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By **Maryse Labriet**, Eneris Environment Energy Consultants, Spain

Laurent Drouet, Fondazione Eni Enrico Mattei and Euro-Mediterranean Center on Climate Change, Italy

Marc Vielle, Ecole Polytechnique de Lausanne, Switzerland

Richard Loulou, Kanlo Consultants Sàrl, France

Amit Kanudia, Kanors Consultants, India

Alain Haurie, Ordecsys, Switzerland

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Summary

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Keywords: Climate Policies, Energy, Techno-economic modelling, Macro-economic Modelling, World

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Address for correspondence:
Maryse Labriet
Eneris Environment Energy Consultants
Calle del Duque de Alba 15
28012 Madrid
Spain
Phone: +34 91 429 4031
E-mail: maryse.labriet@enerisconsultants.com

Assessment of the effectiveness of global climate policies using coupled bottom-up and top-down models

Maryse Labriet[1*], Laurent Drouet[2], Marc Vielle[3], Richard Loulou[4], Amit Kanudia[5] and Alain Haurie[6]

[1] *Eneris Environment Energy Consultants, Spain*
[2] *Fondazione Eni Enrico Mattei, Italy and Euro-Mediterranean Center on Climate Change, Italy*
[3] *Ecole Polytechnique de Lausanne, Switzerland*
[4] *Kanlo Consultants Sàrl, France*
[5] *Kanors Consultants, India*
[6] *Ordecsys, Switzerland*

* Corresponding author. Email: maryse.labriet@enerisconsultants.com. Phone: +34 91 429 4031.

Abstract (150 words) In order to assess climate mitigation agreements, we propose an iterative procedure linking TIAM-WORLD, a global technology-rich optimization model, and GEMINI-E3, a global general equilibrium model. The coupling methodology combines the precise representation of energy and technology choices with a coherent representation of the macro-economic impacts, especially in terms of trade effects of climate policies on energy-intensive products. In climate mitigation scenarios, drastic technology breakthroughs are required as soon as possible, especially in large emitting countries, and in all sectors of the economy. Energy-intensive industries tend to be delocalized in regions where low-carbon production is feasible and cheap, or in regions without emission cap. However, emission leakage remains small, mainly due to global lower oil demand, and energy exporting countries are extremely penalized given lower energy exports. Emission reduction at least in the power sector and in energy-intensive industries of developing countries must be considered to reach the 2°C target.

Keywords: Climate Policies; Energy; Techno-economic modelling; Macro-economic Modelling; World

1. Introduction

The worst impacts of climate change can be mitigated by restructuring the economy along a low-carbon energy path. This will require major changes in both consumption and production patterns (Krey *et al.*, 2013; Capros *et al.*, 2014). The definition of a global agreement based on low carbon energy paths is usually associated with the creation of carbon markets for driving low carbon investments and achieving the environmental objectives in a cost-efficient manner. However, low carbon energy policies might affect the competitiveness of some countries as well as the basic right to economic development of developing and emerging countries. All these factors affect the willingness of countries to endorse any international climate commitment.

This study explores the essential conditions negotiated in the cooperation between industrialized countries and developing or emerging economies to achieve a comprehensive worldwide climate policy that effectively limits the global long-term temperature increase to 2°C. Energy technologies are at the heart of emission mitigation and the cost impacts on the economy of mitigation strategies may be significant in some countries. It is therefore crucial to have a precise representation of technology choices to mitigate climate change and access to welfare gains or losses associated with these techno-economic choices. Two types of models are therefore used in this study: TIAM-WORLD, an integrated climate-energy-technology model, to identify the best technology and fuel options in all sectors to reach the climate goal, and GEMINI-E3, a computable general equilibrium model, to analyze the response of the economy to a tax or a limitation of greenhouse gas (GHG) emissions. The two models are coupled through an iterative exchange of data until convergence of energy demands.

The coupled models are used to evaluate several climate agreements between industrialized and developing/emerging countries. First, a global cooperative climate agreement is implemented; it enters into force in 2020, and involves the entire economies of all countries; it corresponds to the implementation of an international emissions trading system (ETS). In such a cooperative agreement, mitigation costs are shared amongst all countries. Second, the climate agreement is limited to some or all energy intensive sectors of developing and emerging countries, and covers the entire economies of developed countries. This agreement presents two advantages which may facilitate its acceptation: since households of developing and emerging countries are excluded from the climate agreement, the burden imposed to them is reduced; since energy intensive industries of developing and emerging countries are included in the climate agreement, the loss of industrial competitiveness of developed countries is reduced. Bosetti and Victor (2011) and IEA (2009) describe sectoral approaches as interesting second-best climate agreements. However, Hamdi-Cherif *et al* (2011) notice that there have been very few quantified analyses of such climate agreements.

Technology changes, macroeconomic and inter-sectoral effects are assessed with the coupled models. The technology and energy changes required to limit the temperature increase to 2°C are drastic, and must be implemented as soon as possible. Major technology breakthroughs outside the electricity sector are absolutely required. In other words, if the climate agreement is limited to the power sector of developing and emerging countries, the 2°C target is infeasible. If energy-intensive industries are included in climate agreement, both primary energy extraction and industrial production are partially delocalized in regions where low-carbon production is cheaper (Former Soviet Union and Africa for extraction, and Asia for industrial production). Moreover, energy exporting countries are penalized given lower energy exports.

Section 2 provides a brief classification of model coupling. Section 3 introduces the two models TIAM-WORLD and GEMINI-E3, and describes the coupling methodology. In section 4, global and partial cooperation agreements are assessed. Finally, section 5 concludes by discussing the added value of the proposed modelling approach.

2. Toward cooperative worldwide climate strategies: using TD/BU coupling approaches

The objective of the proposed methodology is to couple TIAM-WORLD, a so-called bottom-up (BU) model, and GEMINI-E3, a top-down (TD) model, in order to study global and partial climate agreements between different groups of countries in the world. This section reviews the different coupling methodologies.

2.1. BU and TD models

BU models are very detailed, technology explicit models that focus primarily on the energy dimension of an economy. In these models, the energy system is usually represented by a large number of technologies, energy commodities, energy service demands, and emissions. The production function of a sector, including flows and prices, is implicitly constructed, rather than explicitly specified as in more aggregated models. Such detailed analyses are fast becoming a requirement by the policy advisers for the analysis of energy outlooks and climate policies. Of course, such implicit production functions and the tracing of results back to technological assumptions may be quite complex, depending on the complexity of the reference energy system of each sector. Well adapted to assess technological options, bottom-up models generally fail to represent all the complex market interactions since they do not incorporate all the economy activities and components such as labor, capital, etc.

TD models are either computable general equilibrium (CGE) models, or long-term macroeconomic growth models. They represent the entire economy via a relatively small number of aggregate variables and equations which simulate the main economic variables (labor, consumption, capital, international trade, etc.), the potential substitutions between the main factors of production (energy, capital, and labor) and their interactions with the economic output. The production is often formed by a constant elasticity of substitution (CES) production function, with an energy aggregate that can be substituted by the other production factors. The economic and energy flows are all represented by economic accounting in constant currency. Top-down models lack detailed technological information on the energy system, especially for energy production, conversion, and consumption by end-users.

2.2. Coupling BU and TD models

Four main types of methodology are proposed to couple top-down and bottom-up models.

The *first methodology* consists in linking models via the exchange of data: the two models are run independently until the expected convergence of some selected criterion. This approach minimizes the number of structural changes of the original models. Hoffman and Jorgenson (1977) used this approach to model US energy policies. The MESSAGE-MACRO model (Messner and Schrattenholzer, 2000) links a macroeconomic model (MACRO) with an energy supply model (MESSAGE). The NEMS model (Energy Information Administration, 2009) links several technology-rich modules and a set of macro-economic equations, with an iterative method. Drouet *et al.* (2005) links the Swiss MARKAL model, restricted to the housing sector, to a top-down model, GEMINI-E3. Böhringer and Rutherford (2009) underlines the risk of methodological inconsistencies of this simple methodology, when the two models are very different.

The *second methodology* consists of integrating technology details in top-down models (Böhringer, 1998; Wing, 2006) or calibrating nested CES functions of top-down models with the responses of bottom-up models. Kiuila and Rutherford (2013) propose several methods to approximate the bottom-up cost step functions into piecewise-smooth function, which describe the marginal cost curves in top-down models. They apply four methods (numerical, OLS, analytic and hybrid) to perform the estimations. Schäfer and Jacoby (2005, 2006) apply this methodology to the transportation sector of EPPA based on a simulation with MARKAL, Pizer *et al.* (2003a, b) to the electricity sector, Löschel and Soria (2007) to the electricity module of PACE, a CGE model. The interest of this methodology is that it leaves unchanged the structure of each model. But it does not allow the introduction of a very detailed technological representation - the number of described technologies is often less than 10.

The *third methodology* consists of creating a single integrated model: the bottom-up model is augmented with equations coming from a top-down model, typically an economy-wide single production function. For example, MARKAL-MACRO (Manne and Wene, 1992) combines the technological detail of MARKAL or TIMES with the single-sector production function from ETA-MACRO (Manne, 1981), or MERGE (Manne and Richels, 1992). In TIAM-WORLD, the final energy service demands are elastic to their own prices. Loulou and Kanudia (2000) show that these price elasticities account for most of the energy-economy interactions. For this reason, TIAM-WORLD qualifies as partial equilibrium models that go beyond the optimization of the energy sector.

The *fourth methodology* is the full integration of models within a same optimization framework either via a monolithic program, when both models are written in the same computer language, or via a decomposition method, when solving the combined model is too difficult. In the first case, Böhringer and Rutherford (2008) propose a mixed complementary problem, successfully applied to models of reduced size; the methodology require too much computational power to be applied to more complex models. In the second case, Böhringer and Rutherford (2009) propose the exchange of variables and parameters in a separate module, which optimizes a meta-model to ensure both the consistency of the final solution and the convergence towards an optimal solution. This method has been successfully implemented in Tuladhar *et al.* (2009) and in Lanz and Rausch (2011), where a CGE model of the US economy is coupled with a bottom-up model of the US electricity sector to analyze climate policy scenarios.

Our approach is akin to the first type above, but with an important difference: the two models are modified before being coupled, in order to remove the potential inconsistencies and overlaps between the two. Next section describes the proposed coupling methodology.

3. The proposed methodology to couple TIAM-WORLD and GEMINI-E3 models

Both TIAM-WORLD and GEMINI-E3 models encompass the whole economic production system and calculate an economic equilibrium. However, they differ in the scope of the economic equilibrium they compute. When coupled, they share some common decision or state variables: the demands for energy services of TIAM-WORLD are computed with macro-economic, which are an output of GEMINI-E3; on the other hand, GEMINI-E3 requires a description of the energy mix needed for the production of each sector output; these energy mixes are based on the outputs of TIAM-WORLD;

world prices of fossil fuels needed in GEMINI-E3 are also based on the outputs of TIAM-WORLD.

3.1. Presentation of TIAM-WORLD

TIAM-WORLD (TIMES Integrated Assessment Model) is a global technology-rich bottom-up model that represents the entire energy system of the World divided in regions (15 regions in the version used for this application). It covers the procurement, transformation, trade, and end-uses of all energy forms in all sectors of the economy. The model contains explicit detailed descriptions of more than one thousand technologies and one hundred commodities in each region, logically interrelated in a Reference Energy System (Figure 1). Such technological detail allows precise tracking of capital turnover, provides a detailed description of technological competition, and allows the modeler to simulate almost any type of energy or emissions policy.

TIAM-WORLD is driven by a set of 42 demands for energy services in all sectors: agriculture, residential, commercial, industry, and transportation. Demands for energy services are specified by the user for the Reference scenario, and have each an own price elasticity. Each demand varies endogenously in alternate scenarios, in response to endogenous price changes. The model thus computes a dynamic inter-temporal partial equilibrium on worldwide energy and emission markets based on the maximization of total surplus, defined as the sum of surplus of the suppliers and consumers.

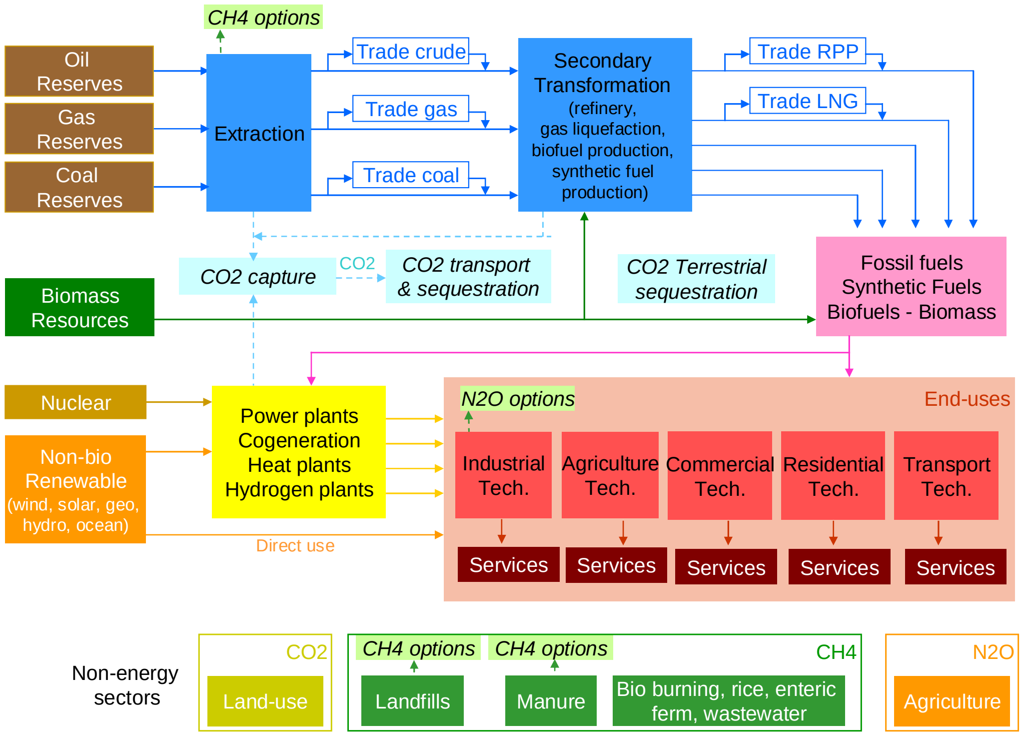


Figure 1. Reference energy system of TIAM-WORLD

Emissions of CO_2, N_2O and CH_4 from all anthropic sources (energy, industry, land, agriculture, and waste) are endogenously modelled at the technology level. Greenhouse gas mitigation options available in the model are: energy substitutions, improved efficiency of installed devices, specific non-CO_2 abatement devices (for example, CH_4 flaring or utilization for electricity production, suppression of leakages at natural gas transmission level, N_2O thermal destruction, anaerobic digestion of wastes with gas recovery, etc.), sequestration (CO_2 capture and underground storage, biological carbon sequestration), demand reductions in reaction to increased carbon prices.

A complete description of TIAM-WORLD appears in Loulou (2008) and Loulou and Labriet (2008). The generic TIMES equations are available at http://www.etsap.org/documentation.asp

3.2. Presentation of GEMINI-E3

GEMINI-E3 is a multi-country, multi-sector, recursive computable general equilibrium model comparable to the models EPPA (Paltsev *et al.* , 2005) or GEM-E3 (E3Mlab, 2010). GEMINI-E3 represents the world economy in 28 regions and 18 sectors. The standard model is based on the assumption of total flexibility in both microeconomic or sector markets (goods, factors of production) and macroeconomic markets (capital and exchange markets). The associated prices are the real rate of interest and the real exchange rate, which are then endogenous.

The model is built on the GTAP database, a comprehensive energy-economy dataset that incorporates a consistent representation of energy markets in physical units, social accounting matrices for each individualized country/region, and the whole set of bilateral trade flows. Additional statistical information accrues from national accounts of the Organization for Economic and Development Cooperation, energy balances and energy prices/taxes of the International Energy Agency, and statistics from the International Monetary Fund. Carbon emissions are computed on the basis of fossil fuel energy consumption in physical units. Non-CO_2 greenhouse gases emissions (CH_4, N_2O and F-gases) are modeled by region and sector specific marginal abatement cost curves provided by the Energy Modelling Forum (van Vuuren, 2006). A detailed description of GEMINI-E3 is provided by Bernard and Vielle (2008). All information about the model can be found at http:/gemini-e3.epfl.ch.

3.3. The harmonisation of the two models

The initial harmonisation of the two models is crucial to guarantee the consistency of the coupling methodology and it requires a meticulous examination of the regional and sectoral definitions in the two models. A detailed mapping framework must be defined between the regions, the activity sectors, and the energy commodities of the two models. This task represents a complex challenge.

Table 1 presents the regions, commodities and economic sectors for which connections between the two models were built. The detailed mapping of these three entities is not presented in this article but is available upon request.

Regions	**Commodities**	
United States of America (USA)	COAL	Coal
Canada (CAN)	COIL	Crude oil
Mexico (MEX)	CGAS	Gas
Rest of America (LAT)	CPET	Refined petroleum products
Western Europe (EUR)	CELE	Electricity
Eastern Europe (XEU)	COTH	Other energy sources
Former Soviet Union (FSU)	CBIO	Biomass
Africa (AFR)	CHHD	Hydrogen
Australia + New Zealand (AUZ)	**Economic sectors**	
India (IND)	AGRI	Agriculture and forestry
China (CHI)	MINE	Mineral products
Japan (JAP)	CHEM	Chemical, rubber, plastic
Middle-East (MID)	META	Metal and metal products
Rest of Asia (ASI)	PAPE	Paper products publishing
	TRAN	Land transport
	SEAT	Sea transport
	AIRT	Air transport
	CONS	Consuming and equipment goods
	SERV	Services
	HOUS	Households

Table 1. Coupled regions, commodities and economic sectors

The basic assumptions behind the Reference cases of the two models were also harmonised: population and GDP growths, energy prices[1] as well as some energy policy, such as the penetration of coal power (limitation in some regions of the world to reflect local air quality policies) and nuclear plants (national and regional policies).

Both GEMINI-E3 and TIAM-WORLD compute nearly the same Reference World CO_2 path until 2030. After this year, the CO_2 emissions of TIAM-WORLD increase faster than those of GEMINI-E3 and reach 84 $GtCO_2$ in 2050 compared to 65 $GtCO_2$ in GEMINI-E3. A 30% difference in World CO_2 emissions in 2050, mainly in industry, is not unusual, as proved by the results of several modelling exercises such as the Energy Modelling Forum (Krey *et al.*, 2013; Loulou *et al.*, 2013), the Asian Modelling Exercise (Labriet *et al.*, 2012). Different assumptions in the characteristics and evolution of technologies used by the models contribute to these different long term emissions.

3.4. The coupling methodology

The intent of the proposed coupling is to benefit from the technological details provided by TIAM-WORLD, and from the macro-economic information provided by GEMINI-E3 in order to define energy or climate policies. The principles of the coupling are as follows (Figure 2):

- In GEMINI-E3, energy and CO_2 prices, the fuel mix (distinguishing electricity and non-electric fuels), the technical progress on energy uses (distinguishing electricity and non-electric sector) and on capital consumption[2] are computed on the basis of results from TIAM-WORLD.
- In TIAM-WORLD, the growths of the GDP and of the monetary value of the industrial subsectors, used to compute the demands for energy services, are based on results provided by GEMINI-E3.

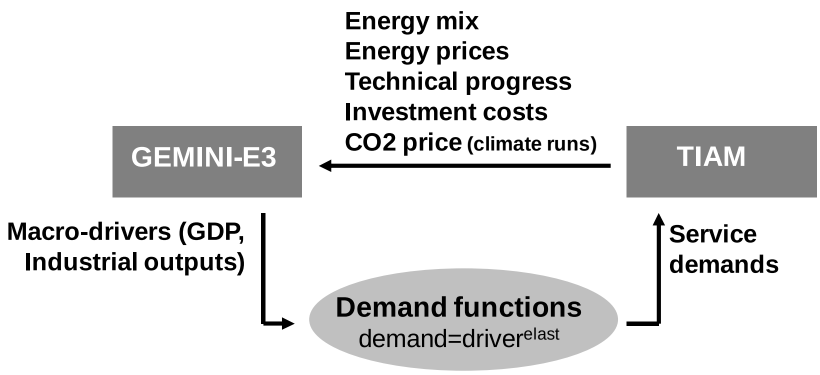


Figure 2. The coupling framework

Fortes *et al* (2013) have adopted a similar approach to couple GEM-E3-Portugal and TIMES-Portugal, inspired by preliminary version of this work. They applied this coupling framework only to the reference case.

[1] In GEMINI-E3, the price of fossil energy (coal, crude oil and natural gas) is established through the balance of demand and supply of energy. In order to reflect in GEMINI-E3 the fossil energy price profiles computed by TIAM-WORLD, the evolution of energy resources used to compute the supply of energy was accordingly modified.

[2] The technical progress on capital consumption measures the productive efficiency of capital; low technical progress corresponds to more capitalistically intensive equipment.

Each model is modified before being coupled. The single major modification of TIAM-WORLD is the deactivation of the own price elasticities of the energy service demands. This is important because TIAM-WORLD must use the exact demand vectors provided by GEMINI-E3 at each iteration of the coupling algorithm. Using non zero elasticities in TIAM-WORLD would trigger undesirable modifications of the demands by the model.

The modifications of GEMINI-E3 are more numerous to insure that the mix of energy forms consumed in each sector is exactly the mix provided by TIAM-WORLD. Several tasks are implemented for this purpose:

- The structure of the model is modified. New energy forms, not present in the standard version of GEMINI-E3, are introduced: biomass, hydrogen, nuclear and other renewable energy forms. These new energy forms correspond to consumptions of capital, energy and other materials. This modification requires the rewriting of the structure of the nested CES functions used in GEMINI-E3: new branches are added. Figure 3 summarizes the changes in the production function used in GEMINI-E3.
- The CES functions are replaced by Leontieff functions, which represent the shares of each energy form. Only the nests that concern total energy consumption (for a sector or a household) and the split between fossil fuel energy and electricity are modified; the other parts of the nested structure are not changed (Figure 3). The coefficients of the Leontieff functions are computed based on the energy mix obteined from TIAM-WORLD (F).
- The technical progress associated to the energy aggregate (θ^E) is computed from TIAM-WORLD results. This coefficient determines the temporal energy efficiency improvement.
- In TIAM-WORLD the decrease of carbon emission comes from carbon free energy (like solar, biomass, nuclear) and by low-carbon technologies, (like carbon capture and sequestration in the electricity sector). The additional capital invested in these new technologies is reflected in GEMINI-E3 through the use of new technical progress incorporated in the capital consumption (i.e. a decrease of the technical progress: θ^K).
- The energy prices (P) and the price of carbon (T) are computed by TIAM-WORLD at each iteration and used by GEMINI-E3.
- At the end of this procedure, all the energy consumptions in GEMINI-E3 are completely determined by the results of TIAM-WORLD.

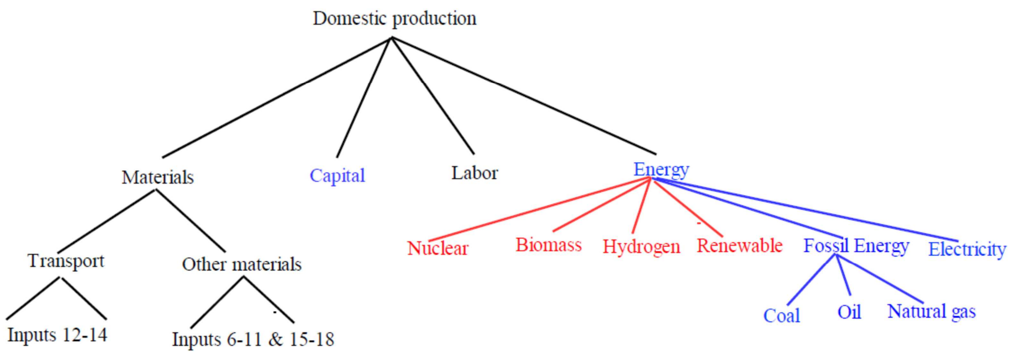


Figure 3. Changes in the GEMINI-E3 nested CES function

(in blue: variables whose coefficients are modified, based on inputs coming from TIAM-WORLD; in red: variables which have been added)

3.5. The coupling algorithm

The coupling variables are indexed by period, region, sector, and/or commodity. For the sake of simplification, the notations do not specify all these indexes in the following text.

The coupling procedure implements a Gauss-Seidel method (Hageman, 1981) which seeks a fixed point for the useful demand vector D through an iterative procedure. First, TIAM-WORLD is run with given useful demands D_0 resulting from the harmonisation phase of the two models. Then, GEMINI-E3 is run using the TIAM-WORLD outputs. This is the first iteration. Next iteration starts with new useful demands D_k, for $k \geq 1$, computed from the GDP and the value added of industrial subsectors provided by GEMINI-E3 and adjusted by a weighted sum of the demands of previous iteration. The adjusted demands D'_k are given by the following formula:

$$D'_k = \frac{2}{(k+2)(k+3)} \sum_{i=0}^{k} (i+1) D_i.$$

The convergence criterion ζ_k at iteration k is defined as the ratio of the Euclidean distance between the two last demand vectors over the norm of the last demand.

$$\zeta_k = \frac{\sqrt{\sum_p (D'_{p,k} - D'_{p,k-1})^2}}{\sqrt{\sum_p D'^2_{p,k}}},$$

where p is the period index. The iteration process stops when the convergence criterion is smaller than a given threshold. The algorithm is given in Figure 4.

1. Set first demands D_0
   Set k=0
2. Run TIAM-WORLD with useful demands D_k
   Get fuel mixes F_k, CO_2 prices* T_k, energy prices P_k, technical progress on energy θ^E_k and capital θ^K_k
3. Run GEMINI-E3 with F_k, T_k, P_k, θ^E_k, θ^K_k
   Get GDP_k and industrial outputs $PROD_k$ from GEMINI-E3
   Compute demand vector D_{k+1}
4. Compute convergence criteria ζ_k
5. Increment k
6. If $\zeta_k \geq$ eps then go to 2, else STOP

* *CO_2 prices in the case of runs with climate constraints*

Figure 4. The coupling algorithm

4. Application to climate agreements

Two kinds of climate agreements are studied with the proposed coupling methodology.

- First, *the global cooperative climate agreement (first best policy)* represents an idealized solution. It contributes to identify the best technology and energy decisions for the World to limit the greenhouse gas emissions. However, it does not indicate which country should *pay* for the mitigation options. The implementation of this agreement is possible with an international emissions trading system or of any future flexible mechanism based on programs or projects inspired from the current Clean Development Mechanism.
- Next, *two alternative partial cooperative climate agreements* are proposed where only the energy intensive sectors of developing and emerging countries participate in the climate mitigation policies. The energy intensive sectors are mineral products, chemical products, metal and metal products, paper). Such agreements might be politically better accepted by developing countries since the households of developing countries are excluded from the climate policies; adverse effects of climate policies on households are therefore limited. These agreements could also be better accepted by industrialized countries since they avoid the loss of industrial competitiveness of developed countries, compared with agreements where industrial sectors of developing and emerging countries do not have to mitigate their emissions.

The climate target is defined by a maximal radiative forcing of 3.5 W/m^2 at all times. It corresponds to a maximal global temperature increase of 2°C compared to pre-industrial times. The Reference and the Climate scenarios consider that OPEC maximizes its net revenues related to oil exports, and imposes suitably chosen production quotas to each of its members.

4.1. Global cooperative climate agreement (S1)

A perfect long-term cooperation between all countries, all sectors is assumed. The preferred decisions constitute the most cost-efficient solution available to the World to limit the radiative forcing (*first-best solution*). This scenario is called S1.

In order to assess the coupling methodology, the analysis compares the results obtained with:

- GEMINI-E3 used in a stand-alone manner, without any coupling (called *GEMINI-E3 alone*);
- TIAM-WORLD used in a stand-alone manner (called *TIAM-Elast*), where the demands are elastic to their own price (see section 3.1.);
- The coupled models TIAM-GEMINI-E3 (called *Coupled-Models*).

Convergence of the climate scenario is obtained after 6 iterations. The convergence of the reference case is immediate, given the preliminary harmonisation of the models.

4.1.1 *TIAM-Elast* and *Coupled Models*

At the World level, differences in emission, climate and energy results between the solutions obtained with the *Coupled-Models* and with *TIAM-Elast* are small.

Emissions and energy results

Global CO2 emissions increase from 7.6 in 2005 to 23 GtC in 2050 in Reference case and to 6 GtC in S1 in 2050. China dominates the future World emissions (up to almost 50% of global emissions in the Reference in 2050) as well as the future reductions (also up to almost 50% of World reductions in 2050). The contribution by India is far smaller, with up to 11% of World emissions and 16% of World reductions. Given the weight of these two countries in emissions and mitigation, technological cooperation agreements or any other cooperative framework to limit greenhouse gas emissions must involve them.

The possible impacts of the inter-sectoral effects of climate policies are assessed. They are taken into account by GEMINI-E3 but not in *TIAM-Elast*. For example, in GEMINI-E3, the growth of the nuclear electricity generation corresponds to an increase of capital needed to build new reactors, as well as of the intermediate consumptions of the equipment goods (mineral goods, metal goods, etc.). These interdependencies between different branches of activity of each country/region are represented in GEMINI-E3 through an input-output table included in the Social Accounting Matrix of the model. Results show differences in sectoral emissions between *TIAM-Elast* and the *Coupled-Models* smaller than 5% over the time horizon. In other words, the inter-sectoral effects of climate policies on sectoral emissions (considered in GEMINI-E3 but not in TAM-WORLD) remain small.

The most important mitigation options are the penetration of low carbon technologies in the power sector - mainly coal and biomass-fired power plants with carbon capture and storage (CCS) and renewable (Figure 5), and the substitution of coal and oil by gas, biofuels, and electricity, especially in energy-intensive industries and transports. Costs and availability of CCS technologies are of course crucial parameters to define the preference and robustness of CCS compared to renewable options. This analysis is beyond the objective of this paper. Either CCS or renewable penetration in developing countries will require collaborative R&D and technology transfer between industrialized and developing/emerging countries. The amount of additional investments needed in the energy system of China in the global climate agreement S1 compared to the Reference represents 17% of the total World additional investments, against 12% for India and 11% for Western Europe (results provided by TIAM-WORLD). The high future emissions of China explain the high level of investment needed in the country to implement the mitigation strategies.
CO_2 price difference is less than 1% between the two approaches (351$\$_{2010}$/t$CO_2$ in 2050 in *Coupled-Models*, and slightly higher in *TIAM-Elastic*, Table 2). The increase of the total discounted of the energy system in S1 over the Reference case is slightly more than 10000 trillions $\$_{2010}$, or 0.6% to the total discounted GDP over the time horizon 2005-2050 in *TIAM-Elastic*. It had occurred to us that a comparison of welfare losses between *TIAM-Elastic* and the *Coupled-Models* would be interesting. Unfortunately, this is not feasible, by the very nature of the coupling method. Indeed, welfare in *TIAM-Elast* is represented by the total surplus (producers plus consumers surpluses). In contrast, in the coupled approach, TIAM-WORLD demands for energy services are not allowed to be elastic to their own prices, and the demands are obtained directly from GEMINI-E3. If we had allowed TIAM-WORLD demands to be price elastic even in the coupled approach, the coupling of the two models would have been internally incoherent, since the demands passed from GEMINI-E3 to TIAM-WORLD would have been immediately modified (i.e. falsified !) by TIAM-WORD due to their elasticity to prices.

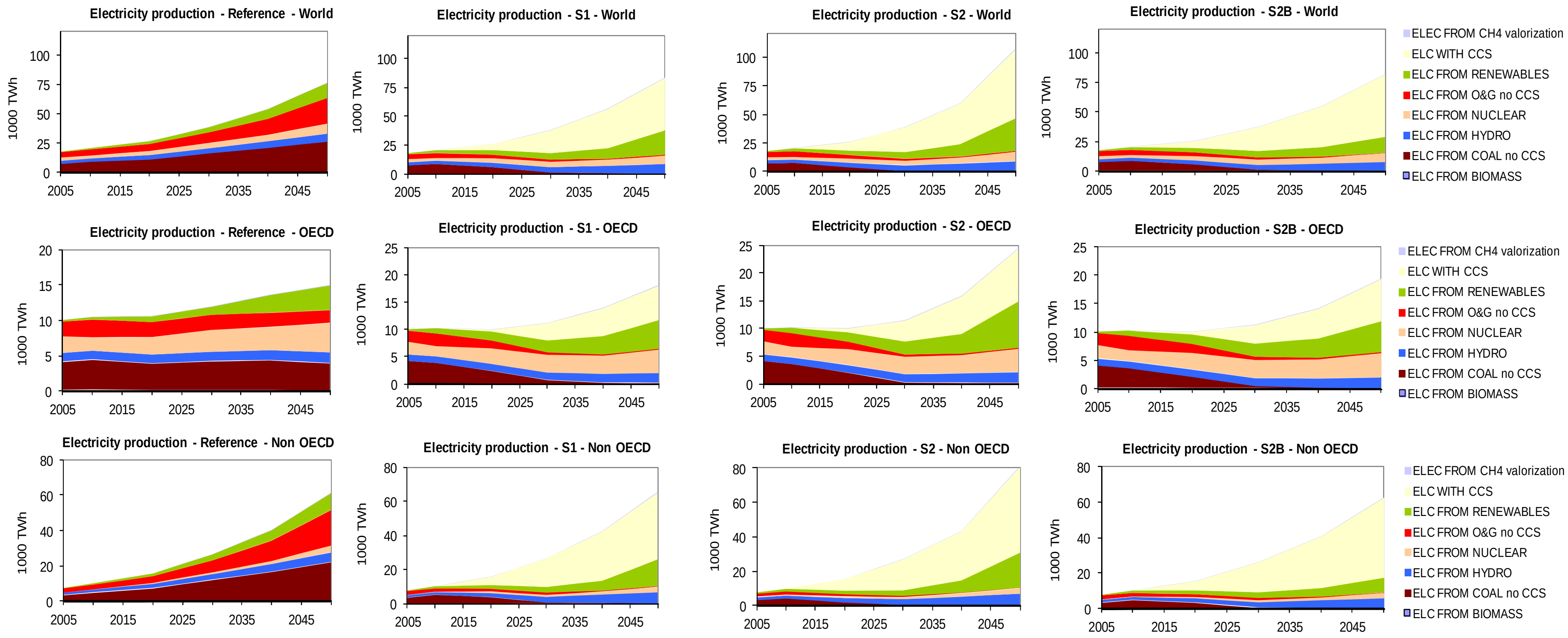


Figure 5. Electricity production in Reference, S1 (Climate Agreement between all Countries, all Sectors), S2 (Climate Agreement Limited to the Energy Intensive Industries) and S2B (Climate Agreement Limited to Electricity generation) - Outputs of TIAM-WORLD in the Coupled-Models.

Demands for energy services
The demands for energy services, especially the industrial products and final services strongly depending on electricity (electric appliances, lighting) are reduced in the climate scenario. This change represents potential changes of behaviors of the consumers. The results of the *Coupled-Models* and *TIAM-Elastic* slightly differ. Differences reflect the different approaches in the representation of the variation of the demands, simplified in *TIAM-Elastic* and more detailed in the macro-economic GEMINI-E3 model. More particularly, the *Coupled-Models* better represent the effects of climate policies on the international trade of products. The results are as follows:

- Agriculture, commercial, residential and road transport behave similarly in *TIAM-Elastic* and in *Coupled-Models*. Demands for aviation and navigation are more drastically reduced in *TIAM-Elastic*. Elasticities of these demands might need to be decreased in TIAM-WORLD.
- All industrial demands decrease in *TIAM-Elastic*. The dynamics are more complex in the *Coupled-Models* and vary from one industrial sub-sector to another.
- In both models, the reductions of industrial demands in China and India are higher than the World average. Indeed, the price elasticities of these demands are higher in developing countries than in industrialized countries.

We focus now on the Iron&Steel sub-sector in order to better illustrate the differences between *TIAM-Elastic* and the *Coupled-Models*. The annual World demand for Iron&Steel decreases by 14% in the *Coupled-Models* against 8% in *TIAM-Elastic* in 2050. The countries with the highest absolute and relative reductions of Iron&Steel production are China and India, which are also the largest producers. Several countries increase their production of Iron&Steel in the *Coupled-Models*: Australia, Eastern Europe, Japan, Other Developing Asia, South Korea, USA and Western Europe, but not in *TIAM-Elastic,* where production decreases in all regions.

The changes in regional production obtained in the *Coupled-Models* are explained by either changes in domestic consumption, or changes in export/exports (Figure 6), as modeled in GEMINI-E3. In other words, when countries have to reduce their emissions, they can:

a) adapt their mode of production of Iron&Steel so that it becomes less carbon intensive,
b) increase their imports of Iron&Steel from countries than can produce it in a low emitting mode,
c) decrease the domestic consumption,
d) decrease their exports.

In results, domestic consumption of Iron&Steel decreases in all regions (Figure 6), as observed in *TIAM-Elastic*. The increase of production observed in the regions identified above is motivated by the increase of their exports to compensate for the decrease of production of other regions, mainly China and India.

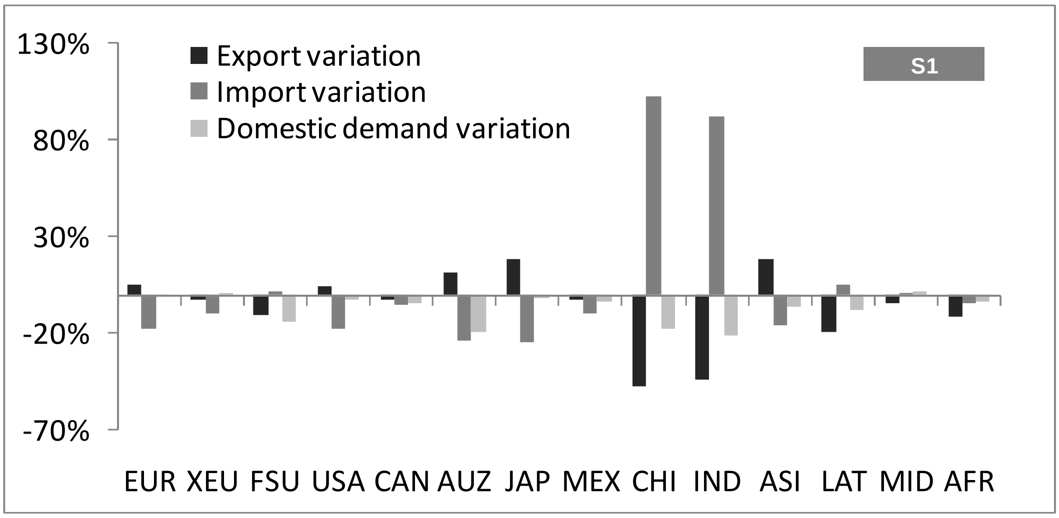


Figure 6. Variation of Iron&Steel consumptions and trade flows in 2050 in S1 (outputs of GEMINI-E3 in the *Coupled-Models*)

The analysis of energy dynamics helps understand these decisions. In the climate scenario, at the global level, coal is substituted by low-carbon commodities, like natural gas and electricity in the Iron&Steel sector. This results in a better energy efficiency of the production (10% increase at the end of the horizon). The production in China and India decreases sharply: these countries prefer importing Iron&Steel from some other countries rather than producing it locally with clean energy and processes. The reason is that the clean production opportunities are almost all used in these countries (electricity production is almost emission free, and the biomass potentials are fully used), contrary to some other countries where some biomass potentials remain unused. These other countries are able to produce Iron&Steel in a cleaner way than China, mainly thanks to biomass-fired power plants with carbon capture and sequestration, which is a powerful mitigation option since it is equivalent to negative emissions.

4.1.2 *GEMINI-E3 alone* compared to *Coupled-Models*

The standard version of GEMINI-E3 without coupling is used in *GEMINI-E3 alone*. It shares a common set of assumptions with TIAM-WORLD (section 3.3.). For consistency purposes, scenario S1 is modelled in *GEMINI-E3 alone* by using the World CO_2 profile computed in *TIAM-Elast*, itself very close to *Coupled-Models*. In other words, the same radiative forcing is reached in all models.

Emission and energy results

CO_2 abatement is achieved through the implementation of a uniform worldwide carbon price without permit trading. The CO_2 price computed by *GEMINI-E3 alone* reaches 356 $\$_{2010}$ in 2050 (Table 2). The same prices reached in 2050 by *GEMINI-E3 alone* and *TIAM-Elast* is a matter of chance. Indeed, lower absolute reduction are reached in *GEMINI-E3 alone* than in *TIAM-Elast*, when considering that the reference emissions are lower in GEMINI-E3 than in TIAM-WORLD. In other words, a similar absolute abatement would have cost more in *GEMINI-E3 alone* than in *TIAM-Elast* at the end of the period. This is in line with the fact that technological models like TIAM-WORLD assume a higher flexibility in carbon abatement than macro-economic models like GEMINI-E3 (Grubb et al., 1993).

Scenario\Period	2010	2020	2030	2040	2050
GEMINI-E3 alone	3	37	89	216	356
TIAM-Elast	25	43	81	152	354
Coupled-Models	25	42	81	151	351

Table 2. World CO_2 price in $\$_{2010}$ – Scenario S1

Input substitution

GEMINI-E3 does not explicitly represent the technologies, but rather uses a technical progress coefficient and the possibility to reduce fossil fuel usage, in order to represent the energy changes. The comparison of the energy results between *GEMINI-E3 alone* and the *Coupled-Models*, where TIAM-WORLD provides a high level of technology details, helps understand the possible advantages of the coupling. The energy mix proposed by *GEMINI-E3 alone* is generally based on a diverse basket of the different energy forms, while the technology representation included in the *Coupled-Models* leads to more frequent cases where one or two energy forms dominate the energy mix. Indeed, the use of nested CES functions in *GEMINI-E3 alone* limits somehow the flexibility in the choice of energy mix. Another difference is that the standard version of GEMINI-E3 does not include CCS, contrary to TIAM-WORLD; it is interesting to note that the share of renewable electricity is the same in both approaches, but the *Coupled-Models* results in a globally less emitting electricity sector than *GEMINI-E3 alone* thanks to CCS in power plants. In other words, the higher technology details of the *Coupled-Models* offer a higher flexibility of the energy system compared to *GEMINI-E3 Alone*.

Macro-economic analysis

Macroeconomic costs of S1 obtained in *GEMINI-E3 alone* show similar dynamics as in GEMINI-E3 in the *Coupled models* (Figure 7).

- Energy exporting countries, represented by MID, FSU and to a lesser extent Africa, are extremely penalized by the introduction of a climate constraint. These countries suffer a significant drop in income due to lower energy exports.
- For industrialized countries that have high energy intensity and are energy importing countries, the cost is small. This is the case of the European Union and Japan.
- China and India experience important losses due to energy consumption mainly based on coal in the Reference scenario.

These results show that the implementation of a World carbon tax without redistribution, or of a tradable permit system without adequate initial allocation rule of burden sharing, would not be acceptable to developing countries, which bear an important portion of the global cost of the climate policy.

Costs are relatively higher in the *Coupled-Models* given the slightly higher reduction efforts needed compared to *GEMINI-E3 alone* since the reference case of TIAM-WORLD includes higher long-term emissions.

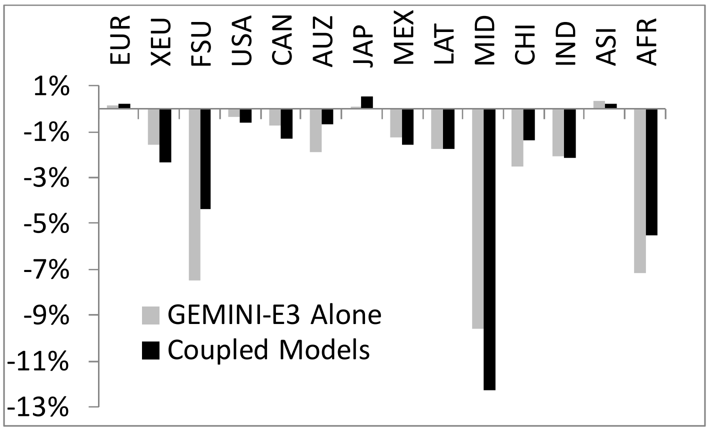


Figure 7. Welfare cost variations between S1 and Reference represented in *GEMINI-E3 alone* and in *Coupled Models* (the welfare cost is equal to the sum of discounted net present surplus divided by the discounted net present household consumption of the baseline).

4.2. Partial climate agreements

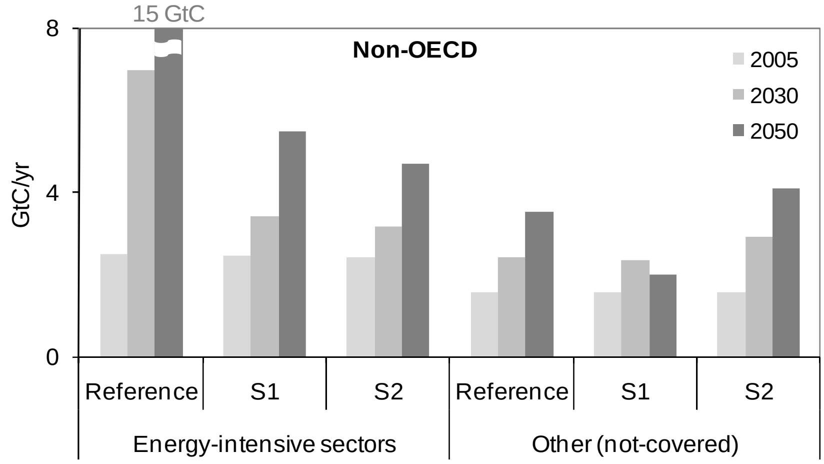
Two alternate scenarios represent partial climate agreement:

- *Scenario 2 (S2) - Climate Agreement Limited to the Energy Intensive Industries*: The climate target remains the same, 3.5 W/m^2. All sectors of the OECD countries are covered by the climate agreement. In Non-OECD countries, only energy intensive industries, including electricity generation and upstream sectors, are covered. This agreement is expected to avoid penalizing too much the households (residential and transport) by excluding them from the agreement, and limiting the loss of competitiveness of developed countries.
- *Scenario 2B (S2B) - Climate Agreement Limited to Electricity Generation*: All sectors of the OECD countries are covered by the climate agreement. In Non-OECD countries, only electricity generation is covered. The modelling of scenario 2B with the target of 3.5 W/m^2 turned out to be infeasible. In other words, the participation of developing countries in the climate mitigation cannot be limited to their electricity generation sector if the radiative forcing target is set at 3.5 W/m^2. A similar result is obtained by Clarke *et al.* (2013) with a large range of models. Therefore, the target used for this scenario was relaxed to 4.0 W/m^2. With additional runs, we have found that the smallest feasible radiative forcing is 3.8 W/m^2. S2B can therefore not be directly compared to the other scenarios (S1 and S2) since the climate targets are different.

The sectors not covered by the Climate agreement in Scenarios 2 and 2B might still indirectly react to the climate constraint because of changes in energy prices and macro-economic factors.

4.2.1. Climate Agreement Limited to the Energy Intensive Industries (S2)

The global techno-economic cost, obtained from TIAM-WORLD in the *Coupled-Models*, reaches 11.2 trillion $\$_{2010}$, what is 1.5 times the cost of S1 where the climate agreement covers all sectors (7.3 trillion $\$_{2010}$). It increases even more in OECD, by a factor of 1.8 (from 3.4 to 6.1 trillion $\$_{2010}$) because these countries have to do more mitigation efforts. However, total cost increases also in Non-OECD, by a factor of 1.3, from 3.7 to 5.17 trillion $\$_{2010}$). In other words, all regions, including the Non-OECD countries, face a higher total cost when only the intensive energy sectors of the Non-OECD countries participate in the climate agreement: the mitigation effort supported by the covered sectors is higher, in all countries (Figure 8), resulting in more costly strategies. The CO_2 price in 2050 reaches 526$_{2010}$/tCO_2 in S2, compared to 357$_{2010}$/tCO_2 in S1.



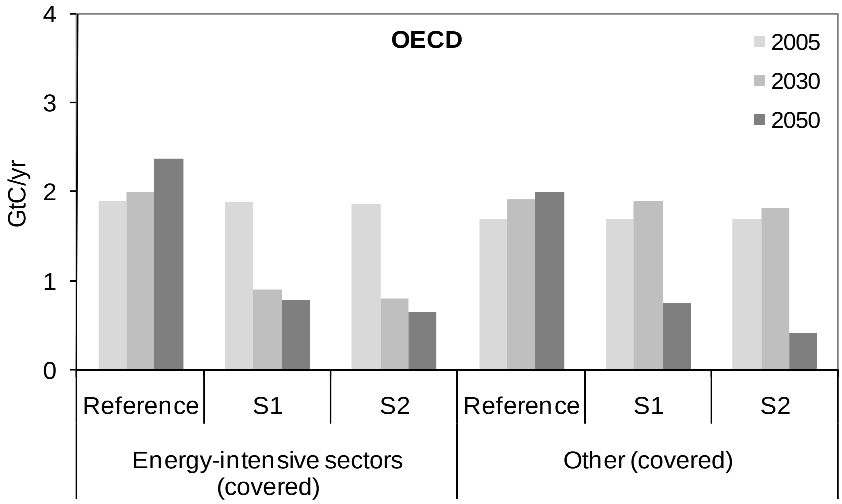


Figure 8. Comparison of CO_2 emissions in Reference, S1 (Climate Agreement between all Countries, all Sectors) and S2 (Climate Agreement Limited to the Energy Intensive Industries) - Outputs of TIAM-WORLD in the *Coupled-Models.*

Since the mitigation efforts are concentrated on a reduced part of the total economy, low-emitting electricity production (renewable and CCS) penetrates more in S2 compared to S1 (Figure 5). The increase is higher in OECD than in non-OECD. A strong penetration of biomass in industry is also observed, but higher in non-OECD than in OECD regions; indeed, non-OECD countries use in industry some bioenergy that is no longer needed in their residential and transportation sectors. As a consequence, the emissions of the residential and transport sector of Non-OECD countries, not included in the climate agreement, increase (Figure 8). They are even higher than in the Reference: some leakage occurs in these sectors. However, total oil consumption in Non-OECD countries remains almost at the same level as in the Reference: there is no incentive to increase the total oil consumption in Non-OECD countries after the OECD countries decrease their own demand.

Industrial production and trade follow the same dynamics occurs in S2 as in S1. In other words, a slight displacement of energy intensive activities is observed to regions with high potential of clean energy and technologies.

At the World level, S2 is less efficient than S1, as also concluded by TIAM-WORLD: the worldwide cost to reach the same emission target increases by 60%. Macro-economic costs assessed by GEMINI-E3 in the *Coupled Models* are higher in S2 than S1 for industrialized countries (Figure 9). Indeed, in S2, the price of CO_2 increases 1.5 times and is applied without exemption to all energy consumption of industrialized countries. In contrast, the welfare of developing countries increases with respect to S1: households are exempted from carbon taxation and benefit from the decrease of fossil fuel prices compared to the Reference. This result is in opposition with the costs obtained in TIAM-WORLD where the costs supported by developing countries also increase. The reason is that TIAM-WORLD accounts for direct costs only and does not reflect the macro-economic impacts modeled in GEMINI-E3.

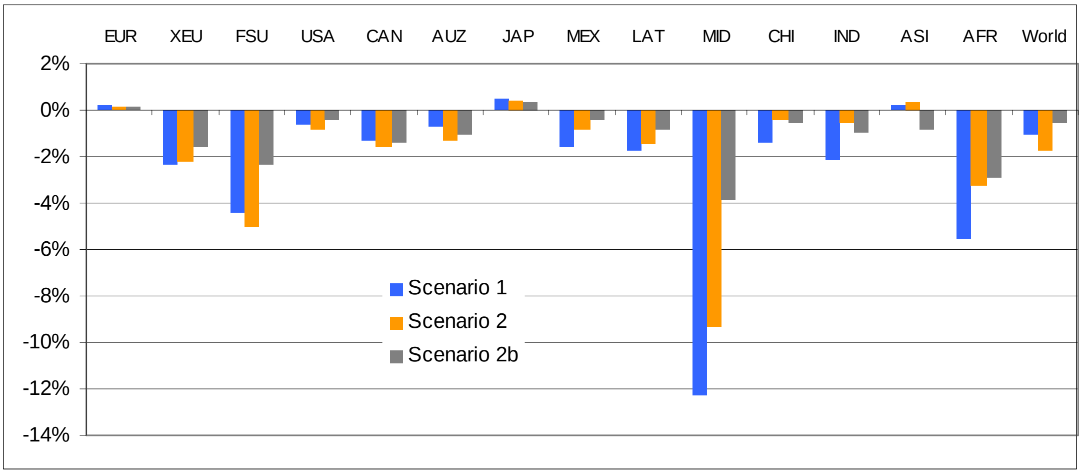


Figure 9. Macro-economic cost in S1, S2, S2B - % of household consumption (outputs of GEMINI-E3 in the *Coupled-Models*)

4.2.2. Climate Agreement Limited to Electricity generation (S2B)

Let us recall that the limitation of the covered sectors of Non-OECD countries to the electricity sector makes infeasible the limitation of the radiative forcing to 3.5 W/m2. A value of 4 W/m^2 was used to solve for Scenario 2B. CO_2 price reaches 392 $\$_{2010}/tCO_2$ in 2050.

Electricity consumption almost does not increase compared to the Reference case, but the structure of the electricity generation is modified in favor of low-emitting power plants, despite the lower climate target (Figure 5). Biomass fired plants with CCS play a crucial role, and biomass consumed in industry is replaced by gas and electricity, while part of the biomass consumed in residential is replaced by coal.

It is interesting to analyze industrial production, not covered by the Climate agreement, and its possible delocalization in such a partial climate agreement. Developing and emerging countries, including China and India, reduce their imports and increase their exports compared to the Reference, while the opposite occurs in OECD countries

(Iron&Steel illustrated in Figure 9): there is delocalization of the production, as measured by the outputs of GEMINI-E3 in the *Coupled-Models*.

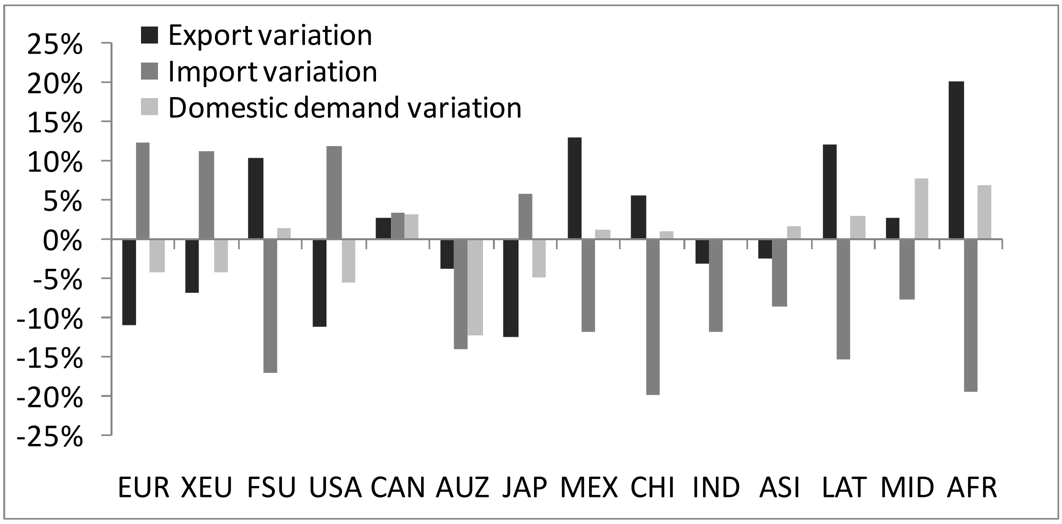


Figure 9. Variation of Iron&Steel consumptions and trade flows in 2050 in S2B (outputs of GEMINI-E3 in the coupled models)

Some gas extraction is delocalized to Non-OECD countries, more particularly to Former Soviet Union and Africa (outputs of TIAM-WORLD in the *Coupled-Models)*, but it does not provoke an important increase of emissions in these countries. Indeed, the increase of emissions of industry and gas extraction in Non-OECD countries is compensated by the reduction of oil extraction activities and of production of synthetic oil from coal, due to the global decrease of oil consumption. There is no rebound of oil consumption in Non-OECD regions.

S2B could be considered as more acceptable than the others since its macro-economic impacts are less than for other scenarios; but the environmental target is also easier to reach, so that a direct comparison is not quite possible.

Conclusion

Greenhouse gas mitigation will deeply affect the energy systems and the macro-economic characteristics of the countries and possibly the trade of energy-intensive products between countries.

The proposed coupling of TIAM-WORLD, a global technology-rich optimization model, and GEMINI-E3, a global computable general equilibrium model aims to building upon the strengths of both models to assess climate agreements: a precise representation of technology choices, energy consumption and energy prices as well as an explicit and coherent representation of the effects of climate policies on GDP, sectoral activities, international trade and other economic factors (labor, consumption, capital, etc.).

The coupling methodology requires a meticulous examination and understanding of both models in order to define the correspondence between energy commodities, regions, economy sectors, and the data exchanges between both models.

It was successful used to study climate agreements and helped understand in a consistent manner the trade effects of climate policies, their macro-economic impacts and the technology and energy preferences.

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References

Baron, R., I. Barnsley and J. Ellis, (2008) Options for Integrating Sectoral Approaches into the UNFCCC. OECD, November, 41 p

Bernard, A. and Vielle, M. (2008). GEMINI-E3, a general equilibrium model of international-national interactions between economy, energy and the environment. *Computational Management Science*, 5(3):173–206.

Böhringer, C. (1998). The synthesis of bottom-up and top-down in energy policy modelling. *Energy Economics*, 20:233–248.

Böhringer, C. and Rutherford, T.F.. (2009). Integrated assessment of energy policies: Decomposing top-down and bottom-up, *Journal of Economic Dynamics & Control*, 33:1648–1661.

Böhringer, C. and Rutherford, T.F. (2008). Combining bottom-up and top-down. *Energy Economics*, 30:574-596.

Bosetti V., David G. Victor (2011). Politics and Economics of Second-Best Regulation of GHGs: The Importance of Regulatory Credibility The Energy Journal, Vol. 32, No. 1

Capros, P., Paroussos, L., Fragkos, P., Tsani S., Boitier, B., Wagner, F., Buschd, S., Reschd, G., Blesle, M. and J. Bollen (2014). European decarbonisation pathways under alternative technological and policy choices: A multi-model analysis. *Energy Strategy Reviews*, 2(3-4):231-245.

Clarke L, Edmonds, JA, Krey, V. Richels, RG, Rose, S. and M Tavoni (2009). International Climate Policy Architectures: Overview of the EMF 22 International Scenarios. *Energy Economics* 31(2):S64-S81.

Dimaranan, B. V. (2006). *Global Trade, Assistance, and Production: The GTAP 6 Data Base*. Center for Global Trade Analysis, Purdue University.

Drouet, L., Beltran, C., Edwards, N.R., Haurie, A.B., Vial, J-P. and Zachary, D.S. (2005). *An oracle method to couple climate and economic dynamics*. In A. Haurie and L. Viguier (Eds), Coupling climate and economic dynamics, Advances in Global Change Research (pp. 69-95). Springer.

E3Mlab (2010). General Equilibrium Model for Economy–Energy–Environment: Model Manual, Available at http://www.e3mlab.ntua.gr/e3mlab/GEM%20-%20E3%20Manual/Manual%20of%20GEM-E3.pdf

Energy Information Administration (2009). *The National Energy Modelling System: An Overview*. Office of Integrated Analysis and Forecasting, U.S. Department of Energy, Washington, DC 20585.

Fortes, P., Simões, S., Seixas, J., Van Regemorter, D. and Ferreira, F. (2013). Top-down and bottom-up modelling to support low-carbon scenarios: climate policy implications, *Climate Policy*, 13(5):285-304.

Grubb, M. J. Edmonds, P. Brink, and M. Morrison. (1993) The costs of limiting fossil fuel CO2 emissions: a survey and analysis. *Annual Review of Energy and the Environment*, 18:397–478,.

IEA, 2009c, Sectoral Approaches in Electricity: Building Bridges to a Safe Climate, International Energy Agency, Paris

Hamdi-Cherif M., Guivarch C. And P. Quirion (2011). Sectoral targets for developing countries: combining ‘common but differentiated re-sponsibilities’ with ‘meaningful participation’, Climate Policy, 11(1), 731-75.

Hamilton, L.D., Goldstein, G., Lee, J.C., Manne, A., Marcuse, W., Morris, S.C., and Wene C-O. (1992). *MARKAL-MACRO: An overview*. Technical Report 48377, Brookhaven National Laboratories.

Hageman, L. A. and Young, D. M. (1981). Applied iterative methods (pp 27-28). New York: Academic Press.

Hoffman, K.C. and Jorgenson, D.W. (1977). Economic and technological models for evaluation of energy policy. *The Bell Journal of Economics*, 8(2):444–466.

Kiuila, O. and Rutherford, T.F. (2013), Piecewise smooth approximation of bottom –up abatement cost curves, Energy Economics, 40:734-742.
Krey V., Luderer, G, Clarke, L. and E. Kriegler (2013). Getting from here to there – energy technology transformation pathways in the EMF27 scenarios. *Climatic Change. Special Issue on "The EMF27 Study on Global Technology and Climate Policy Strategies"*
Labriet M., Kanudia, A. and R. Loulou (2012). Climate mitigation under an uncertain technology. future: a TIAM-WORLD analysis. *Energy Economics,* 34 (3): S366-S377.
Lanz, B. and Rausch, S. (2011) General equilibrium, electricity generation technologies and the cost of carbon abatement: A structural sensitivity analysis, *Energy Economics*, 33:1035-1047.
Löschel, A. and Soria, A. (2007). *Impact of an increased use of renewable electricity: A quantitative assessment with a hybrid CGE model*. In 9th IAEE European Energy Conference, Firenze, 2007.
Loulou, R., Labriet, M. and A. Kanudia (2013). Effectiveness and efficiency of climate change mitigation in a technologically uncertain World, *Climatic Change. Special Issue on "The EMF27 Study on Global Technology and Climate Policy Strategies"*.
Loulou, R. and Labriet, M. (2008). ETSAP-TIAM: the TIMES integrated assessment model. Part I: Model Structure. *Computational Management Science*, Special issue "Managing Energy and the Environment", Vol. 5, Issue 1, pp.7-40.
Loulou, R. (2008). ETSAP-TIAM: the TIMES integrated assessment model. Part II: Mathematical formulation. *Computational Management Science*, Special issue "Managing Energy and the Environment", Vol. 5, Issue 1, pp.41-66.
Loulou, R. and Kanudia, A. (2000). *Using Advanced Technology-rich models for Regional and Global Economic Analysis of GHG Mitigation*. In G. Zaccour, editor, Decision and Control: Essays in honor of Alain Haurie, Kluwer Academic Publishers, Norwell, USA, pp.153-175. (A condensed version of this article was published electronically in the *Proceedings of the International Energy Agency International conference on Climate Change Modelling and Analysis*, held in Washington DC, June15-17, 1999).
Manne, A. (1981). *ETA-MACRO: A user's guide*. NASA STI/Recon Technical Report N, 81:28582.
Manne, A.S. and Richels, R.G. (1992). *Buying greenhouse insurance: the economic costs of CO2 emission limits*. The MIT Press, Cambridge, 1992.
Manne, A. S., &and Wene, C. -O. (1992). MARKAL-MACRO: A linkedLinked model for energy-economy analysis (No.Energy-Economy Analysis, *Bookhaven national Laboratory,* BNL---47161). Brookhaven National Lab., Upton, NY (United States)., 1992.
Messner, S. and Schrattenholzer, L.. (2000). MESSAGE-MACRO : linking an energy supply model with a macroeconomic module and solving it iteratively. *Energy*, 25(3):267–282.
Nordhaus W.D. and Yang Z. (1996). A regional dynamic general-equilibrium model of alternative climate change strategies. *American Economic Review*, 86 (4):741-765.
Paltsev, S., Reilly, J.M., Jacoby, H.D., Eckaus, R.S., McFarland, J., Sarofim, M., Asadoorian, M. and Babiker, M. (2005) The MIT Emissions Prediction and Policy Analysis (EPPA) Model: Version 4, *Joint Program Report Series,* Report 125.
Pizer, W., Burtraw, D., Harrington, W., Newell, R., and Sanchirico, J. (2003a). *Modelling Economy wide versus Sectoral Climate Policies Using Combined Aggregated- Sectoral Models*. Technical report, Resource for the future, Washington D.C.
Pizer, W., Burtraw, D., Harrington, W., Newell, R., Sanchirico, J. and Toman, M. (2003b). *General and Partial Equilibrium Modelling of Sectoral Policies to Address Climate Change in the United States.* Technical report, Resources for the future, Washington D.C.
Schäfer, A. and Jacoby, H. (2005). Technology detail in a multisector CGE model: transport under climate policy. *Energy Economics*, 37(1):1–24.
Schäfer, A. and Jacoby, H. (2006). Experiments with a Hybrid CGE-MARKAL Model. *Energy Journal*, Special Issue: Hybrid modelling of Energy-Environment Policies: Reconciling Bottom-up and Top-down:171–177.
Tuladhar S.D., Yuan, M., Bernstein, P., Montgomery, W. D. and Smith A. (2009). A top–down bottom–up modelling approach to climate change policy analysis, Energy Economics 31:S223–S234.
Wing, I. (2006). The synthesis of bottom-up and top-down approaches to climate policy: Electric power technologies and the cost of limiting US CO2 emissions. *Energy Policy*, 34:3847–3869.
van Vuuren, D.P., Weyant, J., de la Chesnaye, F., (2006). Multi-gas scenarios to stabilize radiative forcing. *Energy Economics* 28(1):102–120 January.

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