Energy, Climate Change and Local Atmospheric Pollution Scenarios Evaluated with the TIAM-MACRO Model.

ETSAP-Project: Introducing external costs for Local Atmospheric Pollution in TIAM-MACRO to study synergies and co-benefits of climate change mitigation

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Abstract: We have extended the Integrated Assessment Model TIAM-MACRO to consider externalities related to Local Atmospheric Pollution (LAP) of 15 world regions. Externalities are changes of welfare due to activities (in our case the impacts of LAP originated from the energy and transportation system) without being reflected in market prices (hence not paid by the polluters). TIAM-MACRO contributes to coherent and consistent policy analyses and insights both at the world and regional level and correlates demand for energy services to macro-economic developments across regions and time until the end of the 21st century. Regions are integrated via a maximization of the global welfare (expressed as the weighted sum of the regional logarithm of consumption), international trade, regional resource use, the storage capacities for captured CO₂ and the regional damages and externalities of LAP and climate change. The external costs of pollution are based on evaluations of the EU Project NEEDS. This project has generated externality cost data for the EU only, and is extended to all world regions following a PSI approach described in Appendix A. Then, two contrasting scenarios are defined with TIAM related to the reference development (BASE) and the 2 °Celsius (2DS) case which is following long term policies on climatic change mitigation in the spirit of the Paris agreement in 2015. The stringency of the 2DS case is strong and requires the complete restructuring of the energy and transport systems to be relying on carbon-free technologies at high costs. The study concludes on the importance of LAP in relation to climate change, performing first a post optimal analysis of external cost without including them in the optimization process. Then, the two scenarios are re-evaluated by taking into consideration LAP externalities in the welfare function. The study favors actions supporting CO₂ reductions and concludes that the internalization of local externalities, when applied together with carbon policies, has the potential to partially compensate for the cost of carbon control and the cost of controlling local pollutants. But the stringency of the 2DS case is such that at even zero discount rates the cost of such policies is above benefits.

Keywords: Energy, Environment, Climate Change, integration of LAP externalities
1. Introduction: Rationale and objectives

The energy system is a key determinant of sustainability as its development prescribes energy efficiency, local and global environmental emissions and damages, drives economic development and has consequences on the social wellbeing of mankind. The overarching objective of energy modelling including the economic and environmental dimension, is the policy assessment of future pathways of the energy system contributing to a sustainable development.

The specific objective of the ETSAP project: *Introducing external costs for Local Atmospheric Pollution in TIAM-MACRO to study synergies and co-benefits of climate change mitigation* is to further develop the integrated assessment model (IAM) by incorporating in the model structure and database the most important parameters from LCA and ExternE methodologies (life-cycle emissions, materials, and external costs) as obtained in the NEEDS project. This general equilibrium growth modeling platform, consistent with other important global energy modeling efforts (Kypreos & Lehtila 2015), (Kriegler, et al., 2015), IEA 2006, US-EIA 2007, OIAFEIA 2003, PRIMES www.e3mlab.ntua.gr) aims at extending the geographical coverage of the methodology for assessing energy, environmental and economic policies both at regional and the global level, in order to support decision making processes and to formulate suitable operative strategies. The global TIAM-MACRO integrates the most important LAP externalities and damage functions, together with the damages of climate change, and becomes a new modeling paradigm of basic importance able to perform cost/benefit (CBA) and second best analysis (SBA) identifying the “best” technological options and prioritizing measures for a cost-efficient energy system.

2. Including Emission Coefficients in TIAM

In order to include the emissions coefficients for SO2, NOx, NMVOC, NH3, PM2.5 and PM10 in ETSAP-TIAM the subsequent steps were followed:

1) **Base Year Calibration.** The base year in ETSAP-TIAM is 2005. In order to calibrate the emission coefficients for each of the average technologies included in the base year the following approach was taken:

   a) The consumption of each energy commodity in the base year technologies was taken from the calibration of TIAM.

   b) The total emissions of each pollutant for each sector in 2005 were taken from the Emission Database for Global Atmospheric Research (EDGAR) Database\(^1\) of the JRC for 2005 (Joint Research Centre Institute for Environment and Sustainability).

   c) The emission coefficients of EMEP/EEA as defined in the Air Pollutant Emission Inventory guidebook 2003, Tier 1 method\(^2\), were used as a starting point and they were adjusted so that when multiplied with the energy consumption defined in (a) the total emissions of each pollutant per sector as given in (b) were derived (see Table 1 for an example).

\(^1\)http://edgar.jrc.ec.europa.eu/overview.php?v=42

With this procedure the emissions of 2005 were reproduced, using the existing calibration of ETSAP-TIAM.

2) Emission coefficients for new technologies. The emission coefficients for each pollutant and energy commodity for the new technologies were calculated as follows:

a) Power Sector. For each one of the new power generation technologies emission coefficients for each local pollutant were included in the model according to the data of the NEEDS project\(^3\) while some missing technologies were defined based on the USA EPA 9r MARKAL database (https://www.epa.gov/air-research/epaus9r-energy-systems-database-use-market-allocation-markal-model).

b) Industrial Sector. In the industrial sector the calibrated emission coefficients calculated for the base year (Step 1) were adjusted in order to take into account the future improvement of the technologies. Therefore, the emission coefficients were reduced in 2010 10% with respect to 2005, by 20% in 2020, by 40% in 2050 and 60% in 2100 with respect to 2005.

c) Residential, Commercial, Agriculture. In these sectors the same approach as the approach described for industry was followed in order to approximate the technology improvement.

d) Transport. The transport sector was modelled with more detail, since more data are available. SO\(_2\) emission coefficients were calculated based on the sulphur content of fuels. For the other emissions the coefficients from NEEDS\(^3\) were used and were allocated to each one of the technologies that exist in TIAM.

Table 1: Example of emission coefficients for existing technologies in transport in 2005.

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\(^3\)http://www.needs-project.org/
3. Methodological approach of the project

3.1. Introduction
The methodology followed in the ETSAP project is based on the “New Energy Externalities Developments for Sustainability” (NEEDS, http://www.needs-project.org/), a four-year Project of the 6th EU Framework Programme. NEEDS, which is a continuation of the ExternE methodology, has undertaken an ambitious attempt to assess the long term sustainability of energy technology options and policies. A basic part of the NEEDS project, which was organized in research streams, is structured around:

- Life Cycle Assessment (LCA) of energy technologies
- Monetary valuation of externalities associated to energy production, transport, conversion and use, and
- Integration of LCA and external costs information into policy formulation and scenario building

The project has extended the boundaries of energy system analysis. The information generated was integrated first with a technology oriented partial equilibrium bottom-up Pan-EU model that integrates LCA and external cost, together with the sub-models of each European country (Cosmi et al., 2006, Kypreos et al., 2008) and is implemented now into the ETSAP TIAM-MACRO model of 15 world regions.

3.2. The reference energy system (RES)
The NEEDS begins with the definition of the RES with the following sectors included: Residential, Commercial, Agriculture, Industry, Transportation, Electricity/Heat production, and Energy Supply. In particular, the structure of the RES was determined by identifying the demand categories, energy carriers, emissions, and materials. Energy carriers were chosen starting from those reported in the Eurostat energy balances (http://epp.eurostat.cec.eu.int.), and then aggregating some of them following the modelling objectives of the project. Materials are either explicit to model energy intensive processes (e.g. scrap steel), or implicitly defined as part of the variable operation cost. The air emissions modelled are Carbon Dioxide (CO2), Methane (CH4), Nitrous Oxide (N2O), Sulphur dioxide (SO2), Nitrogen Oxides (NOx), Particulate (PM2.5 and PM10), Volatile Organic Compounds (VOC) and Ammonia (NH4).

3.3. Technology data
Since the TIMES model is an integrated techno-economic energy model, its database includes technologies in all sectors of the economy, namely: primary energy extraction, energy processing and conversion, energy transport, and end-uses by four main sectors (residential, commercial, industry, transportation). Thus the TIMES database will concern more than a thousand technologies in each country model. In addition, the global model represents the main energy exchanges between world regions, where each energy trade is modelled via a trade technology (pipeline, trucking, shipping, transmission grid). Among these, an important subset of technologies has been targeted for detailed LCA analysis. They concern the vast majority of the electric power generation sector, and the technologies used for the transport of imported oil and gas.
Regarding the types of scenario envisioned the general idea is to build first a Baseline Scenario where all demand drivers are specified in line with the assumptions used in similar projects by international organizations (IEA, EIA). In all other scenarios, we limit ourselves to a partial/global equilibrium framework in the sense that the initial macroeconomic
assumptions remain those of the reference scenario and are adjusted by the model to preserve equilibrium (partial and general) under the policy constraint under examination.

3.4 Life Cycle Data and External Costs
The TIMES model possesses the required features to represent the consumption (or release) of energy and materials during the entire life cycle of each technology and fuel, as well as the atmospheric emissions produced at each stage. The life cycle of a technology may be decomposed into three phases: construction, operation, dismantling. At each phase, some energy forms and materials are usually consumed and/or released, and the production/disposal of these materials and energy forms itself requires additional materials and energy. External costs are briefly defined as those effects inducing costs on individuals or the society, not taken into account by the originator in the price of the product or service provided. An important contribution to external costs is caused by the release of substances from the energy systems. In the case of TIMES, the substances considered are those emitted into the atmosphere. There are several complex intermediate steps between the emission of a pollutant and the damages caused by it. These steps studied in much detail outside the TIMES model are not explicitly modelled in TIMES. Instead, TIMES has a representation of the damage cost induced by one unit of each substance emitted in each country, in the form of a damage cost coefficient, for instance the damage cost due to one tonne of SO$_2$ emitted in France.

Externalities compensate for induced damages of pollution by imposing an external tax per pollutant such that the marginal control costs equal the marginal benefits of avoided damages. The production cost per unit of e.g., electricity could be expressed as function of the annualized specific capital cost, \( (SCI_{jt}, acf_j) \), the fixed \( (fixom) \) and variable \( (varom) \) operation and maintenance cost and the fuel cost. If the emissions generated per unit of kWh \( (se_{pol}) \) contribute to an externality, this can be compensated by applying the corresponding tax \( (XTax_{pol}) \) for the induced damages. The inclusion of the tax will reflect the full cost of power generation, as shown in the following equation and it will change the solution reducing the release of pollutants contributing to environmental damages while the valuation of this tax follows principles of the EU ExternE Project. The reduction of pollutants can be obtained by end-of-pipe measures (e.g., scrubbers) of by technology substitution or fuel switching.

\[
GC_{jt} = (SCI_{jt} \cdot acf_j + fixom_j) / (pf_j \cdot \text{8760}) + var_{om_j} + Pr_{fuel}/\eta_j + XTax_{pol} \cdot se_{pol}
\]
4. Scenarios analyzed

Four cases have been analyzed (optimized) with TIAM-MACRO together with the reference scenario, and refer to a combination of global emissions constraints and local externalities imposed to the reference development:

- The **reference scenario (BASE)** describes the development of the global energy system in agreement with most present policies (including the nuclear phase out where it has been decided), providing a baseline for comparing policy scenarios. A “BASE” scenario solves for least cost predicated on available resources and technologies, technology learning under existing macroeconomic projections. By chance the total CO$_2$ emissions related to energy and cement production are in the same level as the short terms reductions resulting from the INDCs.

- The 2 °C (2DS) climate policy was investigated assuming global cumulative CO$_2$ and other GHGs is compatible with the long term target of 2° Celsius. We have applied burden sharing rules for studying equity issues together with economic efficiency. The 2DS scenarios begins with the same macroeconomic structure as the BASE scenario and a cumulative GHG budget of 1855GtCO$_2$ applied between 2020 and 2100, with a 66% confidence level to remain below 2 °C (Friedlingstein, P. et al., 2014), (Kriegler, E. et al. 2013) and appropriate bounds on other GHGs that correspond to 450 ppm-eq. concentrations.

- POA-BASE & POA-2DS: For the BASE and the 2DS cases we have performed post optimal analysis (simulations) defining the co-benefits of reduced local pollution (by multiplying the estimated pollutant balances with the appropriate taxes per unit of pollutants) and we also estimate the market and non-market damages of climate change. Post Optimization Analysis (POA) applies 6 different burden sharing rules to the energy and economics system results, exploring means of equitable redistribution of the cost of our 2DS mitigation scenario. The burden sharing rules are outlined in Appendix B. Finally, we have applied once more the same burden sharing rules for redistribution of losses, net of benefits, due to reduced LAP externalities and of the reduced temperature change when the 2DS cumulative bound is imposed.

- LAP-BASE & LAP-2DS (internalization of LAP externalities): some world regions have proposed national environmental targets for local pollutants as e.g., the CAFE Program (Clean Air for Europe, http://ec.europa.eu/environment/archives/cafe/general/keydocs.htm). We have just adopted for the BASE case an exogenous emission reduction over time representing technological change as described in Section 2, and simultaneously we have imposed externality taxes to define the new equilibria of the energy system development. Our objective is not to evaluate these policies but to assess the impact of the internalization of the external cost linked to local pollutant (SO$_2$, NO$_x$, PM2.5, PM10, NH4 and NMVOC), with and without cumulative GHGs bounds. The external costs implemented in TIAM are those derived in the NEEDS project as extended by PSI to the global level (Appendix A).
5. Main results

The scenario analysis showed the importance of utilizing an integrated modeling framework for climate and energy policy that includes the whole energy system and takes into account the trade-offs in a consistent way. Some of the most representative results derived from scenario analysis are presented in the following sections.

5.1 The Reference case (BASE)

The Reference scenario is the one generated in the ETSAP project where key socioeconomic parameters like population growth and economic activities are postulated together with the energy intensity. Important is to notice that the carbon emissions of the BASE case in 2030 correspond to the global INDCs pledges and continue with the same slope over time. The economic development assumed in the BASE case is consistent with the projections of the GEM-E3 growth model of applied general equilibrium (https://ec.europa.eu/jrc/en/gem-e3/model). The BASE case economic projection does not take into account environmental damage costs to ecosystem services in the global economy due to climate change as well as the externalities related to the local atmospheric pollutants (LAP).

5.2 The Policy Scenarios of 2 °C

The 2°C scenario (2DS) requires emission trajectories to reverse immediately with annual emission to be halved at no more than 15 GtCO2/yr beyond 2050. Delayed action to 2020 makes solving for a feasible solution increasingly difficult and at a larger abatement cost, considerably so towards the end of the horizon (Tavoni, M. et al., 2015). Significant long term growth in capacity of renewable electricity and bioenergy with CCS, combined with the removal of fossil fuels, enables the required reductions in global emissions with regional negative emissions starting in 2070, with net negative global emissions from 2080 (See the resultant energy system in Figure 2).
Figure 2 (a) Regional emissions for BASE and 2DS scenario (b) World Energy flows 2012 (c) Final Energy use in 2100 2DS mitigation scenario
5.3 Primary energy consumption

Primary energy use (Figure 3) in the BASE case is increased from 580 EJ in 2020 to 900 and 1200 EJ/yr by 2050 and 2100 correspondingly. Significant is also the reduction of Primary energy use in the 2DS case which is attaining levels of around 700 and 810 EJ/yr for the same time periods. Most important is the fuel substitution that takes place in the case of the carbon constraint that shifts production to renewables, biomass and nuclear while it limits the use of oil and gas. The LAP externality taxes have limited impacts on the quantities of energy use and minor shifts in fuel shares (less coal more gas).

Figure 3. Primary energy production by fuel for all cases and the years 2020, 2050 and 2100.

5.4 Electricity generation

The carbon budget transfers power generation technologies towards carbon free systems like renewables (wind and solar), biomass and nuclear, and even biomass is introduced with CCS to remove CO₂ from the atmosphere (Figure 4). Interesting is that at the end of the time horizon the 2DS electricity generation is above the BASE case as the stringency of the carbon constraint forces electricity to substitute for fossil fuels in the end-use markets. This is not the case in the middle of the century. LAP externality taxes reduce demand for electricity but the reduction level is of a few percentages.
5.5 Development of LAP and externalities

The emissions of the local pollutants NO$_x$, NH$_4$, NMVOC, SO$_2$ and particulates generally tend to decrease in all scenarios due to new emission standards and technical improvements in processes. The amount of reductions depends mainly on the employed energy carriers. The effect is accelerated when the carbon constraint is introduced as electricity generation becomes carbon-free and the end-use sectors assume a strong electrification (substituting for fossil fuels) and biofuels for transport. All these changes have resulted into a drastic reduction of LAP emissions by the end of the century (Figure 5) which is a factor of 10 in relation to the emissions in 2020 but for a drastic economic growth mostly for LDCs.

Figure 4. Electricity generation by technology and case for 2020, 2050 and 2100

Figure 5a. LAP balances for BASE and 2DS (simulation without the introduction of taxes).
The local pollutants are further reduced in the case of introducing externality taxes in the BASE and the 2DS cases (Figure 5b). Interesting is to notice that the BASE case under externality taxes assumes a great reduction of emissions that corresponds to almost 50% of the pollutant levels without externality taxes. The same effect takes place in the 2DS cases under externality taxes but the effect is less pronounced. In the accounting case, the reduction due to the carbon budget is about 88% of the BASE case by the end of the century, while in the cases where LAP taxes are introduced, the relative reduction is 75% of the BASE case emissions. For the same reason, the co-benefits of the carbon constraint are reduced (about 0.51% of the cumulative GDP) as the externality tax results to less emissions in the BASE case. (Fig 5b)

5.6 External Costs, accounting only: The following figures 6, refersto the external cost components of air pollution and explain the structure of co-benefits associated with the introduction of cumulative CO₂ budgets (2DS case). First the co-benefits are defined relative to GDP of BASE. Benefits are stronger for China, FSU, Africa and India, while the Figure 6b presents in absolute terms (MER) the reduction of external cost by regions where for China, India, Africa and USA gains are more pronounced. All these co-benefits correspond to 1.05% of the global and cumulative GDP from 2020 to 2100.
Figure 6a, Relative co-benefits of air pollution reduction by region due to 2DS carbon budgets

Figure 6b, Absolute and regional co-benefits of air pollution reduction by region due to 2DS carbon budgets estimated in TIAM-MACRO.

Finally, adding together the benefits of reduced damages (market and non-market damages) when the temperature change remains below 2 °C and the co-benefits due to LAP control, the overall global costs reduction of damages and health impacts are 1.74 % of the cumulative world GDP. In the case of introducing LAP externality taxes in the BASE and the 2DS cases the co-benefits of the carbon budget are reduced to 0.51% of the global GDP. In the optimization cases under LAP policies the co-benefits of 2DS are less as significant pollution reductions take place already in the LAP& BASE case due to the introduction of externality taxes.
Figure 6b. Absolute and regional co-benefits of air pollution reduction by region due to LAP externalities and 2DS carbon budgets estimated via optimization in TIAM-MACRO
6. Burden-Sharing

Burden sharing based on trade of emission permits, is considered as a market based mechanism to establish justice as many LDCs are not able to finance the transition to a carbon-free economy or to accept GDP losses related to policies for carbon control and therefore are not making binding commitments with emission reduction targets. But an initial endowment of their emission permits based on equity principles (rules) allows them to trade their emission surpluses and profit from trade. While global GDP loss is in the range of 5.2% cumulatively over the model horizon, there is considerable disparity in regional GDP losses between least cost efficient, and equitable burden sharing rules (Figure 7). The difficulty in establishing burden sharing rules and global legislation quickly becomes both obvious when examining the GDP impacts established under the efficient second best solution obtained with TIAM-Macro under a cumulative and binding GHG constraint. For the least cost efficient scenario, developed post industrialized, service-based regions with higher GDP per capita and low energy intensity per unit of GDP output have short term economic benefits in efficiency, and, in the long term, suffer smaller cumulative losses than higher intensity newly industrialized regions.

For the Efficient solution, United States of America (USA), Japan (JPN), Canada (CAN), and Western Europe (WEU) have cumulative GDP losses of 2.9% - 3.3% whereas the Former Soviet Union (FSU), China (CHI), Other Developing Asian Countries (ODA), India (IND) and Africa (AFR) have cumulative GDP losses between 3.7% - 11.6%.

Rule I is assuming equal emissions per capita (egalitarian) after a period between 2020 and 2050 where a grandfathering rule applies from present emission levels and up to equal emissions per capita in 2050. Regions with large biomass and renewable energy potentials stand to gain significantly from burden sharing rules based on emissions equalizations per capita. The abundant renewable energy resources and low population density for Australia, Canada and Former Soviet Union, could more-than compensate for fossil fuel revenue losses by meeting the high demand for biomass and biofuels exports. In the long term, most of the emerging economies experience the opposite effect where GDP loss is less in the efficient scenario as opposed to the equal emissions per capita. The Middle East energy export countries suffer the largest economic losses relative to the Baseline. China, Developing Asia and India are seen to have larger economic losses in the equal emissions per capita case (relative to the efficient case) as a result of high growth, starting from a low base of high carbon intensity energy infrastructure lock-in. Central & South America and Africa reduce their losses to near zero as a result of low energy intensity and carbon intensity per capita, starting from a low base and with slower growth than the emerging economy counterparts.

Rules II to IV equalize GDP losses across all regions, compensate LDCs (AFR – Africa, CSA – Central & South America, IND – India, MEX – Mexico, and ODA – Other Developing Asia) for increases in energy costs if there are any, and fully compensate the same set of LDCs for GDP losses. The redistribution of losses is seen in Figure 7. High incomes countries see GDP losses rise, LDC countries see their GDP losses drop to between 6.5% - 0%.

The Burden Sharing rule which requires the least capital transfers is that of compensation of LDC countries for energy cost increases. This rule aims to encourage investment to decarbonize the energy system of LDCs and has the best chances to be approved by the industrialized and the less developed regions. in the most efficient mitigation pathway funded by developed regions where global cumulative GDP losses are in the region of 5.2% over the horizon.
Figure 7. Regional Cumulative GDP change relative to the Base scenario for the efficient (EFF) 2°C 66% scenario, Rule (I) Egalitarian with equal emissions per capita after 2050, Rule (II) Capital Transfers to Equalize regional GDP losses, Rule (III) Full Compensation for developing countries GDP Loss, Rule (IV) Full Compensation of energy system costs, for developing countries.
Each burden sharing rule presents different winners and losers. Regions that may benefit in the short term, do not necessarily gain in the long term, nor cumulatively over the model horizon to 2100. Such is the case for India & China in the equal emissions per capita case: rule I. This observation points out the difficulties to reach an agreement. China and the Former Soviet Union benefit the most from GDP equalization rule II, with China receiving the majority of the permits in the short to medium term commensurate with the transformation their energy system must undergo, while the FSU receives the majority share measured in undiscounted value of permits towards the end of the century. Africa, Developing Asia and India benefit from inward investment in their energy systems from compensation rules III and IV. India receives the majority of the short term carbon permits from rule IV, compensating for the increases in energy system costs. The
volume of permits smaller than the other burden sharing rules but all LDCs as a set together benefit most by full compensation of GDP losses.

7. BS Rules net of Global Climate Change (GCC) damages and LAP externalities

Finally, we proceed with the re-definition of BS rules net of benefits due to climate change mitigation and reduction of LAP externalities as defined in the subsequent Figures 9a and 9b.

Figure 9a: Climate change relative damages (market and non-market) and LAP externalities for the BASE and 2DS cases and the Net-Benefits (difference) of the climate change mitigation of the 2 °C.

Figure 9b: Regional distribution of Net Benefits (Difference of the Climate change market and non-market and LAP externalities for the BASE and 2DS cases). Winners (above the global average) are China, India, FSU and MEX.

The Gams code for BS rules and the estimation of market and non-market damages as well as the externalities due to local pollution are defined in Appendix C. There are winners and losers in the specification of regional net benefits as shown in Fig. 9b and this has as consequence the change of the regional transfers required for the equity
rules. Using this regional improvement in the cost structure we have re-evaluated the Burden Sharing rules as defined in the following Figure 10. The world GDP losses are reduced from 5.14% to 3.74% (undiscounted) and this confirms that even at zero discount rate benefits are less of control cost. Clearly, one has to re-evaluate properly both scenarios at almost zero discount rate to claim the above statement but it is expected that overall losses will not change to gains.

Figure 10: GDP losses per region and burden sharing rule, net of Benefits. The world GDP losses are reduced from 5.14% to 3.74% (undiscounted and this confirms that even at zero discount rate benefits are less of control cost.

Summarizing the BS rules, we realize that the Egalitarian rule I) with equal emissions per capita after 2050 is not ideal for the LDCs in the long term, for reasons explained in the previous chapter. Similarly, rule II) with equal relative GDP losses looks well balanced but LDCs are having significant GDP losses and are not prepared to undertake such commitments. The rule III) with full compensation of GDP losses is balancing exactly these losses but the consequence is an almost doubling of the losses that correspond to the efficient case for the industrialized regions. Finally, rule IV) with less capital transfer requirements is the one that compensates fully LDCs for their capital investments in the restructured energy systems to become carbon-free. Clearly, such a compromise with a minimum of capital transfer from the industrialized world to LDCs to cover the investments to carbon-free technologies could be justified. But, the market prices for energy use and power generation tariffs should reflect the high carbon control prices to adjust the demands for energy services accordingly.

8. Conclusions

The scope of the study was to search for an efficient 2 °C scenario by imposing global CO₂ budgets while the BASE case by chance respects the INDCs for up 2030 and then continues increasing following the same slope. We have completed a Second Best analysis (SBA) not a Cost Benefit one, but we evaluate benefits in a POA simulation like e.g., the reduction of expected Climate Damages of the 2°C policy and the expected benefits of the reduced LAP of the 2°C case versus the BASE case, like as in the case of a CBA. Then, we apply burden sharing rules and capital transfers aiming to present arguments that might convince LDCs to participate into a global commitment (potential extension of the present INDCs pledges).
The main methodological achievements of the modeling work carried out in the project is the development of a global integrating framework for 15 regional energy system models reflecting all regional details and specific situations. Moreover, based on this model a ‘full cost’ analysis of the global energy system was performed demonstrating the possibilities of such a tool evaluating a few key socio-economic-energy-environment scenarios. This integrated framework provides an important platform for future refinements and enhancements of full cost analyses.

The main policy conclusions are summarized in the following:

- The scenarios analyzed showed that it is possible to attain very stringent CO₂ reductions with a total discounted welfare loss of 5.2% compared to the reference. This cost is the cost within the economy and the energy system exclusive of the side benefits from the reduction of local air pollutants and the reduction of climate damages when assuming a cumulative CO₂ bound, i.e. an efficient instrument while the consideration of burden sharing between regions define more equitable scenarios. (The 2°C is technically feasible and with burden sharing can also be equitable).
- The climate policy brings also ancillary benefits by reducing damage from local pollutants (SO₂, NOx, PM, NMVOC) by exploiting the synergies.
- The reduction in damage through the internalization of local externalities applied together with a carbon policy has the potential to pay part of the cost of carbon control and the cost of controlling local pollutants.
- The mitigation costs can be reduced if avoided damages (0.71%) and the co-benefits of LAP control (1.05%) are considered together resulting to a net benefit of about 1.76% of the GDP of the BASE case. However, the control costs are not fully balanced and remain higher than benefits even at zero discount rates.
- Equal relative GDP losses is a balanced burden sharing allocation but not perfect for LDCs while the full compensation of the energy system cost in favor of the LDCs requires the lowest capital transfers and compensates LDCs for their investments to carbon-free technology switch.
- There is not one key technology or one energy stream dominating the future picture; all technologies have a role to play. We should therefore refer to a number of key technologies for carbon mitigation as wind, solar PV, Nuclear, Coal/Gas with CCS, and BECCS, however BECCS based on biomass while good for CO₂ reduction, generate PM.

9. REFERENCES


NEEDS “New Energy Externalities Developments for Sustainability”, http://www.needs-project.org


PRIMES model description and manual are available at: www.e3mlab.ntua.gr


Appendix A; External LAP cost by region and time; PSI methodology

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1. Background and Motivation
The calculation of the external costs of local air pollutants (LAP) caused by the activities in the global energy system (e.g. power generation, transport, heating) requires the definition of specific external-cost factors for each LAP. These external-cost factors describe the relation between a certain amount of pollutant and the cost it induces on society (e.g. €/t SO2 emission). For this project, not only the specific external-cost factors of the LAP emissions in one region are defined, but they are derived for all regions (r) and time steps (t) of the ETSAP-TIAM model. The methodology developed for this purpose is presented in [1] and shortly described below.

2. Methodology

2.1. Basic data
The basic specific external cost factors for each LAP (eLAP, WEU,2010) stem from the European NEEDS project [2]. The NEEDS values are assumed to represent the ETSAP-TIAM region Western Europe (WEU) in 2010. For the external cost analysis with the ETSAP-TIAM model, these basic values need to be transferred to the other 14 TIAM regions on the one hand (regionalization) and projected to the future time periods represented in the ETSAP-TIAM model on the other hand (projection). The concept of the regionalization and projection is schematically illustrated in Fig. 1.

2.2. Regionalization
The external costs of LAP emissions depend on (A) the willingness-to-pay (WTP) for clean air as well as (B) the population, which is actually affected by the emission, in each region. The regionalization of the specific external cost factors of Western Europe (eLAP, WEU,2010) from NEEDS are thus based on the WTP and the population densities in the other ETSAP-TIAM regions. Formula (1) shows the WTP adjustment developed within the NEEDS project which is based on unit value transfer [3]. Analysing surveys, the income elasticity of WTP (α) was found to lie between 0.38 and 0.69 depending on the country addressed and the model used in [4]. The most relevant model to our study from the ones described in [4] is Model 1, which considers the WTP of all respondents in the survey and their individual income, and resulted in α = 0.080 for EU16 countries and α = 0.527 for New Member Countries (NMC) [4]. Based on this information α = 0.080 and α = 0.527 are used for developed and developing regions in the ETSAP-TIAM model, respectively, to calculate the unit value transfer factor (α_r).

\[ a_r = \frac{WTP_r, WEU,2010}{WTP_{WEU,2010}} = \left( \frac{\theta_r, WEU,2010}{\theta_{WEU,2010}} \right)^{\alpha_r} \]

To estimate the people affected by the LAP emissions in each ETSAP-TIAM region, population density values are used. This assessment takes the assumption that the higher the population
density is, the more people are affected by the pollution and the more social costs are incurred. Instead of using average population densities of the ETSAP-TIAM regions, which takes into account not inhabitable land areas, only population densities of the densely populated areas of each region are considered in the analysis. This is based on the fundamental assumption that the LAP emissions occur where people actually are and human activities are, hence, intense.

The calculation of the population density factor \( b_r \) is shown in Formula (2). In accordance with literature about the minimum urban density definition \([5]\), a threshold of 400 people per km\(^2\) is used to distinguish densely populated areas from less densely populated area.

\[
b_r = \frac{P_{r,2010}}{PW_{EUI,2010}}
\]

### 2.3. Projection

In order to define the external cost factors of the LAP for future time periods, i.e. from 2020 onwards, two factors must be considered in each ETSAP-TIAM region: (A) the development of the WTP; and (B) the development of the population density.

The GDP uplift factor \( c_{r,t} \), which takes into account the development of the WTP in the ETSAP-TIAM regions, is calculated from the GDP growth as shown in Formula (3). In \([6]\), the elasticity factor \( \beta \) is reported to lie between 0.7 and 1.0, with 1.0 to be used as a default and 0.7 when air pollution costs prove to contribute an important part of the benefits quantified in an assessment. For the present study the factor which was used in the NEEDS project, i.e. \( \beta = 0.85 \), was adopted \([7]\).

\[
c_{r,t} = \frac{WTP_{r,t}}{WTP_{r,t-1}} = 1 + \frac{g_{r,t} - g_{r,t-1}}{g_{r,t-1}} \cdot \beta
\]

To project the population densities to the future, i.e. to estimate the people affected by the LAP emission and thus the social cost incurred in future time periods, the growth of the urbanization rate is used. It is assumed that the urbanization growth represents the growth in population density and thus the increase in the social costs incurred. The calculation of the urbanisation factor \( d_{r,t} \) is based on the urbanization rates \( u_{r,t} \) and shown in Formula (4).

\[
d_{r,t} = 1 + \frac{u_{r,t} - u_{r,t-1}}{u_{r,t-1}}
\]

The urbanisation rates can be provided exogenously (i.e. from projections from UN or IIASA Global Energy Assessment studies) or they can be estimated from the following two equations:

\[
r \cdot d_{r,t} \cdot k_r + l_r \cdot g_{r,t} , \text{ with } r \cdot d_{r,t} \leq 0.9
\]

\[
upop_{r,t} = upop_{r,t-1} \cdot \frac{pop_{r,t-1}}{pop_{r,t}} + rd_{r,t} \cdot pop_{r,t} \cdot \frac{pop_{r,t-1} - upop_{r,t-1}}{pop_{r,t-1}}
\]

\[
u_{r,t} = \frac{upop_{r,t}}{pop_{r,t}}
\]

The parameters \( k_r, l_r \) are given in the table below for the TIAM 15 regions, and were obtained by time-series analysis based on the UN Population Division data. Note that the GDP per capita should be expressed in k$2005 PPP per capita, otherwise appropriate scaling of the parameter \( l_r \) is required.

<table>
<thead>
<tr>
<th></th>
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<tbody>
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<td>AFR</td>
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</tr>
<tr>
<td>AUS</td>
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</tr>
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<td>CAN</td>
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</tr>
<tr>
<td>FSU</td>
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<td>0.000163</td>
</tr>
<tr>
<td>IND</td>
<td>0.067114</td>
<td>0.000626</td>
</tr>
</tbody>
</table>
3. Results

The four factors calculated above, i.e. unit value transfer, population density, GDP uplift and urbanisation, are multiplied to find the total (combined) adjustment factors \( f_{r,t} \) as shown in Formula (5) for the base year 2010 and in Formula (6) for the time periods from 2020 onwards.

\[
\begin{align*}
   f_{r,2010} & = a_r \times b_r \\
   f_{r,t} & = f_{r,2010} \times \prod_{2020}^{t} (c_{r,t} \times d_{r,t})
\end{align*}
\]

The adjustment factors \( f_{r,t} \) are then multiplied with the external costs for Western Europe as the have been estimated in the NEEDS project \( (e_{\text{LAP,WEU},2010}) \) to calculate the specific external cost factor \( (S_{\text{LAP,r,t}}) \) for the LAP of interest for each region \( r \) and period \( t \) of the ETSAP-TIAM model as shown in Formula (7).

\[
S_{\text{LAP,r,t}} = f_{r,t} \times e_{\text{LAP,WEU},2010}
\]

The total (combined) adjustment factors \( f_{r,t} \) for the different regions and periods in the ETSAP-TIAM model are displayed in Figure A1.

![Graph showing total (combined) adjustment factors for different regions and periods](image-url)

**Figure A1:** Total (combined) adjustment factors \( f_{r,t} \) [-] for the 15 regions in the TIAM model and the time periods 2010-2100. 1 = WEU in 2010.
List of symbols

GDP  Gross Domestic Product
LAP  Local Air Pollutant
WTP  Willingness to pay
α   WTP income elasticity
β   GDP per capita growth elasticity
a   unit value transfer factor
b   population density factor
c   GDP uplift factor
d   urbanization factor
e   specific external cost factor
g   GDP per capita PPP 2005
k   constant for rural population migration equation
l   slope of the rural population migration equation based on GDP per capita PPP 2005
p   population density of the densely populated areas
r   region (15 TIAM regions)
pop  total population
rd  population internal migration (% of rural population)
s   specific external cost factor
t   time period (2010-2100)
u   urbanization rate
upop  urban population

References

Appendix B: TIAM-MACRO and Burden Sharing Methods

Figure B1. TIAM Regional divisions of the world

B.1 TIAM-MACRO

TIAM-MACRO is the hybrid TIMES Integrated Assessment Model (TIAM) developed within the Energy Technology Systems Analysis Programme (ETSAP), a global implementing agreement of the International Energy Agency (IEA) member countries. The hybrid version of the model used in this work is hard linked with a general equilibrium MACRO module (Manne and Wene, 1992), (Messner & Schrattenholzer, 2000), (Kypreos & Lehtila, 2015). TIAM independently calculates a dynamic inter-temporal partial equilibrium on global energy and emissions markets based on minimization of total discounted energy system cost with perfect foresight to 2100 (Loulou, 2008), (Loulou and Labriet, 2008). The model has global coverage, with 15 regions, their resource potentials and trade connections. The model uses exogenous macroeconomic drivers to generate 45 price-elastic energy service demands across all sectors of the global economy. It has a rich technology database of over 1500 energy technologies, and their relevant commodities. TIAM encompasses a full cradle to grave representation of the energy system from resource production, refining, transport, trade, generation, consumption and sequestration of final energy commodities and the investment, operation, maintenance, and decommissioning of intermediary technologies. Energy commodities include a full spectrum of resource potentials and their costs for fossil fuels, nuclear, bioenergy, both traditional and modern renewable technologies, while endogenously accounting for three main greenhouse gases emitted: Carbon Dioxide (CO2), Methane (CH4) and Nitrous oxide (N2O). An integrated climate module models greenhouse gas concentrations, radiative forcing and temperature changes.

This model allows the estimation of regional GDP changes as a result of trade, investment, consumption, energy costs, resultant energy service demand price adjustment, and carbon permit trade. The hybrid global integrated energy system model, TIAM-MACRO, is used to quantify the least cost optimal mix of low carbon technologies for a 2°C pathway, while, giving additional insight into the overall macroeconomic consequences of decarbonizing the
energy system. Further to estimates of the GDP loss, capital transfers from developed to developing countries are estimated in a post optimal analysis (POA) to make burden sharing equitable. The four burden sharing rules employed are outline below.

**B.2. The reference energy system (RES) of TIAM**

From a methodological point of view, the first decision taken refers to the definition of the RES with the following sectors included: Residential, Commercial, Agriculture, Industry, Transportation, Electricity/Heat production, and Energy Supply. In particular, the structure of the RES was determined by identifying the demand categories, energy carriers, emissions, and materials to include in brief:

- **Transportation** includes road and rail for passengers and freight, navigation and aviation. In road transport, there are five demand categories for passenger travel (cars – short distance, cars -long distance, buses – urban, buses - intercity, and three-wheelers/off road), and trucking. In rail transport, there are three demand categories (passengers – light trains (metros), passengers - heavy trains and rail freight). The aviation and navigation sectors are modelled using a single generic technology each and a single generic demand each that reproduces the energy consumption.

- In **Residential** there are different end-uses (Space heating, Space Cooling, Water heating Cooking, Lighting, Refrigeration, Cloth washing, Cloth drying, Dish Washing, Other electric, Other energy), and the first three are differentiated by building categories (Single house – rural, Single house - urban, Multi Apartment). Similarly, the RES structure of the **Commercial** sector has nine end-uses (Space heating, Space Cooling, Water heating, Cooking, Refrigeration, Lighting, Public Lighting, Other electric, Other Energy Uses), with the first three being differentiated by building categories (Small / Large). **Agriculture** is modelled as a single generic technology with a mix of fuels as input and an aggregated useful energy demand as output.

- **Industry** is divided in two different sets: energy intensive industries and other industries. For the energy intensive industries, a process-oriented RES was adopted, whereas for other industries a standard structure consisting in a mix of five main energy uses (Steam, Process heat, Machine drive, Electrochemical, Others processes) was adopted. In order to start moving in the direction of LCA/I and ExternE, different material demands of the industrial sector (as for example steel or limestone) were modelled separately.

- **Electricity and Heat production**: this sector regroups public power plants, auto production of electricity and CHP. In the RES, three types of electricity (High voltage, Medium voltage, and Low voltage) and two separated (not connected) grids for long distance (high temperature) and short distance (low temperature) heat are distinguished.

- **Supply**: Each primary resource (Crude Oil, Natural Gas, Hard coal, Lignite) is modelled by a supply curve with several cost steps. There are three categories of sources: located reserves (or producing pools), reserves growth (or enhanced recovery), and new discovery. In addition, five types of biomass are modelled: wood products, biogas, municipal waste, industrial waste-sludge, and bio fuels.

Energy carriers were chosen starting from those reported in the Eurostat [13] energy balances, and then aggregating some of them to adapt the list to the modelling objectives of the project. As materials are concerned, it was decided to explicitly model only energy intensive processes (e.g. scrap steel). Other materials are implicitly modelled as part of the variable costs and their related emissions are accounted for in the process emissions. The air
emissions modelled are Carbon Dioxide (CO₂), Methane (CH₄), Sulphur dioxide (SO₂), Nitrogen Oxides (NOₓ), Nitrous Oxide (N₂O), Particulate (PM 2.5 and PM 10), Volatile Organic Compounds (VOC), Sulphur Dioxide (SO₂) and Ammonia (NH₄).

**B.3 MACRO STAND ALONE – DECOMPOSING TIMES-MACRO**

The additional MACRO STAND ALONE (MSA) module (Kypreos & Lehtila, 2015) allows multi-regional macroeconomic impacts to be calculated. MSA is a multi-regional, intertemporal general equilibrium optimal growth model which maximizes discounted utility of a single consumer-producer agent. The MSA module objective function supersedes the least cost minimization objective of TIAM. GDP is comprised of consumption, investment and energy system costs. Total economic production is determined as a function of energy, capital and labor, where energy substitutes with a capital-labor composite via an elasticity of substitution. Decomposing the energy system solution into a quadratic cost function and price responsive demand, decoupling factors estimated from the calibration routine are the coupling link between TIAM and MSA. MSA solves a general equilibrium in an iterative convergent process, re-estimating price responsive energy service demands in TIAM.

**B.4 Post Optimal analysis with Burden sharing**

The following burden sharing rules redistribute the cost of reaching an efficient least cost global energy system consistent with a 2°C world. The required inputs to the post optimization analysis are the CO₂ emissions, energy costs, consumption, gross domestic product (GDP), all per region, time and scenario. Historic national emissions are aggregated into TIAM regions. Past and future regional median fertility UN population projections are used in both TIAM and in the POA where population projections are required. In order to define the climate change market and non-market damages the actual temperature change per scenario must be defined together with some parameters defining the shape of the damage function and the willingness to pay to avoid such damages. Also, in order to define the co-benefits of the 2DS scenario due to the reduction of the local atmospheric pollution related to the carbon-free technologies, the pollution balances must be defined per scenario, region, sector and time. Then, multiplying the emission balances with the externality tax we can estimate the external cost of LAP per scenario. The difference in the costs defines the co-benefits associated with the 2DS carbon policy.

**B.4.1 Economic-efficiency via optimization**

The Efficient rule represents the constraint on the energy system, and simply specifies a cumulative emissions constraint as per the literature over all regions and time steps.
\[ \sum_{r,t} E_{r,t} \times n_{yp}p_t \leq RCEQ_{2^\circ C, 66\%} \quad \forall t \in \{2020, 2030, ..., 2100\} \]

Equation 1

- \( n_{yp}p_t \): Years per period (10)
- \( E_{r,t} \): Regional emissions at time \( t \)
- \( RCEQ_{2^\circ C, 66\%} \): Remaining cumulative CO2 emission quota for 2°C with 66% probability, at time \( t \)

### B.4.2 RULE I – Egalitarian; Contraction and Convergence

The first burden sharing rule (Rule I) specifies a proportion of global emissions budget per time step to each region, interpolating between current emissions and a future equalization of emissions per capita. The resultant annual emissions allowances per capita are plotted in Figure B2. Regions emitting more than this budget in the 2DS must purchase permits at the marginal price of CO2.

\[
\frac{E_r(t)}{E_w(t)} = \frac{T_2 - t}{T_2 - T_1} \times \frac{E_r(T_1)}{E_w(T_1)} + \frac{t - T_1}{T_2 - T_1} \times \frac{Pop_r(t)}{Pop_w(t)} \quad \forall t \in \{2020, 2030, ..., 2050\}
\]

Equation 2

- \( E_r(t) \): Regional emission at time \( t \)
- \( E_w(t) \): World emissions at time \( t \)
- \( Pop_r(t) \): Regional population at time \( t \)
- \( Pop_w(t) \): World population at time \( t \)
- \( T_1 \): Reference year for grandfathering convergence rule (2020)
- \( T_2 \): Target year for grandfathering convergence rule (2050)

Figure B2. Emissions Budget Per capita rule - interpolated contraction and convergence from 2020 emission per capita to equalization in 2050 with a grandfathering rule
B.4.3 RULE II – GDP loss equalization

Rule II equalizes the economic impacts incurred by meeting the efficient 2DS. Regions with lesser macroeconomic impacts purchase carbon permits as a function of their relative GDP loss and of the marginal price of carbon. Regions with larger GDP impacts receive these capital transfers again as a function of their relative GDP loss above the global world rate of GDP loss.

\[ \frac{\Delta Y_{r,2DS,t}}{Y_{r,BASE,t}} = \frac{\Delta Y_{w,2DS,t}}{Y_{w,BASE,t}} \]

\[ \Delta Y_{r,2DS,t} = \left( \frac{Y_{r,BASE,t}}{Y_{w,BASE,t}} \right) \Delta Y_{w,2DS,t} = P_{w,t} \cdot (IE_{r,t} - AE_{r,t}) \]

Equation 3

- \( \Delta Y_{r,sc,t} \) Regional GDP change per scenario at time t
- \( P_{w,t} \) Price of carbon dioxide (abatement) at time t
- \( IE_{r,t} \) Regional emissions budget at time t
- \( AE_{r,t} \) Actual emissions at time t
- BASE Reference scenario run
- 2DS 2°C scenario with 66% probability

B.4.4 RULE III – Compensation for the energy cost increase of LDCs.

Rule III utilizes a similar method to rule II with an additional constraint to subdivide regions into receiving regions and donor regions. If an LDC experiences an increase in their energy system cost, relative to the base case, the LDC is compensated for that cost. The non-LDC regions pay in proportion to their ability to pay as measured e.g., by their relative GDP share.

If \( Sh_{rd} = Y_{rd} / \sum_{rd} Y_{rd} \) is the share of a donor region \( rd \), to the payments for a receiving region \( rc \), the losses of a receiving region compensated by a given donor region are:

\[ \Delta EC_{rc,t} \cdot Sh_{rd} \]

Thus, the increased energy system cost of a receiving region should be compensated by transfers of permits from all donor regions such that:

\[ \Delta EC_{rc,t} \cdot \sum_{rd} Sh_{rd} = \Delta EC_{rc,t} = P_{w,t} \cdot (IE_{rc,t} - AE_{rc,t}) \]

Equation 4a

This relation specifies the IE of receiving regions and they are higher than the actual emissions AE. While the IE of a donor region are:

\[ \sum_{rc} \Delta EC_{rc,t} \cdot Sh_{rd} = \Delta COST_{rd,t} = P_{w,t} \cdot (AE_{rd,t} - IE_{rd,t}) \]

Equation 4b

The IE of a donor region are lower than the actual emissions of this region.

- \( \Delta EC_{Cr,t} \) Developing Receiving Region’s change in EC at time t
- \( \Delta COST_{rd,t} \) Extra cost of donor region \( rd \), compensating for energy cost losses
B.4.5 RULE IV – Compensation of LDCs for their GDP losses

Rule IV, again builds on rule III, but gives full compensation to LDCs for GDP losses instead of the EC increase, as a result of the 2DS energy system costs. Again these payments are allocated on an ability to pay basis. Therefore, relations are as before when replacing EC with Y.

\[
\Delta Y_{rc,t} \cdot \sum_{rd} S_{rd} = \Delta Y_{rc,t} = \bar{P}_{rc,t} \cdot (IE_{rc,t} - AE_{rc,t}) \tag{Equation 5a}
\]

\[
\sum_{rc} \Delta Y_{rc,t} \cdot S_{rd} = \Delta COST_{rd,t} = \bar{P}_{rd,t} \cdot (AE_{rd,t} - IE_{rd,t}) \tag{Equation 5b}
\]

\begin{align*}
\Delta Y_{rc,t} & \quad \text{Developing Receiving Region’s change in GDP at time t} \\
\Delta COST_{rd,t} & \quad \text{Extra cost of donor region rd, compensating for GDP losses}
\end{align*}

rc \quad \text{Receiving regions (AFR, CSA, IND, MEX, ODA)}

rd \quad \text{Donor regions (AUS, CAN, CHI, EEU, FSU, JPN, MEA, SKO, USA, WEU)}

References:


