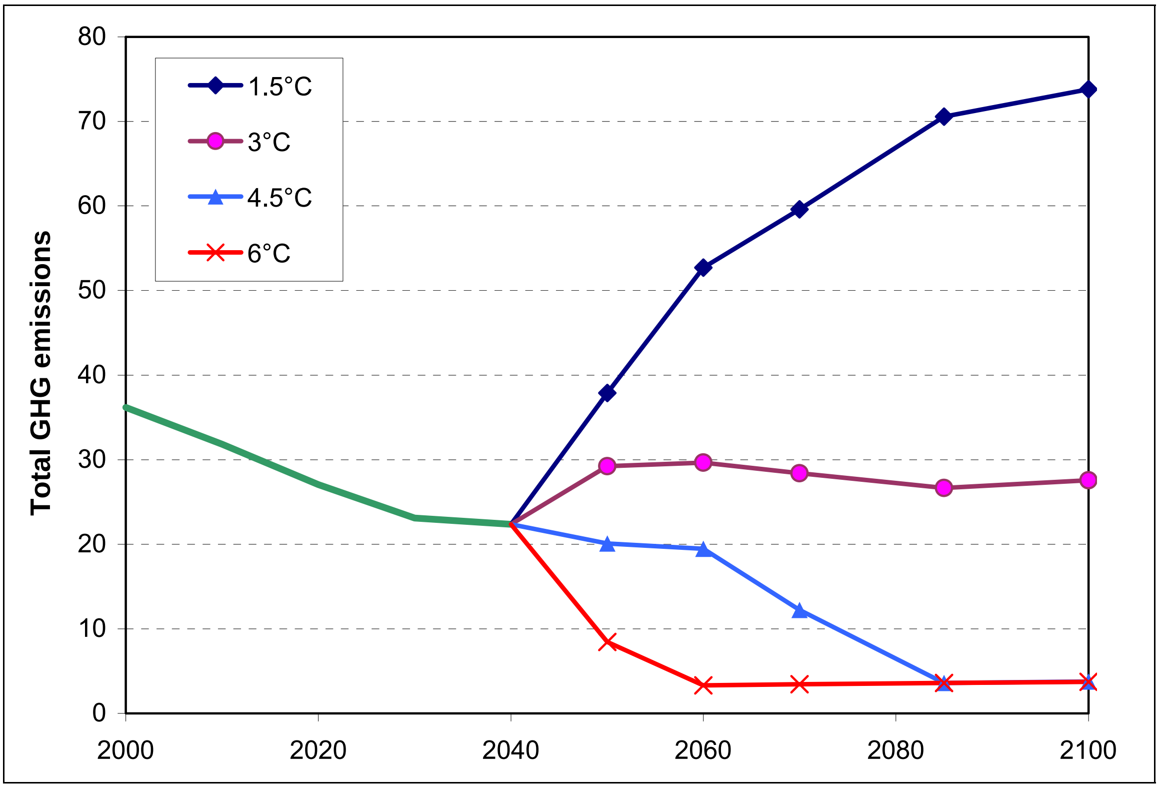

Figure 23. Development of global greenhouse gas emissions in the stochastic analysis with 2 °C limit for global warming and uncertain climate sensitivity.

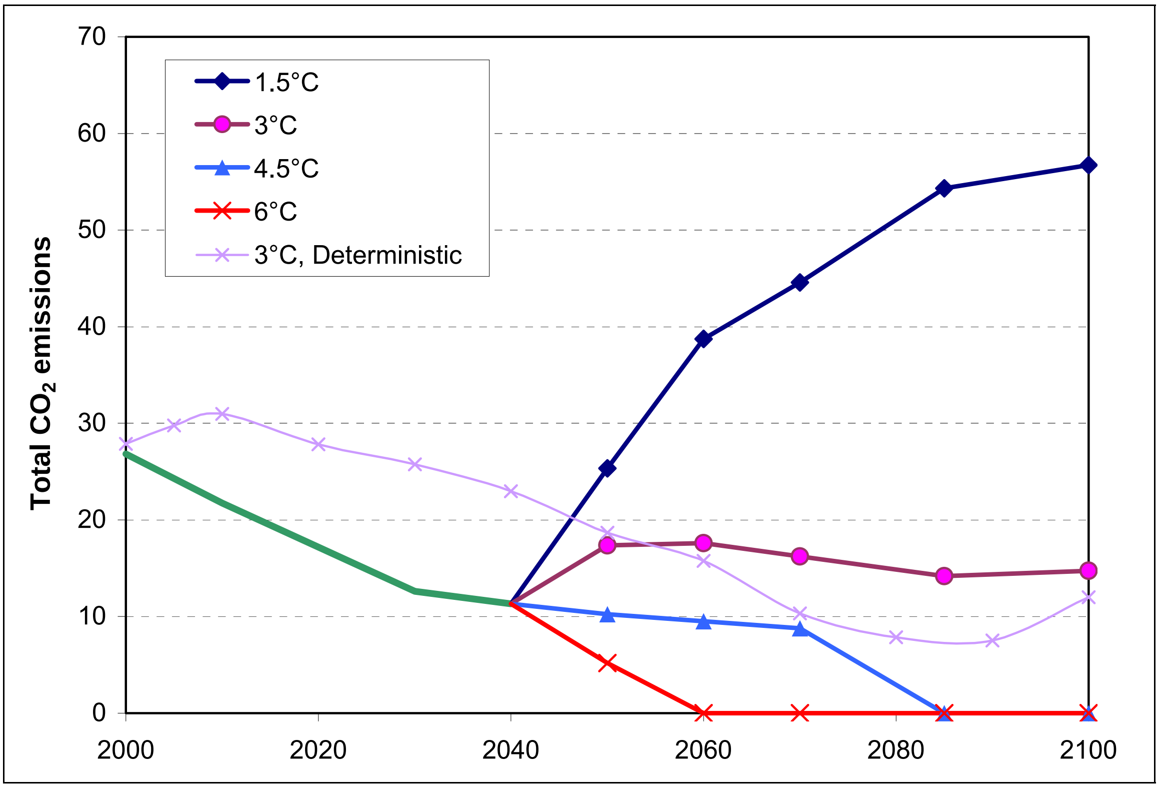

Figure 24. Development of global CO_2 emissions in the stochastic analysis with the 2 °C limit for global warming and uncertain climate sensitivity. The corresponding emission path in the deterministic scenario with the 2 °C limit is also shown for comparison.

Figure 24 illustrates also the comparison between the global CO_2 emission pathways in the deterministic mitigation scenario, where the climate sensitivity was assumed to be 3°C, and in the stochastic scenario results.

This modelling experiment illustrates the importance of what is assumed about the climate sensitivity to increased CO_2 concentrations. If there is a risk that the climate sensitivity is actually larger than the present IPCC recommendations (2001), then optimal hegding strategies would imply considerably stronger, immediate emission reductions. Climate sensitivity is likely to be in the range 2 to 4.5 °C with a best estimate of about 3 °C, and is very unlikely to be less than 1.5 °C. Values substantially higher than 4.5 °C cannot be excluded, but agreement of models with observations is not good for those values (IPCC 2007).

5. Conclusions and recommendations for further work

There is a quite good international agreement that the achievement of the 2 ºC stabilization target of the EU is very challenging. Based on recent studies by e.g. (Meinshausen et al. 2006) and on the preliminary findings of the IPCC 4AR, there is about 50% risk of overshooting for the 2 ºC target with a stabilisation target of 450 ppm CO_2-eq. In most of the recent long-term scenario studies, the CO_2-eq. concentrations first shoot over the 450 ppm limit, and later on decline below the limit.

In this work, the 2 ºC warming target was set to be achieved in 2100. In practise this target setting means that the temperature would continue to slowly increase after 2100 before reaching equilibrium. In further work, it would be useful to study also an even more stringent scenario, where the equilibrium temperature change would be set at 2 ºC warming.

This study investigated the possibilities of achieving the the 2 ºC stabilization target of the EU with the VTT version of the TIAM model. The study indicates that the target is very challenging. Even though major energy efficiency measures were assumed to be implemented, final energy demand increases significantly, more than twofold during this Century. This is one key reason why the global energy system has to transform very strongly towards carbon-free energy technologies.

With most of the low-carbon energy technologies that were taken in large-scale use in the mitigation scenarios, there are indications that serious questions regarding the resource availability may come up towards the end of the Century. In this report, the questions related to wind power and the required land areas and network technologies were treated in-depth. Concerning the availability of biomass resources, uranium resources and hydropower expansion possibilities, there are only rather few studies available. Furthermore, the questions related to public opinion and political acceptability are important in determining the amount of actually realised expansion. Nuclear energy has substantial potential for an expanded role. However, the problems of potential reactor accidents, nuclear waste management and disposal, and nuclear weapon proliferation have to be managed successfully also in cases of substantial expansion in the magnitude and geographical spread of nuclear energy.

Also the forestation rate indicated in the cost-optimised mitigation scenario is in practise extremely challenging. The current trend of net deforestation should be reversed in the next decades.

The global economic growth scenario used in this work assumed a rather modest economic growth. A scenario with more rapid growth and thus a more rapid increase in energy demand would make the achievement of strigent climate targets even more challenging.

Especially in a long-term scenario work, sensitivity studies regarding all the main assumptions of future development of technologies are essential. In this work, only a limited set of sensitivity runs were possible. This has to be remembered when interpreting the results and further sensitivity studies should be included in future work.

Based on this analysis, it appears evident that major energy efficiency measures are needed in all regions. The actual realisation of energy saving and energy efficiency measures described above will require strict international standards. E.g. energy prices are often such a small direct expense to many consumers especially in indusrialised countries, that it is not a sufficient way of achieving savings.

Concerning large penetration of wind power in the electricity system, there are three main issues that need attention and have to be solved to enable this development:

- the available wind resources and required land or sea areas
- the required industrial capacity to manufacture and install the wind turbines
- the management of the large amount of wind energy in the power system.

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