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Regional Economic and Energy Implications of Reaching Global Climate Targets – A Policy Scenario Analysis

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SEVENTH FRAMEWORK PROGRAMME

Report on "Policy Scenarios"

Regional Economic and Energy Implications of Reaching Global Climate Targets – A Policy Scenario Analysis

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1. Introduction

The main objectives of this work-package 5 (WP5) report are (1) the formulation of climate scenarios (also called policy scenarios) that can serve as input for the current climate debate in both the policy making and scientific communities, (2) their simulation via an ensemble of distinct energy-economy models, and (3) the presentation, analysis, and comparison of the modeling results in order to extract from them robust policy insights. It is fully *ex ante* expected that at least some modeling results will be model-dependent: this observation constitutes an important caveat for policy makers and analysts.

In this report, we first provide a brief description of the six models used in WP5 (section 2), followed by a description and justification of the selected policy scenarios (section 3), and the presentation and analysis of results (sections 4 to 9). Section 10 is reserved for an exposition of results from the EU wide model PEM. The concluding section 11 is an attempt to summarize the main lessons learned from the entire exercise. The electronic Annex provides a complete list of detailed results for all model runs.

2. The six models

The six models used in WP5 cover an interesting and varied range of model philosophies, and have been chosen to provide contrasted views of the energy and climate questions raised in the current global debate on climate change. Examining the same policy scenarios with a variety of lenses can be useful for shedding new light on the difficult challenges offered by the warming of our planet's climate. Among the six models, three may be called Top-Down and three Bottom-Up, although such a rough classification is sometimes challenged by features that tend to blur the frontier between these two main classes of models.

For instance, WITCH's basic paradigm is that of a (cooperative or non-cooperative) intertemporal general equilibrium computation, but it is enriched by the presence of key technologies in the energy sector, as well as by the modelling of endogenous technological learning and innovation. In addition, the electricity sector in WITCH is modeled via a Leontief fixed coefficient production function, which is a departure from usual top-down models that brings WITCH closer to a technology-based model (at least for the electricity sector). WITCH is resident at Fondazione Eni Enrico Mattei (FEEM, Italy).

Another example consists in the three partial equilibrium models based on the TIMES generator, which combine bottom-up detailed technological databases in all sectors with economic demands that are elastic to their prices, thus endogenizing the main link between the energy system and the economy. Among these three TIMES based models, two are global multiregional and possess their own internal climate equations (ETSAP-TIAM, resident at KANLO Consultants Sàrl, France) and TIAMEC, at ECN, The Netherlands), whereas the third (PEM, Universität Stuttgart) is a detailed model of the European Union with separate representation of each EU country's energy system, with a 2050 horizon.

The DEMETER model is a single-region global growth model that focuses on the relation between current climate change policies and the climate in the very long term (up to 2300). The model is resident at University of Manchester (UK) and at UniTil (NL).

GEMINI-E3, a top-down model, has a very fine sector disaggregation, and focuses on economic variables (including interregional trade) during the first half of the century only. The model is resident at the French Commissariat à l'Énergie Atomique (France) and at ORDECSYS (Switzerland).

The rest of this section contains descriptions of the six models and of the key assumptions of their reference scenario. These are very useful for interpreting correctly the results produced by each model.

2.1 The WITCH Model

2.1.1 Model description

WITCH – World Induced Technical Change Hybrid – is an optimal growth model of the world economy that integrates in a unified framework the sources and the consequence of climate change. A climate module links greenhouse gas (GHG) emissions produced by economic activities to their accumulation in the atmosphere and the oceans. The effect of these GHG concentrations on the global mean temperature is derived. A damage function explicitly accounts for the effects that climate change can have on the economic system. WITCH is thus an Integrated Assessment Model[1].

The world economy is disaggregated into twelve regions: US, OLD EUROPE, NEW EUROPE, KOSAU, CAJAZ, TE, MENA, SSA, SASIA, CHINA. EASIA, LACA. These groups of countries share similar economic, geographic, resource endowment and energy characteristics. Regions interact with each other through the presence of economic and environmental global externalities. For each region a forward-looking agent maximises her own intertemporal social welfare function, strategically and simultaneously with other regions. The intertemporal equilibrium is calculated as an open-loop Nash equilibrium, but a cooperative solution can also be implemented. Through the optimisation process, regions choose the optimal dynamic path of the control variables, namely investments in different capital stocks, in R&D, in energy technologies and consumption of fossil fuels.

WITCH is a hard-linked hybrid model because the energy sector is fully integrated with the rest of the economy and therefore investments and the quantity of resources for energy generation are chosen optimally, together with the other macroeconomic variables of the model. The model can be called hybrid because the energy sector features a bottom-up characterisation. . A broad range of different technologies can be used for power generation: nuclear and hydroelectric power plants, traditional coal, gas oil power plants, coal with CCS, wind turbines and photovoltaic panels. Final energy use includes the use of biofuels along with traditional energy carriers (traditional biomass, coal, oil and gas). The energy sector endogenously accounts for technological change, with considerations for the positive externalities stemming from learning-by-doing and learning-by-researching.

The length of the time horizon (from 2005 to 2100 in five-year steps), the regional dimension, and the game theoretical setup, make the WITCH model suitable for the assessment of intertemporal, geographic and strategic aspects of climate change policies.

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[1] Climate change damages have not been included in this analysis (the damage function has been turned-off) and therefore climate policy costs are gross of climate change benefits.

Input	Source	Remarks on if and how the translation was made
GDP	EET/WETO	Total factor productivity for Europe and other main players adjusted to match the harmonization conditions
Population	UN	Sum up country level data to match WITCH regions. Use 2004 estimates for after 2050 projections
Energy prices (oil and optionally coal)	PLANETS agreed paths	Adjusted specification of supply/demand relation to match price paths
Overall discount rate	3% declining (2% in 2100)	
Policy assumptions		
Subsidies and taxes	Regional markups	
Coal		
Nuclear	No exogenous constraint. Waste management costs set at Yucca mountain estimates, growing with cumulative capacity	
Renewable electricity	Subject to Learning by doing (LbD)	
Sulphur policies	none	
Climate policies	none	
Efficiency standards for cars	none	

Table 1. WITCH reference scenario assumptions

2.1.2 Emissions and mitigation options

WITCH models Kyoto gases. Besides CO2, it includes N20, CH4, and short and long lived fluorinated gases. The data for nonCO2 gases baseline and for abatement opportunities are taken from EPA and the EMF21 study. CO2 emissions from land use and change are also included, but the option of mitigating them from baseline under a carbon policy was not activated in the simulation runs.

Key mitigation options in the power sector

The WITCH model features a series of mitigation options in both in the power generation sector and in the other usages of energy carries, e.g in the non-electric sector.

Mitigation options in the power sector include nuclear, hydroelectric, IGCC-CCS, renewables and a backstop option that can substitute nuclear.

Nuclear power is an interesting option for decarbonized economies. However, fission still faces controversial difficulties such as long-term waste disposal and proliferation risks. Light Water Reactors (LWR) — the most common nuclear technology today — are the most reliable and relatively least expensive solution. In order to account for the waste management and proliferation costs, we have included an additional O&M burden in the model. Initially set at 1 mUSD/kWh, which is the charge currently paid to the US depository at Yucca Mountain, this fee is assumed to grow linearly with the quantity of nuclear power generated, to reflect the scarcity of repositories and the proliferation challenge.

Limited deployment potential of controversial technologies such as nuclear suggests that the possibility to invest towards the commercialisation of innovative technologies should be a desirable feature of models that evaluate long-term policies. For this reason, a breakthrough technology has been included in the power sector as linear substitute to nuclear.

Hydroelectricity is also a carbon free option, but it is assumed to evolve exogenously to reflect limited site availability.

One technology that has received particular attentions in the recent past is carbon capture and storage (CCS). In the WITCH model this option can be applied to integrated coal gasification combined cycle power plant (IGCC-CCS). In fact, CCS is a promising technology but still far from large scale deployment.

CCS transport and storage cost functions are region specific and they have been calibrated following Hendriks et al. 2004. Costs increase exponentially with the capacity accumulated of this technology. The CO2 capture rate is set at 90% and no after-storage leakage is considered. Other technological parameters such as efficiency, load factor, investment and O&M costs are described in Table 2. In the case of CCS there is no learning process or research activity that can either reduce investment costs or increase the capture rate.

In general the assumed potential for CCS is quite low. Non-perfect capture rate disfavors CCS vis à vis other low carbon technologies (i.e. nuclear and renewables), all things equal otehrwise. Assuming 100% capture rate would double the model uptake of CCS.

Electricity from wind and solar is another important carbon free technology. The rapid development of wind and solar power technologies in recent years has led to a reduction in investment costs. In fact, beneficial effects from learning-by-doing are expected to decrease investment costs even further in the next few years. This effect is captured in the WITCH model by letting the investment cost follow a learning curve. As world-installed capacity in wind and solar doubles, investment cost diminishes by 13%. International spillovers in learning-by-doing reflect the assumption that information and best practices in cutting-edge technological sectors dominated by a few major world investors quickly circulate. The model has a five-year time steps, a lag that is sufficient for a complete flow of technology know-how, human capital and best practices.

Technical details on technologies in the power sector

Costs for new investments and maintenance in power generation are region specific and constant over time, except for renewable and backstop technologies.

Investment costs in renewable energy decline with cumulated installed capacity at the rate set by the learning curve progress ratios, which is set equal to 0.87 — i.e. there is a 13% investment cost decrease for each doubling of world installed capacity.

Electricity production is described by a Leontief production function that combines generation capacity, fuels and expenditure for operation and maintenance (O&M) in a Leontief production function. The fixed proportions used to combine the three inputs (two in the case of wind and solar electricity generation which does not need any fuel input) have been derived by plant operating hours, fuel efficiencies and O&M costs described in Table 2 and are constant across regions and across time. The parameters governing the production function take into account the technical features of each power production technology, such as the low utilization factor of renewables, the higher costs of running and maintain IGCC-CCS and nuclear plants.

	Investment costs World average USD_{2005}/KW	**O&M** World average USD_{2005}/KW	**Fuel Efficiency** %	**Load factor %**	**Lifetime** years	**Depreciation %**
Renewables (W&S)	1904	30	100%	30%	30	7.4%
Nuclear	2540	176	35%	85%	40	5.6%
Hydropower	1780	70	100%	50%	45	5%
Coal	1530	47	45%	85%	40	5.6%

Oil	1010	36	40%	85%	25	8.8%
Gas	810	30	60%	85%	25	8.8%
IGCC-CCS	3170	47	40%	85%	40	5.6%

Table 2: Initial investment costs and O&M costs of electricity generation technologies

Key mitigation options in the non-electric sector

Less flexible is the non-electric sector. The energy carriers that are used for use are traditional biomass, biofuels, coal, gas and oil. Oil and gas together account for more than 70% of energy consumption in the non-electric sector. Instead the use of coal is limited to some developing regions and it is assumed to decrease exogenously.

Traditional biomass as well is used mostly in non-OECD regions and its share declines over time, from 11% in 2005 to 7% in 2030, as rural population in developing countries progressively gains access to standard forms of energy.

Ethanol is labelled "traditional biofuels", whereas "advanced biofuels" are obtained from biomass transformation. Biofuels consumption is currently low in all regions of the world and the overall penetration remains modest over time given the conservative assumptions on their large scale deployment. Therefore the mitigation potential coming from this option is quite limited.

The main mitigation option remains the deployment of a breakthrough technology that could substitute oil in the non-electric sector, pending sufficient R&D investments. This option can be thought of as next generation biofuels or carbon free hydrogen to be used in the transport sector.

The non-electric sector being characterized by strong rigidities, and given that the backstop technology is costly, contraction of energy demand in the non-electric sector is another important mitigation option. This explains why, in a policy scenario, the WITCH model reduces significantly the use of energy.

Other mitigation options: energy efficiency and the role of innovation

In WITCH, an important mitigation option is the increase in overall energy efficiency. Improvement in energy efficiency is modelled as an endogenous process, driven by dedicated investments in energy R&D.

In the WITCH model dedicated investments in energy R&D have two effects. They improve overall energy efficiency and they increase the competitiveness of breakthrough technologies.

In this setting, the carbon price is an important signal that provides the right stimulus for investment in R&D targeted to enhance energy efficiency and to increase the competitiveness of innovative low carbon technologies.

When a stabilization target is imposed, the world carbon price increases rapidly especially in the first half of the century in order to give a sufficiently strong signal to stimulate a reallocation of resources towards energy innovation and low carbon technologies.

2.2 The ETSAP-TIAM and TIAMEC Models

These two models are two incarnations of the TIAM bottom-up, technology rich linear optimization model, describing the development of the global energy system, from resource extraction to final use, over a long period of time, usually 100 years. TIAM is based on the TIMES model generator, developed and maintained by ETSAP. The regional disaggregation used in both versions separates the world into 15 different regions, as follows: Africa, Australia, Canada, Central and South America, China, Eastern Europe, Former Soviet Union, India, Japan, Middle-East, Mexico, Other Developing Asia, South Korea, USA, Western Europe.

Both models contain explicit descriptions of more than one thousand technologies and one hundred commodities (energy forms, materials, emissions) in each region, logically interrelated in a Reference Energy System. Each technology has its specific set of technical and economic parameters. Such technological detail allows precise tracking of capital turnover, and allows a precise description of technological competition. The models' scope covers extraction, processing, conversion, trading, and end-uses of all energy forms. Primary resources are disaggregated by type (e.g. proven vs. future natural gas reserves, connected vs. not, frontier gas, CBM, associated gas, etc). Each type of resource is described in each region by means of cumulative amounts in the ground, technical annual extraction limits and fixed and variable costs, constituting step-wise supply curves for each primary energy (coal, oil, gas, biomass).

TIAM includes a complete Climate Module that consists of three sets of equations (ref). The first set simulates the life cycles of CO_2, CH_4, and N_2O, and therefore computes their concentrations at each year of the horizon. The second set calculates the atmospheric radiative forcings of these three gases via classical formulas. The total forcing is then computed by adding up these three forcings plus a fourth forcing (exogenous) due to GHG's not explicitly modeled. The third set of equations calculates the change in mean global temperature in two layers (atmosphere and deep ocean) again at each year. The climate module was calibrated to more sophisticated climate models and found quite accurate in the range of emissions usually considered. The module allows the user to set climate targets as a driver to some policy scenarios.

The TIAM models are driven by a set of some 42 demands for energy services in all sectors of the economy (Agriculture, Residential, Commercial, Industries, Transportation services, non energy uses). Demands are exogenously specified only for the Reference scenario, and have each a user-defined own price elasticity. Therefore, each demand will vary endogenously in alternate scenarios in response to varying energy prices. The model thus computes a partial equilibrium on world-wide energy and emissions markets that maximizes total surplus. The engine used for the computation is Convex Optimization via a commercial Linear Programming optimizer. The management of the large TIAM database is made possible by the VEDA custom designed interface, which also permits the user to exploit the model results.

We now give some additional details on each TIAM incarnation separately.

2.3 ETSAP-TIAM Model

Table 3 shows some additional details on the ETSAP-TIAM reference scenario assumptions, and some database particularities. More detail on the PLANETS Reference case assumptions are described in Deliverable D6 *Report on Baseline Scenarios*.

Input	**Source**	**Remarks on if and how the translation was made**
GDP	PLANETS guidelines for global GDP, plus GEMINI-E3 model for regional breakdown	TIAM is driven by demands for energy services. The latter are obtained via a set of socio economic drivers (GDP, POP, Households, sectoral outputs etc.) which are obtained via a

		reference run of the GEMINI-E3 model. These drivers are then used to compute the demands via a set of elasticities.
Population	PLANETS guidelines plus UN projections for regional breakdown	
Energy prices (oil, gas, and optionally coal)	Endogenous prices for oil, gas, coal and all other energy forms	Because prices are endogenous in TIAM, the prices do not exactly follow the guidelines.
Overall discount rate	5%	There are also sector specific hurdle rates, used to calculate each technology's annualized cost of production.
Policy assumptions		
Subsidies and taxes	None	
Coal	Upper limits on coal in each region, in Reference scenario only. Used to reflect local policies regarding local pollution.	
Nuclear	Capacity limits in each region, derived from the literature	
Renewable electricity	Annual Potentials in each region, derived from published sources	
Sulphur policies	Indirectly represented via upper bounds on coal use	
Climate policies	None in Reference case	
Efficiency standards for cars	CAFE standards for internal engine vehicles. Car vintages include progressive efficiency improvements until 2050.	
Other	Biomass potentials derived from existing studies	

Table 3. ETSAP-TIAM reference case assumptions

Emissions and Mitigation options in ETSAP-TIAM

The emissions of CO_2, CH_4, and N_2O from all sources are explicitly modeled. Land CO_2 emissions are calibrated exogenously from Prinn et al (2008) and have no mitigation options. CH_4 and N_2O emissions have mitigation options modeled according the EPA MAC study (ref). Some CH_4 and N_2O sources in agriculture have no abatement options (e.g. N_2O emissions from fertilizers, CH_4 from cattle raising and from rice paddies). Long lived GHG's that are not modeled are fully accounted for by adding an exogenous radiative forcing term to the forcing obtained from the three modeled gases.

One important CO_2 mitigation option consists in the capture and storage (CCS) of CO_2 from large plants. In ETSAP-TIAM, that option is available for the following technologies:

- Coal, gas, or biomass fired power plants
- Hydrogen production from coal or gas
- Synthetic diesel and other fuels from coal
- Alcohol production from fossil fuels

The CCS from biomass fired power plants is a particularly powerful option as it amounts to negative emissions. It plays a significant role in the policy scenarios, in spite of relatively low steam performance and smaller scale than coal fired plants.

2.4 TIAMEC

The current version of TIAMEC is a slightly altered version of the original TIAM [1 – 2][2]. The technology database of the original TIAM model is extensive, covering the full range of the energy chain from resource extraction to the final end-use consumption. The exogenously defined demands for energy services are modeled with price elasticities, so that they react to price changes. Figure 1 shows a simplified sketch of the modeled reference energy system.

[2] As it existed in March 2008, when the model was acquired.

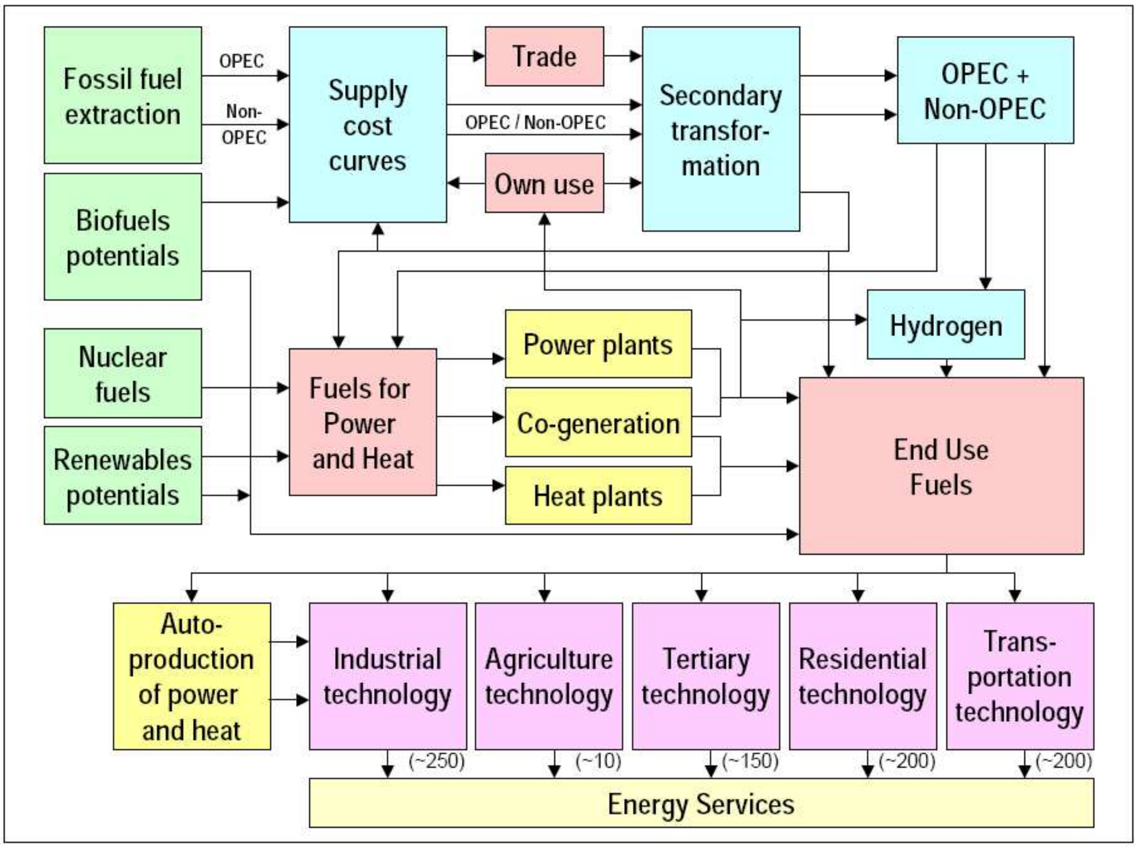

Figure 1. Structure of the reference energy system of TIAMEC [3].

Key assumptions for climate, emissions and mitigation

In addition to the energy flows and conversion stages shown in figure 1, environmental variables, such as emissions related to the energy processes are fully represented. In order to provide complete emission inputs for climate calculations, most of the greenhouse gas emissions originating outside the energy sector are included within the modeled system.

TIAMEC includes all the sources for the main greenhouse gases, CO_2, CH_4 and N_2O, within the modeled framework. Non-energy related emissions for these gases are included as exogenously given emission paths (based on assumptions concerning the related drivers of such emissions) and mitigation technologies are available for some of these non-energy emissions; for example for N_2O emissions from nitric and adipic acid production, CH_4 emissions from landfills and manure. For some, however, only exogenous emission paths are given and no mitigation technologies are included. For example, CO_2 emissions from land use change[3], CH_4 emissions from enteric fermentation, rice production and wastewater as well as N_2O emissions from agriculture are assumed to remain approximately at the current levels throughout the modeled time horizon. While many integrated assessment models rely on emissions for their climate proxy, TIAMEC also has the option of using a climate module [4] to directly constrain climate related indicators (e.g. radiative forcing or temperature change). Other emissions, affecting the climate, but not directly included in the model, can be included to the climate module as an exogenous forcing component. For the runs done here, we have excluded the impact of aerosols and assume that the rest of the emissions of the rest of the non-modeled gases reduce linearly from the values of today and reach the forcing of 0.1 W/m^2 by 2100.

For the energy sector, a large number of mitigation options are available. The main clusters of options are 1) the reduction of carbon intensity of the fuels used (e.g. switch from coal to gas or from fossils to renewables or nuclear), 2) reductions in the use of energy (use of more efficient technologies on the supply side, demand reductions in the end-use of energy) and 3) add-on emission reduction options (carbon capture and storage (CCS), CH_4 reduction in oil, gas and coal production).

The first two clusters of mitigation options in the energy sector emerge mainly from the detailed description of the energy system; as emissions constraints are implemented, the energy sources with low carbon content become more competitive, as do the technologies that require less fuel inputs to provide the same energy service (and produce therefore less emissions). Emissions constraint will also increase the price of energy services provided, therefore leading to a lowered demand (modeled using demand elasticities).

Assumptions concerning the respective potentials of carbon free/low carbon fuels as well as the range of efficiency improvements available limit the use of these options. Furthermore, as mitigation options they are also limited by their baseline use; if a carbon free fuel is assumed to have large potential, but this potential is almost completely used already in the baseline, its potential as a mitigation option is low. Our current assumptions concerning nuclear fall somewhat in this category, as there is little potential for additional nuclear production beyond the baseline.

[3] Accordingly, we do not currently include the increase of natural carbon sinks as a mitigation option.

CCS is available in the power sector as well as for hydrogen production. A large number of storage options are also available. There are a number of combinations of power plants and capture technologies available for coal and gas. However, we currently do not have CCS available with biofuel production.

In order to be consistent with the agreed baseline assumptions, the growth rates for population and GDP were altered and new energy demands were drawn based on the new assumptions. Some further assumptions had to be made concerning, for example, the regional distribution of the changes as well as on the altered number of households.

Resource extraction and use is endogenously described in TIAMEC, and therefore an iterative process was adopted to approximate the oil prices: 1) an additional variable cost was given to upstream technologies that provide crude oil for refineries, trade and other purposes 2) the model was run and 3) the shadow price of crude oil available for trading was compared against what was required by the agreed reference scenario definition, 100 USD_{2005})/barrel, and the three steps were repeated, if necessary. In of the reference scenario, gas and coal costs were also increased in order to be coherent with oil price.

2.5 GEMINI-E3 Model

In the PLANETS project the fifth version of the GEMINI-E3 model is used. Compared to the fourth version, several improvements were made:

- A new classification is adopted allowing one to describe more regions and more goods;
- The reference year of the model is updated. The model is now calibrated on the year 2001 instead of 1997 and the database is completely rebuilt;
- The electricity sector has been enhanced to handle nuclear and renewable power plants explicitly and the carbon capture and storage (CCS) technology.
- A new GEMINI-E3 web interface is available to explore the assessment of World climate policies.

The current version of GEMINI-E3 describes 28 countries/regions instead of 21 in the previous version, and 18 sectors/goods instead of 14. This new classification is given in table 4. The nomenclature that has been chosen allows to individualize the main economic countries/regions and GHG emitters. Concerning sectors and goods as it was done in all economic models applied to energy and climate change policies, we distinguish 5 energy goods and sectors (Coal, Crude Oil, Natural Gas, Refined Petroleum Product and Electricity). We try to describe the main energy intensive sectors (Mineral Products, Chemical Products, Metal Products, Paper Products) and we isolate three sectors concerning transport activities (Sea Transport, Air Transport and Other Transport). The 6 remaining sectors and goods are Forestry, Agriculture, Consuming Goods, Equipment Goods, Services and Dwelling.

We use an aggregated version of GEMINI-E3 describing 13 regions/countries: E.U., Otehr Europe, USA, Japan, Canada-Australia-New-Zealand, FSU, India, China, Rest of Asia, Brazil, Rest of Latin America, Middle East, Africa.

The full sector and region list, the population and GDP assumptions are given in tables 4, 5, an 6 respectively.

Countries / Regions		***Sectors***
Annex B		***Energy***
Germany	DEU	01 Coal
France	FRA	02 Crude Oil
United Kingdom	GBR	03 Natural Gas
Italy	ITA	04 Refined Petroleum
Spain	ESP	05 Electricity
Netherlands	NLD	*Non-Energy*
Belgium	BEL	06 Agriculture
Poland	POL	07 Forestry
Rest of EU-25	OEU	08 Mineral Products
Switzerland	CHE	09 Chemical Rubber Plastic
Other European Countries	XEU	10 Metal and metal products
United States of America	USA	11 Paper Products Publishing
Canada	CAN	12 Transport n.e.c.
Australia and New Zealand	AUZ	13 Sea Transport
Japan	JAP	14 Air Transport
Russia	RUS	15 Consuming goods
Rest of Former Soviet Union	XSU	16 Equipment goods
Non-Annex B		17 Services
China	CHI	18 Dwellings
Brazil	BRA	
India	IND	*Household Sector*
Mexico	MEX	
Venezuela	VEN	*Primary Factors*
Rest of Latin America	LAT	Labor
Turkey	TUR	Capital

Rest of Asia	ASI	Energy
Middle East	MID	Fixed factor (sector 01-03)
Tunisia	TUN	Other inputs
Rest of Africa	AFR	

Table 4. Geographic and sector disaggregation in GEMINI-E3

The population development is assumed to be constant in all scenarios, based on UN World Population Prospects: The 2006 Revision and World Urbanization Prospects: The 2005 Revision.

	2000	2010	2020	2030	2040	2050
FRA	59187	62507	64825	66605	67819	68270
EUR	392028	403200	405653	403371	397457	389134
XEU	70502	69270	68027	66120	63547	60568
USA	284857	314692	342547	366187	385868	402415
JAP	127034	127758	124489	118252	110651	102511
CAZ	53682	59399	64622	69287	72936	76004
FSU	267718	262700	257782	249733	240542	229795
BRA	174161	198982	219992	236480	247814	254085
IND	1046235	1220182	1379198	1505748	1596719	1658270
CHI	1269962	1351512	1421260	1458421	1448355	1408846
MID	241783	289574	340447	385411	424477	456028
ASI	967128	1120054	1268150	1397421	1500133	1572282
LAT	348887	394715	439570	476361	501856	515144
AFR	820959	1032013	1270528	1518310	1765372	1997935
World	6124123	6906558	7667090	8317707	8823546	9191287

Table 5: Population Development in GEMINI-E3

	2010-2020	2020-2030	2030-2040	2040-2050
EUR+FRA	2.0%	1.8%	1.4%	1.4%
XEU	2.9%	2.2%	2.0%	1.9%
USA	2.6%	2.2%	2.3%	2.4%
JAP	1.8%	1.2%	1.2%	1.1%
CAZ	2.2%	1.5%	1.5%	1.4%
FSU	3.9%	2.7%	2.0%	1.9%
IND	6.9%	5.7%	4.2%	4.1%
CHI	6.7%	4.8%	2.7%	2.6%
ASI	4.9%	3.3%	2.4%	2.3%
BRA	3.5%	2.7%	2.6%	2.5%
LAT	3.7%	2.7%	2.2%	2.1%
MID	4.5%	3.3%	2.0%	1.9%
AFR	4.4%	3.5%	3.4%	3.3%
World	3.2%	2.6%	2.2%	2.2%

Table 6: GDP Growth Rates in GEMINI-E3

GHG Emissions

GEMINI-E3 describes CO_2 emissions coming from fossil fuel combustion and takes also into account non CO_2 greenhouses gases. For non CO_2 greenhouse gases data on emissions and abatement costs come from the U.S. Environmental Protection Agency [5]. We take into account all the direct GHGs covered by the United Nations Framework Convention on Climate Change: Methane, nitrous oxide, and the high global warming potential (GWP) gases. Emissions of non carbon greenhouse emissions are converted to a CO_2-equivalent basis using the 100-year GWPs defined by the Intergovernmental Panel on Climate Change [6]. Table 7 provides details on GEMINI-E3 emissions.

Methane (CH_4)	Nitrous Oxide (N_2O)	Fluorinated Gas
Biomass Combustion	Biomass Combustion	HFC and PFC Emissions from ODS Substitutes - Aerosols (Non-MDI)
Coal Mining Activities	Stationary and Mobile Combustion	HFC and PFC Emissions from ODS Substitutes - Fire Extinguishing
Oil Sector	Agricultural Soils	HFC and PFC Emissions from ODS Substitutes - Foams
Natural Gas Sector	Manure Management	HFC and PFC Emissions from ODS Substitutes - Solvents
Stationary and Mobile Combustion	Other Agricultural Sources	HFC and PFC Emissions from ODS Substitutes - Aerosols (MDI)
Other Industrial Non-Agricultural Sources	Adipic Acid production	HFC and PFC Emissions from ODS Substitutes - Refrigeration/Air Conditioning
Enteric Fermentation	Nitric Acid production	HFC-23 Emissions from HCFC-22 Production
Manure Management	Other Industrial Non-Agricultural Sources	SF6 Emissions from Electric Power Systems
Rice Cultivation	Human Sewage	PFC Emissions from Primary Aluminum Production
Other Agricultural Sources	Other Non-Agricultural Sources (Waste and Other)	HFC, PFC, SF6 Emissions from Semiconductor Manufacturing
Wastewater		SF6 Emissions from Magnesium Manufacturing
Landfilling of Solid Waste		
Other Non-Agricultural Sources (Waste and Other)		

Table 7: Non CO_2 greenhouses gases

Technological description

As other Computable General Equilibrium models GEMINI-E3 does not take into account any technological information on energy uses. Energy consumption is describes through Nested CES functions, the elasticies of these CES functions determine the possibilities of substitution. These Nested CES functions are described in figure 1. When a carbon price is fixed, firms use more capital, materials and labor, and less energy, this substitution could be analysed as a development of non carbon energy but without describing explicitly these "new energies".

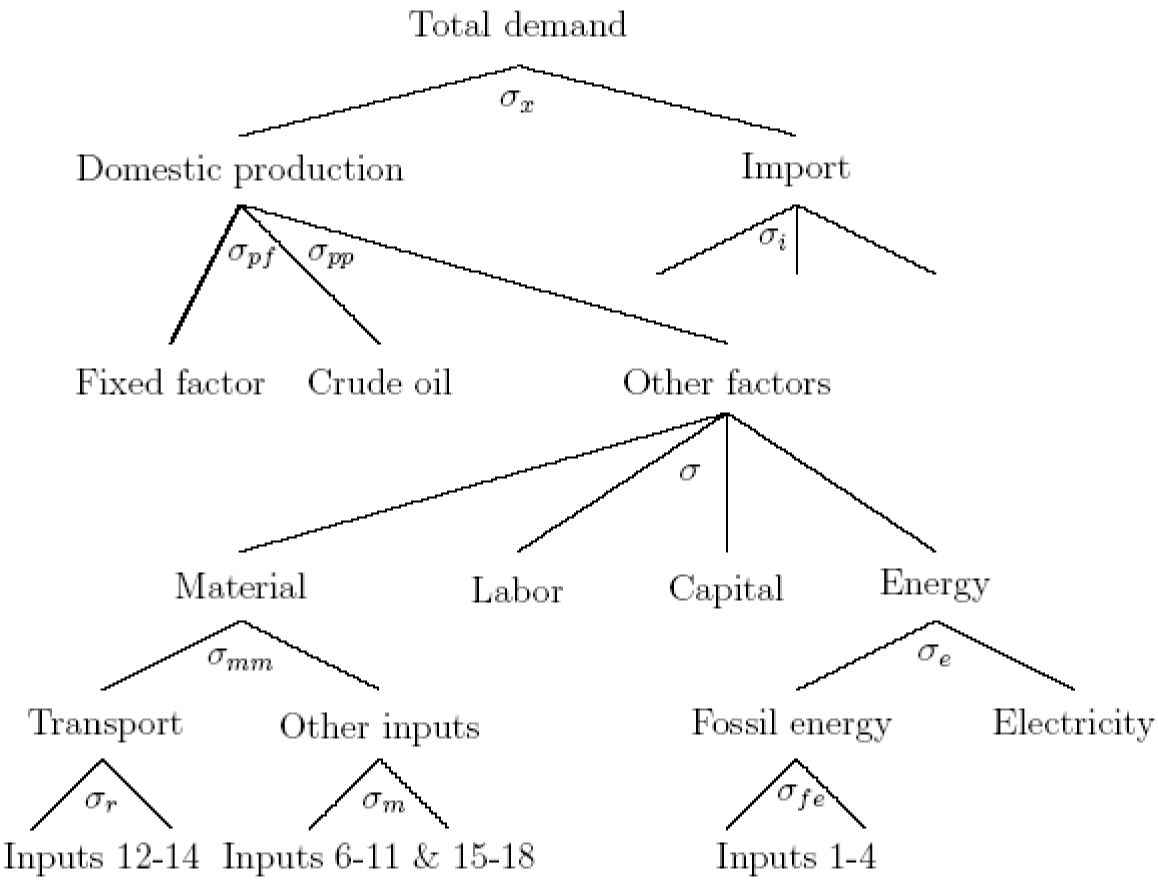

Figure 1. Structure of the Production in GEMINI-E3

Electricity generation

In the case of the electric sector, we try to represent better the technological choices. We enhance the representation of the electricity generation to model in particular especially the expansion of renewables and the Carbon Capture and Storage (CCS)

technology. The electricity production is now represented by a nested CES function that describes installed capacities in each type of power plants. Figure 2 gives this nesting structure. We distinguish the activity of generation to the other activities (i.e. transmission and distribution) that are supposed to be common to all types of electricity power plants. Theses two activities (transmission and distribution) are described at the top of the nesting structure. Generation activity is supposed done by two inputs: capital (representing power plants) and fuel. In some cases the fuel input is missing (e.g. for renewable). Note that we do not handle labor input for generation activity. We suppose that labor inputs are not too much different between power plants (nuclear, coal, etc) and we do not associate to each type of power plant a specific labor remuneration. Labor remuneration is globalized and described at the top of nesting structure.
We distinguish six types of power plants

- nuclear power plant;
- coal power plant;
- natural gas power plant;
- petroleum power plant;
- hydro power plant;
- other renewable power plant (mainly wind).

We assume that CO2 Capture and Storage (CCS) can only be used in the generation of electricity with coal. We do not take into account any CCS potential, there is no constraint on the use of CCS.

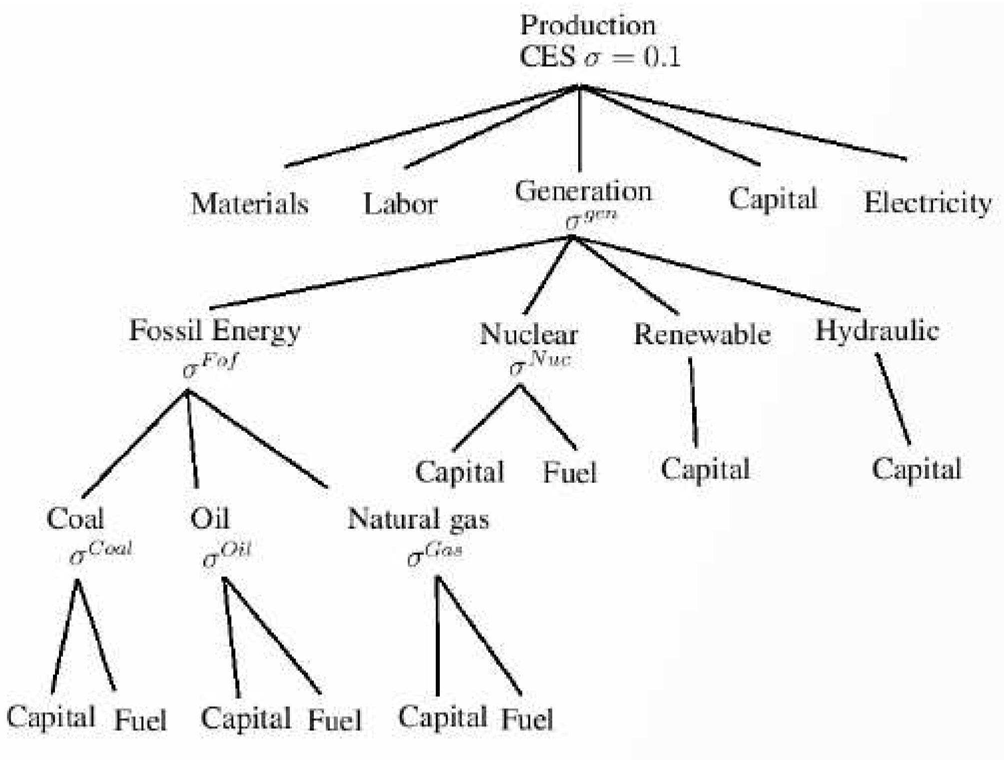

Figure 2. Nested structure of Electricity Production

CLIMATE Scenarios

In the First Best Scenarios (FB1 and FB2), the GHG emissions pathway is given by the TIAM model because GEMINI-E3 does not integrate a climate module. In all scenarios a Worldwide GHG tax is implemented, the revenue of the GHG tax is redistributed to households through a lump sum transfer. Tradeable permits are implemented only in the second best policy scenarios and the commitments are equal to those defined in the Planets guidelines.

2.6 TIMES PanEU Model (PEM)

The Pan European TIMES energy system model (in short TIMES PanEU, or PEM) is a model of 30 countries that contains all countries of EU-27 plus Switzerland, Norway, and Iceland. The model minimizes and objective function equal to the total discounted system cost over the time horizon from 2000 to 2050. A perfect competition among different technologies and paths of energy conversion is assumed in the model. The TIMES PanEU model covers at the country level, all sectors connected to energy supply and demand, for example the supply of resources, the public and industrial generation of electricity and heat, and the industry, commercial, households and transportation sectors. Both greenhouse gas emissions (CO_2, CH_4, N_2O) and also pollutant emissions (CO, NO_x, SO_2, NMVOC, PM_{10}, $PM_{2.5}$) are modelled in TIMES PanEU.

The generation of electricity and heat in electric power plants, combined heat and power (CHP) plants and heating plants is differentiated into public and industrial production. The model contains three different voltage levels of electricity (high, medium, and low voltages) and two independent heat grids (district heat and local heat).

In the transport sector the 4 areas road transport, rail traffic, navigation and aviation are separately described. Road traffic includes five demand categories for passenger transportation (car short distance, car long distance, bus, coach, motor bikes), and one for freight service (truck). Rail traffic includes the three categories: rail passenger transportation short and long distance, and rail freight transportation. The transport modes navigation and aviation are represented each by a non specified general process.

The residential sector contains eleven demand categories (space heating, air conditioning, hot water, cooking, lighting, refrigeration, washing machines, laundry dryer, dishwasher, other electrics, other energy use) of which the first three are specified according to building types (single family houses in urban and rural areas and multi-family houses each with stock and new buildings). The commercial sector is represented by a similar reference energy system (RES) and consists of nine demand categories (space heating, air conditioning, hot water, cooking, refrigeration, lighting, public street lighting, other electrics, other energy use). The first three of them are subdivided according to different building types (large/small).

The agriculture sector is described by a general process with a mix of several energy carriers as input and an aggregated demand of end use energy as output.

Industry is divided into energy intensive and non intensive branches. While the intensive ones are modelled via a process orientated approach, the other industries have a similar generic structure consisting of five energy services (process heat, steam, machine drive, electrochemical, others). The industrial sector is subdivided into several branches (for example iron and steel, cement, lime, etc.).

In the supply sector all primary energy resources (crude oil, natural gas, hard coal, lignite) are modelled by supply curves with several cost steps. Three categories can be differentiated: discovered reserves (or developed sources), growth of reserves (or secondary and tertiary extraction) and new discoveries. In addition, seven bio energy carriers are defined: mature forest, biogas, household waste, industrial waste, as well as sugary, starchy and lingo-cellulosic crops.

Due to its regional resolution TIMES PanEU allows a consideration of country specific features, for example different structures of the stock of power plants, different extension potentials for renewables as well as potentials for storing CO_2. An interregional electricity trade is implemented in the model, so that exports and imports of electricity according to the existing border capacities are endogenous to the model.

Input	**Source**	**Remarks on if and how the translation was made**
GDP	European Commission 2008	
Population	European Commission 2008	
Energy prices (oil and gas)	Agreed paths	coal = constant
Overall discount rate	4.5 %	
Policy assumptions		
Subsidies and taxes	Regional markups	
Coal		regional minimum quota for domestic coal production
Nuclear		Phase out in respective countries Commissioning of new plants in countries with existing capacity (except Poland – additional capacity investments possible)

Renewable electricity	European Commission 366-2004, ECN 2004	Minimum shares of renewable energy electricity production according national policies
Sulphur policies	none	
Climate policies	none	
Efficiency standards for cars	e.g. CONCAVE, TankToWheel-Report	Country specific efficiencies and improvements of new vehicles
Efficiency improvements industry	IEA: ETP 2008	Technology related efficiency improvements

Table 8. TIMES Pan EU reference case assumptions

2.7 The DEMETER Model

2.7.1 Model description

The DEMETER model is a global model describing the energy-economy-climate interaction. It is written in GAMS, as a set of equilibrium conditions solved using the CONOPT solver. For policy scenarios, the dynamic paths for policy variables are calculated that maximize aggregated and discounted welfare subject to instrument and climate change constraints.

The model distinguishes one representative consumer, three representative producers (also referred to as sectors), and a public agent that can set emission taxes to reduce carbon dioxide emissions. Figure 3 presents a schematic overview of the model flows. The time lag between investments and capital used as a production factor is represented through an “L” on top of the flow arrows.[4]

[4] The complete GAMS code is available through the internet, via the web-page of the first author: www.vu.nl/ivm/organisation/staff/reyer_gerlagh.html.

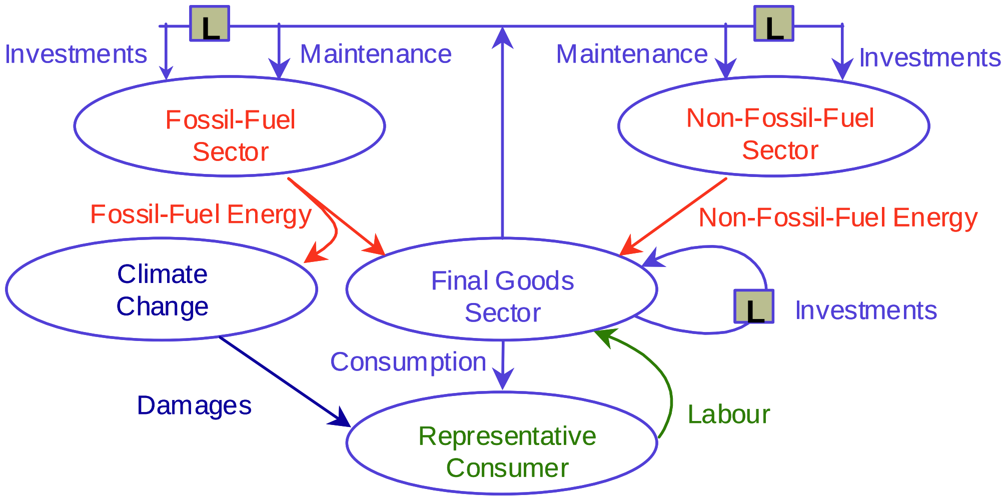

Figure 3. DEMETER schematic overview of flows

The final good is used for consumption, investments *I* in all three sectors and for operating and maintenance *M* (as usually distinguished in energy models) in both energy sectors. We also distinguish a separate carbon capture and storage (CCS) activity for which investments and maintenance are required.

To fully account for CCS leakage, the time horizon of the model has been extended substantially for this project. But, while CCS leakage in 3000 may matter for current decision making, investments in overall productivity in 3000 are beyond current interest. Therefore, we have extended the time range of the model to 1000 years, but split this period in three sub-periods. We have the full second-best equilibrium (as the previous DEMETER version) for the years 2010-2200. The next 100 years from 2200 to 2300, we assume constant productivity and calculate efficient investment levels omitting the first-order conditions that link carbon taxes to the use of fossil fuels, non-fossil fuels, energy savings, and CCS. We end the model horizon with only the climate module running for 2300-3000. Temperature changes in this period are linked to damages which are included in the welfare function.

We have decoupled the consumer's time preference from the social rate of time preference used for optimal climate policy calculations. That is, rather than assuming that capital markets reflect the social indifference for spreading consumption over time, we assume a constant savings rate of 25% that is beyond the reach of the central planner who maximizes aggregated welfare. We use a utilitarian framework with logarithmic utility and a 1%/yr pure rate of time preference for aggregation over time. The discount rate can be set at a prescribed value, and gross investments are then set to 25% of gross production, divided over different sectors to yield the same rate of return.

We have converted the welfare unit of measurement to euros at 2000 prices. Gross World Product in 1997 is 32 trillion €/yr; fossil fuel price in 1997 is 4.1 €/MJ (primary energy eq).

We have adjusted the forcing of a doubling CO2 concentration from 4.1 W/m2 to 3.7 W/m2, but we maintain the central assumption of 3K climate sensitivity. We use 4% of GDP as central estimate for climate change damages.

We have added an oil price shock ('peak oil') at the start of the simulation: 2010. Price of fossil fuels jumps at 2010 from 4.1 €/MJ to increase with 50%. The increase is in (marginal) production costs. (If increase is mark-up, then this acts as a fossil fuel tax, which implies that the carbon tax is only part of the implicit emission tax. This in turns means that CCS should receive full redemption of carbon tax.)

We have added Decreasing Returns to Scale for the non-fossil fuel sector, such that Marginal costs double when output increases from 0 to 320 TJ/yr (1997 overall energy demand). As a result, there are now two opposing forces: non-fossil fuel Learning by Doing versus the DRS. Marginal costs for non-fossil fuels decrease less compared to previous version.

We re-calibrated the population data to fit most recent UN data using logistic curve + constant. Population converges to a maximum of 10.25 billion people by 2100. We have added two-box CCS leakage model as described in a paper now published in Climatic Change. We have added hedging to the model.

2.7.2 Climate Module

The climate module is based on DICE99 (Nordhaus and Boyer 2000), and describe a multi-stratum system, including an atmosphere, an upper-ocean stratum, and a lower-ocean stratum. We recalibrated the DICE99 climate module parameters to fit our five-year periods, whereas DICE99 uses periods of 10 years,

$$ATM_{t+1} = (EnEm_t + \bar{\bar{E}}m_t + \delta_2^{CCS} S2_t^{ccs}) + TR_{atm}^{atm} ATM_t + TR_{ul}^{atm} UL_t \quad (1)$$

$$UL_{t+1} = TR_{atm}^{ul} ATM_t + TR_{ul}^{ul} UL_t + TR_{ll}^{ul} LL_t \ , \quad (2)$$

$$LL_{t+1} = TR_{ul}^{ll} UL_t + TR_{ll}^{ll} LL_t \ , \quad (3)$$

$$F_t = 4.1^2 \ln(ATM_t / ATM_0) + EXOFORC_t \ , \quad (4)$$

$$TEMP_{t+1} = TEMP_t + \delta^T (F_t / 4.1)(\bar{T} - TEMP_t) - TR_{TEMP}^{TLOW} (TEMP_t - TLOW_t) \ , \quad (5)$$

$$TLOW_{t+1} = TLOW_t + CA_{TLOW}^{TEMP} TR_{TEMP}^{TLOW} (TEMP_t - TLOW_t) \ , \quad (6)$$

where ATM_t is the atmospheric CO_2 content, UL_t is the CO_2 content of the upper ocean layer, LL_t is the CO_2 content of the lower ocean layer, F_t is the radiative forcing, $TEMP_t$ is the atmospheric temperature increase relative to pre-industrial, and $TLOW_t$ is the ocean temperature increase. The exogenous variables are $\bar{E}m_t$ for the exogenous path of non-energy related CO_2 emissions, and $EXOFORC_t$ is the forcing caused by non-CO_2 greenhouse gases. The parameters are TR_{atm}^{ul} = 0.2128 for the per-period CO_2 transport share from the atmosphere to the upper ocean layer; TR_{ul}^{atm}=0.1760 is the per-period CO_2 transport share from the upper layer to the atmosphere, TR_{ul}^{ll}=0.0625 is the per-period CO_2 transport share from the upper layer to the lower layer, TR_{ll}^{ul}=0.0023 is the per-period CO_2 transport share from the lower layer to the upper layer, TR_{atm}^{atm} =1–TR_{atm}^{ul} is the CO_2 share remaining in the atmosphere, TR_{ul}^{ul} =1–TR_{ul}^{atm}–TR_{ul}^{ll} is the CO_2 share remaining in the upper layer, and TR_{ll}^{ll} =1–TR_{ll}^{ul} is the CO_2 share remaining in the lower layer. Finally, δ^T=0.120 is the temperature adjustment rate due to the atmospheric warmth capacity, $\bar{T}$ is the long-term equilibrium temperature change associated with a doubling of atmospheric CO_2 concentrations, TR_{TEMP}^{TLOW}=0.051 is the relative heat transport from the atmosphere to the ocean, and CA_{TEMP}^{TLOW}=0.201 is the relative warmth capacity of the atmosphere relative to the ocean.

The exogenous forcing sums forcing from short-lived and long-lived gases. The short-lived related forcing increases from –0.81 W/m2 by 2010 to 0.59 W/m2 by 2100, and remains constant thereafter. Under BAU, the long-lived non-CO2 forcing increases from 1.113 W/m2 in 2010 to 1.330 W/m2 in 2145, and then slowly decrease again. Under the stabilization scenarios, the forcing increases from 1.057 in 2010 to 1.181 in 2130, and slowly decreases thereafter.

2.7.3 Various Assumptions

Input	**Source**	**Remarks on if and how the translation was made**
GDP	DICE	GWP is set at 25.1 trillion euro in 1995, and grows at 2% per year per capita. We have added scenarios where per capita GWP grows at 2%/yr up to 2025, at 1.5%/yr up to 2050, at 1%/yr up to 2075, and at 0.5%/yr thereafter.
Population	UN	Used sigmoid curve plus constant to fit 1950-2050, average error of 0.3%
Energy prices (oil and optionally coal)	Project data	Fossil fuel costs of 4.1 €2000/MJ. Increasing in 2010 with 87% or 175% in 100$/b and 150$/b scenario, resp. Non-fossil fuels 21 €/MJ, decreasing through LbD
Overall discount rate	Assumed fixed gross investment	From 5.5%/yr to 3.9%/yr as growth slows down.
Policy assumptions		
Subsidies and taxes		Mainly use of carbon taxes for policy scenarios
Coal		
Nuclear	Constant	Excluded from reported energy
Renewable electricity		Learning by doing, but also decreasing returns to scale
Sulphur policies		
Climate policies		
Efficiency standards for cars		
Other		

Table 9. Other DEMETER assumptions

In the comparison policy scenarios, we find the following DEMETER assumptions to be important:

- DEMETER assumes a maximum CCS efficiency of 95%, meaning that 5% of emissions related to fossil fuels cannot be abated. We consider this a rather optimistic assumption. Marginal costs of CCS are about linear in the share of fossil fuels to which CCS is applied, with a maximum of 100 euros/tonne of carbon. The energy penalty of 30% (energy content used for CCS) is added to that. There is no differentiation between coal, oil and gas. Furthermore, there is no biomass+CCS option, implying that there are no future ‘negative’ emissions possible to compensate for current emissions. This assumption implies that a future ceiling on concentrations translates in strict current emission ceilings.

- The renewables have substantially higher marginal costs when applied large-scale. Upscaling renewables so that they can support current energy supply is assumed to double the marginal costs. On the other hand, the model assumes learning by doing at 20% per doubling of capacity. We consider these assumptions on the optimistic side.

- Primary and final energy consumption and supply are all taken together, measured in primary energy equivalents. For renewables feeding into electricity, we use a conversion of 0.35 to calculate a fossil fuel equivalent primary energy level. Thus, final energy and electricity production are not explicit in DEMETER. Furthermore, energy prices are only calculated for an aggregate fossil fuel and an aggregate non-fossil fuel. For fossil fuels, we assume that oil prices determine about 75% of the overall price fluctuations, as gas prices are linked to oil prices.

- With a sustained oil price hike, emissions drop in the first decades, and pick up thereafter.

- DEMETER is sensitive to carbon taxes, and oil price changes, alike. With a high oil price, the need for climate change policy is much reduced.

- We carried out an extensive sensitivity which showed that the elasticity of substitution between fossil fuels and non-fossil fuels, and the learning rate for non-fossil fuels stood out as important parameters.

3. The common scenarios

3.1 Objectives

The choice of common policy scenarios was guided by several considerations:

- First, we want to explore what appears to be a central concern at the current stage of global climate negotiations, namely the articulation between short or medium term negotiated actions, and the long term attainment of certain climate objectives such as stabilization of key climate variables. More precisely, we want to test the extent to which *ad hoc* region-specific agreements on GHG emissions up to 2050 would be compatible with some target on a global climate variable such as radiative forcing, or concentration of greenhouse gases.

- Second, we want to be able to compare these *ad hoc* agreements with idealized benchmark (also called First Best) scenarios where the entire planet acts as soon as possible in a fully efficient manner to attain the long term climate objective.

- Third, we want to use alternative values for the climate target, in order to reflect the uncertainty that exists on what constitutes a “safe“ climate target.

- Fourth, we also want to assess whether the same targets could be achieved (and how, at what extra cost) when permit trading is somewhat restricted.

In addition to the policy scenarios, each modeler also ran a *reference scenario* used as a basis for comparing policy scenario results. The common assumptions used to define the reference scenario have been described in deliverable D6 issued in November 2008. We note here that although the main socioeconomic assumptions have been partially harmonized across the models, there of course remain considerable differences between the models, that contribute to making the scenario results different.

In the next subsection, we describe the ten policy scenarios that were chosen to fulfill the above criteria.

3.2 The ten policy scenarios

The ten scenarios are obtained by combining:

- 2 alternate climate targets with
- five different modes of achieving the targets.

3.2.1 The two climate targets

We chose to set *targets* on the total atmospheric radiative forcing resulting from Long Lived Greenhouse gases. The two targets are:

- Target 1: LLGHG radiative forcing not to exceed 3.2 Watts/m2 at any time during the 21st century. This roughly corresponds to 500ppm CO2eq.
- Target 2: LLGHG radiative forcing not to exceed 3.5 W/m2 at any time during the 21st century. This roughly corresponds to 530ppm CO2eq.

<u>Remark</u>: Target 1 has been relaxed somewhat for some scenarios, as discussed in subsection 3.2.3.

Note that GEMINI-E3 and PEM do not have a climate module. Therefore, they used as binding targets the respective emission trajectories obtained with the ETSAP-TIAM model for each scenario.

In order to appreciate the severity of the two targets, it is useful to indicate the resulting increases in mean global surface temperature resulting from each target. The temperature increase depends on several other parameters besides atmospheric LLGHG radiative forcing, such as: the assumed values of the extra forcing caused by non LLGHG's, and, most importantly, on the values of the climate sensitivity parameter (Cs) and of the Lag parameter. To take a typical example, the temperature increases obtained with the ETSAP-TIAM model and the two First Best scenarios are shown in Table 11 for Cs=3^{o}C and for Cs=4.5 ^{o}C. The definitions of the two scenarios are given in subsection 3.2.2.

	Cs=3°C		Cs=4.5°C	
	DeltaT(2100)	DeltaT(max)	DeltaT(2100)	DeltaT(max)
FB-3p2	2.06 °C	2.33 °C	2.75 °C	3.34 °C
FB-3p5	2.23 °C	2.52 °C	2.98 °C	3.61 °C

Table 11. Mean surface temperature increases achieved for the two First Best scenarios with the ETSAP-TIAM model.

The max temperature increase was calculated using the standard climate equations of TIAM and the assumption that after 2100, GHG emissions decrease linearly to zero over the next 200 years, reaching 0 emissions in 2300.
We now turn to the five alternate modes of attaining each target.

3.2.2 The First Best mode

Each target is applied along with the assumption that the entire planet acts as early as 2012 in a fully cooperative manner to achieve the climate target efficiently. Efficiency also implies that emission trading is allowed as early as 2012. This gives rise to the two alternative First Best scenarios named FB-3p2 and FB-3p5.

3.2.3 Two Second Best modes

Each Second Best scenario is obtained by combining each target with one set of *emission quotas (*also called *Specific Commitments,* denoted SC*)*. An emission quota for a given region of the world is defined as the cumulative amount of emissions that the region is entitled to, from some well defined starting date to 2050. In order to propose meaningful quotas, we divided the world into four sets of countries as follows:

- OECD countries (OECD)
- Energy Exporters (EEX): consisting of the Middle East and Russia (or some acceptable approximation of these regions, depending on model disaggregation)
- Developing Asia (DevAsia), i.e. Asia minus Middle East and minus Asian OECD countries
- Rest of the World (ROW).

The two sets of emissions quotas (commitments) are defined in table 12, by specifying two parameters:

- The starting date of the commitment (before that date, emissions are assumed to be those in the reference case)
- The percentage emission reduction in 2050 with respect to emissions in 2005.

For example, Table 12 tells us that for commitment SC1, OECD reductions in 2050 must reach 80% of 2005 emissions, and that these reductions start in 2015.

It is also assumed that the reductions occur *linearly* from start date to 2050, but in order to reflect the flexibility often mentioned in various recent pre-negotiation statements, we allow each group of countries to deviate from the annual quota, *provided the cumulative quota from start date to 2050 is respected* (hence, in the same example, OECD could delay or anticipate reductions defined by its quota, provided the cumulative quota is respected). *The net result of these assumptions is that quotas are in fact defined as cumulative amounts of emissions for each group of countries*.

Additional assumptions:

- Emission trading starts in 2020 for all countries (a single, gobal ETS system is then assumed);
- In addition, the E.U. region is assumed to pursue its objective of at least 20% emission reductions (relative to 1990) by 2020
- After 2050, all countries cooperate fully to attain the chosen target.

Important remark: Both sets of quotas have been chosen so as to be *globally* compatible with the 3.5 W/m2 target, which means that if the quotas are respected, it is also possible for the models to respect the 3.5 target at all times before or after 2050. However, such is not the case for the 3.2 target: the quotas are indeed too lax to allow the LLGHG forcing to stay below 3.2 w/m2 at all times. Therefore, for the two Second Best scenarios with 3.2 target, the 3.2 target is interpreted as *a 3.2 target in 2100 only* (i.e. overshooting the target is allowed).

Hence, the second best scenarios with the 3.2 target explore the feasibility of ‘catching up‘ after 2050, even though less-than-optimal emissions trajectories have been followed before that date. In order to simulate such a scenario, it is necessary to proceed in two phases: in the first phase lasting until 2050, the only constraint for each country group is that the group's cumulative emissions from start date to 2050 be equal to the set quota. In the second phase, the actions until 2050 are those found in Phase 1, and the new objective is that the world must collectively cooperate to reach a radiative forcing value of 3.2 W/m2 in 2100. All models that have foresight must indeed proceed in two phases in order to simulate the second best scenarios with the 3.2 target.

Table 12 also shows that in spite of being globally very similar, the two sets of quotas are regionally quite different. In comparison to SC1, SC2 is more severe for OECD and for Developing Asia, and less severe for Energy Exporters and for the rest of the world. These significant differences do not impact on global emissions or on climate, and they may not even have large differences in regional energy choices (because emission trading tends to induce the same regional reductions irrespective of emission quotas), but they are expected to have a serious impact on regional costs.

	STARTING DATE OF QUOTAS	**SC1** **QUOTAS in 2050 WRT 2005 (reduction in brackets)**	**SC2** **QUOTAS in 2050 WRT 2005 (reduction in brackets)**
OECD	2015	20% (reduction=80%)	10% (reduction=90%)
ENERGY EXPORTING -EEX	2025	50% (reduction=50%)	100% (reduction=0%)
DEVELOPING ASIA - DevASIA	2025	125% (increase of 25%)	100% (reduction=0%)
ROW	2025	155% (increase of 55%)	200% (increase of 100%)
WORLD		**72% (reduction of 28%)**	**73% (reduction of 27%)**

Table 12. The two sets of quotas used for the Second Best scenarios

In addition, each region may deviate from its annual quota provided the cumulative quota is respected.

3.2.4 The four Variant scenarios

These scenarios are identical to the four second best scenarios, with an additional limit on the purchasing of carbon permits between 2020 and 2050: during that period, at least 80% of emissions abatement (defined as BAU emissions minus the quota) has to be undertaken domestically by each region, and so at most 20% of the abatement can be done with international offsets in the form of permit purchases. The trade restriction is cancelled after 2050.

Final remarks:

- For DEMETER, only global commitments are meaningful. Therefore, only SC1-3p2 and SC1-3p5 were simulated. The other two second best scenarios as well as the four variants are identical to these two.

- For GEMINI-E3 and PanEU models, the horizon is limited to 2050, whereas it is extended to 2100 for WITCH and the two TIAM models. DEMETER's horizon extends to 2400.

4. Results: generaL comments

4.1 Presentation OF RESULTS

- Generally speaking, we show results from 2010 to 2050 only, with some exceptions when results beyond 2050 help stress a particular result (for example, costs).

- Similarly, results are first shown for the entire planet, and regional results are only shown when they help prove or disprove a particular argument.

- Even though the European Union is not a separate region in the definition of quotas, we show a few results for that region, first because the PEM model is a EU model, and second because of the particular interest of the FP7 program for the EU.

- Finally, results for some scenarios will not be shown or discussed because they are too similar to those obtained for other scenarios.

- Full results from all models are provided in the electronic appendix.

4.2 A brief summary of Relevant model characteristics

We restate here some important characteristics of the models, that will be key in explaining some of the differences in results. These characteristics are either intrinsic to each model, or linked to particular assumptions regarding the model's database.

ETSAP-TIAM is a detailed technology model with a rich set of technologies. In particular, there are many options for emission abatement, including CO_2 Capture and Storage (CCS) options in processes that produce electricity (from coal, oil, gas, and biomass), and those producing hydrogen or synthetic fuels (likewise from fossil fuels and biomass). In addition, there are fairly large potentials for Solar, Wind, and Biomass, and also for CO2 geological storage. These options are expected to provide a wide scope for GHG abatement, at relatively low cost.

TIAMEC and PEM are based on the same paradigm as ETSAP-TIAM, but they happen to have fewer abatement options. For instance, electric plants based on biomass fuel and equipped with CCS are absent from these two models, a major difference from ETSAP-TIAM. Another (small) difference is that TIAMEC is free to start implementing changes as early as 2006 whereas ETSAP-TIAM's solution is frozen up to 2011 to the values in the Reference scenario. This difference has usually very little impact in the long term.

GEMINI-E3, WITCH, and DEMETER are top-down CGE models. One characteristic of these models is that they do not explicitly describe the entire set of technologies that produce or consume energy. Rather, they represent sub-sectors of the economy via production functions that allow substitutions of energy types, and substitution of energy with capital and labor. The elasticities that define the ease of such substitutions are calibrated to replicate observations from the past. When facing new and drastic constraints on emissions, a CGE model will therefore usually be more conservative than a bottom-up model in effecting substitutions. Therefore, it is expected that CGE models will produce higher costs of abatement especially for more severe climate targets.[5] DEMETER departs somewhat from this general statement, one of the reasons for which is the high potential simulated for endogenous technological change (through *learning curves*). WITCH also has a mechanism by which a *breakthrough technology* will appear if sufficient R&D investments are decided by the model.

[5] This brief exposé by no means intends to criticize either type of model philosophy. It is simply intended to shed some light on the generic results obtained by each model type.

DEMETER accounts only for CO_2 emissions (but of course the forcing target has been adjusted accordingly).

Generally speaking, models that have many detailed technological options will respond to climate targets by making large technological substitutions in all sectors. Models that operate under the production function paradigm will tend to respond by substituting capital for energy, as well as some substitution among energy types, but less so than in technology models.

4.3 The set of completed runs

Table 13 summarizes the runs actually achieved by each model. Reasons for which some runs are missing are a) that particular scenario is *redundant* for the model, b) the model was unable to complete the run (usually because the run was *infeasible*), or c) the modeler decided to restrict the set of runs for practical or other reasons. These three categories of missing runs are indicated in Table 13.

	ETSAP-TIAM	WITCH	GEMINI-E3	DEMETER	TIAMEC	PEM
Reference	Y	Y	Y	Y	Y	Y
FB-3p2	Y	Y	Y**	Y	Y	Y
SC1-3p2	Y	Y	INFEASIBLE	INFEASIBLE	INFEASIBLE	Redundant
SC2-3p2	Y	Y	INFEASIBLE	INFEASIBLE/ Redundant	INFEASIBLE	Redundant
VAR1-3P2	Y	Y	INFEASIBLE	INFEASIBLE/ Redundant	INFEASIBLE	Redundant
VAR2-3P2	Y	Y	INFEASIBLE	INFEASIBLE/ Redundant	INFEASIBLE	Redundant
FB-3p5	Y	Y	Y	Y	Y	Y
SC1-3p5	Y	Y	Y	Y	Y	Y
SC2-3p5	Y	Y	Y	REDUNDANT	Y	Redundant
VAR1-3P5	Y	Y	Y	REDUNDANT	Y	Y
VAR2-3P5	Y	Y	Y	REDUNDANT	Y	Redundant

** In this run, GEMINI-E3 found the problem infeasible in year 2050 only

Table 13. The set of runs effected by each model

The cells shaded in yellow indicate the runs for which results are essential, whereas the unshaded ones indicate runs where results are similar to results for other runs. The latter will thus be discussed only if needed to clarify certain issues.

The results are presented in three separate subsections, dealing respectively with economic results, climate results, and energy results.

5. economic indicator: the costs of scenarios

5.1 Global cost

The *cost* that a model attaches to a scenario (along with the feasibility of a scenario via the model) is probably the most important result obtained from the model. It is a condensed indicator of the difficulty of realizing the scenario. It is not the absolute cost value that matters, but its relative value (relative to that of other scenarios, and to the overall size of an economy, which we measure via its GDP).

The cost of a scenario is diversely defined by each type of model. In ETSAP-TIAM, TIAMEC, and PEM, the cost is the loss of total surplus (suppliers surplus plus consumers surplus relative to the surplus of the Reference scenario. In WITCH, it is measured as a consumption loss (change in consumption levels relative to the Reference scenario. In GEMINI-E3 the cost is computed on the basis of the loss of total surplus divided by households consumption of the reference baseline. In DEMETER, costs are expressed in terms of GDP, i.e. in total production opportunities and the cost of a scenario as the loss of GDP relative to the reference (BAU) scenario. In spite of these differences, it is possible to draw several useful conclusions from these results.

A common feature to all models is that costs are gross of the benefits from climate change mitigation, which are not included. Therefore, our comparative study qualifies as a cost-effectiveness approach.

Figure 4 shows the global costs attached to each scenario, model, and region, expressed in absolute units (Million euros of 2005), and figure 5 shows the same costs expressed as percentages of GWP or GDP, in selected years. Examination of the two figures allows us to make the following observations and comments:

- Until 2050, the cost of FB-3p2 is much higher than those of other scenarios, reflecting the facts that a) the target is severe and requires early action, and b) that all SC and VAR scenarios have relatively easy quotas until 2050, and may thus delay their drastic reductions until later. The latter reductions, while costly, are discounted significantly as they occur later in time, so that they are less felt in the overall net present value of the cost.

- Among the most important results is that three out of five models (TIAMEC, DEMETER, GEMINI) could not solve for the 3p2 target with quotas. Only ETSAP-TIAM and WITCH found feasible strategies to satisfy these scenarios. This points out that the planet may already be unable to reach certain ambitious climate targets, unless drastically effective new technologies do penetrate early and massively in the global energy system.

- After 2050, ETSAP-TIAM and WITCH results show that the scenarios with the more severe 3.2 target are more costly than those with the 3.5 target, but also, and importantly, that the second best scenarios with severe target are much more costly than the first best scenario with same target, thus showing how costly it is to adopt relatively lax quotas until 2050, when a severe target is pursued. Of course, the other models reinforce this conclusion by finding the combination of quotas and severe target infeasible.

- TIAM costs are less differentiated than other model's, a result due to the already mentioned fact that TIAM has greater abatement "depth" and thus is not yet close to using all its abatement potential. It appears (and will be discussed further down) that the Storage options of ETSAP-TIAM are one main cause why the model finds reasonable costs for the most severe target. Of course, it still needs to be confirmed whether indeed the Storage options as currently foreseen by ETSAP-TIAM will materialize in the future.

- A comparison of the costs from TIAMEC and ETSAP-TIAM (two models with the same meaning for "cost") shows much larger costs for TIAMEC (and, even more drastically, infeasibility of the quota scenarios with the severe target). This is in line with the observations in section 4.1.2 on TIAMEC characteristics.

- Another view of costs as they relate to GWP, is provided in figure 5 for the four most relevant scenarios: FB-3p2, FB-3p5, SC1-3p2, SC2-3p5. The SC2 scenarios and the VAR1 and VAR2 scenarios have global costs very similar to those of the SC1 scenario with the same target. One sees from that figure that the models yield widely different costs for the 3p2 target, as already noted. For the 3p5 target, three models (ETSAP-TIAM, DEMETER, WITCH) have very similar cost trajectories, even though they use different cost concepts. This tends to show that the three models are able to solve for the 3p5 target relatively easily.

- The costs per GWP from the three aforementioned models stay below 2% of GWP for the 3p5 scenarios, but increase several fold for the 3p2 scenarios, exceeding 7% of GDP at some periods in the WITCH results.

- One final comment that will be useful for the rest of the report is that the two quota systems and the two variants *do not produce significantly different global results*.

- Extending the last remark, one can say, and this is borne by these and other results, that the SC1 and SC2 (and similarly VAR1 and VAR2) scenarios are only useful when one is interested in regional costs. In the sequel, we shall therefore increase clarity by showing global results only for a subset of scenarios, namely: REF, FB-3p2, FB-3p5, SC1-3p2, SC1-3p5. Other scenarios will be discussed only if and when they present results that are sufficiently different from these five.

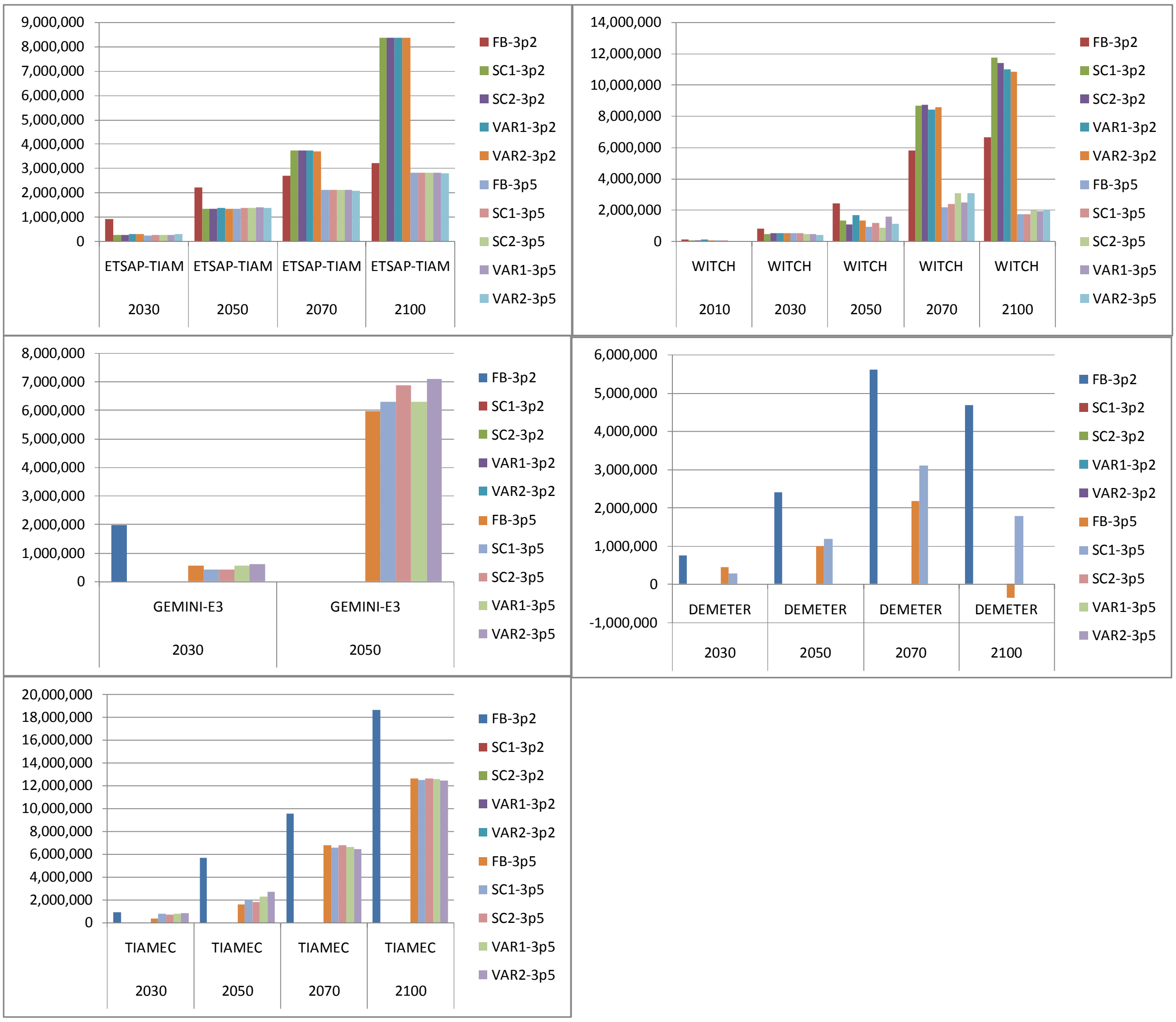

Figure 4. Global cost of the 10 scenarios (M€/year)

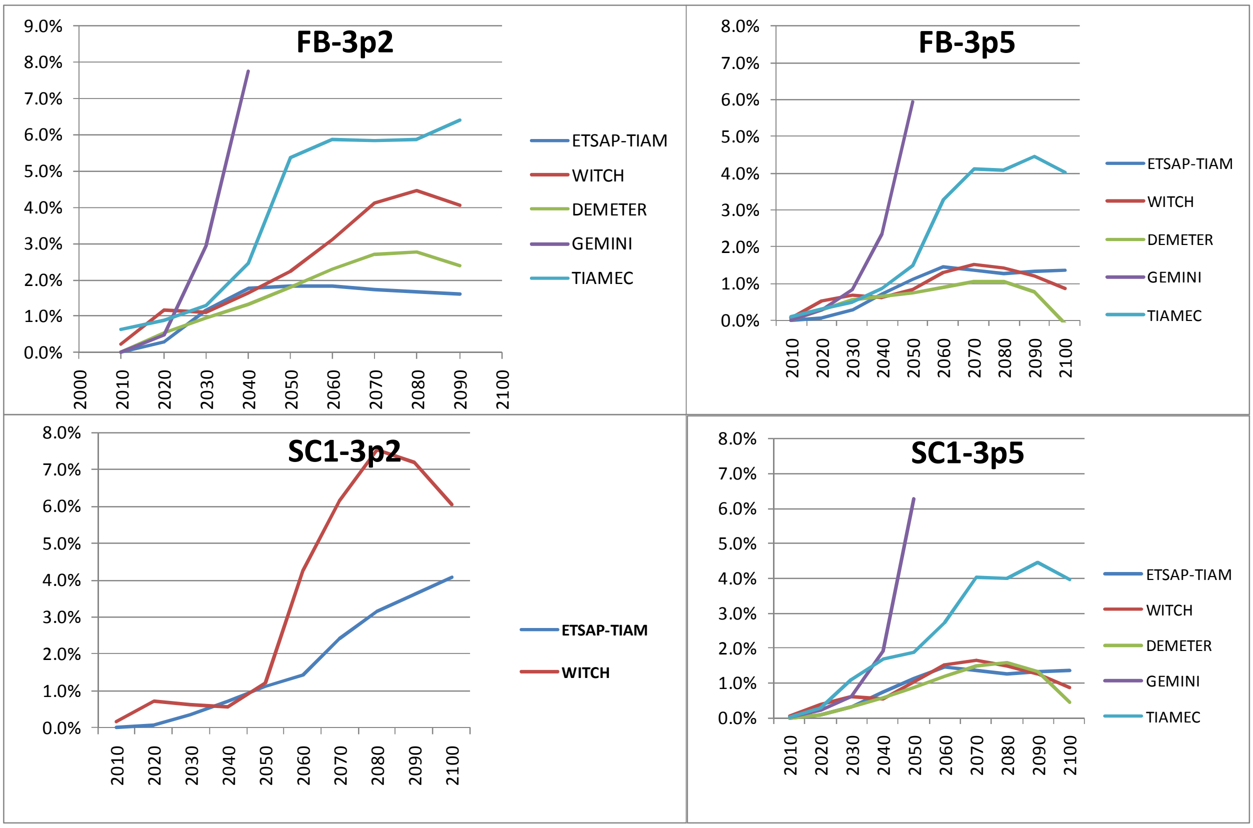

Figure 5. Global costs as percentages of GWP

5.2 *Regional Costs*

Recall that the two sets of quotas have been designed to describe two contrasted sets of commitments for the four groups of countries. Thus SC2 is more demanding than SC1 for OECD and for DevAsia, and less demanding than SC1 for EEX and ROW. It is expected that the policy costs incurred by each region will show significant differences. Figure 6 shows the costs up to 2050, in each of the four groups of countries, for the SC1-3p2 and SC2-3p2 scenarios (the results for SC1 and SC2 associated with the 3p5 target behave qualitatively similarly, although in a less contrasted manner). Note that only two models produced results for the two 3p2 scenarios.

Our first general comment is that costs remain below 1% of GDP in most regions until around 2040, and then grow substantially. One notable exception is EEX, whose costs are closer to 2% even before 2030-2040.

The tightening of the OECD quota in SC2 (from 80% to 90% reductions in 2050) about doubles that region's policy cost with ETSAP-TIAM, and even more so with WITCH, at almost all periods. This strongly indicates that the additional 10% reduction required by SC2 is very costly to achieve by OECD. Note also that OECD incurs generally larger costs than other regions (again except EEX) even when expressed as % of GDP, as one would expect from the very tight quotas (i.e. large reductions) in both SC1 and SC2. EU has slightly smaller costs per GDP that the entire OECD, showing once more that EU is better positioned to make large reductions than the faster growing other OECD countries.

For energy exporters (EEX), the situation is reversed, since SC2 represents a relaxation of that region's reduction commitment (going from 50% to 0% in 2050 wrt 2005). For SC1, EEX incurs the largest costs per GDP (by far) of all regions. reflecting the expectations of high emission growth in their baseline and the reduced revenues of the oil market. The costs in SC2 are much lower, and both models support this conclusion, but the spread of costs provided by WITCH is more dramatic than that from ETSAP-TIAM, showing very small cost for SC2 where ETSAP-TIAM costs remain substantial even in SC2. The change in the carbon trading position of EEX explains why the path of consumption losses in the two scenarios diverges. Energy exporting countries are net buyers in the SC1 scenario, but net sellers in the SC2 scenario. The different magnitude produced by the two models is due to higher carbon price in the WITCH model (see figure 9 in the next section).

For Developing Asia (DevAsia), just like for OECD, SC2 is a more demanding scenario than SC1. This is borne out by both models, but again with a more dramatic spread from WITCH. In fact, WITCH indicates large *negative* costs for that region, quite certainly due to largef revenues from selling emission permits at a higher CO2 price than ETSAP-TIAM. According to WITCH, in the SC1 scenario, DevAsia supplies more than 90% of the carbon market, leaving only a marginal role to ROW as a second supplier. In the SC2 scenario carbon market is dominated by three suppliers and therefore gains are redistributed between EEX, DevAsia and ROW.

ETSAP-TIAM also indicates sales of permits by DevAsia but in smaller amounts than WITCH, and at a lower CO2 price (see next section for carbon prices), again because in ETSAP-TIAM, all regions have larger reduction potentials, and thus are more "self-sufficient" in their abatement actions.

For ROW, SC2 is less demanding and both models show lower costs (even negative) for that scenario, again with WITCH exhibiting larger cost differentials than ETSAP-TIAM.

Final remark: it would be interesting to also look at costs after 2050, but the comparison between the model results is not very useful, since it appears that WITCH and ETSAP-TIAM have made somewhat different assumptions on the permit allocations beyond 2050. While permit allocations have no impact whatsoever on the abatement strategies or on global costs, they do have an impact on regional costs, since different allocations entail different amounts of permit trading and thus of revenues derived from them.

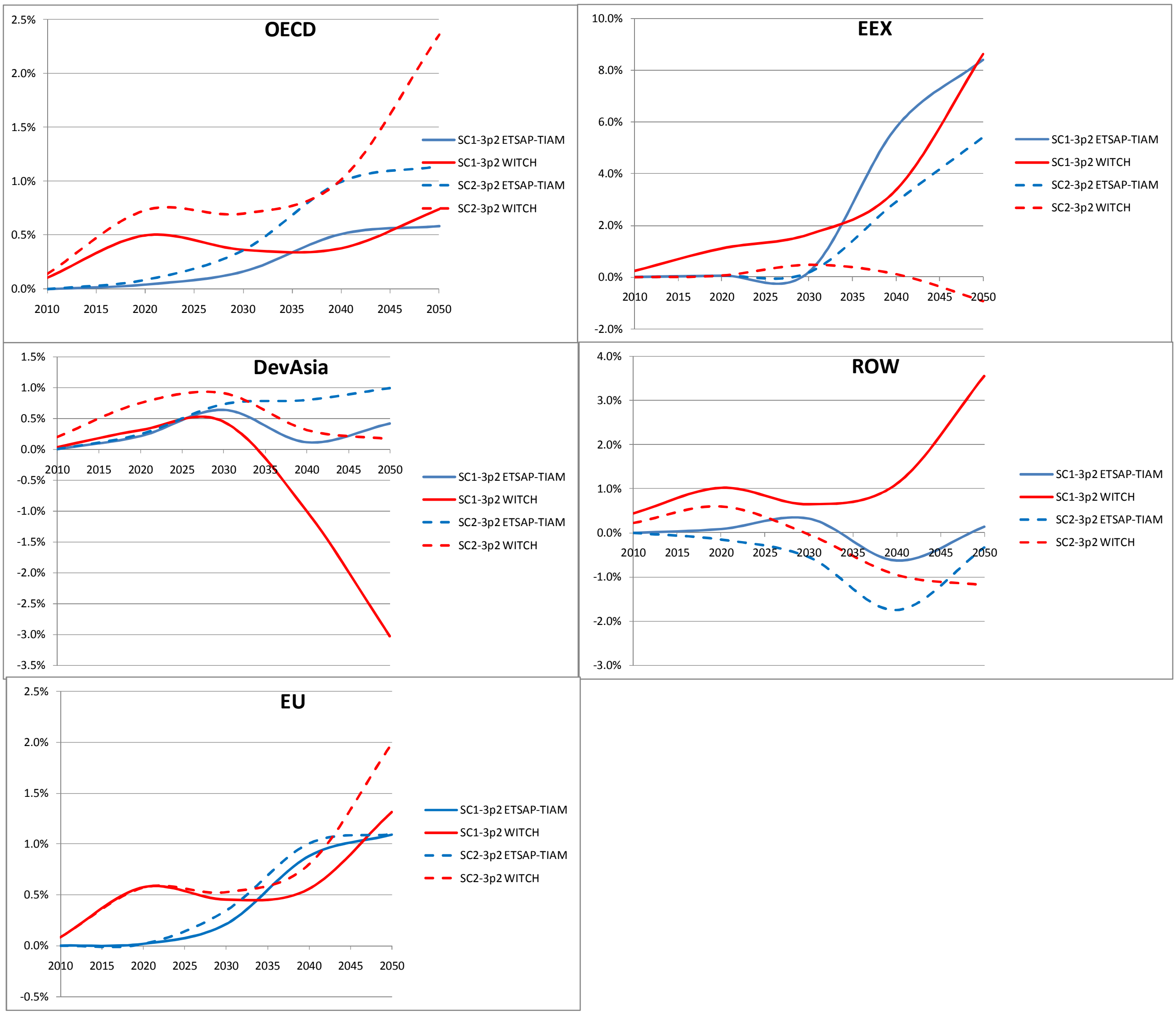

Figure 6. Regional policy costs as percent of GDP for two scenarios

5.3 Conclusion on costs

Policy cost is a convenient measure of the difficulty of satisfying a particular climate scenario. The results from the five models show that the 3p2 target is very significantly harder to achieve than the 3p5 target even with full and immediate cooperation. The cost results from two models (and the infeasibility of these scenarios with the other three), show that the difficulty is further enhanced in scenarios with quotas (which one of the two quota systems is used has little impact on global cost). For the two models that could solve the quota scenarios with the 3p2 target (WITCH and ETSAP-TIAM), global costs stay below 2% of GDP before 2050, but reach up to 5-7% at some later periods. ETSAP-TIAM shows smaller costs than WITCH, and this may be traced to the a larger set of abatement options, as will be discussed in subsequent sections. The two models thus can be seen as two different views of the energy system. The WITCH model is more conservative, especially regarding the decarbonization of the non-electric sector. The other three models show larger costs for the quota scenarios with 3p5 target, and cannot solve with the 3p2 target, due to a more conservative set of abatement potentials (DEMETER, GEMINI-E3, TIAMEC). These observations indicate that an extended set of abatement options seems essential to attain strict targets such as 3p2, when relatively lax quotas are used until 2050. In simpler words, if a laxer target (3p5) is initially pursued until 2050, it appears difficult to later steer the global economy toward a stricter target (3p2). In contrast, the First Best scenario cost shows that immediate and coordinated action by the entire planet does achieve the 3p2 target, and at a much lower cost.

As already mentioned, global cost is not much affected by which of the two quota systems is utilized, and neither is it by the 20% restriction on permit trading imposed in the variant scenarios. However, the two contrasted sets of quotas entail very different costs by each region. In the case of the stricter target, SC1 reduces OECD cost by about 50%, and reduces DevAsia cost even more, making it even negative at some periods. The reverse is true for the other two regions: EEX and ROW costs are greatly increased with SC1, and in some cases switch from negative to positive and large. Again here, WITCH costs show a much larger spread between the two quota systems than ETSAP-TIAM costs, for the same reason evoked earlier.

6. Carbon prices

All five models, being equilibrium models, provide shadow prices of CO2, which are the marginal costs of CO2 abatement. As was already found for total cost, and as is confirmed by the examination of CO2 prices, there are only four sets of CO2 prices that offer any significant differences, namely the two First Best scenarios, and the two second best scenarios with the two different targets (irrespective of what set of quotas is used, and irrespective of whether or not the constraint on trade is imposed). This is a finding that may be commented on via the following two observations from the results:

- First, the fact that GHG trading is allowed from 2020 on, means that there is a single CO2 price trajectory, irrespective of the chosen quota system, and that trajectory is more or less *dictated by the cumulative global quota* (which is the same for both SC1 and SC2). *This was not a priori obvious*, inasmuch as it might well have happened that given two different sets of cumulative quotas, the *timing* of global reductions could have been different. As it happens, this is not the case, indicating that the climate objective in effect supersedes other considerations.

- Second, it might also have happened that given the restriction on CO2 trade imposed in the variant scenarios, the CO2 prices –which are no longer global in the variant scenarios, could have significantly differed from those in the SC cases. For the variant scenarios, we have calculated an average GHG price by averaging the four regional prices. As it happens, the average GHG prices in the Variants differ only modestly from the global GHG prices in the SC scenarios. However, there are significant differences in regional prices prior to 2050. In addition, the restriction is temporary, and therefore perfect foresight models (WITCH, DEMETER, and the TIAM models) can anticipate that after 2050 trade will be unconstrained. Although in the short-term different carbon prices emerge, as soon as trade is opened, different prices converge to a path similar to the one observed with no restriction.

As a result of these two observations, it is again only necessary to examine the CO_2 prices in the four cases shown in figure 7.

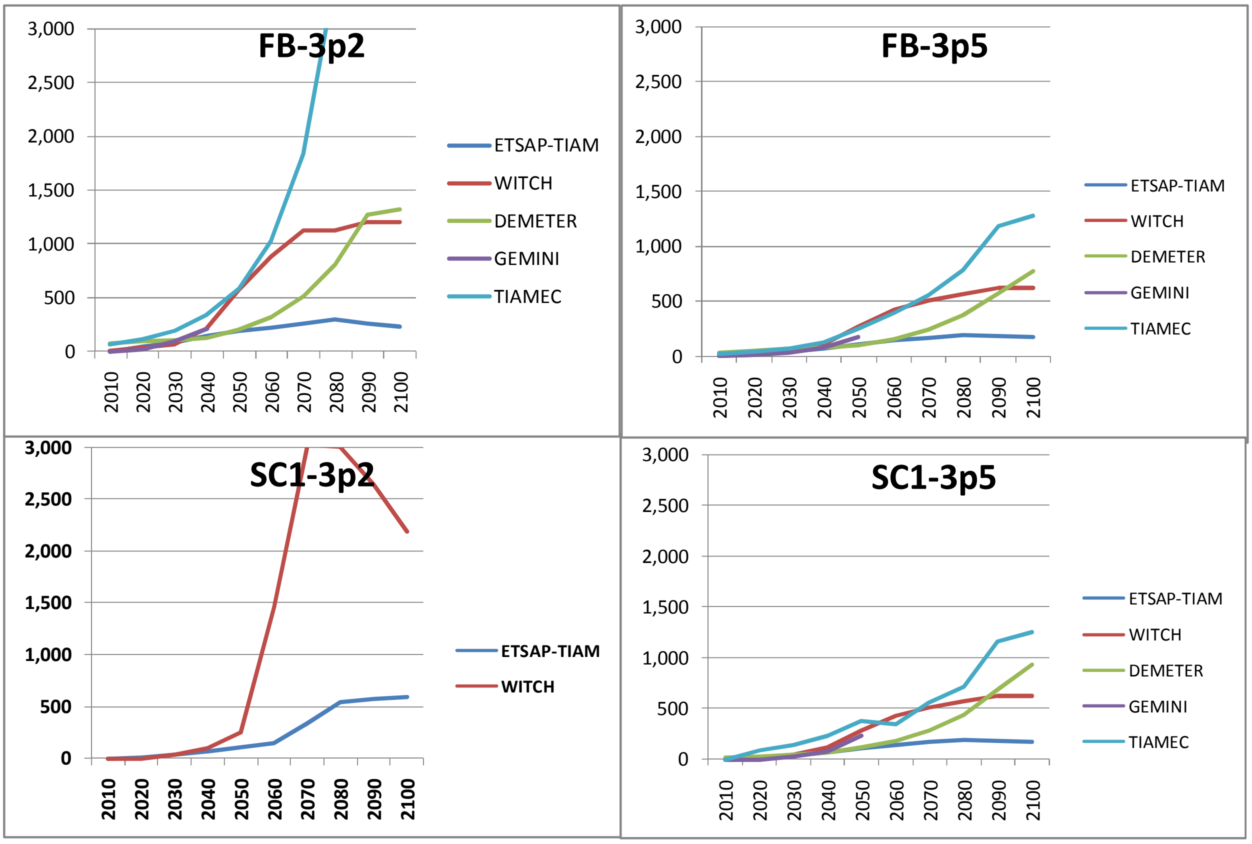

Figure 7. CO2 prices in four scenarios (€/tCO_2)

The following remarks may be made:

ETSAP-TIAM produces the lowest carbon prices, not exceeding 300€/t except in the SC-3p2 scenario, where it reaches 600€/tCO2-eq after 2060. The five models produce carbon prices that are similar initially, but grow quite differently after 2030, ranging from 100€/t to 220€/t in 2050 for the 3p5 target, but ranging from 250 to 500 in 2050 for the 3p2 target. After 2050, the range is even broader. As in the case of policy costs discussed in previous sections, the differences are due to model characteristics and assumptions on abatement potentials. The large carbon prices are due to the more restricted set of abatement options available. To this, one must add that the substitution elasticities in the three top-down models are usually calibrated to make large amounts of substitution more difficult to achieve than technology oriented models. As expected, the future price of carbon is heavily dependent on the availability of large potentials of abatement measures (this point is further explored in subsequent sections), on the rate of economic growth, and on the ability of the global economy to effect drastic changes in its technological portfolio in response to severe climate targets. Our results confirm these expectations, and quantify the range of carbon prices that may be expected. It appears that the 3p2 target would entail prohibitively large carbon prices in the second half of the century, unless abundant abatement options are available (and adopted), as illustrated by the ETSAP-TIAM results.

In the WITCH model, energy savings and breakthrough technologies (whose competitiveness depends on innovation), are important mitigation options. The price of carbon is the main stimulus to innovation and is therefore indicative of the effort required. This feature also explains why at the beginning the WITCH model has a higher carbon price, together with the TIAMEC model.

The comparison between left- and right-panels also suggests that departure from first best is much more costly if the long-term target is stringent. This is because in the second best scenario both *when* and *where* flexibilities are somewhat limited. Short-term emissions are constrained by the quotas, and therefore after 2050 emissions must decrease more in the stringent scenario (see also section 7.2). The *where* flexibility is reduced because of the 10-years delay in emission trading. These results suggest that the possibility of trading abatement over time and across regions is particularly valuable if long-term objectives are very ambitious.

7. Emissions and Storage

In the First Best scenarios, emissions are governed by the climate target that must be attained, but in the quota scenarios, emissions are initially governed by the quota system (until 2050) and only later by the target. Two questions arise:

- will the two quota systems induce different timings *of global emissions* from 2010 to 2050?, and,

- will the two quota systems induce different timings *of regional emissions* from 2010 to 2050?

As it turns out, the answer to these two question is no. This confirms again the observations made in the previous section on costs.

- Finally, it will be interesting to examine the general shape of the emission trajectories after 2050, when quotas are used and the stricter target is applied.

7.1 Emissions in the Reference case

We first present the Reference case emissions produced by the models (figure 8), and explain any differences in model results, thus providing a useful background for discussing model results for policy cases. ETSAP-TIAM, WITCH, and GEMINI-E3 have very similar emission trajectories. The DEMETER reference emissions start low because the model accounts for CO2 emissions only (it should however be strongly emphasized that the model includes a correction term in the forcing targets, that compensates for the missing emissions). After 2010, TIAMEC, ETSAP-TIAM, GEMINI, and WITCH have rather similar emission profiles, with however small differences due to different assumptions on regional economic growths (only the World GDP growth was calibrated for these four models). In contrast, and still after 2010, DEMETER emissions grow at a faster rate than all other models, by assumption. *This constitutes a genuine difference in the assumptions made by DEMETER and those in all other models.*

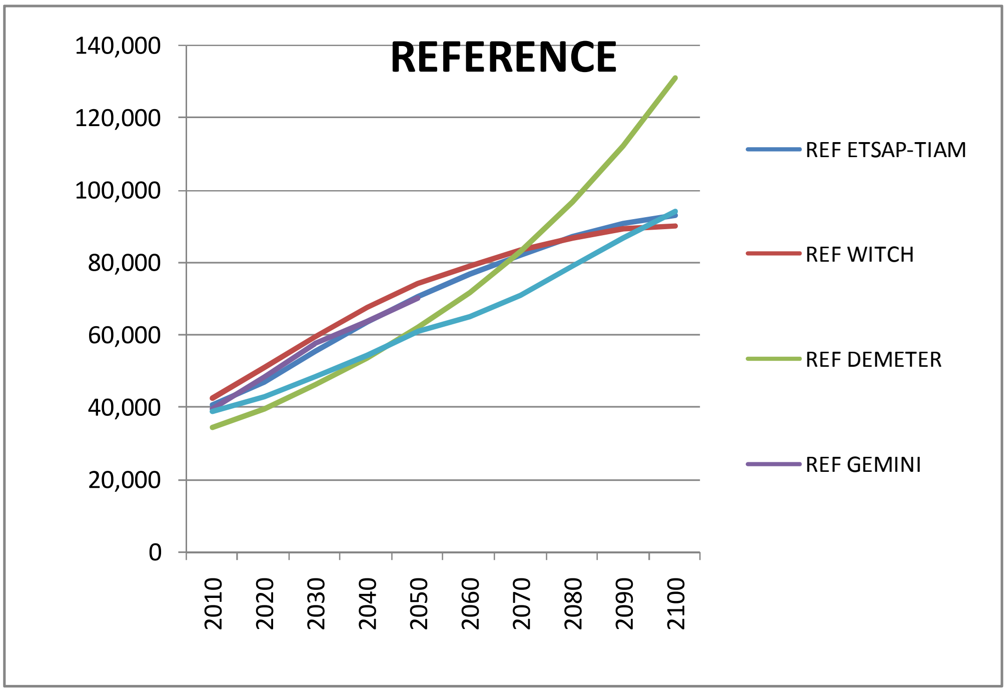

Figure 8. GHG emissions in the reference scenario (Mt of CO2-equivalent)

7.2 GLOBAL Emissions in policy cases

We now turn to emissions in the same four contrasted cases previously mentioned. As mentioned in the introduction to this section, the choice of quota system and the variant make little difference in the global emission trajectory.

Figure 9 confirms (after correction of each model's idiosyncrasies) that for the 3p5 target, the FB and SC scenarios have very similar emission trajectories, since the SC-3p5 scenarios have been devised to be compatible with a long term 3p5 target. For the stricter 3p2 target, the situation is different: until 2050, global emissions in SC-3p2 are dictated by the quotas and hence are close to those of the 3p5 scenarios. Later, the emissions *have to* be decreased more markedly to make up for the relatively large early emissions. Thus, in FB-3p2, global emissions in 2050 are about 23000 Gt CO2 (a 45% reduction wrt 2010), compared to more than 30000 in SC1-3p2 (a 25% reduction wrt 2010), for the two models that can solve these two cases.

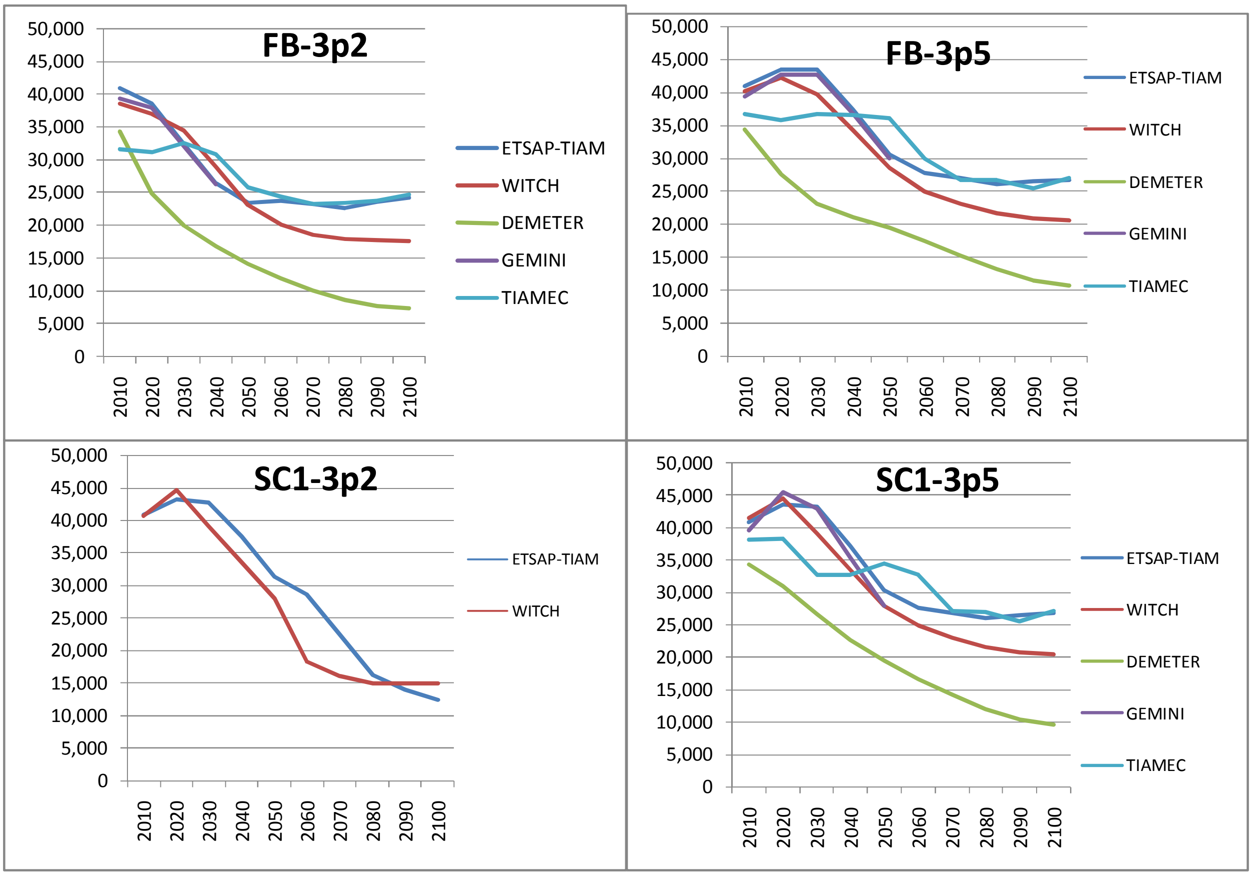

Figure 9. Global GHG emissions in four scenarios

In 2100, FB-3p2 requires emissions around 17000-24000 GtCO2 (i.e. 40% to 55% reductions wrt 2010), compared to less than 15000 GtCO2 in SC1-3p2 (i.e. 65% reduction wrt 2010). Note that the lower WITCH emissions are due essentially to a different accounting of land CO2 emissions than in TIAM. Another small difference occurs in 2010, when TIAMEC has lower emissions in the severe scenarios: as explained earlier, this model is left free to start implementing reductions earlier than the other models.

7.3 Regional emissions and trade

Before 2050, the regional emissions are not influenced by the target, since the latter is replaced by quotas. Regional emissions may then depend on which set of quotas is assumed, and also on the imposition of the 20% limit on permit trading. In this subsection, we examine the extent of these dependencies.

We first examine whether or not the choice of the quota system has an impact on regional emissions. Figure 10 shows that the answer is a clear no: the regional emissions for the five regions under SC1-3p5 and SC2-3p5 are remarkably close together, whether SC1 or SC2 is chosen (the curves for SC1 and SC2 are almost undistinguishable in the figures). This confirms the largely expected result that, under a trading system, each region continues to implement only the most efficient abatement actions, irrespective of the allocation of quotas. The different commitments are satisfied by simply varying the amounts of traded permits.

The next question therefore is: what impact does a trade restriction have on regional emissions? The expected direct consequence of the Variant is a decrease in permit trading, and figure 11 shows to what extent this is indeed true, using the SC1 quota system. All models show that when trade is restricted, the “buying” regions (OECD, EEX) do more reductions domestically (i.e. emit less), and as a consequence the “selling” regions (DevAsia, ROW, not shown) emit more (sell fewer permits). OECD emissions decrease by about 5-10% for most models with the exception of GEMINI which shows a 20% decrease in 2030-2050. EEX emissions decrease by about 10-15% in 2030 when the variant is assumed, and somewhat more in 2040-2050, GEMINI showing again the largest decrease in the latter years. One should also remember that the trade limit in GEMINI was relaxed to 30% (instead of 20%) in order to make the solution feasible.

Overall, one may conclude that the 20% restriction of trade has a significant effect on the emissions effected in each region. The impact of regional costs is even more significant, as was shown in a previous section.

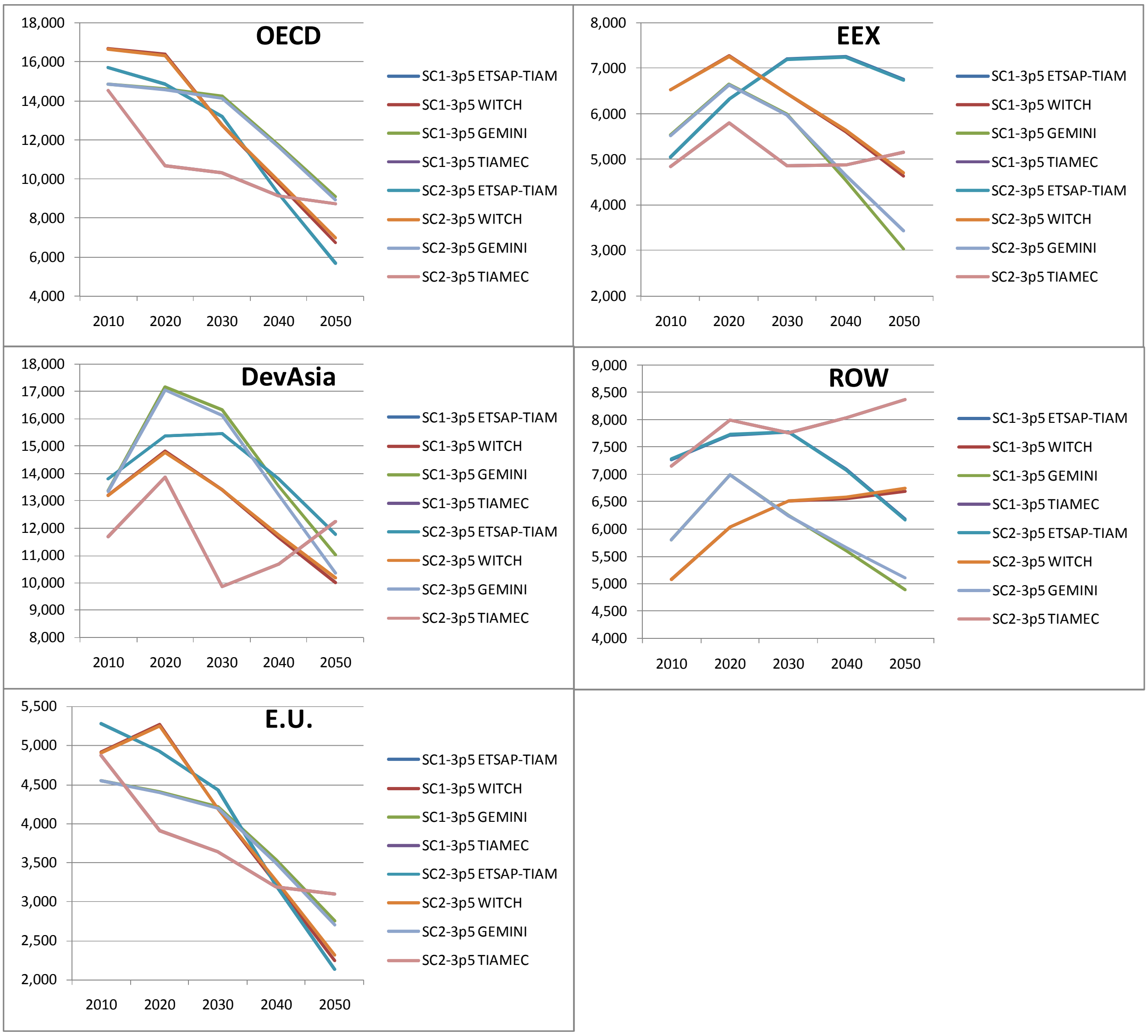

Figure 10. The lack of impact of the two quota systems on regional emissions – the 3p5 target (MtCO2eq)

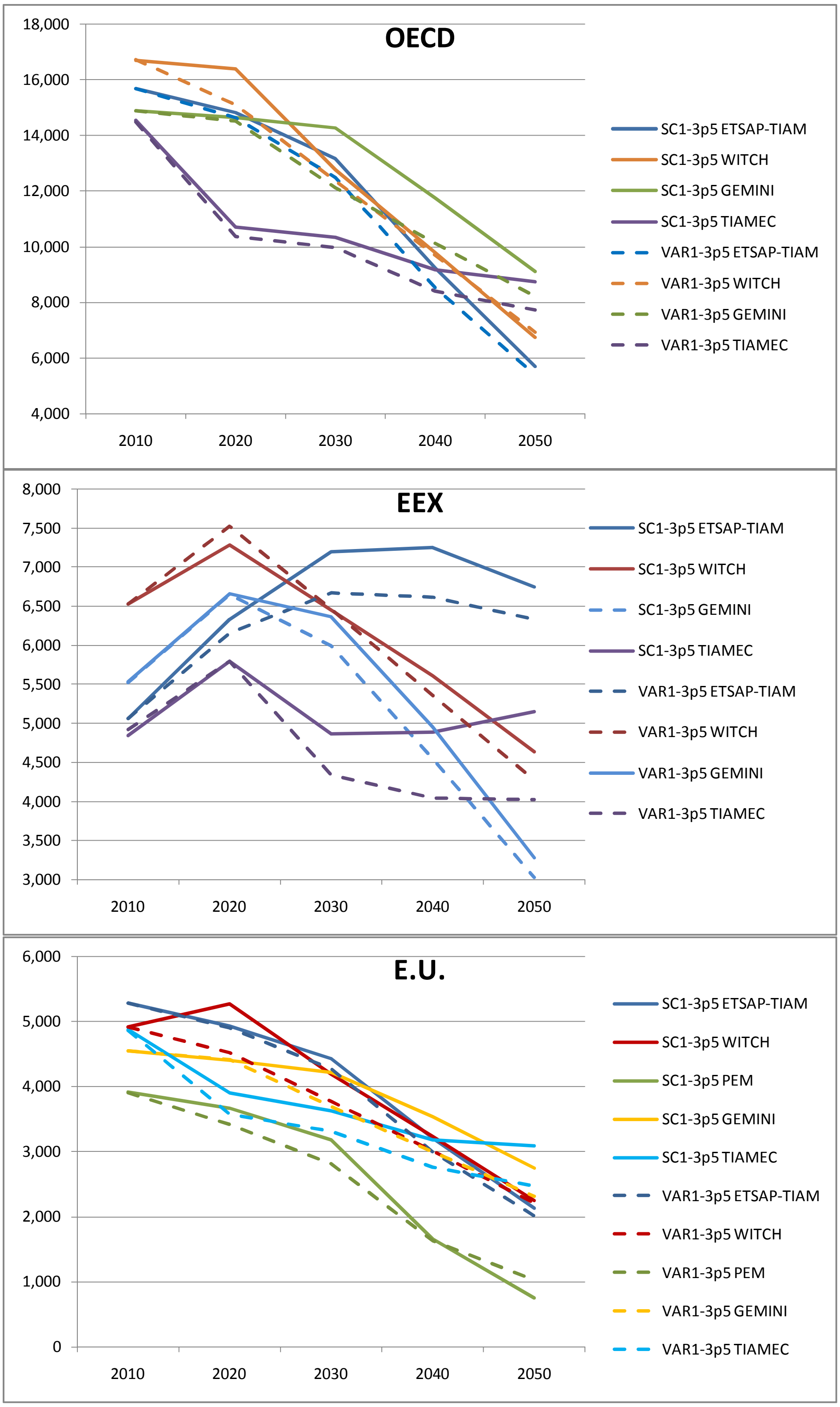

Figure 11. Impact of the trade restriction on regional emissions – the 3p5 target (MtCO2eq)

7.4 CO2 storage

Figure 12 reports global Storage in 2030 and 2050. The five models show very different amounts of CO2 capture and storage, ETSAP-TIAM having the largest amount, followed by DEMETER and TIAMEC, with GEMINI and WITCH last. Tables 14 and 15 indicate the percentages of CO2 emission reductions that are done via CCS in 2050 and in 2100 respectively. CCS appears to play a major role in the ETSAP-TIAM approach to CO2 abatement, an important role for DEMETER and TIAMEC, and a more modest role for WITCH and GEMINI. These wide differences come from widely different assumptions on the potential for storage allowed in each model, but also from the fact that ETSAP-TIAM is the only model having technological options for producing electricity, hydrogen and synthetic fuels from biomass with CCS, which result in *negative emissions of CO2*. Such technologies are powerful ones when strong reductions are needed, and they are heavily adopted by the ETSAP-TIAM model, even though the techno-economic characteristics of pure biomass fired plants (such as steam data and logistics constrained plant size and cost) compare unfavorably with Coal fired plants. The Biomass+CCS option goes a long way toward lowering the cost of abatement and thus the price of carbon, as we saw in previous sections. An interesting side observation is that the percentage reductions from CCS in 2100 are less than in 2050, especially for the most severe SC-3p2 scenarios. This is due to the fact that CCS is not a CO2 free technology (it captures only around 90% of CO2), and therefore, when the need for very strong reductions arises, the models switch to technologies that are 100% CO2 free, such as renewable.

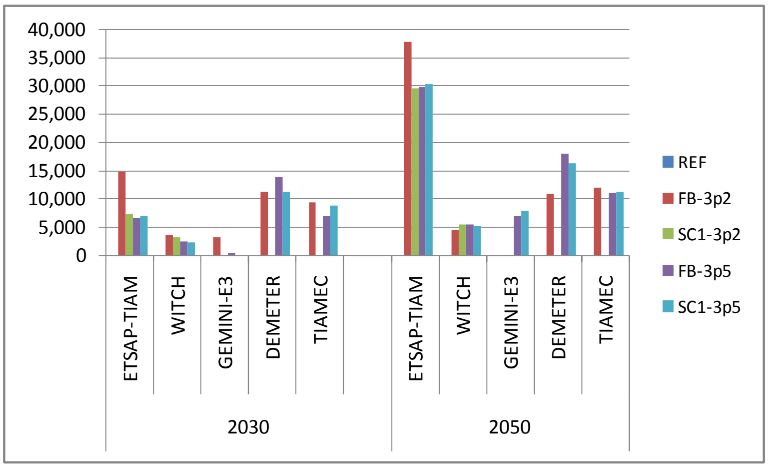

Figure 12. Global CO2 storage (Mt/year)

	ETSAP-TIAM	WITCH	GEMINI-E3	DEMETER	TIAMEC
FB-3p2	80%	9%	INFEASIBLE	23%	34%
other scenarios	75%	11%	19%	38%	43%

Table 14. % of emission reductions effected via CCS in 2050

	ETSAP-TIAM	WITCH
FB-3p2	77%	6%
other 3p2 scenarios	59%	4%
other 3p5 scenarios	76%	8%

Table 15. % of emission reductions effected via CCS in 2100

8. PRIMARY and final Energy consumption

8.1 Primary energy

Figure 13 exhibits the total amounts of primary energy consumed globally from four models (GEMINI-E3 does not produce such results). There is a marked contrast between the results obtained via the top-down models and those obtained from the bottom-up models. The former show clearly that the policy scenarios induce a large decrease in primary consumption relative to REF, while the latter do not show any significant decrease (they even show small increases). The explanation, to be illustrated and be made more precise in later sections, is as follows:

- the top-down models implement important energy savings (amounting to 25-30% of reference TPER in 2100), as a result of the substitution of capital for energy in their production functions. They also adopt renewable energy forms (wind, solar, etc.), but since the latter are accounted for in units of output energy, rather than input energy, their penetration has the effect of decreasing total primary energy[6] .

[6] For example, if 1PJ of coal fired electricity is replaced by 1PJ of solar electricity, the former is imputed say 2.5 PJ of coal (an efficiency of 40%), while the latter is by convention, imputed only 1 PJ of primary energy (the sun).

- The bottom-up models also adopt solar and wind, just as the top-down models do, but one main difference is that they make a larger use of CCS (in conjunction with coal or biomass fired power plants, hydrogen plants, and synthetic fuel plants), but since these plants are not very efficient, they have the effect of increasing the consumption of primary energy, which is not entirely compensated by the favorable accounting of solar and wind energy. Another difference with top-down models is that TIAM based models tend to adopt most of the available energy conservation measures even in the Reference scenario (as “no-regret” measures), so that a smaller additional potential for conservation is left for the policy scenarios.

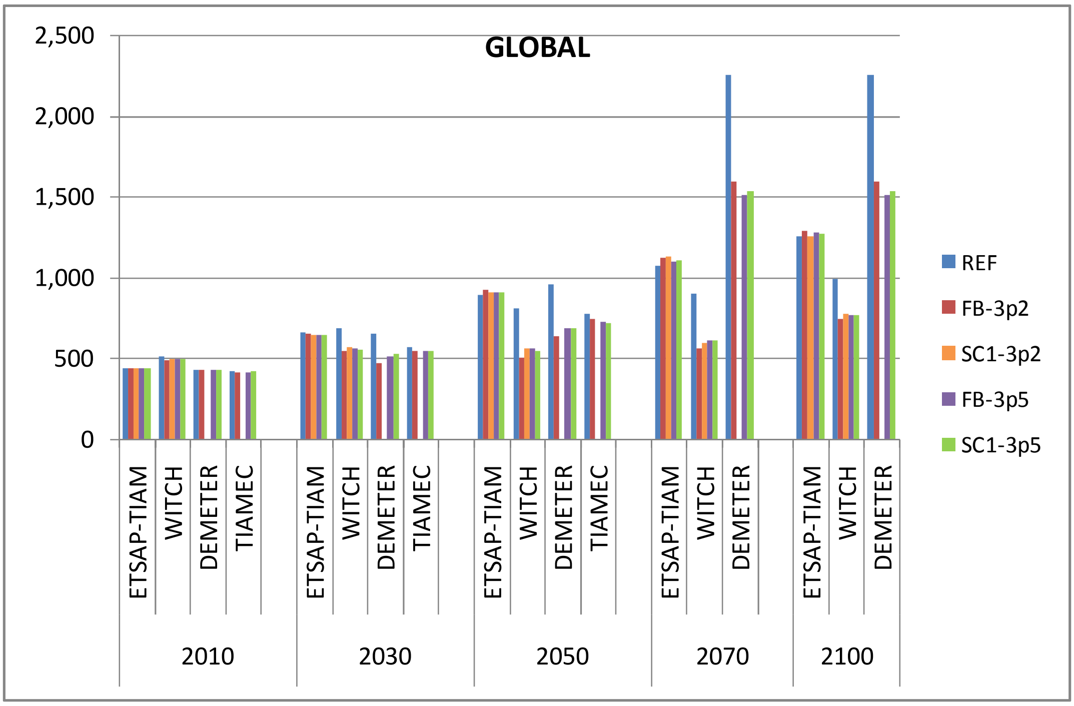

Figure 13. Total Global Primary energy (EJ/yr)

8.2 Final energy consumption

Figure 14 shows final energy consumption for four models (DEMETER does not produce such results). Here the situation is different from that for TPER, and all models show final energy savings compared to REF, although the two top-down models show larger savings that the two bottom-up models, for the same reason evoked in the previous section, i.e. that the substitution of energy by capital is one main element of their abatement strategy.

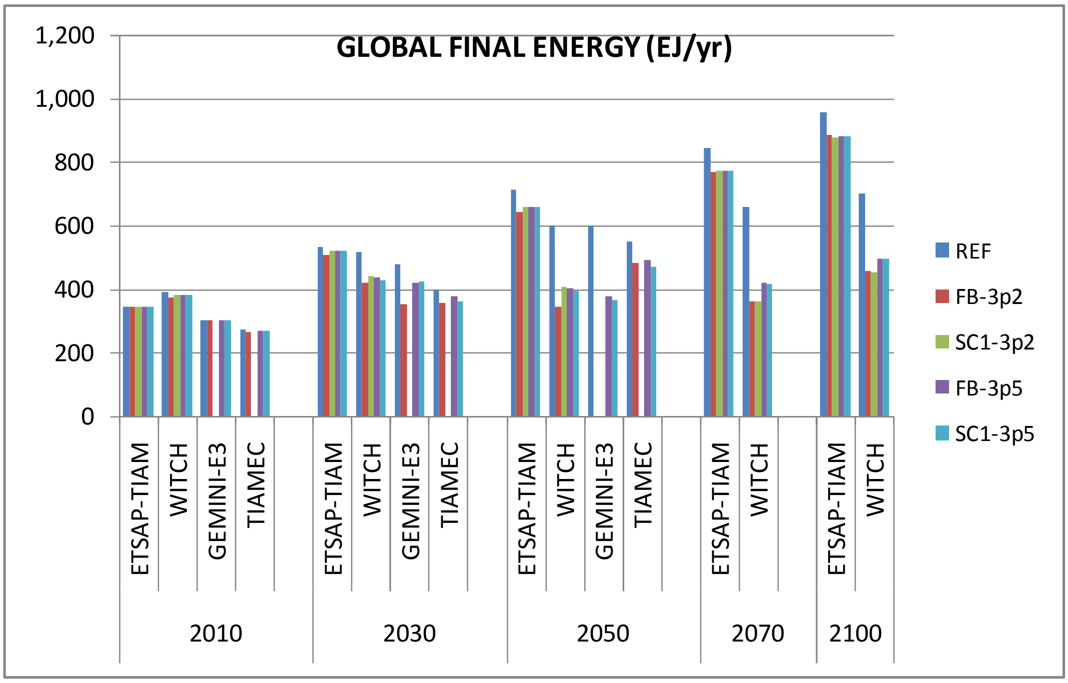

Figure 14. Total Global Final energy (EJ/yr)

8.3 Overall system efficiency

By taking the ratio of final over primary energy, a global measure of the overall energy efficiency of the world energy system is obtained, as shown in figure 15. The results are shown for the three models that allow the calculation. Three observations:

- In the Reference scenario, efficiency stagnates then decreases a little as time goes on. This is due to the important role played by coal in REF (coal fired power plants are relatively inefficient).

- In policy scenarios, all models show a further decrease in system efficiency, showing that the final energy savings mentioned earlier are not large enough to compensate for the increased primary energy consumption of coal and biomass. This may come as a mild surprise, but is perfectly explained by the presence of CCS in the policy scenarios.

- The 3p2 target induces more use of coal (with CCS) and biomass in the later years of the century, and thus a further decrease of efficiency relative to the 3p5 target, thus confirming the above analysis.

- We may conclude that the pursuit of a climate objective is not necessarily totally congruent with the systematic pursuit of efficiency improvement.

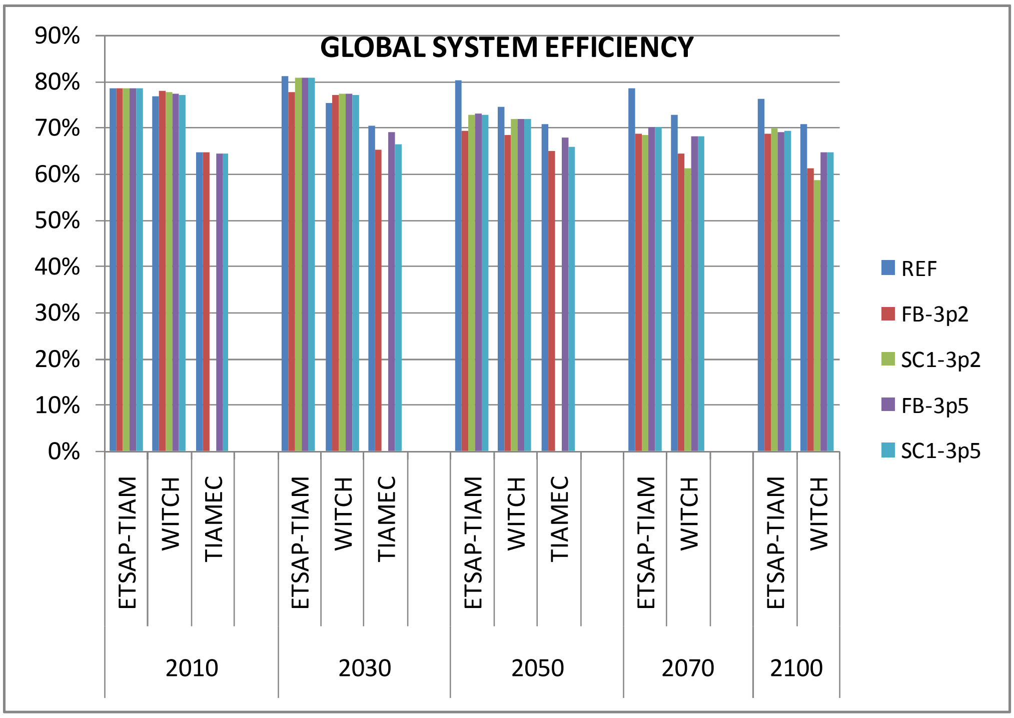

Figure 15. Global Energy Efficiency

9. Electricity

Electricity is a particularly important secondary energy in any energy system, and its role in emission mitigation is quite fundamental. The detailed analysis of electricity production sheds additional light on the strategies followed by the different models and already discussed in broad terms in previous sections. Note that the DEMETER model does not produce results on electricity production.

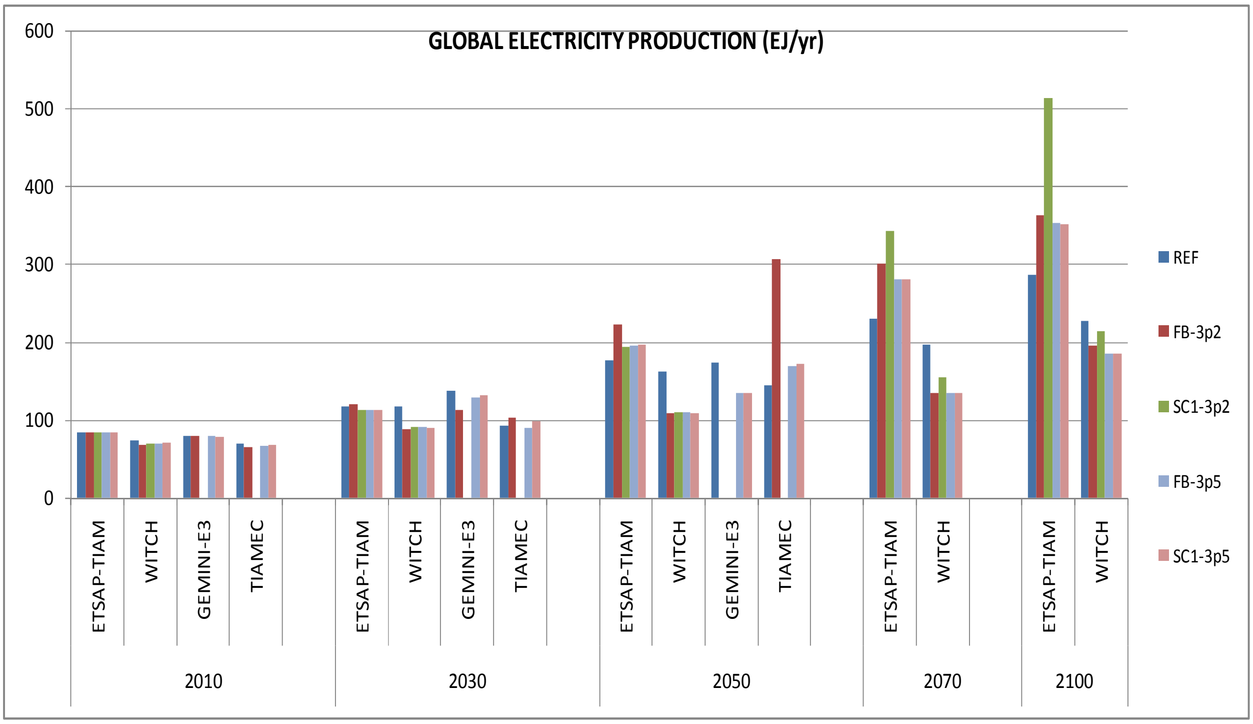

Figure 16. Aggregate global electricity production (EJ/yr)

We start with the observation that the two top-down models and the two bottom-up models show very different amounts of total electricity produced, when confronted with climate targets (figure 16). WITCH and GEMINI react by *decreasing* the amount of electricity produced whereas ETSAP-TIAM and TIAMEC decide to *increase* electricity, sometimes quite dramatically. The contrast is visible at all periods, and is particularly marked at later periods (2050 and later). For instance, in 2030, WITCH and GEMINI show a 15-20% decrease in electricity for the FB-3p2 scenario as compared to REF, whereas ETSAP-TIAM and TIAMEC show a slight increase. The contrast is more pronounced in 2050, when ETSAP-TIAM (resp. TIAMEC) indicates 20% (resp. 100%) *more* electricity in FB3p2 than in REF, whereas WITCH and indicates a 35% *decrease* in FB-3p2 wrt REF. In later years, roughly the same percentages are observed with ETSAP-TIAM and WITCH (TIAMEC and GEMINI do not produce results beyond 2050).
These two different behaviors correspond to the two broad strategies already described in the previous sections. WITCH and GEMINI-E3, by their very nature, take the route of energy savings, including electricity savings, while the two TIAM models take the route of technological substitutions in end-use sectors: end-use energy is heavily replaced by more electricity, precisely because consuming (and producing) electricity –rather than

other fuels, may be done with little or no CO2 emissions thanks to the CCS option (or even negative emissions, when the Biomass+CCS option is used in ETSAP-TIAM). The fact that ETSAP-TIAM and TIAMEC have larger CCS potentials than other models helps make this contrast even more dramatic. Only in the most stringent scenario (SC1-3p2) does WITCH show a long-run increase in electricity production (compared to FB-3p2) that materializes in an expansion of nuclear and renewable energy.

We now turn to the composition of electricity production, which is shown for periods 2030, 2050, 2070, and 2100, grouped into four categories in figure 17.

- Fossil fuel fired power plants without CO2 capture and storage
- Fossil fuel fired power plants with CO2 capture and storage
- Biomass fired power plants
- Other non emitting power plants (nuclear, hydro, solar, wind, ocean)

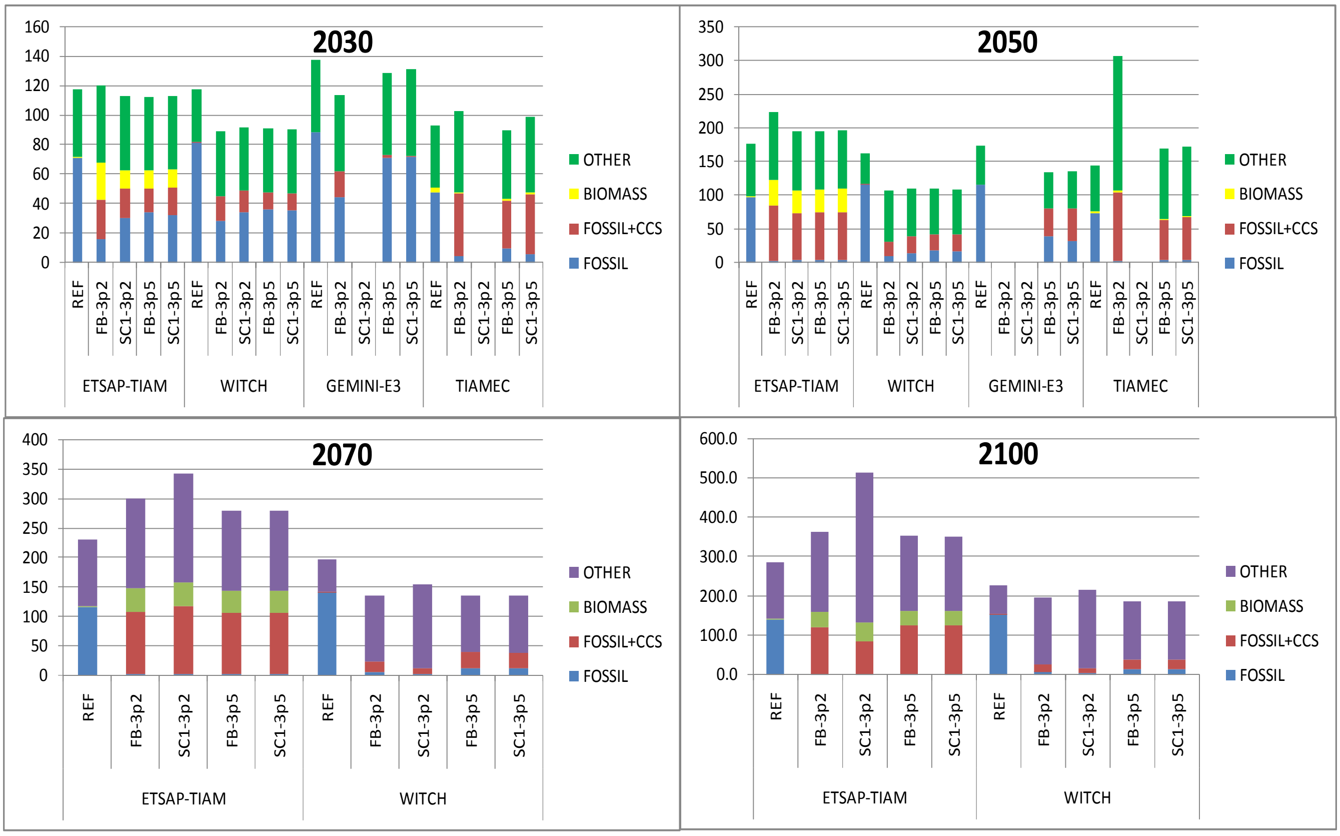

Figure 17. Electricity produced by type of plant (EJ/yr)

What figure 17 confirms is that CCS plays a prominent role in B-U models and less so in T-D models. The latter models rely more heavily on renewable. All models use CCS even more heavily in the mid-term and somewhat less so in the very long term, due to the fact that, as the climate target becomes more demanding, CCS is no longer the best or only response, since it is not a truly non emitting technology, whereas renewable and nuclear power plants are.

10. Results from the EU model PEM

10.1 Emissions and certificate price

The TIMES PanEU model is used to analyse the effects of the different climate restrictions of the different scenarios on the European energy system. Since the model is not global, the climate scenarios are driven by emission trajectories calculated for the EU by the TIAM model (see section 7). It is assumed that a general emission trading system is in place between all EU member states.

The breakdown of emissions is shown in Errore. L'origine riferimento non è stata trovata. for each of the five simulated scenarios: REF, FB-3p5, FB-3p2, SC1 3p5, VAR1-3p5. Focussing on the four policy scenarios, the lowest emissions occur in SC1-3p5, followed by Var1-3p5, FB-3p2 and FB-3p5. The different sectors of the energy system (conversion-production, industry, residential-commercial-agriculture [RCA], transport) show different contributions to reach the climate protection targets. These different contributions reflect the different abatement costs of the sectors. The strongest decrease of CO_2 emissions takes place in the conversion-production sector, followed by RCA and industry. The highest abatement costs can be observed in the transport sector. Only a very strong climate restriction leads to clear reduction in the transport sector. For that reason, the main differences between the four climate policy scenarios occur in the transport sector.

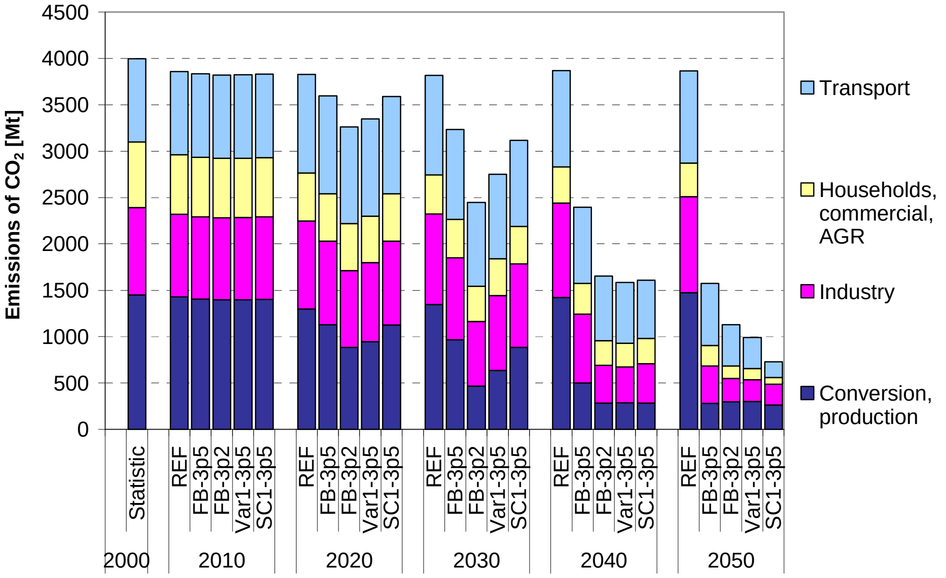

Figure 1018. CO2 emissions by sector in the EU-27

The different reduction targets between the scenarios lead to different CO_2 certificate prices for a European wide trade covering all sectors (**Errore. L'origine riferimento non è stata trovata.**). The certificate prices increase between 2020 and 2040 from a level of 15 €/t CO_2 (2020; FB-3p5) to 211 €/t CO_2 (Var1-3p5). In 2050, the price rises to levels even higher than 800 €/t CO_2 depending on the scenario.

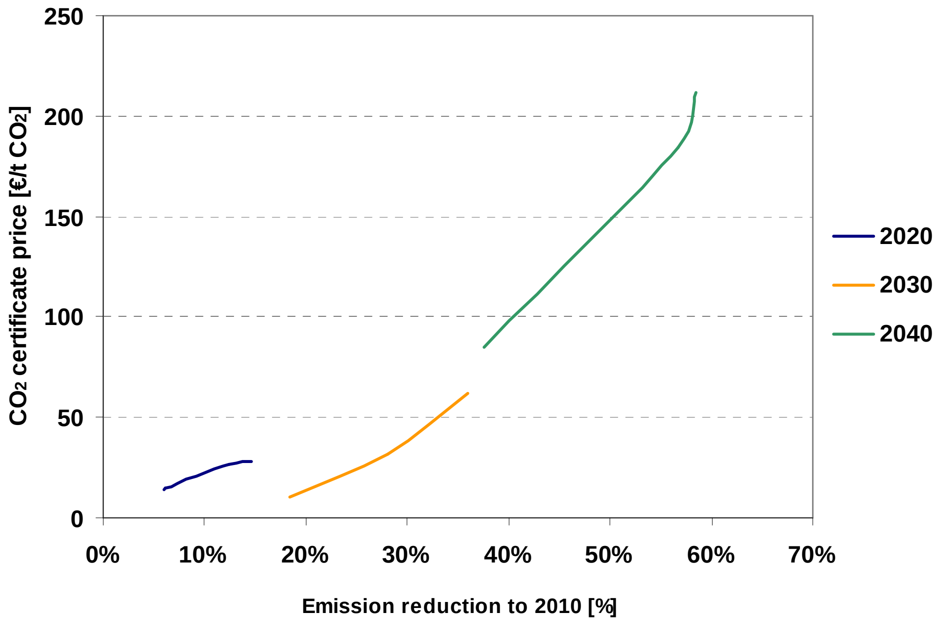

Figure 19. Certificate price over emission reduction in the EU-27

10.2 Intra EU emission reductions

The emission constraint for Europe which, as explained above, is a result of the global optimization is a Europe wide, overall cap. Due to different reduction potentials and therefore different abatement costs between the European countries, the reduction rate differs between the countries. The EU wide reduction target of scenario FB-3p5 amounts to 59 % of 2010 emissions in 2050, with each country contributing unevenly as shown in Errore. L'origine riferimento non è stata trovata..

One observation is that the new member states of the EU show strong reductions, for example Czech Republic (-74 %), Poland (-72 %), Romania (-69 %) or Slovenia (-63 %). This is due to the ongoing reformation of the electricity supply and industrial sector of these countries. But other countries also show a clear reduction, such as Finland (-76 %), mainly due to the almost complete decarbonisation of the electricity generation by the strong use of nuclear energy and renewables (wind, hydro, biomass). If the restriction gets more severe, other countries also have to reduce clearly more. Compared to the lowest European reduction target of -59 % in scenario FB-3p5, the strongest target of -81 % in scenario SC1-3p5 leads to a clear increase of reduction in countries like Spain, Greece, Italy or UK (Errore. L'origine riferimento non è stata trovata.). Because the cheaper mitigation potentials are already used (like the ones in the Finland, Czech Republic etc.) more expensive technologies are needed to reduce the emissions even more. Consequently other sectors than conversion or industry sectors (like the transport sector) and other countries are contributing at a higher level to the overall European target.

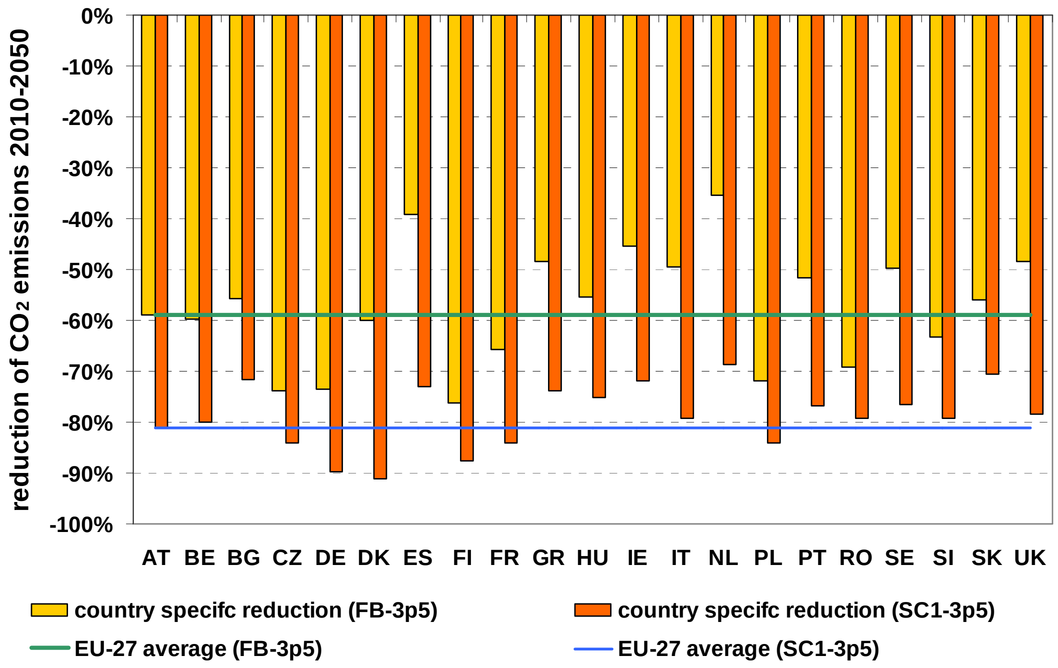

Figure 20. Reduction of CO2 Emissions by country in scenarios FB-3p5 and SC1-3p5 in 2050

10.3 Electricity generation and electricity prices

To understand the reasons for the different reduction in the particular countries, first of all the way to reach the overall European reduction target of -59 % to -81 % in the different scenarios is analysed. Due to the key role of the conversion/production sector, the electricity generation is described first (Errore. L'origine riferimento non è stata trovata.).

The total amount and also the structure stay almost the same between the scenarios till 2030. Till this point of time, the highest net electricity generation takes place in the REF scenario (3514 TWh in 2030). The reasons therefore are efficiency improvements in the climate policy scenarios. Afterwards, the electricity generation increases in the policy scenarios showing the lowest amount under reference conditions. To fulfil the emission reduction targets, electricity with low carbon intensity is generated and substitutes other more carbon intensive fuels in the end use sectors. This finding is fully congruent with those of the other two bottom-up models at the global level.

Taking a closer look at the electricity generation by energy carrier, there is a clear structural change between 2010 and 2050. Focussing at the beginning on the -59 % scenario (FB-3p5), the strongest increase can be observed at the renewable energy sources. In total, between 2010 and 2050 +828 TWh come from renewable sources (FB-3p5), mainly from wind (+415 TWh) and other renewables (+181 TWh).

Next to renewables, the clearest rise is electricity from coal fired power plants, showing +488 TWh comparing 2050 and 2010 (FB-3p5). This increase is dominated by hard coal, lignite is even decreasing. While also nuclear is increasing (+259 TWh), other fossil fuels apart from coal reduce their total amount (oil -105 TWh, gas -276 TWh). The reason for this strong use of coal is the use of CCS. Just under the strictest climate conditions (SC1-3p5) there's a clear switch from coal CCS to gas CCS.

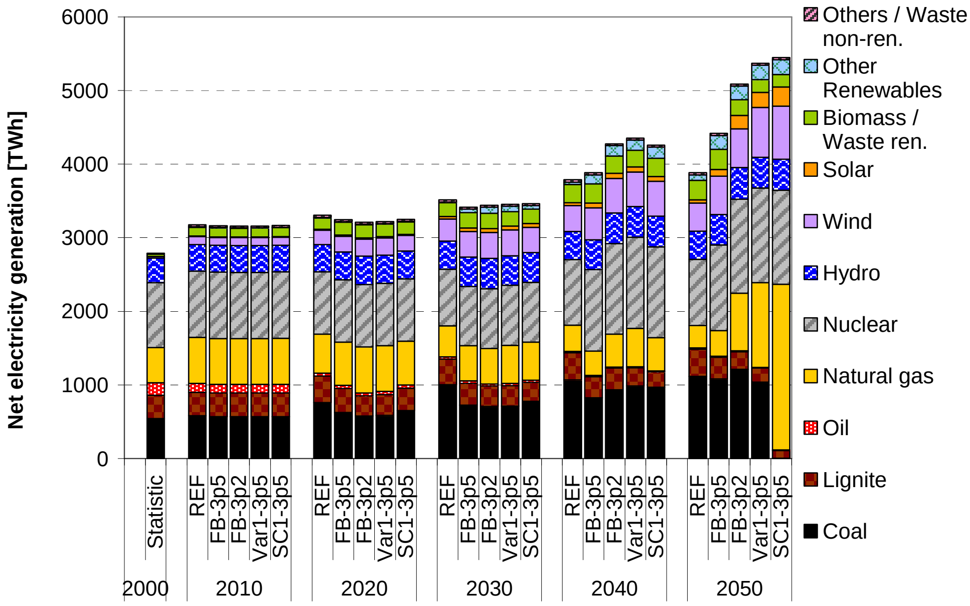

Figure 10. Net electricity generation in the EU-27

At the country level, the highest reduction in this sector appears in Finland (-96 % in 2050 to 2010 in scenario FB-3p5). Due to the almost complete switch to renewable energy sources (+42 TWh in 2050 compared to 2010 in scenario FB-3p5) and nuclear energy (+14 TWh) Finland's electricity is almost carbon free. Key renewable energies in Finland are biomass, hydro and wind.

The second strongest reduction is in Romania with a value in 2050 which is 91 % below the amount of 2010 (reduction in conversion/production sector in scenario FB-3p5). Romania is one of the countries with the highest overall emission reductions

(-69 % at FB-3p5 see Errore. L'origine riferimento non è stata trovata.) and the lowest abatement costs. That is the reason why almost the whole reduction potential in Romania is already used in scenario FB-3p5. The reductions in other sectors are of course clearly lower than in the conversion-production sector, especially in the industry sector (-26 %) due to strong economic growth. Key driver of the development in Romania is the replacement of electricity from lignite by electricity from renewable energy sources. While in 2010 25 % of the electricity is produced in lignite fired power plants, this amount is almost reduced to zero in 2050. On the other hand, 42 TWh more than in 2010 is coming from renewables in 2050, mainly from wind and biomass. In addition, there is a slight expansion of nuclear energy.

Electricity prices are displayed in Errore. L'origine riferimento non è stata trovata.. In the reference case, the prices stay almost constant over the modelled time horizon at a level of about 47 €/MWh. These prices are the average European electricity prices quantity-weighted. They reflect the interaction between demand and supply. On the demand side, the electricity demand increases slightly under reference conditions (see total amount of electricity generation **Errore. L'origine riferimento non è stata trovata.** or electricity consumption of the end-use sectors Errore. L'origine riferimento non è stata trovata.23) by 817 TWh between 2010 and 2050. They increase clearly more in the climate policy scenarios showing the highest demand in the strictest scenario (SC1-3p5). The price reduction apparent in 2020 is due to the emergence of CCS technologies.

In the climate policy scenarios, the electricity prices are clearly higher beyond 2040 compared to the reference case. Next to the higher demand, also more expensive, carbon free electricity generating technologies (i.e. geothermal energy, wave or tidal) are needed.

The level and the order of the electricity prices in the long run (2050) reflect the strictness of the climate protection target (highest in SC1-3p5, followed by Var1-3p5, FB-3p2 and FB-3p5, and due to the higher use of electricity in the end-use sectors to fulfil these targets also the demand for electricity (highest in SC1-3p5).

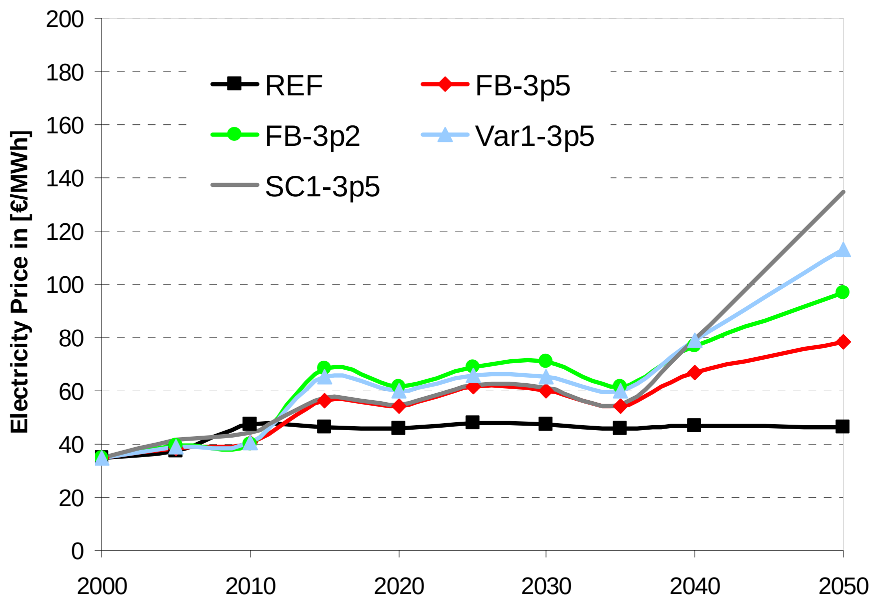

Figure 10. Average electricity prices of the EU-27 (quantity weighted)

10.4 Final and primary energy consumption

Figure 23 shows EU final energy consumption by type. Till 2020, there are no clear differences between the scenarios showing the dominating rule of petroleum products (35 % of the final energy consumption in 2020 in scenario REF), followed by electricity (22 %), and gas (19 %). Beyond 2020, there occur structural changes in the final energy consumption in the policy scenarios compared to the reference results. The changes are characterised by two main effects. Firstly, energy efficiency improvements reduce the total consumption (-8561 PJ or 16 % in scenario SC1-3p5 compared to REF in 2050). Secondly, there's a shift from fossil fuels to renewables and electricity.

The use of gas and petroleum products decline in the policy scenarios clearly over the period of time and also compared to the reference case. Compared to scenario REF, the use of gas in scenario SC1-3p5 is 4 136 PJ lower in 2050 compared to the value of 2010 even 6 289 PJ (compared the SC1-3p5 numbers of 2010 and 2050). The comparable numbers for petroleum products are 12 467 PJ (compared to REF in 2050) and 17 002 PJ (2010-2050). The use of renewables and electricity is strongly increasing, using 7 523 PJ more electricity in 2050 than in 2010 (SC1-3p5) and 10 339 PJ more renewables (again SC1-3p5 2050 compared to 2010).

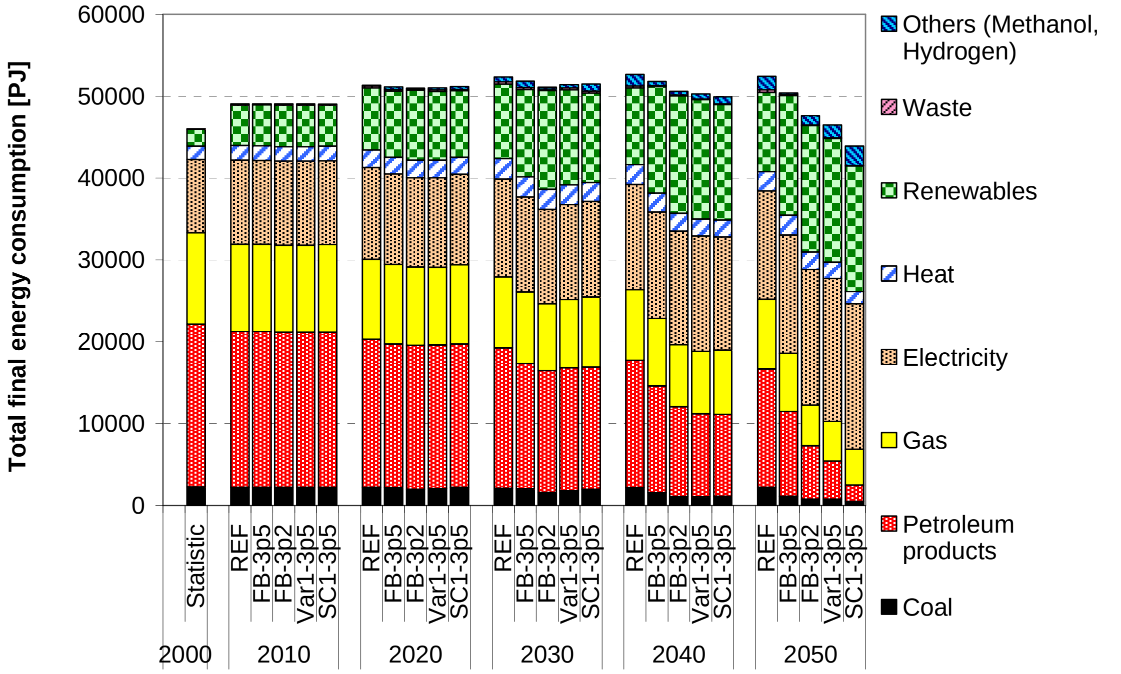

Figure 24. Final energy consumption

The effects described above are reflected in the primary energy consumption (Errore. L'origine riferimento non è stata trovata.). To sum it up, the key effects comparing the policy scenarios and the reference case are a higher use of electricity in the policy scenarios and thereby a higher fuel input in the conversion/production sector, stronger use of renewables for electricity generation and in the end use sectors und a decreasing role of petroleum products. The use of CCS leads to a constant amount of coal in the policy scenarios compared to REF except for the strictest policy scenario (SC1-3p5) with a clear switch from coal CCS to gas CCS.

Despite the use of more efficient technologies and reduced final energy consumption the primary energy consumption is in general higher in the policy scenarios than under reference conditions (+2 288 PJ in 2050 comparing Var1-3p5 and REF). The reasons therefore are the use of biomass for heat and electricity generation (lower thermal efficiency), the extended use of nuclear (lower statistical efficiency compared to fossil fired power plants) and the stronger use of CCS (also lowering the efficiency). Just when the climate target is very strict (-81 % at scenario SC1-3p5) the primary energy consumption is lower than under reference conditions (-1 458 PJ in 2050). Facing this high reduction target and therewith an even higher CO_2 price further efficiency improvements become profitable. These findings are congruent with those from the other technology models discussed in section %%

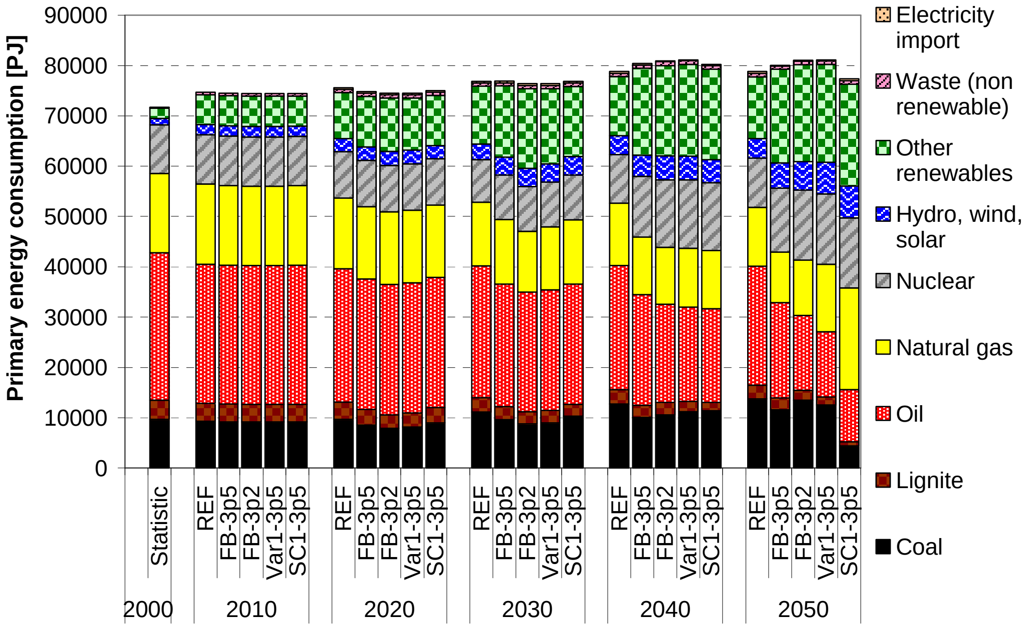

Figure 25. Primary energy consumption

10.5 Renewable energy sources

Next to the use of nuclear energy, CCS technology or efficiency improvements, renewable energy sources play a key role to reach the climate restrictions. The available potential of renewable energy sources in the different member states could be used for the generation of electricity and district heat in the conversion/production sector or directly in the end-use sectors (Errore. L'origine riferimento non è stata trovata.).

Concerning the use of renewable energy sources, there's a clear increase in all scenarios between 2010 and 2050. In 2010, the gross final energy consumption of renewables is 7 405 PJ (scenario REF) whereof 66 % are directly used in the end-use sectors. This total value increases by 7 210 PJ up to 2050 (scenario REF) and therewith almost doubles (+97 %). The shares of the total gross final consumption stay almost the same, still dominated by the direct use. In 2010, the highest amount of this direct use of in total 4 925 PJ (REF) are consumed by the household sector (53 %) followed by the industrial sector (23 %). The main use in both cases is in the generation of heat and also steam (industry).

In 2050, the use of renewables reflects the level of the climate restrictions showing the highest value in scenario SC1-3p5 (21 850 PJ), which represents an increase of 14 331 PJ (+191 %). The direct consumption of renewable energies in the end-use sectors remains dominant at a level of about 70 %.

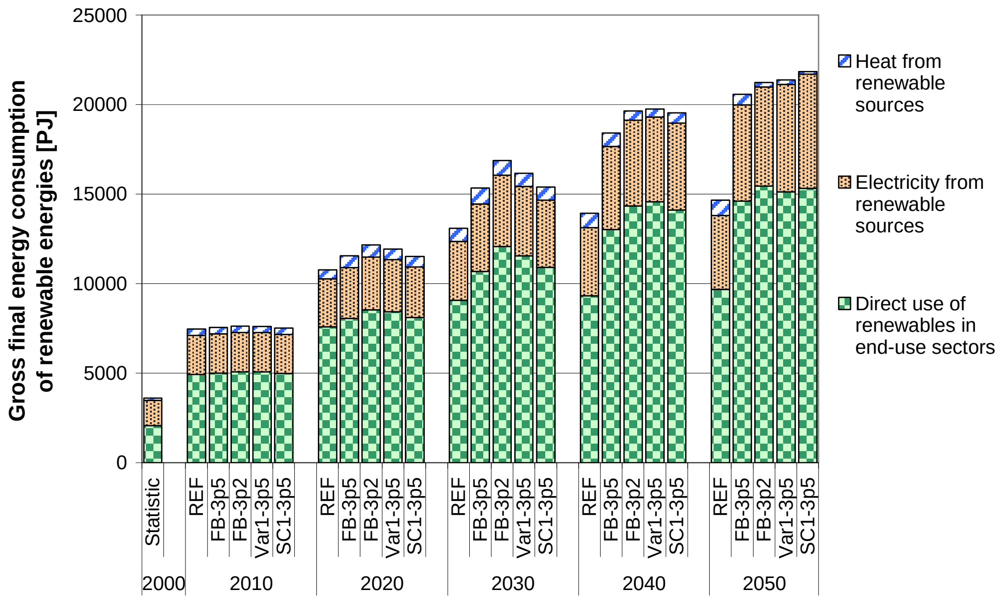

Figure 26: Gross final energy consumption of renewable energies

In 2030, the emission reduction targets are the strictest in scenario FB-3p2 facing a reduction target of -36.4 % compared to 2010, followed by VAR1-3p5 with 28.7 %. That is the reason why in this period the use of renewables are the highest of all five scenarios.

10.6 Conclusions on EU results

- One of the key findings is the fact that the CCS technology plays an important role as an emission reduction option, especially when the use of nuclear energy is limited.
- The most cost effective emission reduction potentials exist in the conversion-production sector, followed by RCA and the industrial sector. Only if the climate

restriction is very strict, a considerable amount of emissions is reduced in the transport sector.

- A stricter target leads to a higher use of electricity in the end-use sectors. This electricity is almost carbon free in the long run, using renewables, nuclear and CCS technologies.

- If a reduction target is above 50 % in 2040 compared to 2010, the CO_2 price is above 100€/t CO_2.

- Strongest reduction as part of the European burden sharing at a reduction target of 59 % in new member states (CZ, RO, PL, SI) and other countries with high reduction potential in the electricity generation (e.g. FI). These countries have a high potential for emission reduction via decarbonizing their electricity generation, and therefore tend to have lower abatement costs and reduce more. When the restriction is stricter other countries like Spain, Italy, or the UK have to reduce more.

- In the long run, the electricity prices increase according to the intensification of the climate targets.

- A strong increase in the use of renewables is necessary to reach the climate targets, especially as direct use in the end-use sectors.

- Due to the use of CCS, biomass and nuclear energy, the primary energy consumption is higher under climate restrictions than in the reference case. Only when the target is very strict, additional efficiency improvements lead to lower primary energy consumption.

11. Conclusion

11.1 ON the usefulness of multi-model comparisons

What may be expected of the comparison of results coming from different models? Broadly speaking, one may expect two types of insights: those derived from results where the models broadly *agree*, and those where they *differ*. Actions on which models -in spite of their intrinsic differences, agree, are deemed *robust* (and thus confidence inspiring). When models disagree, the analyst must be careful to distinguish between two different types of model divergence: the one that comes from differing assumptions on the models' input data, and the one coming from the differing natures ("philosophy") of the models. In some cases, the two types of divergence are hard to separate.

Regarding input data, we have only made a loose attempt at harmonizing the global growth assumptions of population and economic output at a very aggregate level (in addition, of course, the models are all calibrated to a recent year). Even so, one model (DEMETER) assumes a faster growth of emissions than other models. Generally, input data assumptions differ in many important ways, concerning regional socioeconomic drivers, technology availability and characteristics, economic demands, and resource potentials. The important point is that when data differ but the models' paradigms are similar (e.g. ETSAP-TIAM and TIAMEC), the divergence of results may be safely attributed to input assumptions.

When input assumptions are similar but models' paradigms are contrasted, the analyst must exercise his skill in order to discover the insights hidden in the contrasted results. Modeling paradigms differ in important ways, and these differences are more difficult to quantify, while often extra interesting, since they refer to distinct methodological approaches. The three models that are based on technological choice (usually named bottom-up) follow the same paradigm: the agents in the energy system construct a technological portfolio so as to reach the climate target at minimum social cost (global total surplus). The choice is very finely delineated by a long list of technology characteristics (technical and economic) that in the end determine the relative competitiveness of each individual technology. The three other models are loosely grouped in the top-down category, inasmuch as the agents in the energy system do not in general (there are exceptions in some sectors) choose specific technologies by comparing their detailed characteristics, but rather switch from one fuel to another via production functions that allow fuel switching by means of elasticities of substitution. The typical production function allows each agent to choose a point in a continuum of mixes of capital, energy, and sometimes materials and labor. But there are variants; for instance, in the WITCH model, a "breakthrough" technology may emerge more or less rapidly if certain R&D investment decisions are made (endogenously) by the model. Additionally, WITCH allows Learning by Doing in the electricity sector.

Confronted with such variance in data and modeling approaches, what can the analyst expect from the comparison of results? Our view is that *the variety of models and data may well represent the lack of perfect knowledge on how the economy really functions*. In this view, the ‘cloud’ of model results is considered as representing a true range of uncertainty, and thus provides a range within which the future lies. This view may be altered if the analyst superimposes his own beliefs in order to qualify certain results, eliminate outliers, etc.

Insights of type I: A clear and unambiguous insight is gained whenever certain actions are selected by all or most models even though they operate under different assumptions or paradigms. These actions are then deemed to be robust.

Insights of type II: a second benefit of multi-modeling exists even when the models produce very different, perhaps contradictory results. In such cases, the analyst is alerted to the possibility that certain unforeseen strategies might be relevant *if certain conditions prevail*. An example is the role of electricity production in the climate scenarios: two models show a decrease in electricity production (and use), the other three indicate an increase. In both cases, the model’s choices are perfectly justified and traceable to the assumptions and/or to the model’s ‘philosophy’. Such situations do not provide clear cut suggestions of robust actions, but nevertheless enlarge the field of vision of the analyst by indicating *actions that might become desirable under certain conditions (contingent actions).*

In what follows, we review these two types of insight as they are revealed by the results of the runs. We also indicate, whenever pertinent, what issues have not been resolved by the project.

11.2 Main issues raised by this work and at least partially answered

The following is a list of the main issues raised and at least partially resolved by our study.

- How feasible are the targets? What are the welfare losses attached to them? How useful is early cooperation? (i.e. how detrimental are delays in acting ?)
- Are the two issues of equitable sharing and of global efficiency decoupled or inextricably linked?
- What is the impact of a 20% restriction on emission trading?
- What early actions appear to be robust for achieving climate targets?
- What actions are contingent on still uncertain determinants?

We briefly summarize our answers to these issues in the rest of this section.

11.2.1 The targets feasibility

All models agree on the feasibility of achieving the 3.5 W/m2 forcing target, under either quota system studied (as well as in the absence of a quota system). This is an important finding.

As observed in our study, this target entails a change in mean global surface temperature (MGST) increase of roughly 2.2 ℃ in 2100 under an average climate sensitivity of 3℃. This temperature change is a little short of the often quoted 2℃ "acceptable" threshold. The global cost of achieving this target is not negligible, but stays within 1% of the Gross World Product until 2040. After 2050, cost per GWP is larger but stays within 2% of GWP in most models.

The 3.2 W/m2 forcing target is much more difficult to attain. Four out of five models find that target achievable but at much higher costs than the laxer target, and on the condition that abatement actions start at full speed from 2012. The fifth model finds this target infeasible even with early action, but the reason is clearly traced to the assumption of a much higher economic growth in that model. In contrast, when either quota system is assumed, only two models find the target reachable, and the global cost attached to it is again much higher than for the laxer target, especially after 2050, when global cost reaches up to 7% of GWP.

The clear conclusion is that if the 3.2 target is to be reached, the rapid creation of a global climate coalition is a requisite condition to success. To say this differently, the world had better start on a course of deep emission reductions as early as possible, rather than aim at mild reductions initially, followed by more drastic reductions after 2050.

We note that this target implies a change in MGST of 2℃ in 2100 under an average climate Sensitivity of 3℃. It is thus interesting and useful to observe that a relatively "small" difference of 0.2℃ in 2100 means very large additional global costs, or even potential infeasibility.

11.2.2 Comparing the two quota systems

The two quota systems studied in this research are regionally very contrasted but globally equivalent, since they are both globally compatible with the long term 3.5 target. However, the two quota systems have very different impacts on regional costs, and this is exclusively due to the costs and revenues derived from permit trading. OECD and Developing Asia see their costs under SC2 increase more than twofold compared to SC1, and the situation is reversed for the other two country groups.

- The study clearly indicates that the additional 10% reduction required by SC2 is very costly to achieve by OECD. Note also that OECD incurs generally larger costs than other regions (except EEX) even when expressed as % of GDP, as one would expect from the very tight quotas (i.e. large reductions) in both SC1 and SC2. EU has slightly smaller costs per GDP that the entire OECD, showing once more that EU is better positioned to make large reductions than the faster growing other OECD countries.

- For energy exporters the situation is reversed, since SC2 represents a relaxation of that region's reduction commitment. For SC1, this region incurs the largest costs per GDP (by far) of all regions, reflecting the expectations of high emission growth in their baseline and the reduced revenues of the oil market. Energy exporting countries are net buyers in the SC1 scenario, but net sellers in the SC2 scenario.

- For Developing Asia just like for OECD, SC2 is a more demanding scenario than SC1. This is borne out by the study. In fact, under SC1, one model indicates large *negative* costs for that region, quite certainly due to large revenues from selling emission permits at a higher CO2 price than the other model. According to the results, in the SC1 scenario, Developing Asia may supply up to between 40% and 90% of the carbon market, leaving the rest of the permit supply to ROW, the second major supplier.

- The Rest of the World has negative costs under SC2, due to a large amount of permits sold. Under SC1, the cost for that region remains under 1% of its GDP.
- We note that under either quota system, the costs per GDP continue to show significant differences between regions. In particular, Energy exporting countries continue to incur costs that are up to 3 times the cost per GDP of the other groups, even in the more favorable SC2 system of quotas. Additional investigation of fair quota systems would therefore be a desirable further research topic.
- As mentioned above, the two quota systems are globally equivalent in terms of global costs. But our work also shows that choosing between the two quota systems has a negligible impact on the *timing* of the global reductions. Still more interestingly, *even regional reductions are quasi unaffected by which one of the two quota systems is selected*. In other words, the same abatement actions are taken *in each region* irrespective of which of the two quota systems is used. The explanation of this observation resides in the fact that emission trading strongly determines where (and how much) emission reductions are made, irrespective of "who pays".

11.2.3 The impact of a 20% limit on permit trading

Most results indicate that the overall global cost of emission control is only mildly affected if a limit on emissions trading of 20% is imposed on each group of countries until 2050. This encouraging result means that the vast majority of emission reductions may happen inside each country grouping, with little impact on global cost.

However, the adoption of the trading limit does have significant impacts on abatement cost in individual regions. OECD and Energy exporting countries see a rather large increase in their cost, while Developing Asia and the Rest of the World see a corresponding decrease of their abatement costs (when costs and revenues from permit trading are accounted for).

11.2.4 Some robust actions

There is unanimity in all models to recommend strong energy savings and large amounts of renewables (biomass, wind, solar) and nuclear, when climate targets are imposed. In fact, energy savings are the preferred strategy chosen by T-D models, along with adoption of renewable power plants, and modest amounts of Carbon Capture and Storage in the electric power sector.

B-U models also choose to implement energy savings in end-use sectors, and electricity from renewable sources and nuclear, but their strategy also includes a larger amount of CCS. All models consider CCS as an effective and efficient technology in the mid-term, but tend to reduce recourse to CCS in the very long term (post 2050). This is congruent with the fact that CCS is not a truly non-emitting technology, whereas renewable and nuclear power plants are.

11.3 Diverging results (contingent insights)

One difference worth noting occurs with respect to the role played by electricity in final energy. The B-U models recommend large increases in the use (and production) of electricity, which therefore replaces other end-use fuels (whether fossil, renewable, or conservation). In effect, B-U models use the increased recourse to electricity as a means of implementing large amounts of CCS. On the contrary, T-D models indicate less electricity in climate scenarios than in the reference case, a strategy that is coherent with the fact that these models implement larger energy savings than their B-U counterparts.

These two contrasted strategies constitute a true difference in approach. Both are coherent with the respective paradigms of the two classes of model, as well as with the assumptions made on the potential for CCS.

The contingent conclusion emerging from such diverging recommendations is that the CCS technology must be studied in more depth and detail before major decisions are taken on its massive implementation. If CCS proves to be relatively cheap and abundant, it will deserve a truly large role in GHG abatement. If not, energy savings, nuclear, and renewable would be used more heavily, at least for the next 3 or 4 decades.

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Electronic Appendix: complete results from all models