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Multidimensional Impact of the Low-carbon European Strategy on Energy Security, and Socio-Economic Dimension up to 2050 Perspective

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Abstract:
This report is about global and macroregional key trends and scenarios emerging from literature and from previous analysis. It presents a critical comparative review of macro-regional energy scenarios proposed in the scientific literature, considering different technological options for energy generation and comparing institutional and non-institutional energy scenarios.

It finally proposes a geographical-chronological analysis of different technological solutions and future trends.

Disclaimer

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1. Executive summary

This deliverable is part of WP1 from the MILESECURE-2050 project dedicated to analyze energy security policies, trends and existing scenarios from the national to the worldwide level. This deliverable conducted in the framework of task 1.2 presents a critical review of prominent long term modeling exercises using integrated modeling assessment conducted since the fourth IPCC Assessment Report published in 2007. Their findings confirm the main messages put forward in the fourth IPCC report: (i) the confidence that a coherent deployment of technologies will ensure a meaningful shift in the energy system given carbon constraint and the depletion of fossil fuel, (ii) and the moderate cost of the transition at the global or macro-regional levels. This report however underlines one main flaw of these modeling exercises: the lack of interest for the linkage with other issues in particular security issues. This is the result of a climate centric drift of international negotiations which has to some extent impacted most modeling exercises. Moreover, although models are more complex and integrate various issues, the complexity of social dynamics and transition patterns (inertias and irreversibilities of technical choices, pre-existing domestic policies….) towards a low carbon society are not fully addressed by Integrated Assessment models. Considering that the energy transition is multi-objective and occur in a world full of imperfections (inertias of infrastructures, imperfect foresights…) these mechanisms are crucial to better understanding the synergies and the trade-offs between climate change and energy security issues. Finally, following recommendations from D1.1 deliverable, the report provides new perspectives to assess the interdependencies between climate policies and energy security issues, thanks to an innovative modeling framework. Its first results at the global and European level require therefore further methodological improvements which will be under the umbrella of the MILESECURE-2050 project.

2. Introduction

The intellectual debates expressed by the Club of Rome about the "Limits to Growth" (Meadows, 1972) and the oil crisis in the 70's of the 20th century revealed at that time the close interactions between environmental, economic development and energy security issues. In particular, energy security issues have been one of the main drivers to put a climate Convention on the international agenda, for the G7 meeting held in 1990 at Houston on George H. Bush's initiative (Kirton, 2007). Recent rise of fossil fuel prices and the difficulties encountered to set a global climate architecture have led to a renewal of interest for energy security issues.

Furthermore, since the late 80's, the rise of climate change on the public agenda and more recently of the concept of "Low carbon society" [4] have accelerated the need for quantitative assessment of mitigation and adaptation strategies, in particular in view of the IPCC reports[5].

An "industry" of scenarios produced by energy-environment-economy (3E) models to explore the feasibility of long term development pathways have emerged: the database of emissions scenarios developed by T. Morita and Y. Matsuoka at the National Institute for Environmental Studies (NIES, Japan) since 1992 contains more than 1000 scenarios[6].

In the energy field, projections have rapidly become necessary because of (i) the complexity of energy supply and demand mechanisms forecasted (ii) the emergence of long term challenges such as energy security issues, risk posed by nuclear technology (dissemination, waste management…) and climate change.

These scenarios provide long term development pathways, with different Greenhouse Gases Emissions trajectories, and give insights on the cost of climate policies, the distributive impacts of climate policies, changes in the energy mix or energy security issues. Quantitative scenarios follow a similar methodological approach. They are based on coherent storylines of socio-economic drivers (demography, macro-economic, social and technology trends), then projected with quantitative models. Quantitative models picture future states of complex systems in order to ensure the consistency of long term storylines, conduct sensitivity analysis and assess the impact of specific policies. The scientific community and policy makers have collectively agreed this approach in the late 90's, in particular for the elaboration of the SRES scenarios before the third IPCC report (Nakicenovic et al.,

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[4] In particular after the G8 leaders met at Gleneagles in 2005, LCS – low carbon society

[5] Four IPCC reports have been released since 1992 (IPCC, 1992,1995, 2001, 2007)

[6] http://www.cger.nies.go.jp/db/scenario/index.html Last update was conducted in 2009

2000)[7]. Integrated assessment modeling (i.e. models that integrate climate science, economic and environmental dynamics see Weyant et al., 1996) has been more precisely the method of choice for assessing costs of climate change mitigation and the associated transformation of economic systems. In the Fourth Assessment Report (AR4), Working Group III of the IPCC surveyed a total of 177 climate mitigation scenarios from the recent literature (Fisher et al. 2007)[8]. In view of the next IPCC report (AR5) which will be published in 2014, a number of prominent assessments of the future energy use and carbon emissions have been carried out to update the scenarios produced for (AR4). (IPCC, 2007) has indeed pointed out that stringent reduction of greenhouse gas emissions within the next fifty years should be adopted to limit the rise of world temperature below 2°C by the end of the century[9] .
This deliverable is part of WP1 from the MILESECURE-2050 project dedicated to analyze energy security policies, trends and existing scenarios from the national to the worldwide level. Following D1.1 which provides a comprehensive conceptual review of various energy security approaches and methodological requirements for analyzing a secure energy system, D1.2 report aims at providing a critical assessment of long term macro-regional scenarios by focusing on some key recent modeling exercises developed since the AR4[10], inside the IAMs (Integrated Assessment Models) community. This community is relatively well structured around few modeling teams mainly based in research centers[11]. It gathers economists, engineers and experts of the energy field. Regular intercomparison model exercises are carried out principally under the umbrella of the EU Framework Program (EUFP) or Stanford University (Energy modeling forum). Results are generally published in peer reviewed journals which will feed group III of the IPCC report dedicated to mitigation policies. In addition to these institutional exercises, key political actors such as national governments, the EU or NGOs (Greenpeace, WWF) can support

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[7] Special Report on Emissions Scenarios. Published in 2000, the SRES scenarios cover a wide range of the main driving forces of future emissions, from demographic to technological and economic developments. Each scenario corresponds to one out four main storylines and was produced by modeling IIASA team (Nakicenovic et al., 2000), more explanation see http://www.ipcc.ch/publications_and_data/ar4/syr/en/mains3.html#3-1

8 Since the SRES report, models comparison projects such as the Energy Modeling Forum EMF-19 (Weyant, 2004) and EMF-21 (Weyant et al., 2006), as well as the Innovation Modeling Comparison Project, IMCP (Edenhofer et al., 2006) have generated and analyzed mitigation scenarios in view of the Fourth Assessment Report (AR4).

[9] The fourth assessment report points out that a 450ppm concentration objective in 2050 requires to peak emissions between 2015 and 2020 (IPCC, 2007)

[10] Non modeling prospective exercises are out of the scope of this study. A review of these exercises can be found in Sessa et al., 2010 in the framework of the EUFP7 Pashmina project.

[11] Not only as international organization such as the IEA supports its own modeling team

modeling development to put forward their own vision of the future transition given their own political agenda.

This deliverable analyzes how scenarios have been produced, what main messages they deliver on the transition toward a low carbon and energy society at a global, regional and sectoral level and incidentally on energy security challenges. The ambition of this deliverable is not to proceed to a meta-analysis like the ones conducted by Nakicenovic et al., 2006 or Barker et al.2008[12], part of scenarios in view of AR5 being currently under way. Rather, it will point out the "blind" issues tackled in modeling exercises, in particular and paradoxically, the energy security issues. Indeed energy security policies and climate policies are often considered as two sides of a same coin (Hartley and Medlock, 2008) or complementary, but in some cases, they might prove contradictory. Although models are more complex and integrate various issues, the complexity of social dynamics and transition patterns (inertias and irreversibilities of technical choices, pre-existing domestic policies….) towards a low carbon society are not fully addressed. These mechanisms are however crucial to better understand the synergies and trade-off between environmental, economic and social issues such as climate change and energy security.

Section 3 presents in more depth methodological approaches of these modeling exercises analyzed in this deliverable. Section 4 analyses how the scenarios consider the future transformation of the energy systems involved by the transition toward a low carbon society at a multi-scale level (regional and global). Section 5 highlights the challenges for key OECD countries (the EU and the US) and developing countries (India and China) in particular in terms of energy security issues. Section 6 analyzes the implications of these potential transformation of the energy system in terms of energy security issues and underlines some methodological perspectives and requirements for modeling at a global and regional level the synergies and trade off between climate policies and energy security issues.

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[12] These meta-analysis share a common approach. The set of trajectories is considered as an indicator of the diversity of long term perceptions given the current state of knowledge of the scientific community (Nakicenovic et al., 2006). These trajectories analyze the range of emissions of scenarios. Beyond the emissions volumes, authors use the Kaya « identity » which enables to split up the evolution of emissions with respect to population, GDP growth rate (GDP per capita) and the structure of the energy system (GDP energy intensity and carbon intensity of the energy system). Statistical properties, median value, distribution of each determinant yet isolated are then examined in details, revealing a measure of the uncertainty about long term trajectories. One has to be careful that the different components of the Kaya identity are not independent (Crassous, 2008).

3. Macro-economic scenarios: approach and methodology

3.1 Presentation of the scenarios set and models

This section provides a short presentation of modeling exercises. Note this only takes into account those modeling exercises which have already been published in peer reviewed journals or have delivered reports[13].

3.1.1 Modeling exercises considered

ADAM project (2006-2009)

Coordinated by the Tyndall center, ADAM was an integrated research program funded by the EUFP6 whose objective was to analyze the interactions between adaptation and mitigation policies at the EU and global level. Using five energy-economy models, part of the project focuses on the technological feasibility and the cost of a low greenhouse gases stabilization scenario of 400ppm CO2 The teams involved were Laboratoire d'Economie de la Production et de l'Intégration Internationale (LEPII), Potsdam Institute for Climate Impact Research (PIK), and Cambridge University[14] . The project assessed the option values of key technologies given stringent climate targets at the world level. It also estimated the competitive potential of certain technologies/resources, i.e., the biomass potential or the cost-effective storage potential under carbon capture and storage (CCS), excluding social acceptance aspects (See: http://www.adamproject.eu/). The Energy Journal, published a special issue on the project in 2010.

RECIPE project (2008-2010)

Coordinated by the PIK the Recipe project received financial support from Allianz SE and WWF. It gathered three structurally different energy-economy models developed by PIK, *Centro Euro-Mediterraneo per i Cambiamenti Climatici* (CCMC) and CIRED/SMASH to provide consistent scenarios for Europe and the World given the availability of key technologies and different climate regime architectures. The results have been delivered in a final report and a special issue of Climatic Change in 2011 (See:http://www.pik-potsdam.de/research/sustainable-solutions/research/ClimatePolicies/recipe-groupspace/)

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[13] EUFP7 project Ampere and EMF24, 27 are currently under way and are hence out of the scope of this study. They would be included in a future revised version of the report. However, preliminary results confirm those put forward in the ADAM and RECIPE projects, the approach and the models used being relatively similar.

[14] Centre for Climate Change Mitigation Research

EMF 22 (Energy modeling forum) 2007-2008

Coordinated by Stanford University, the 22nd edition of EMF exercise used a collection of 10 IAMs (Integrated assessment models) to assess i) the feasibility of low stabilization scenarios given an emission reduction target, whether or not this target can be temporarily exceeded prior to 2100 ("overshoot") allowing for greater near-term flexibility, ii) and the nature of international participation in emissions mitigation. The teams involved were The Pacific Northwest National Laboratory (PNNL) , the Joint Global Change Research Institute (JGRI), the International Institute for Applied Systems Analysis (IIASA), Electric Power Research Institute (EPRI), Princeton Environmental Institute, *Fondazione Eni Enrico Mattei* (*FEEM)/* CMCC. Energy Economics published a special issue in 2009.

(See: http://emf.stanford.edu/research/emf22/)

WEO (World Energy Outlook) and ETP (Energy technology perspective)

The annual IEA World Energy Outlook provides projections of the future energy mix by 2030 or 2035 with a specific focus on a key dimension of the energy sector. This deliverable puts the latest projections of 2012 WEO into perspectives of the previous editions projections in particular with WEO 2007 which is dedicated to long term development of China and India given. The projections for each of the scenarios are derived from the IEA's World Energy Model (WEM) – a large-scale partial equilibrium model that is designed to replicate how energy markets function over the medium to long term[15].

ETP (Energy technology perspective) report published in 2010 and 2012 focus more precisely on the technological potential for energy technologies to contribute to deep CO2 emissions towards 2050 while WEO scenarios stop at 2030.

GEA (Global Energy Assessment, 2012):

Coordinated by IIASA and launched in 2012 for Rio+20, GEA pathways explore some 40 pathways that satisfy simultaneously the normative social and environmental goals: stabilizing global climate change to 2°C above pre-industrial levels to be achieved in the 21st century, enhancing energy security, eliminating air pollution, and reaching universal access to modern energy services by 2030. 500 independent experts from academia, business, government, intergovernmental and non-governmental organizations from all the regions of the world have contributed to GEA in a process similar to the IPCC. Long term energy and economy pathways are based on the IAMs IMAGE and MESSAGE models. (See:

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[15] A full description of the WEM is available at *www.worldenergyoutlook.org/weomodel*

http://www.iiasa.ac.at/web/home/research/Flagship-Projects/Global-Energy-Assessment/Home-GEA.en.html)

The database of scenarios is available at:

http://www.iiasa.ac.at/web-apps/ene/geadb/dsd?Action=htmlpage&page=about

Greenpeace-EREC *(European Renewable Energy Council):* (2007, 2008, 2010, 2012)

Since their first publication in 2005[16], Greenpeace Energy [R] evolution scenarios advocate for a large scale deployment of renewables at the expense of fossil fuel and nuclear in the energy system with respect to the objective to halve world GHG emissions by 2050. The modeling analysis articulates projections from the MESAP/PlaNet simulation model for the supply scenarios, energy demand projections developed by Ecofys (2010) and Utrecht University (2012), and analysis of future potential productions for biomass[17] and transport[18]. The Energy [R]evolution scenario is based on a "bottom-up" (technology driven) approach with particular optimist assumption on the development of renewable technologies. (See: http://www.greenpeace.org/international/en/campaigns/climate-change/energyrevolution/)

Other studies are also included in our report with specific points:

- The Special Issue of Climate Policy Modeling Long-term scenarios for low carbon societies (Strachan et al., 2008a) which gather studies exploring ambitious emissions reductions targets;
- Official documents released by the EU putting forward the articulation between climate change policies, energy policies and competitiveness: the 20-20-20 policy objectives adopted in 2008, the Roadmap for moving to a competitive low carbon economy in 2050 (COM/2011/112) adopted by the Commission and the recent Green Paper (COM 169 2013) *A 2030 framework for climate and energy policies* ;
- The IPCC Special report on Renewable Energy Sources published in 2011 (SRREN);

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[16] At that time, scenarios cover only Europe

[17] German Biomass Research Centre. Biomass potentials have been further reduced in the 2012 edition

[18] Special report produced in 2008 by the Institute of Vehicle Concepts, DLR for Greenpeace International.

- The EUFP7 AUGUR project (2009-2012) which explores through a set of scenarios the main features of Europe and the World in 2030 given changes in economic and social patterns.
- In line with the AUGUR project, the scope of the analysis is broadened to specific studies dedicated to the synergies between climate policies and energy security issues. This deliverable will more precisely refer to the findings of modeling scenarios conducted by the IMACLIM model developed at CIRED and SMASH relative to energy security issues for Europe.

3.1.2 Types of models

The models surveyed in this deliverable share common traits:

- They use economics as the primary criteria for decision making, in particular cost minimization at a global and/or macroregional scale;
- They focus on a long-term and often global perspective that integrates various human and natural systems;
- They include, at various degrees, other issues such as climate dynamics, land use changes, multi-gas objectives… ;
- They project long term trajectories. While WEO projections cover a period until 2030-35, Greenpeace-EREC study, ETP and intercomparison modeling exercises (ADAM, RECIPE, EMF22) reach 2050 or 2100. Integrating near term and long term perspective is therefore a key dimension in the dynamics of the transition.

Beyond these similarities, modeling approaches that seek to generate transformation pathways vary.

The following paragraph proposes an attempt to classify models inspired from Zhang and Folmer (1998), Chapter 7 of the third IPCC report (IPCC, 2001), Crassous (2008), Guivarch (2009), Amerighi et al (2010).

Schematically, the models differ along two dimensions:

(i) Optimization vs. simulation, or normative approach vs. positive approach,

(ii) Bottom-Up (BU) vs. Top-Down (TD), or engineers' models vs. economists' models.

Bottom up models give the priority to a detailed description of technologies and sectoral systems in order to provide energy services. Natural resources availability, economic growth and final demand of energy services are exogenous assumptions. On one hand, BU using intertemporal optimization of the energy system search for the technology mix to minimize the costs of providing energy services, at given environmental protection level (GHG reduction emission target for example). On the other hand, BU models based on partial equilibrium simulation (i.e. equilibrium between supply and demand in different sectors more or less depend on models calculated independently with exogenous macro-economic trends) of the energy system build exploratory scenarios on the base of routines behaviours of some economic agents or some major economic or energy variables.

Conversely, top down models represent macro-economic consistency but encapsulate a limited description of technologies. Top-Down models or economic models include three main groups:

(i) Optimal growth models, built on the principle of intertemporal maximization of one single representative agent;

(ii) Macroeconometric models, which project future scenarios from econometric relations between economic variables, calibrated on past data;

(iii) General equilibrium models, representing all markets and their interdependencies as well as all the budget equations of representative agents.

The gap between both families has narrowed[19] since the 90's with the increasing number of hybrid models characterized by a comprehensive top-down representation of the macro-economic processes complemented by a technologically explicit bottom-up representation of energy systems.

In our survey, MESSAGE (Messner and Strubegger, 1995; Riahi et al., 2007), POLES (European Commission, 1996), TIMER (Bouwman et al., 2006), WEM, MESAP/PlaNet, MINICAM/GCAM (Calvin et al., 2009), ETSAP TIAM (Loulou et al., 2009) are bottom up energy systems with a high resolution of different technologies.

MERGE (Kypreos and Bahn, 2003; Manne and Richels (2004a; 2004b)), Kypreos, 2005), ReMIND-R (Leimbach et al., 2009), WITCH (Bosetti et al. 2006; De Cian et al. 2011), IMACLIM-R (Sassi et al., 2010, Waisman et al., 2012), IMAGE/TIMER (van Vuuren et al., 2006), E3MG (Barker et al., 2006; Barker et al., 2008), SGM (Calvin et al., 2009), PRIMES (Capros et al., 2008) are hybrid models with a top-down macro-

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[19] If the Bottom-Top Down dichotomy tends to disappear with the development of hybrid tools (Hourcade et al., 2006), combining detailed representations of technical systems with a consideration of economic interdependence, it gave rise to intense controversies. Schematically, Top Down models are criticized for their poor representation of technical possibilities (Grubb et al., 2002), and for their aggregated and purely monetary character, while BU models, in particular the first versions built in early 90's, ignored the role of the whole economic system in price-signals and budget-constraints evolutions that are crucial for the bifurcation of technical systems (Jaffe and Stavins, 1994 ; Sutherland, 1996). The new BU families have been developed and/or integrated with CGE modules by internal or external iterative convergence process.

economic model more or less linked to a bottom-up energy system model. The macroeconomic core of ReMIND-R, WITCH, MERGE, MESSAGE is based on intertemporal optimizing (Ramsey-type growth model) whereas POLES, IMACLIM, SGM, TIMER, MiniCam/G-CAM, IMAGE, E3MG[20] are recursive dynamic computable general or partial equilibrium models.

Table 1 proposes a classification of most models used in the selected modeling exercises.

Model	**Model classification**	**Modeling approach**	**Objective Function**
MERGE *ReMIND-R* *WITCH*	Intertemporal general equilibrium model	Optimization with perfect foresight over whole period	Welfare maximization
POLES *TIMER/IMAGE* *WEM* *MESAP/PlaNet*	Energy system model	Recursive Dynamic	Cost minimization (recursive)
ETSAP/TIAM *MESSAGE*	Energy system model	Optimization with perfect foresight over whole period	Cost minimization (all periods linked)
IMACLIM ; *PRIMES*	Hybrid: general equilibrium with technology explicit modules	Recursive Dynamic Mixed : interlinked CGE module and optimization of energy system modules	No objective function Cost minimization
E3MG	Econometric simulation model	Initial value problem; limited foresight	No objective function

Table 1 Classification of the models included in the modeling exercises selected (adapted by SMASH from Edenhofer et al., 2011)

3.1.3 Structure of the scenarios

The set of modeling exercises of this survey mainly focus on decarbonizing the economy, assessing the economic and technology feasibility of long term reduction emissions objectives. The originality of GEA exercises and the AUGUR project is to include additional objectives such as energy security, energy poverty reduction, and limiting air pollution.

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[20] This model has the specificity to be an econometric model.

Some scenarios are mainly normative or more radical in the way they envisage the shift in future demand and supply side systems, in particular Greenpeace[R]evolution scenarios (its primary goal is to show that the 100% Renewable objective in 2050 is technically achievable) and the GEA pathways, whereas the other modeling exercises are more descriptive. However the boundary between normative and descriptive is tenuous.

The scenarios carried out are labeled as business-as-usual, reference, baseline, without climate policy, central, current policies, without carbon constraint, mitigation, stabilization, with climate policy, with carbon constraint, new policies[21]. In general, the use of one or more reference scenarios is a necessary starting point for global mitigation costs estimation.

Baseline scenarios provide projections of the energy system evolution, the resulting greenhouse gas emissions and their key drivers, including growth in population, economic output, energy demand, and technology availability, as they might evolve in a future in which no explicit actions are taken to reduce greenhouse gas emissions. Baseline scenarios play several roles. From a methodological point of view first, they allow to analyze the behavior of models and the parameterization adopted: assumptions on parameters include, for example, hypothesis on growth drivers, on the acceptability of a civilian nuclear use, on demand price elasticity , on oil reserves, on the degree of international openness and financial integration, etc. Secondly, this methodological interest is combined (in the scenarios surveyed) with a substantive interest in the evaluation and design of climate policies where the production and analysis of a baseline scenario allows the identification of mechanisms responsible for the upward drift of emissions.

It is important to note that a model never contains other mechanisms than those that the modelers have previously identified and included in the system of representation. But the model can reveal non-trivial system effects, due to the interaction of the different mechanisms represented (Guivarch, 2009).

Some authors have objected to this approach in that baselines or reference scenarios are in most cases normative which limits the interest of the comparison. Hence, some modeling exercises such as the GEA scenarios assume no baseline and follow a methodology similar to the SRES scenarios (Nakicenovic et al., 2000).

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[21] We limited to the most common labels but there is a profusion of labels for the scenarios: benchmark, laissez-faire, no-intervention and by opposition with-intervention and so on.

Their goal is rather to cover the entirety of the feasible scenario space under a common storyline for future population, economic development and resulting energy demand growth, using statistically corroborated "middle-of-the-road" assumptions from the scenario literature (Nakicenovic et al., 2006; The GEA scenario development process (Source: IIASA, 2012), Figure 1).

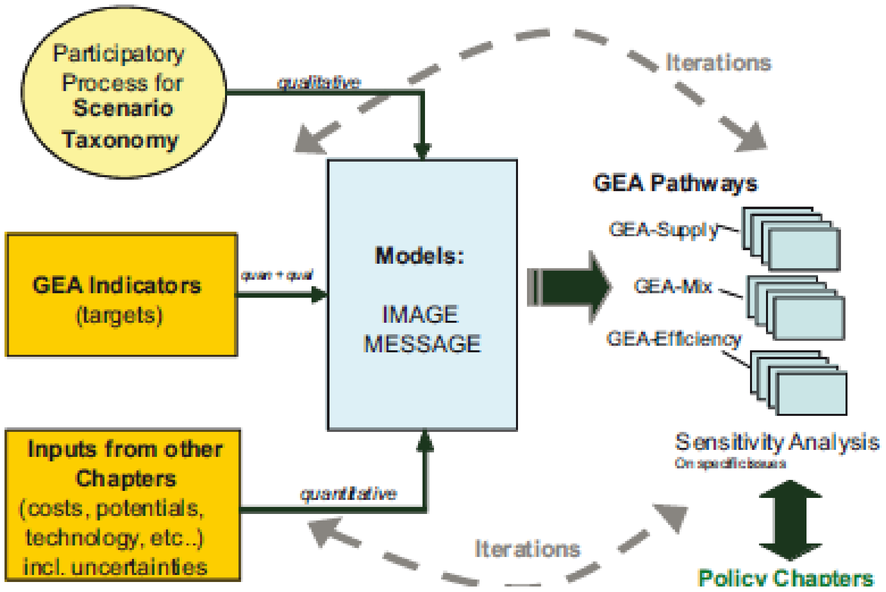

Figure 1 The GEA scenario development process (Source: IIASA, 2012)

In the next section, the report moves to a more in depth view of the main macroeconomic and technology hypothesis contained in the models.

3.2 Socio-Economic drivers

In this sub section we concentrate on the key forces in the Integrated Assessment models (IAMs) including population, baseline GDP or labor productivity growth, and technological change which are typically inputs to the models[22]. All the drivers impact more or less directly the energy security issues.

3.2.1 Population growth

Population growth is a key driver of energy consumption, carbon emissions and hence global warming. Global population has been growing at approximately 1.8% over the second half of the 20th century. Increasing incomes and the setting of demographic transitions in a large number of developing countries have started to

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[22] These are obviously a mere part of socio-economic drivers. Other such as urbanization, education are poorly taken into account in the set of scenarios surveyed.

reduce the population growth. However, the large majority of demographers agree in their evaluation that the world's population will keep growing until at least the middle of this century, putting additional pressures on the natural environment[23].

The selected modeling exercises in our survey are based on population forecasts from the UN Department of Economic and Social Affairs, Population Division (DESA) or IIASA[24]. The average population forecast is used in most scenarios[25] with slight differences. Differences in regional population trajectories between models are mainly owing to how individual countries are aggregated into macro-regions in each model.

Over the course of this century, global population is assumed to reach a plateau around 2050-2070 (peak at around 9.5 billion in 2070) and stabilize at roughly 9 billion in 2100 (Figure 2). In 2035, in IEA population projections based on biannual revised projections for UNDP, global population projections reach 8.6 billion people. In ADAM, RECIPE, GREENPEACE-EREC projects, population reaches around 9 billion people in 2050.

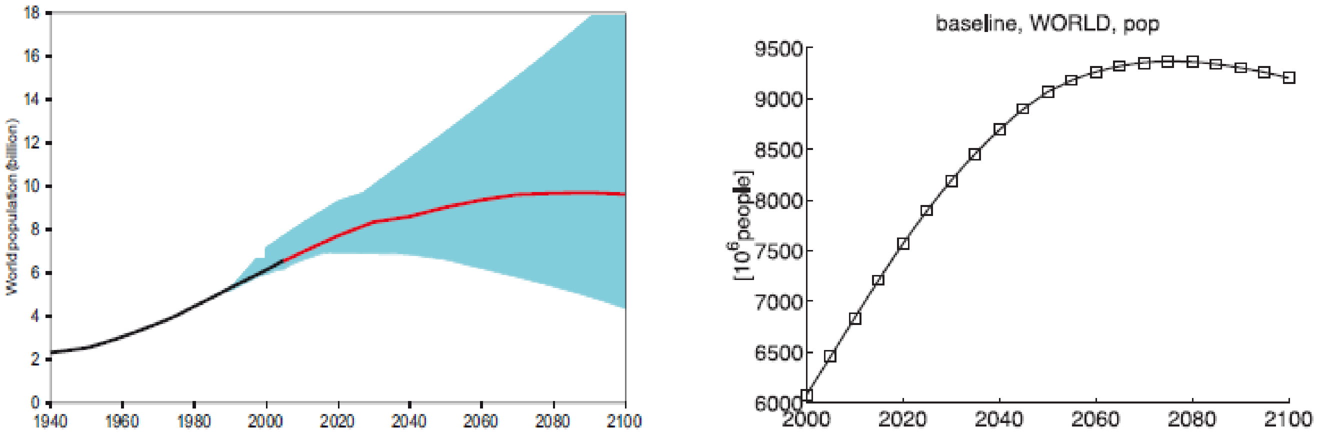

Figure 2 Population trend (upward GEA Source: IIASA, 2012, and downward by ADAM project , Source: Edenhofer et al., 2010)

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[23] Long term projections of population trends have been reexamined since the 90's : the highest trend for world population in 2100 decreased from 19 to 15 billion inhabitants , the lowest trend increased from 6 to 5 billion.

[24] World Population Program, http://www.iiasa.ac.at/Research/POP/proj01

[25] http://esa.un.org/unpp/

Growth rates by regions vary significantly as shown by projections of IIASA in Table 2 or in the RECIPE project in Figure 3. Population in developed countries at present is assumed to stabilize around 1.2 billion. The most dynamic development with respect to population is foreseen to take place in the rest of non-Annex 1 countries[26], which are expected to account for the increase of 2.5 billion people over the century, corresponding to an almost doubling of their current population.

The structure of population impacts the economy through labor productivity and therefore dynamics of the labor market. Across OECD countries, only the US maintains a certain demographic dynamism (+26% in 2050 for North America). Although confronted with a significant ageing population, its demographic growth allows the US to maintain their employment rate beyond 60%. Developing countries gradually face a demographic transition with a decrease of their average birth rate from 2.9 to 2.0 children/ woman[27]. As a result of its one-child policy and higher incomes, China will suffer from a significant ageing population which could potentially entail a decrease of savings.

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[26] Non-Annex I countries are developing countries, under the Kyoto Protocol. Non-Annex I countries do not have legally binding emissions reductions targets.

[27] See Duncan and Wilson (2004) for a complete analysis on UN assumptions on fertility rates.

	Total Population (millions)		
	2010	2050	2100
North Africa	208	307 *(+48%)*	324–346 *(+56%–+66%)*
Sub-Saharan Africa	799	1,617 *(+102%)*	2,074–2,247 *(+160%–+180%)*
North America	339	427 *(+26%)*	421–468 *(+24%–+38%)*
Latin America	595	834 *(+40%)*	909–977 *(+53%–+64%)*
Central Asia	65	96 *(+48%)*	101–108 *(+55%–+66%)*
Middle East	215	359 *(+67%)*	392–417 *(+82%–+94%)*
South Asia	1,625	2,289 *(+41%)*	2,016–2,140 *(+24%–+32%)*
China & CPA	1,468	1,342 *(–9%)*	829–881 *(–56%–-40%)*
Pacific Asia	542	699 *(+29%)*	649–689 *(+20%–+27%)*
Pacific OECD	152	137 *(–10%)*	85–103 *(–44%–-32%)*
Western Europe	462	449 *(–3%)*	320–364 *(–31%–-21%)*
Eastern Europe	120	94 *(–22%)*	54–60 *(–55%–-50%)*
Former Soviet Union	228	169 *(–26%)*	103–111 *(–55%–-51%)*
WORLD	6,816	8,816 *(+29%)*	8,280–8,920 *(+21%–+31%)*

Table 2 Population projections by regions used in the GEA pathways (Source: IIASA, 2012 from Lutz et al., 2008)

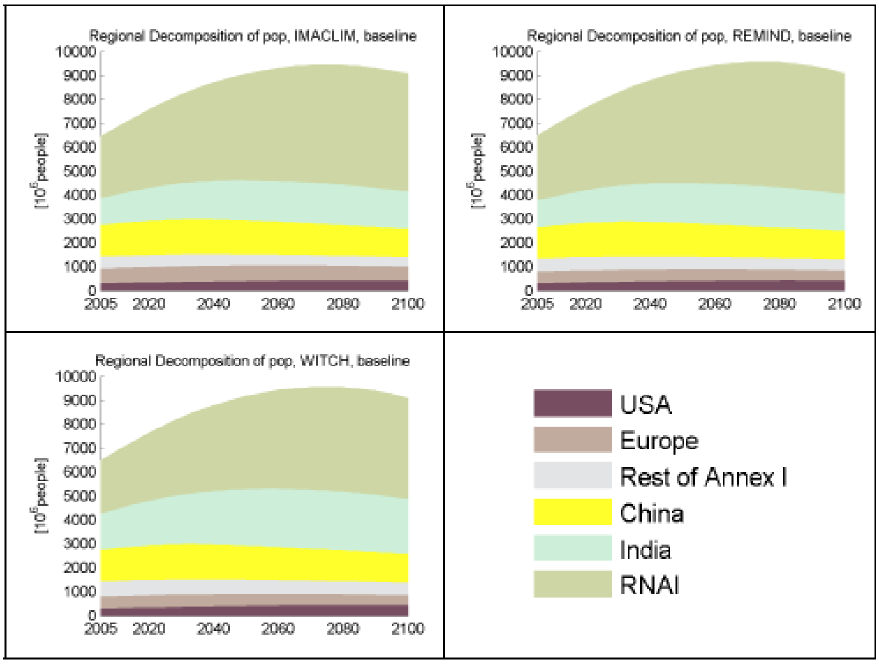

Figure 3 Long term population trend by region (Source: RECIPE project Luderer et al., 2012)

No sensitivity analysis on the populations trends have been conducted in the selected scenarios. Indeed, policymakers neither consider reducing population growth nor the reduction of economic output as a way to reduce greenhouse gas emissions or to enhance energy security; hence the focus of climate change mitigation is principally on achieving emissions cuts, by reducing the energy intensity and carbon intensity of the economic system in particular so far in OECD countries.

3.2.2 Macro-economic development

Economic growth is a key driver for energy demand. As people become richer, they consume larger amounts of goods and services and increase their demand for energy for residential use and transport. The content of the economic growth (energy mix, technical change, consumers' behaviors, investments dynamics and so on) will raise energy security issues specific issues at the regional and country level. Since 1971, each 1% increase in global Gross Domestic Product (GDP) has been followed by a 0.6% increase in primary energy consumption (IIASA, 2012). The decoupling of energy demand and GDP growth is therefore a prerequisite for reducing demand in the future. This decoupling varies among the regions and inside regions and between countries.

For most models considered in our survey, particularly those with a bottom up structure, GDP trend is exogenous[28]. For instance, IEA (2012) uses the OECD projections (Table **3**) by 2035. Global GDP is assumed to growth at a rate of 3.5% between 2010 and 2035[29]. Average annual growth rate in the Greenpeace scenarios decreases after 2030 to around 2.5% by 2050. In the RECIPE and ADAM projects, models were calibrated such that they project world GDP to grow at an average rate of 2.1% to 2.4%, resulting in year 2100 income levels which are between 8 and 10 times their 2005 value. Given their normative dimension, GEA pathways share a median economic development path, built on the updated IPCC B2 scenario (one out of the four main storylines of the SRES scenarios (Nakicenovic et al., 2000) projections by Riahi et al. (2007)). Socio economic development pathway chosen is consistent with global aspirations toward a sustainable future while also attaining this goal with a high degree of confidence. Global real per capita income in the GEA pathways grows at an annual average rate of 2% over the next 50 yrs.

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[28] Two exceptions, the hybrid CGE IMACLIM-R in the RECIPE project calcules endogenously a GDP trajectory annually and E3MG in the ADAM project.

[29] Greenpeace-EREC also relies on IEA (WEO2009) projections for 2005-2030

	Compound average annual growth rate (%)			
	1990-2010	2010-15	2010-20	2010-35
OECDE	2.2	2.1	2.2	2.1
Americas	2.5	2.6	2.7	2.4
United States	2.5	2.5	2.6	2.4
Europe	2.0	1.5	1.8	1.8
Asia Ocenia	1.9	2.0	2.0	1.8
Japan	0.9	1.2	1.2	1.2
Non OECDE	4.9	6.1	5.9	4.8
E.Europe/Eurasia	0.5	3.9	3.8	3.4
Russia	0.4	4	3.9	3.5
Asia	7.5	7.5	7	5.5
China	10.1	8.6	7.9	5.7
India	6.5	7.3	7.1	6.3
Middle East	4.3	3.7	3.9	3.8
Iraq	3.1	10	10.6	6.9
Africa	3.8	4.4	4.6	3.8
Latin America	3.4	4.2	4.1	3.4
Brazil	3.1	3.6	3.8	3.6
World	3.2	4	4	3.5
European Union	1?8	1.3	1.7	1.8

Table 3 GDP projections in the IEA scenarios (Source: IEA, 2012 from IMF (2012); OECD (2012))

These projections assume more rapid catch-up growth and partial convergence in most of developing countries driven by labor productivity. Labor productivity in developed countries increases at a constant rate. Between 2010 and 2035, the average Asian growth rate slightly exceeds 5%, Africa and Latin America reach respectively 3.4% and 3.8% on average while the US and especially Europe have more modest growth rates. At the end of the period, China and India growth rates decline as these countries move from catch up growth to a stage of maturity. At the end of the 21st century, the US, Europe, and Japan are expected to remain the regions with the highest incomes per capita, with other countries, especially China and India, closing the gap[30]. As in the case of population long term estimates, these projections refined regularly are consensual and not best guest projections based on

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[30] In baselines scenarios developed in the RECIPE project, World-wide GDP of about 42 trillion $US3 in 2005 increases to almost $US 345 trillion in 2100. China already provides a significant share of global GDP in the coming decades. But its growth rate of 1.5% in 2100 is comparatively low with India's growth rate (2.7%). Conversely, the US, Europe, Japan are characterized with the lowest growth rates (less than 1% by 2100) while they still account for one-third of world GDP by 2100. Per capita GDP levels between regions converge rather slowly. In particular, Africa's per capita GDP in 2100 is more than 80% below the world level of $US 38,000 (Jakob et al., 2009).

OECD or IMF works which off course cannot take into account possible shocks due to the energy or the financial system. They also cannot integrate all the potential changes in consumption patterns or future technical revolution.

Embarking these socio-economic drivers and given environmental and socio-economic policies, models project an economic and technical trajectory (optimal or not depending on the structure of the model as shown in section 3.1) to comply with the trend.

Modeling calculations - PPP vs MER debate

In modeling exercises GDP can be expressed in Purchasing Power Parities (PPP) or in Market Exchange Rates (MER). Purchasing power parities compare the costs in different currencies of a fixed basket of traded and non-traded goods and services and yield a widely-based measure of the standard of living. Market exchange rate places countries in a common currency for estimation and calibration.

Most global energy/economic/ environmental models constructed in the past have relied on market exchange rates. This approach has been the subject of considerable discussion in recent years in the assessment of long term projections, and the alternative of purchasing power parity (PPP) has been proposed. Castle and Henderson (2003) argue for instance that using MER underestimates the real size of developing economies and overestimates their convergence rate.

Depending on the issues tackled one or the other measure can be more appropriated. GDP import- export balance and most of investments are strictly depending on MER whereas PPP assessments although still relatively imprecise, compared to statistics based on national income, product trade and national price indexes, are more suited for assessing domestic standard of living. GDP projections and global pathways costs are mostly expressed in recent modeling exercises surveyed in PPP. PPP is supposed to better assess the impact of climate policies on developing countries as MER underestimates the real size of developing economies and overestimates their convergence rate, therefore leading to excessive growth their economic activity, energy consumption and emissions.

Discounting

The discount rate determines the present value of future interest payments received by the investor. It also reflects the risk and uncertainties associated with an investment (higher risk projects command higher returns, hence higher discount rates). Its value may impact to some extent on the cost of capital intensive projects, in particular low carbon infrastructures which require huge upfront investments, and hence the cost of climate policies.

The debate on the appropriate discount rate was very intense in the 90s (see Portney and Weyant, 1999 and Newell and Pizer, 2001). It was revived by the release of the Stern Report (2006). Stern used a discount rate considered too low by some economists (Tol and Yohe, 2006; Nordhaus, 2007; Weitzman, 2007; Gollier et al., 2008; etc.). Indeed, adoption of a low/high discount rate means a lower or higher preference for the present versus future costs and hence when applied to mitigation costs; highlights the significance of long or short term costs. The RECIPE and ADAM projects follow (IPCC, 2007); global mitigation costs (expressed in losses of consumption or GDP) are discounted with a median value of 3%. One can acknowledge that this value is completely arbitrary and in principle would require sensitivity analysis in modeling exercises given the uncertainties around it. Note that Hourcade et al. (2009) moderate the importance of these debates on the discount rate. It shows that, in an uncertain world, it is only one of the parameters to be taken into account when the choice has to be made between consumption and investments, while the value of information is a parameter at least as important for this trade-offs between short term and long term perspectives.

3.2.3 Energy Intensity

Energy intensity (EI) is a key indicator for Energy security issues. It is defined as primary energy use per GDP, or primary energy rise to growth of GDP (based on proper incremental datasets). The final energy intensity of the global economy has fallen at a rate of about 1,2 % /yr since the early 1970's (China about 4%/yr between 1990 and 2000, 4,3%/yr in Poland between 1995 and 2010) and the two oil shocks (IIASA, 2012). Several factors can explain these improvements in terms of energy efficiency:

- Technological improvements in individual energy and end-use appliances and technologies combined with substitution among fuels;

- Increased intensity of urbanization (characterized by generally higher system efficiencies);
- Changes in the structure of the economy including i) higher shares of the less energy-intensive services sectors ii) and changing lifestyles which affect both the type and the level of energy services demanded (Nakicenovic et al., 1998).

The literature shows that energy intensity may be reduced by of a factor of 10 in the very long run (Nakicenovic et al., 1993, Gilli et al., 1995, Nakicenovic et al., 1996).

Scenarios analyzed in this review assume a global decrease in the energy intensity of GDP over the century. The ADAM and RECIPE projects find similar trends in terms of energy efficiency improvements in baselines. In the ADAM project, energy intensity reduces in the baseline from 0.8% to 1.2% per annum across the models, which is in line with the historical record (Nakicenovic et al., 2000; Fischer et al., 2007). In the RECIPE project, the average annual declines in energy intensity ranges from 0.9% (IMACLIM) to 1.1% (WITCH).

Climate policies strengthen the decoupling between growth and energy consumption and therefore emissions. In the GEA projections, the global average reduction in energy intensity varies between about 1.5% (faster than the historical experience) and 2.2% annually to 2050 (roughly double than the historical trend and corresponds to a reduction in energy intensity of 60% by 2050). The decrease is particularly significant in the scenarios, which include strong support for energy efficiency and large scale investments.

3.3 Technical change: deployment of technologies

Technological change has become a key point in modeling exercises as their objective is to assess the technical and economic consequences of targets consistent with the 2°C reduction target and the role of technologies in the decarbonisation process (ADAM, RECIPE, EMF22, ETP). Technical change driven by climate policies will impact energy security issues (see section 6).

One of the major modeling issues that has received attention and efforts in recent years addressed the representation of induced technical change (investment in research and development, learning by doing ...) in IAMs. The debate has concentrated on the need to abandon the traditional representations of exogenous technical progress in which the climate policies cannot influence the course of technological developments. Therefore, most models have progressively adopted an endogenous representation of technical change and include mechanisms for technological evolutions induced by price pressure and (or) by R&D policies (learning by doing, learning by searching). This is the case in particular for most of the models in this review

The IPCC AR4 acknowledges these efforts from modeling teams:

“A major development since the Third Assessment Report (TAR) has been the treatment of technological change in many models as endogenous, and therefore potentially induced by climate policy, compared to previous assumptions of exogenous technological change that is unaffected by climate policies.” (Barker et al., 2007, section 11.5.1)

These developments are used in the set of scenarios surveyed in this report to assess the availability of critical technologies to support ambitious mitigation policies: nuclear, renewables, biomass and CCS.

Table 4 pictures for instance the different options the ADAM project envisages in terms of availability of these technologies and the sensitivity analysis conducted. For each mitigation target (400ppm and 500ppm), each model provides a scenario with full availability of technologies and then 8 alternative scenarios with specific constraints on the deployment of each technology considered. The next section will highlight the main results.

Scenario Name	**Description**
500ppm400ppm	All options, unlimited CCS potential, biomass potential limited to 200 EJ/yr
norenew	Investments into renewable energy and biomass are fixed to baseline values
noccs	Amount of CCS is fixed to baseline values (zero)
nonuke	Amount of nuclear energy is fixed to baseline values
biomin	Biomass potential is limited to 100EJ/yr
biomax	Biomass potential is limited to 400EJ/yr
ccsmin	CCS storage potential is limited to 120 GtC
nuke phaseout	No investments into nuclear from 2000 on
fbr	Inclusion of the fast breeder option

Table 4 Technology Options and Sensitivity Scenarios in the ADAM project (Source: Edenhofer et al., 2010)

3.4 Energy and carbon prices

3.4.1 Oil reserves/resources

The geopolitics of oil market regularly renew the debate on energy security in oil importing countries. The assumptions on future resources and fossil prices are characterized by intense debates, in particular around Peak oil (PO). Most analyses have been focused on the anticipated date of the Peak Oil and in most cases assume exogenous assumptions on the total amount of oil reserves. Oil production levels at a given point in time are therefore only determined by remaining reserves in the earth, in turn depending on the sum of past production (see Al-Husseini (2006) and Waisman et al. 2012 for a review)[31]. Following the latest projections, modeling exercises surveyed here assume a plateau of oil production around 2030 rather than a dramatic decrease after a peak year (the undulating plateau in Figure 4). For instance, in its *New Policy Scenario*, WEO2012 projects that global oil demand would rise by 12,3 mb/d from 2011 to 2035, and reach 99,7 mb/d in this period (corresponding to the dotted line in Figure 4). Oil production will probably become more geographically concentrated in the Middle East and demand for oil will continue to increase, primarily in Asia (Figure 5). Conversely, OECD countries know a significant decline due to lower growth rates, higher oil prices, energy efficiency savings and the effect of an already more matured economy.

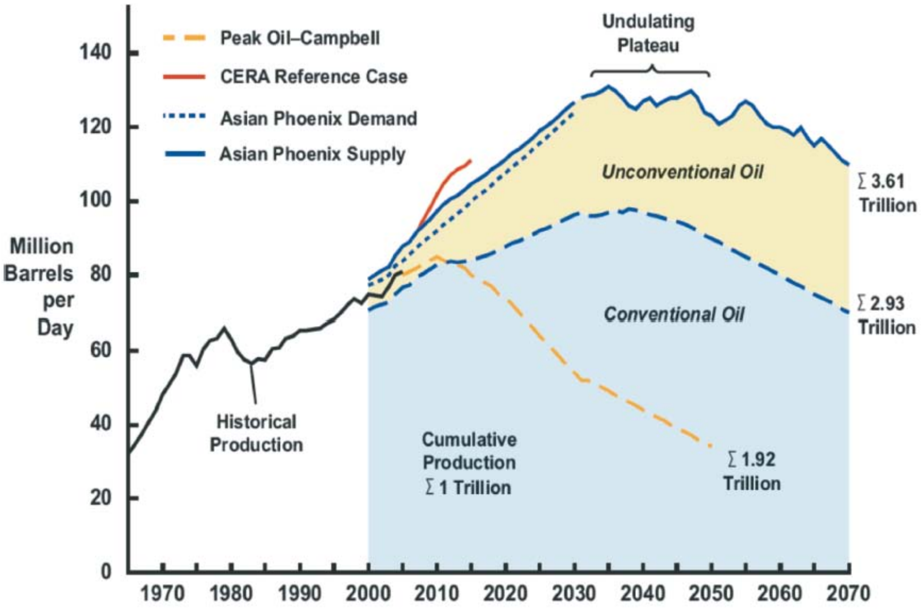

Figure 4 Undulating plateau versus peak (Source: IIASA, 2012 from Witze, 2007)

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[31] This vision is supported by the generalization, at a global level, of bell-shaped profiles used by Hubbert to predict the decline of US production in the 1970s (Hubbert, 1956, 1962; Deffeyes, 2002).

Furthermore, as oil production stabilizes or declines and demand increases in particular in developing countries, crude oil prices increase. This fosters the penetration of nonconventional fossil fuel in scenarios. The specific impact of the recent surge of shale gas production is more precisely analyzed in WEO 2010 and 2012.

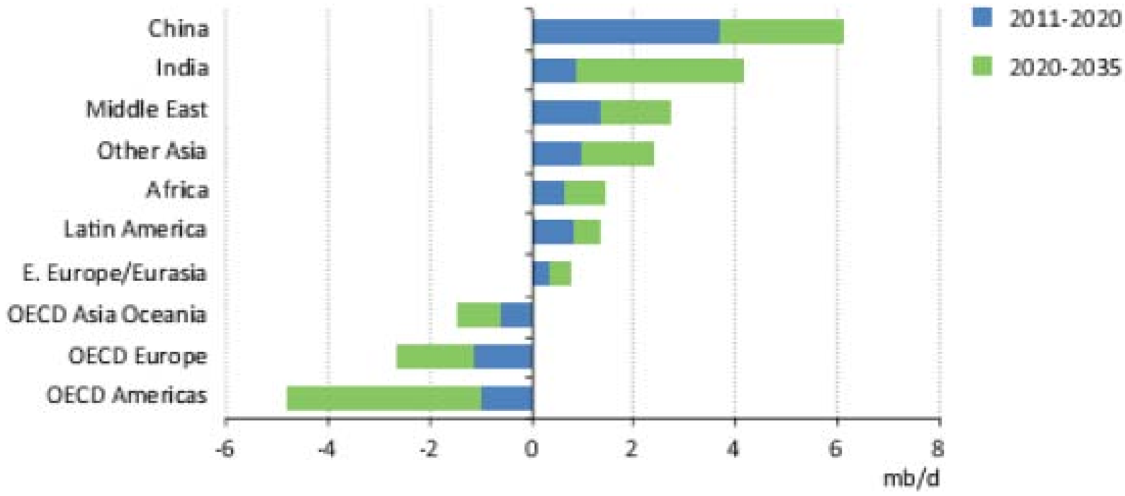

Figure 5 Oil demand growth by region in the New Policies Scenario (Source: IEA, 2012)

As shown in Table **5**, models project a moderate but significant rise of oil prices after 2030 (corresponding more or less to the aforementioned plateau of production). In addition to different assumption about production and reserves among the different scenarios, prices also depend on the evolution of the energy mix and technology pathways determined by: relative prices, capital and operating costs determining technological choices, learning by doing, climate policies and *in fine* by the very structure of the model. However it is important to note that few models endogenize the cost of fossil fuel and most refer to the IEA trajectories[32].

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[32] In IMACLIM, MERGE, REMIND and POLES the costs are endogenous to the model. However, MERGE and REMIND give shadow prices which correspond to the marginal costs of strengthening the constraint. In optimization models based, it is the value of the Lagrange multiplier at the optimal solution, which means that it is the infinitesimal change in the objective function arising from an infinitesimal change in the constraint. In the IMACLIM model, oil prices are derived from the geological, technical, macroeconomic and geopolitical determinants of supply and demand under non-perfect expectations (Waisman et al., 2012).

	2035	2050	2100
ADAM (Baseline)	30-60	35-90	40-230
Greenpeace 2010 (Baseline IEA 2009, $2008)	115	na	na
ETP2010 (Baseline ($2008)	na	120	na
WEO2012 (current policies) ($2011)	145	na	na
WEO2010 (new policies) ($2009)	110	na	na
ADAM (450ppm, ReMIND) ($2008)	60	65	75
WEO2009-2010 (450ppm) ($2008)	90	na	na
WEO2012 (450ppm scenario)($2010)	97	na	na
ETP 2010 (Blue scenario) ($2009)	na	70	na
Greenpeace Energy Revolution 2010, 2012 ($2009)	150	150-152	na

Table 5 Long term oil prices in selected modeling exercises in baseline and climate policies scenarios (US$/bl) (Source: SMASH)

Gas market

Projections show that the decrease of gas production observed in OECD countries in the coming decades is offset by a strong increase in emerging countries in particular in China and India. According to IEA (2012), total gas reserves (resources technically recoverable) are estimated to be 790 tcm. Off this, 42% is non-conventionnal gas (25% of which is shale gas). Demand in gas should continue to rise according to IEA scenarios, from 50% for the New Policies Scenario to 60% for the Current Policies Scenario in 2035, corresponding respectively from 3307 bcm to 4955 and 5286 bcm. This rise is largely due to the emergence of Asian countries (6.6% annual growth on average for China, 4.2% for India), Middle East (2.1%), Africa (2.2%) and South America (2.2% , 4.3% for Brazil).

Conventional gas resources are in majority located in the Middle East and Russia (34% of the total).

Furthermore, the increase in the global production of gas is highly correlated to the increase in non-conventional gas. Recent projections from IEA (2010, 2011, 2012) show a significant rise in the proportion of unconventional gas in overall gas production (Table 6). Non-conventional resources are based principally in Pacific Asia, the US and Canada (49% of global resources).The enthusiasm for shale gas has been disturbing the IEA projections for some years and makes more uncertain the previsions on the importance of gas in the world energy overview.

IEA/WEO published	**Total natural gas production by 2035 (bcm)**		
		Unconventional (bcm)	**Unconventional (%)**
2010	4535	816,3	18%
2011	4750	1045	22%
2012	4955	1288,3	26%

Table 6 World natural gas production evolution by 2035 (Source: New Policy Scenario, IEA, 2012)

These estimations should also be interpreted with caution given the uncertainties on the reserves and shale gas production. Recently, drilling sites for shale gas have migrated toward more competitive light tight oil (petroleum that consists of light crude oil contained in petroleum-bearing formations of low permeability) under the current gas infrastructure conditions (network and storage congestions), and have given higher oil profitability. This has entailed a decline in part of the US shale gas production[33].

Coal market

Most modeling exercises assume large and cheap abundance of coal over the century. By 2030, according to IEA (2012) coal remains the second most important fuel behind oil and the backbone of electricity generation. In the absence of climate policies, coal plays a key role in the projections of economic growth of emerging countries, among them China which could represent almost 50% of coal demand by 2035 in the New Policy scenario of IEA (2012) (Figure 7 and see section 4)[34]. Indeed, China and India alone account for nearly 75% of non-OECD growth. Reserves are mostly concentrated in China, the US and Australia (Figure 6).

Current climate policies decrease coal use in the power and residential sectors or accelerate the deployment of CCS systems (see section 2.1).

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[33] The *Annual Energy Outlook* 2013 carried out by EIA (*Energy Information Administration)* forecasts a production of 888 bcm in 2035 vs 800 in the *New Policies Scenario* of WEO 2012. Caution should be exercised over these projections given the uncertainties on reserves and unconventional gas production. The recent development of *light tight oil* also raises many uncertainties.

[34] Even in the New Policies Scenarios which include the more recent climate policies, coal remains the second most important fuel behind oil and the backbone of electricity generation by 2035 while coal's share of global primary energy demand falls.

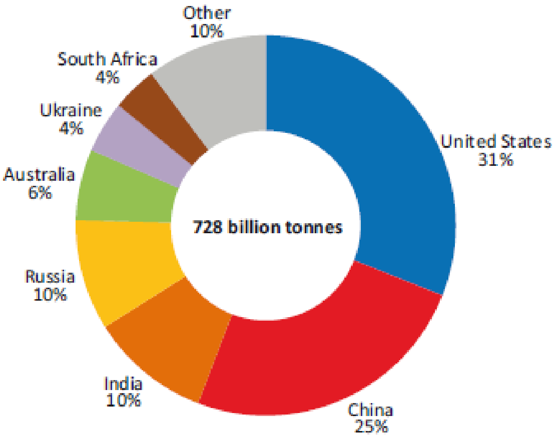

Figure 6 World hard coal reserves by country, end-2010 (Source: IEA, 2012, BGR, 2011)

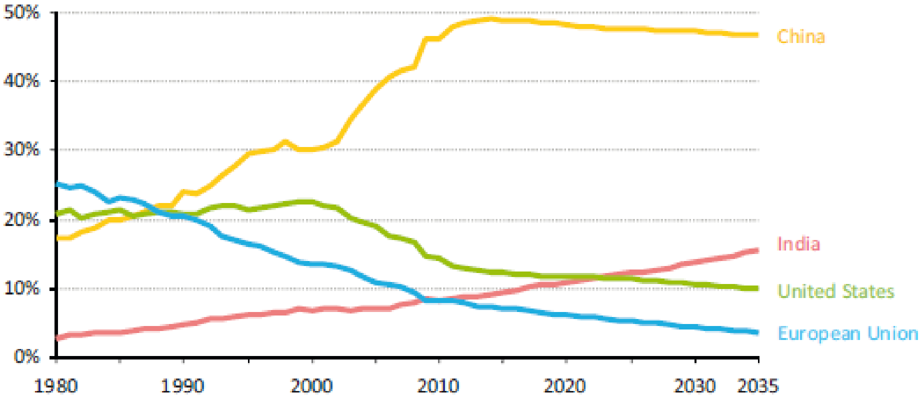

Figure 7 Share of key regions in global coal demand in the New Policies Scenario (Source: IEA, 2012)

These assumptions on fossil fuel reserves and costs will impact the geopolitics of energy and the future change in the energy mix of long term pathways as we will see in the next section, in particular in a setting of stringent carbon constraints. Impacts on energy security issues will be underlined in section 6.

3.4.2 Emission pathways

Energy-related emissions are driven in IAMs by population, per capita GDP, energy intensity of economic output, and the amount of CO2 emitted per unit of primary energy consumption. Therefore, emissions by 2100 depend on assumptions on fossil fuel reserves, the substitution between certain technologies, the structure of the economy, consumptions patterns and climate policy constraints. A common characteristic of all baseline scenarios as shown in Figure 9 for the RECIPE baselines is that the majority of emissions over the next century occur in regions currently outside the OECD while in 2005 industrialized countries accounted for roughly half of global carbon emissions.

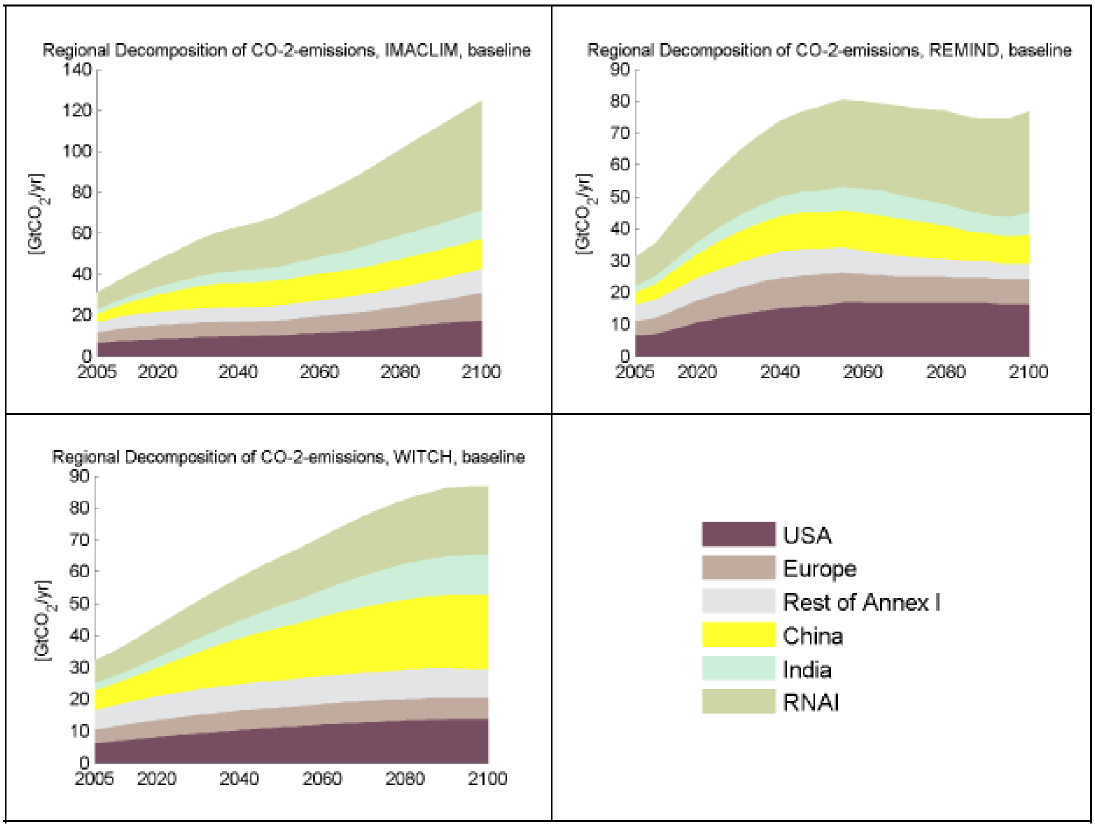

Figure 8 Carbon emissions in the baselines of the RECIPE project (Source: Jacob et al., 2009)

But as pictured by figure 9, emissions trajectories can vary significantly in the relation to the structure of the model. For instance, the RECIPE project opposes a green baseline vs a black baseline. The ReMIND-R model projects an energy demand 25 % lower than in IMACLIM-R in the year 2100, owing to more optimistic assumptions around the development of carbon-free energy technologies (biomass and other renewable energy, e.g.: solar, wind). Conversely, IMACLIM assumes a higher availability of cheap coal as a substitute for oil, which prevents the penetration of non-fossil energies and limits a large decoupling between energy demand and economic growth[35].

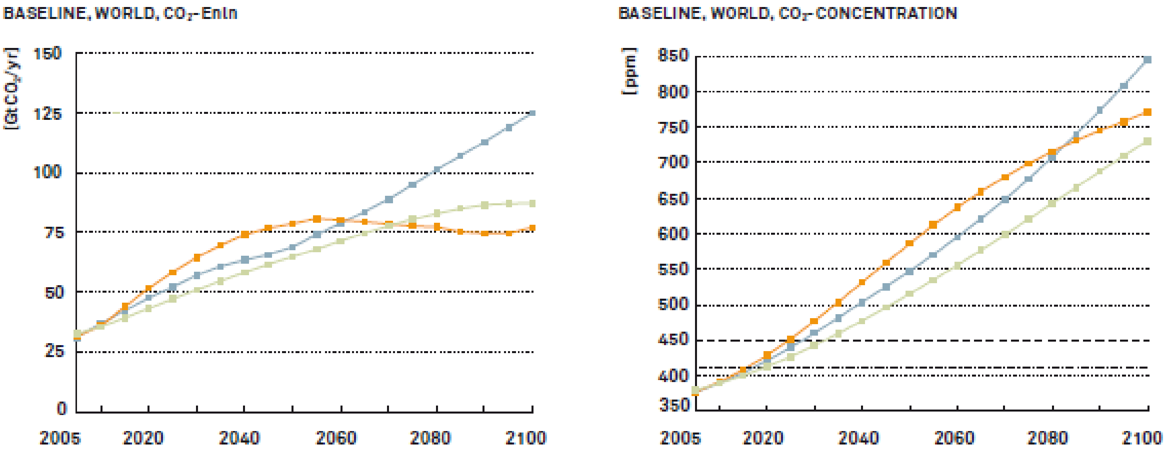

Figure 9 Global energy-related CO2 emissions in the reference scenario for IMACLIM – R (blue line), REMIND-R (orange line) and WITCH (green line) (left), atmospheric concentration of CO2 in the reference scenarios for IMACLIM-R, REMIND-R and WITCH (Source: Luderer et al., 2012)

All modeling exercises assess long term stabilization objectives more or less compatible with the 2°C reduction target included in the international agreements (EU 2005, G8 2008, Copenhagen 2009, Cancun 2010)[36]. As shown by Table 7, the 450ppm CO2-eq target implies a 50% to 80% reduction of CO2 emissions by 2050 compared to 1990 levels (IPCC, 2007). It also implies a peaking of emissions by about 2020 and emissions reductions of about -85 to 50% in 2050 relative to 2000 level[37]. This feature has been confirmed by more recent studies (Table 8).

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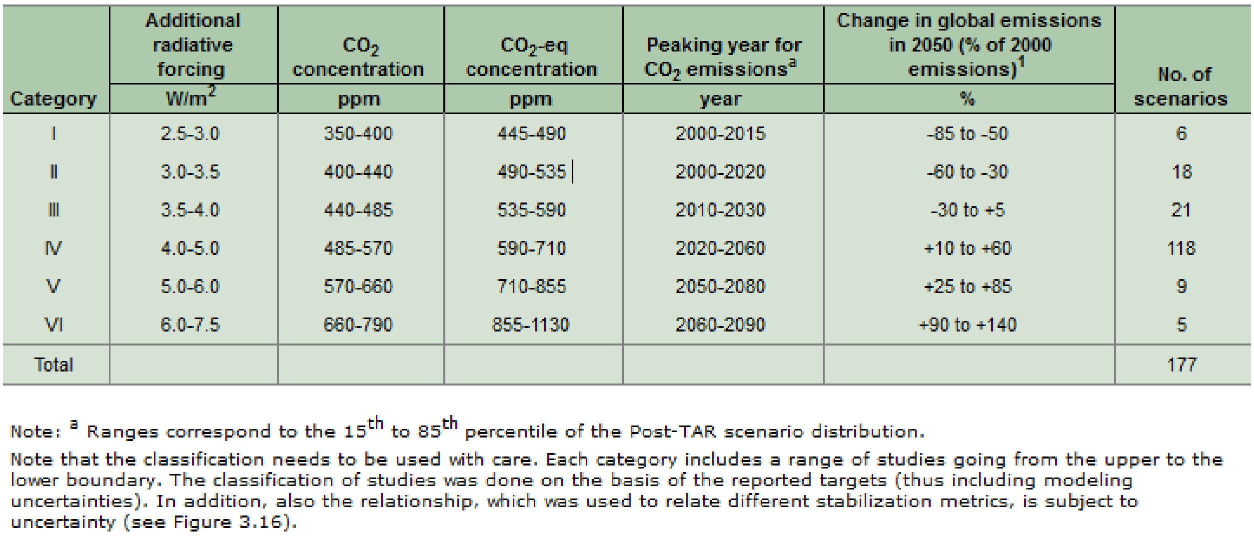
[35] In the IMACLIM model, this is reinforced by the inertias of infrastructures. The baseline of the third model WITCH can be classified as a less energy-intensive baseline with a 86 GtCO2 emissions in 2100 with a decreasing emission growth rate in the second half of the century.

[36] Since AR4, a large body of literature focuses specifically on the lowest scenario categories from the IPCC (i.e concentration targets leading to a radiative forcing of 4W/m2 or less). Based on O'Neill et al. (2010) and Den Elzen et al. (2007) which assess a wider range of trajectories, they show that there is more flexibility for short term emissions than suggested by a normative interpretation of AR4. In fact, the emission peak in these studies occurs even later than in the literature overview.

[37] GEA pathways follow emissions trajectories defined by the RCP (Representative Concentration Pathways) process in the perspective of the next IPCC report (AR5). The RCPs are part of a process in which climate and Integrated Assessment modelers will work in parallel toward the generation of new integrated scenarios of climate change to support the IPCC's Fifth Assessment Report. The selection of the four RCP models is documented in Moss et al (2008). One objective corresponds to a very low radiative forcing e.g. 2.6 W/m^2 to comply with the 2°C objective.

Two main targets are considered by scenarios: 550ppm and 450ppm CO2-eq[38]. RECIPE and ADAM projects assess more stringent targets, 410 and 400ppm CO2-eq corresponding to a 1.5°C increase in average global temperature by 2100.



Category	Additional radiative forcing	CO_2 concentration	CO_2-eq concentration	Peaking year for CO_2 emissions[a]	Change in global emissions in 2050 (% of 2000 emissions)[1]	No. of scenarios
	W/m^2	ppm	ppm	year	%	
I	2.5-3.0	350-400	445-490	2000-2015	-85 to -50	6
II	3.0-3.5	400-440	490-535	2000-2020	-60 to -30	18
III	3.5-4.0	440-485	535-590	2010-2030	-30 to +5	21
IV	4.0-5.0	485-570	590-710	2020-2060	+10 to +60	118
V	5.0-6.0	570-660	710-855	2050-2080	+25 to +85	9
VI	6.0-7.5	660-790	855-1130	2060-2090	+90 to +140	5
Total						177

Note: [a] Ranges correspond to the 15th to 85th percentile of the Post-TAR scenario distribution.

Note that the classification needs to be used with care. Each category includes a range of studies going from the upper to the lower boundary. The classification of studies was done on the basis of the reported targets (thus including modeling uncertainties). In addition, also the relationship, which was used to relate different stabilization metrics, is subject to uncertainty (see Figure 3.16).

Table 7 Total global CO2 emissions pathways comparison with selected scenarios from the literature (Source: IPCC, 2007)

Emission reduction pathways depend strongly on the pace climate policies are implemented and the technological assumptions. Peaking emissions around 2020 requires a rapid introduction of climate change mitigation policies, emissions reductions of about 30-70% by 2050 compared with 2000 and a further strengthening of climate policies. The possibility of overshooting the optimal GHG emissions trajectory to comply with the 2°C reduction target (2,6wh/m2) is increased (Figure 10 shows one possible trajectory included in the ADAM project with limited overshoot). It prevents from negative emissions to get net negative emissions by the end of the century (Wigley et al., 2007, Den Elzen and Van Vuuren, 2007). This is made possible in scenarios (RECIPE, EMF22) through the implementation of specific technologies in particular biomass combined with CCS (BioCCS or BECCS) (see part2.2). In terms of allowable emissions budget, the GEA pathways assume that the headroom of total 1180 Gt CO2 (full range is 940-1460 GtCO2) compatible with the 2°C reduction target between 2010 and 2100 would be spent on average in about 38 years (full range is 30-45 years) at today's trend of emissions.

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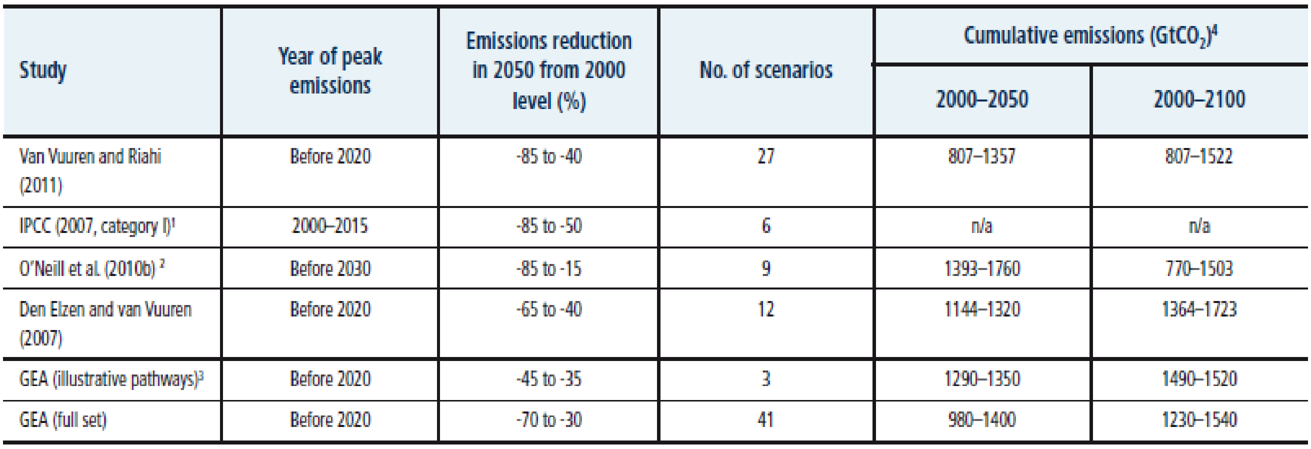
[38] This encompasses the all well-mixed Kyoto greenhouse gases (CO2, methane, nitrous oxide, sulfur hexafluoride, tetrafluoromethane, and halocarbons). However, no scenario assesses the impact of specific GHG beyond CO2.



Study	Year of peak emissions	Emissions reduction in 2050 from 2000 level (%)	No. of scenarios	Cumulative emissions ($GtCO_2$)[4]	
				2000–2050	2000–2100
Van Vuuren and Riahi (2011)	Before 2020	-85 to -40	27	807–1357	807–1522
IPCC (2007, category I)[1]	2000–2015	-85 to -50	6	n/a	n/a
O'Neill et al. (2010b) [2]	Before 2030	-85 to -15	9	1393–1760	770–1503
Den Elzen and van Vuuren (2007)	Before 2020	-65 to -40	12	1144–1320	1364–1723
GEA (illustrative pathways)[3]	Before 2020	-45 to -35	3	1290–1350	1490–1520
GEA (full set)	Before 2020	-70 to -30	41	980–1400	1230–1540

Table 8 Total global CO2 emissions pathways comparison with selected scenarios from the literature (Source: GEA, 2012)

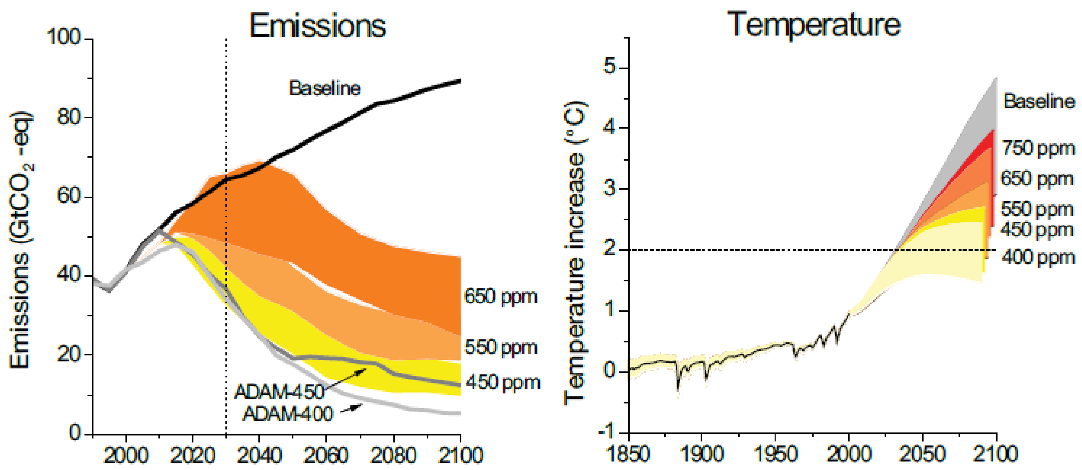


Figure 10 a Emission trends in the GEA pathways 10b indications of emissions profiles and global-mean temperature outcomes of different stabilization targets (Source: ADAM project, Edenhofer et al., 2011)

Carbon price

In selected scenarios, the range of CO2 prices depends on the pace of climate policies (see part 2.3) but also on the structure of the models and assumptions on technical change. Given a stabilization target, carbon prices range can therefore differ significantly across models. For instance, Figure 11 pictures the carbon prices measured in the scenarios of the ADAM project. The range varies from 20 to over 200$ t/CO2 (550ppm case) and 100-500$ t/CO2 (400ppm) in 2050, 0-450$ t/CO2 (550ppm) and 250-3000$ t/CO2 (400ppm) in 2100.

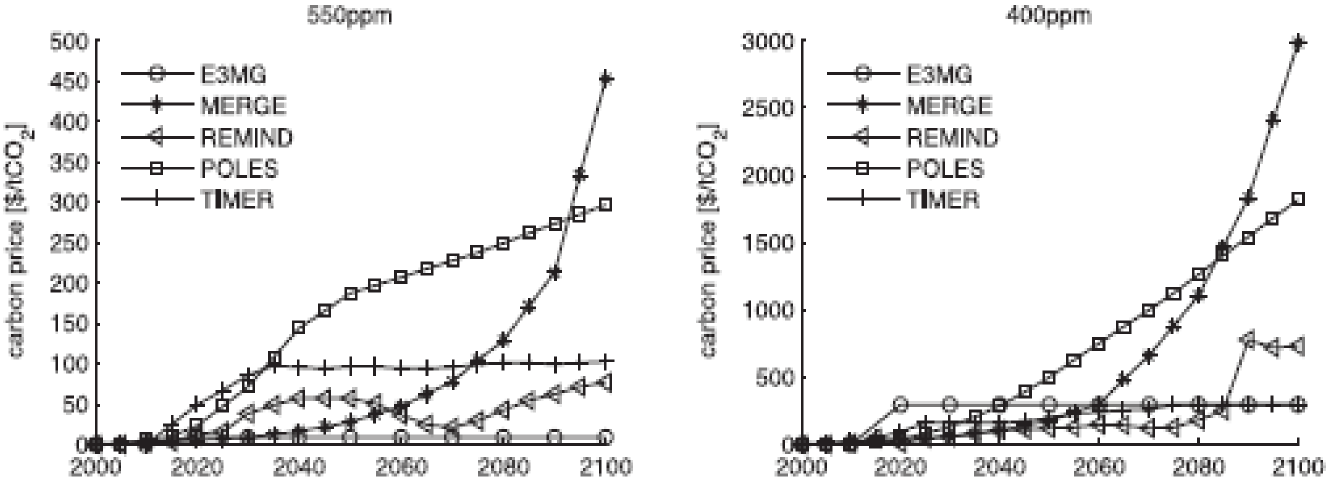


Figure 11 Carbon price for the 550 ppm and 400 ppm scenario (Source: ADAM project, Edenhofer et al., 2010)

In most models, carbon prices increase approximately exponentially over the first half of the century, roughly following a Hotelling path (Hotelling, 1931). After 2050, endogenous technical change in key mitigation technologies (learning effects) can in some scenarios limit this exponential trend (Edenhofer et al., 2010)[39]. In other scenarios, carbon price can go beyond 1000$ /tCO2 reflecting the high global cost of decarbonizing, hard to eliminate C02 emissions.

Chapter 1 presented an overall picture of the assumptions for main parameters used in models. A relative consensus emerges on some key assumptions (mostly exogenous to most models) such has GDP, population, rate of productivity while values of learning rates of technologies and difference of modeling structures (despite attempts to harmonize key drivers, endogenous trajectories still vary owing to modeling approach) are more specific to models. The parameterization of models will impact the transformations of the energy sector in different ways in function of the structure of the model.

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[39] Conversely, in IMACLIM-R very high carbon prices are required initially to create a sufficiently strong signal to trigger a transition to a low-carbon energy system. This is caused by imperfect foresight in combination with (a) inertias that limit the short-term substitutability between production factors, and (b) endogenous technological change due to which short-term investments have a critical effect on long-term availability and cost of mitigation options. The high prices result in very high transitional mitigation costs and welfare losses in the first 30 years of the modeled period. Once this transition is accomplished, IMACLIM-R projects negative mitigation costs due to additional technical change that is induced by climate policies allowing economies to be more efficient than in the sub-optimal baseline (Luderer et al., 2011, Waisman et al., 2012).

Section 4 and 5 will more precisely address the long term transformations (on the demand and supply side) given carbon and energy constraints in the set of scenarios surveyed at the global, regional and sectoral level. Section 6 will show how these transformations interact with energy security issues.

4. Features of the low carbon and energy transition given climate constraints (globally and by sector)

4.1 The low carbon transition requires significant transformations of the energy system

A first message to emerge from the scenarios is that long term low carbon pathways imply significant changes in the energy mix with respect to the baseline. These are characterized by a continuous decrease of fossil fuel (whereas in the baseline the amount of fossil fuel consumed still increases thanks in particular to a growing penetration of coal), a higher share of renewables (photovoltaic, wind energy, hydro, biomass), and a relatively stable or decrease in nuclear. A low carbon objective also entails a decarbonization of the power sector by the adoption of carbon-free power plants (gas or biomass powered plants combined with CCS process, and renewables), to a lesser extent of the transport system (hybrid and/or electric cars) and the residential sectors. Changes on the supply side are complemented by a reduced demand resulting from a combination of improvements in energy efficiency and some reduction in economic output.

Depending on models, different roadmaps of the transition toward a Low Carbon Society (LCS) can be envisaged. Interestingly, the GEA pathways point out that the low energy and carbon society can be achieved in two distinct ways:

- either with current infrastructures and supply systems based on centralized production and liquid fuels (oil, gas, coal to liquid, gas to liquid, hydrogen, more or less combined with CCS) or
- through a major shift driven by a huge deployment of RES combined with a decentralized production. The latter vision is particularly illustrative of the most radical Greenpeace scenarios.

Depending on the pathway followed, challenges for the energy systems and hence energy security issues will vary.

4.1.1 Global changes in the Energy mix

A decrease of Global primary energy demand growth rate

Across the scenarios, several fundamental historical energy trends persist such as :

- Rising incomes and population push energy needs higher;
- Energy-market dynamics are increasingly determined by the emerging economies;
- The development of decentralized energy production generation (so called micro- and mini- generation) based on RES, and also including natural gas and waste gases utilization. This vision is in parallel supported by the progressive implementation of intelligent network development;
- The implementation of policies to reduce energy demand is confronted to uncertainties around behavioral patterns, which can lead to rebound effect.

Table **9** features the evolution of Global Energy primary demand in scenarios (with or without specific policies) of some of the case studies surveyed. The increase in global energy demand varies according to the type of policies implemented. Stringent carbon targets (450ppm CO2eq) imply for instance a significant reduction in primary energy demand as it can be observed in the WEO 450ppm scenario in 2035 compared to a more conservative scenario (WEO2O12 current policies) or in the Blue Map scenario in 2050. Climate policies[40] limit the increase in global energy demand, they foster energy efficiency (on the supply side and demand in business sphere, i.e. industry, transport, commercial services), and encourage energy saving in particular in the residential and public sectors (see section 4.1.2).

However, different trajectories to comply with the 2°C target are conceivable. For instance, the GEA exercise developed three different pathways. The first one focuses on supply side options mainly based on liquid fuels, gas and optimistic assumptions on the development of CCS whereas in GEA Efficiency scenarios main drivers of the decarbonization rely on Energy Efficiency, a large scale deployment of RES and high efforts of energy savings.

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[40] In scenarios, either climate policies encompass different measures (carbon price, energy efficiency, feed in tariff for the renewables, norms…) on the supply and demand side or are integrated in broader development strategies such as in the GEA pathways.

Type of scenarios	**Global Primary Energy Demand, in (Mtoe)**					
	2005	**2015**	**2020**	**2030**	**2035**	**2050**
WEO2012 (current policies)	na	na	15332	17499	18676	na
WEO 2012 (New Policies[1])	na	na	14922	na	17197	na
WEO2012[2] (450ppm)	na	na	14176	14453	14793	na
ETP2010 (Baseline)	na	na	na	17000	na	22000
ETP2010 (Blue Map)	na	na	na	na	na	16000
GEA[3] (efficiency)	11703	na	na	na	na	16719
GEA[4] (supply)	11703	na	na	na	na	25078
GEA (mix pathway)	11703	na	na	na	na	22690

Table 9 Global Primary Energy Demand (Mtoe) in selected scenarios

1) WEO- new policies –the scenario takes into account existing policy commitments and “assumes that those recently announced are implemented”, whereas the current Policies Scenario assumes “no implementation of policies beyond those adopted by mid-2012”.
2) WEO2012 (450ppm) The 450 Scenario assumes “policy action consistent with limiting the long-term global temperature increase to 2 °C”.
3) ETP2010 blue map scenario provides a technology roadmap to comply with a 450ppm GHG target
4) GEA – global energy assessment, develops three contrasted groups of scenarios. *GEA efficiency* scenarios focus on energy efficiency as a main driver of the decarbonization (large scale deployment of RES and high efforts of energy savings) whereas *GEA supply* provides supply side options mainly based on liquid fuels, gas and optimistic assumptions on the development of CCS. *GEA mix pathway* includes both dimensions (efficiency and supply)

Energy mix: penetration of RES (renewable energy sources) , decrease of fossil fuels

The energy mix is a function principally of the characteristics of technologies embarked in the models (the availability and investments required, learning rates) and resource prices. The global current energy mix is mainly based on fossil fuels. About 81% of primary energy supply today still comes from fossil fuels. In 2009, renewable energy sources accounted for 13% of the world’s primary energy demand. Biomass, which is mostly used for heating, was the main renewable energy source. The share of renewable energy in electricity generation was about 18% in 2009. (IEA, 2010)

In all scenarios, by 2030, fossil fuels – oil, coal and natural gas – will continue to meet most of the world's energy needs. In WEO 2012 scenarios for instance, fossil fuels, which represented 81% of the primary fuel mix in 2010, remain the dominant sources of energy through 2035, although their share of the mix in 2035 varies markedly. Demand for renewable sources of energy rises at a faster rate, giving them a considerably higher share of the energy mix in each scenario of table 9. Under climate policies, a fundamental transformation of the energy sector is involved after 2030 through a decrease of fossil fuel, a strong penetration of RES (Wind, solar, hydro), biomass, and a moderate increase of nuclear (some scenarios assuming a nuclear phase out). Greenpeace scenarios represent an extreme case by assuming 100% RES in the energy mix by 2050 and an early phase out of nuclear.

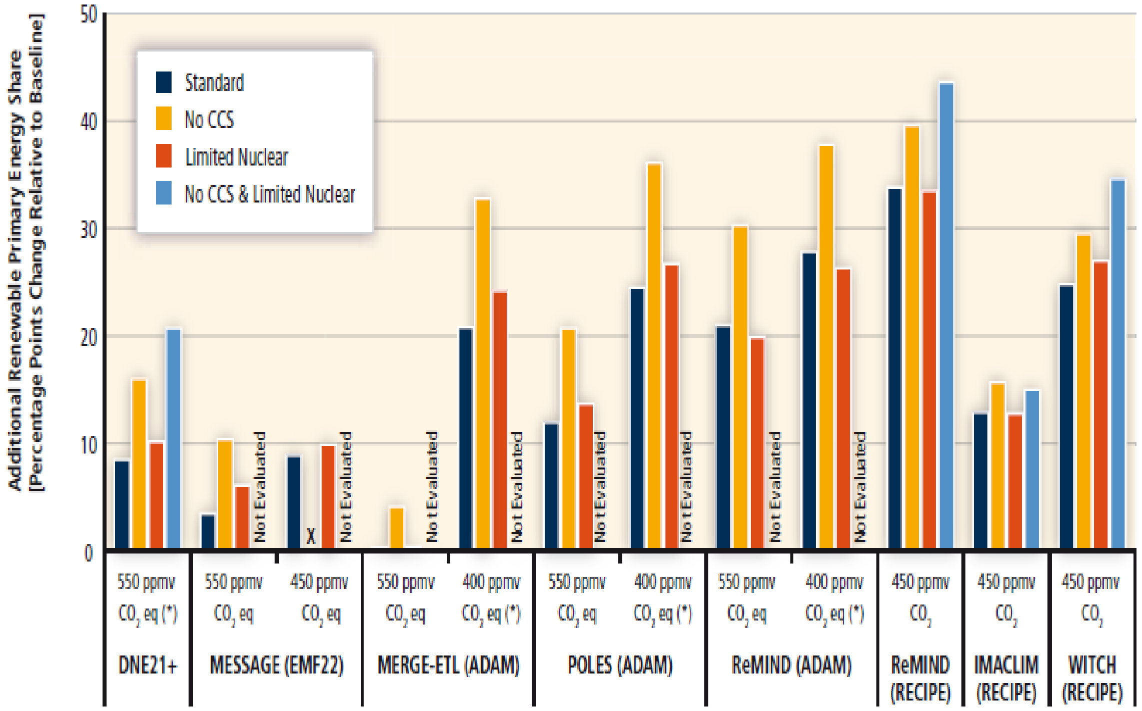

Figure 12 Increase in global renewable primary energy share in 2050 in selected technology constrained scenarios compared to the respective baseline scenarios. Projects taken into account are ADAM, RECIPE, EMF22 and DNE21+ projects (Source: SRREN, 2011).

Figure 12 extracted from the SRREN published in 2011, gathers findings of models in the respective modeling exercises: EMF22, ADAM and RECIPE projects regarding variations of RES relative to baseline scenarios. Modeling exercises have analyzed more precisely the impact of incomplete portfolio of low carbon technologies. The deployment of RES varies with respect to the deployment of other key low carbon technologies including CCS and nuclear. At a global level, results show that additional renewable primary energy share is necessary when CCS and nuclear are constraint (this option has only been evaluated in the RECIPE scenario). A higher share is also more required in the NoCCS case than in the limited nuclear case because of the high penetration of CCS in low carbon pathways. In parallel, much more energy savings are required.

4.1.2 Regional potentials of RES

In general, according to SRREN (2011), the deployment of RES will depend on economic development and technology maturity. Less mature technologies will likely require significant investments capacities and infrastructures, more located in rich countries (Europe, North America, Australia and parts of Asia) whereas more mature technology such as wind will see a greater geographical distribution of development “to be needed to achieve the higher deployments indicated by the scenario literature”.

Potentials at the regional level vary considerably and are more precisely addressed in GEA pathways (IIASA, 2012). In these scenarios, potentials depend on the quantity of reserves, “the availability of low-carbon supply-side alternatives (nuclear energy and fossil CCS) and the tradability of renewable energies or of secondary energy carriers”[41]. In regions with advantageous wind conditions, such as North America and Europe, wind power becomes the largest or second-largest source in terms of secondary energy provided[42]. In most other regions, by 2050, solar energy can become the “dominant renewable energy source” (IIASA, 2012). Hydropower continues to provide a sizeable share in OECD, FSU (Former Soviet Union) and Asia. The deployment of renewables in Asian regions is nevertheless hindered by high population density and potential conflicts around land use. As a result, renewable shares are less than 50% by 2050. Conversely, sub-Saharan Africa and Latin America (mainly through the production of bioenergy) have the highest renewables deployments by 2050, corresponding to a range of 40%-90% of primary energy supply coming from renewables.

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[41] Liquid biofuels are easier to trade and can even rely on existing infrastructures than electricity (e.g., from wind, solar photovoltaic and CSP, and hydropower) at the global scale. In GEA pathways this generally leads to higher exploitation rates of bioenergy potentials than of other renewables. For example, sub-Saharan Africa and Latin America, with the largest sustainable bioenergy potentials, export significant quantities of liquid biofuels starting after 2020 across almost all GEA pathways.

[42] The specialization in terms of RES in European countries are analyzed more in depth in section 3

Furthermore, in most scenarios, land use for production of bioenergy is assumed to grow. In some areas, abandoned agricultural areas due to a stabilizing population, further increases in yields, and rising food imports could be used for bioenergy production, in Latin America and sub-Saharan Africa (which also retain vast forest areas). Further details on these assumptions will be presented in section 6.

The deployment of CCS in the power and transport sector is crucial in most of stringent scenarios. It depends regionally on available alternatives such as non biomass renewable energy sources and above all on costs of fossil fuels and bioenergy. The regions with the highest storage volumes are those with large coal resources and correspondingly high utilization of coal with CCS (in particular in Asia or Former Soviet Union), large bioenergy potentials (sub- Saharan Africa), a combination of the two (North America) or a lack of alternatives (South Asia). However, the estimations of capacity storages, in particular in saline aquifers, are quite uncertain (IPCC, 2005, Hendricks et al., 2004)[43].

4.1.3 Sectoral changes in the Energy supply

Power sector

At present, power production accounts for approximately 40% of the overall global primary energy consumption. In baselines projections, the electricity generation mix is dominated by fossil fuels, mainly coal. Looking at scenarios, almost all predict that electricity demand will increase due to population growth, higher income and economic activity.

Furthermore, all scenarios demonstrate a dynamically growing share of renewables and other new energy technologies in the power production (RECIPE, ADAM, GEA, Greenpeace, ETP), in particular when climate policies are applied. On the supply side, according to Greenpeace Reference scenarios, fossil fuels are the main electricity source (67%), renewables amounts to 24% of total electricity generation, while by 2050, between 50% (Krewitt et al. 2009)[44] and 94% of the electricity produced worldwide will come from renewables (Energy [R]evolution scenario (2012)) .

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[43] It must be acknowledged that the global best estimate of Hendriks et al. (2004), about 1660 Gt CO2 , is almost 20% lower than the best estimate of the IPCC Special Report on CCS (IPCC, 2005) published shortly afterward.

[44] While this goes along with a corresponding reduction of the share of fossil and nuclear electricity, the electricity generation from fossil fuels remains nearly constant over time, with a strong shift however from coal to gas.

World Energy Outlook – Energy Technology Perspective (IEA, 2012) pictures almost similar trends with Greenpeace in terms of electricity growth and penetration of renewables in the total energy mix under the BLUE hi REN scenario. By 2050, electricity increases in the Baseline scenario from 17% (in 2007) to 23% of total final energy use and in the BLUE Map scenario to 28%. Without a significant change in policies, global electricity generation will continue to be largely based on fossil fuels to 2050. Fossil fuels increase their share of electricity production slightly to reach almost 70% by 2050 as pictured by Figure 13 and Figure 14 which gather projections of global electricity generation by fuels up to 2050 for three modeling exercises (ETP, E[R], WEO). Conversely, in the BLUE Map scenario, by 2050, renewable energy accounts for almost half of total global electricity production, while nuclear energy's share is just less than one-quarter. This report suggests the possible future contribution of the most important electricity generation technologies and fuels in the Baseline scenario and in few variants of the BLUE Map scenario which is broadly optimistic for all technologies;

- High nuclear (BLUE hi NUC) which assumes high penetration nuclear technologies;
- no carbon capture and storage (BLUE no CCS) which assumes that CCS is not commercially deployed;
- high renewables (BLUE hi REN) which assumes that renewables provide 75% of global electricity production in 2050.

As shown on Figure 13 and Figure 14, electricity demand in 2050 in the BLUE Map scenario is 13% lower than in the Baseline scenario owing to increased energy efficiency in the end-use sectors. In BLUE no CCS total electricity demand is 4% lower and the share of renewables increases to 54%. In the BLUE hi NUC variant, almost all of the nuclear potential is used and the share of nuclear generation increases to 39%. In the BLUE hi REN variant, the share of renewables in total electricity generation is set at 75% in 2050. The increased generation from renewables is mostly at the expense of coal with CCS and nuclear, whose respective shares in the total electricity supply become 2% and 12%.

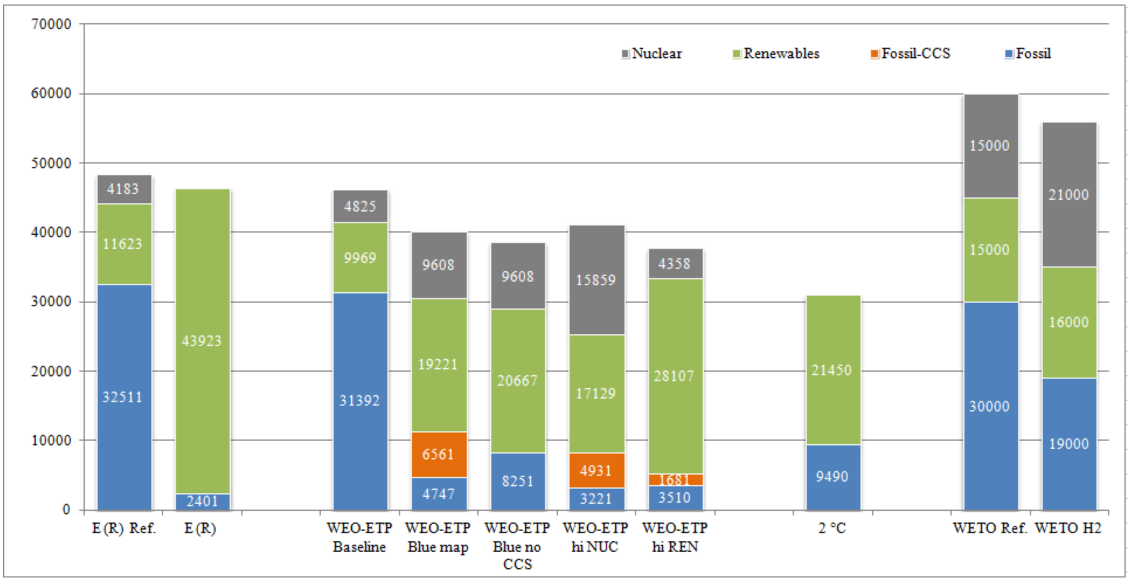

Figure 13 World electricity generation in 2050, in TWh Sources: Energy [R]evolution (Greenpeace, 2012), Energy Technology Perspective (IEA, 2010), Krewitt et al. (2008)

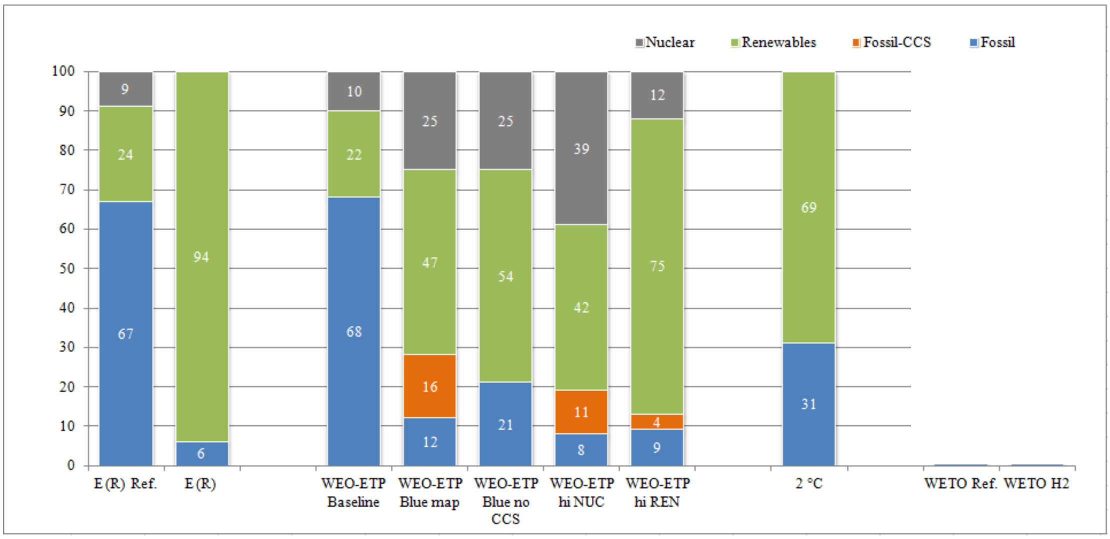

Figure 14 World electricity generation in 2050, in % Sources: Energy [R]evolution (Greenpeace, 2012), Energy Technology Perspective (IEA, 2010), Krewitt et al. (2008)

Concerning electricity price it is important to note that the introduction of renewable technologies under most scenarios, among them the Energy [R]evolution scenario slightly increases the costs of electricity generation compared to the Reference scenario. Indeed, the deployment of renewables plants is more capital intensive than gas or coal plants. However, in long-term perspective, the electricity prices reduce. Because of the lower CO_2 intensity of electricity generation, electricity generation costs will become economically favorable under the Energy [R]evolution scenario and by 2050 costs will be lower those in the Reference version. Conversely, under the Reference scenario, the combined effect of growing demand and the increase in fossil fuel prices (as mentioned before in section 3*.4 Energy and carbon prices*) result in total electricity supply costs rising. Shifting energy supply to renewables lead to long term costs for electricity supply that are 22% lower in 2050 than in the Reference scenario in the Energy [R]evolution scenarios.

In terms of structure of the power production, many scenarios, in particular Greenpeace and the GEA pathways insist on the development of a more decentralized types of production (at the regional and also house level) given the penetration of RES in the system marked by a larger instability of production. This vision is in parallel supported by the development of intelligent networks the so-called smart grids.

Nuclear

This sub section is specifically devoted to the nuclear technology as its deployment has been considered as a promising alternative to fossil fuel or rejected given the risk of dissemination and waste management. It is hence interesting to analyze the impact of the Fukushima accident in 2011 on how the scenarios address the short and long term deployment of the nuclear energy.

Scenarios carried out before Fukushima by IEA (WEO 2009) showed a lower rise by 2030 (+10%) than world power consumption (+ 62%). Therefore, the share in the world power mix decreases from 16% today to 9% in 2030 and world nuclear capacity passes from 370 GW in 2000 to 420 GW in 2030. Social acceptability (waste, proliferation), competitive and financial risk of nuclear in the medium term in main countries (USA, Germany), take off of power Renewables supported by policies and some development of big hydro projects in developing countries can explain this relative low increase in the short term.

After 2030, models either project a strong development of nuclear electricity production up to 2100; when it exceeds current levels by a factor of four (ReMIND-R, WITCH) to nine (IMACLIM-R) in the RECIPE project, or it is considered as an *interim* energy source to around 2050 (ADAM and ReMIND-R in the RECIPE project). In ReMIND-R, nuclear contributes significantly to electricity production during a transition period (Edenhofer et al., 2010, Luderer et al., 2012). In IMACLIM-R the period from 2015 through 2035 is characterized by a substantial contraction of electricity demand. This coincides with the period during which the bulk of the economic burden induced by the low-carbon transition is borne. Afterwards, a pronounced increase in electricity demand occurs, largely induced by a switch from non-electric to electric energy sources in the industry sector (Luderer et al., 2012).

After the Fukushima accident, nuclear deployment in scenarios has been revised downwards. WEO2011 developed a scenario with “low development of nuclear” assuming no new reactor building in the OECD and the non OECD countries only support half of their projects. The share of nuclear goes down from 13% to 7% in 2035. It is compensated by an increasing use of Renewables but also of fossil fuel. The cumulative share of coal and gas in this scenario would reach 60% of power production vs. 55% in the reference scenario.

The cost of higher constraints on nuclear energy is moderate in scenarios analyzed. RECIPE and ADAM projects envisaged the impact of a limitation or a nuclear phase out on the feasibility of ambitious low carbon trajectories given the risk of proliferation of this technology, nuclear waste management and social acceptability issue. It appears that ambitious reduction emissions remain achievable and global cost increase only moderately when nuclear is held in the baseline (Figure 15). When no investments are made in nuclear power after the year 2000 (i.e., assuming an extreme nuclear phase-out scenario), costs increase moderately in the 550ppm scenario but by up to 0.7 percentage points under low stabilization given the availability of other energy production sources in the scenarios (RES, biomass…). Indeed, the share of nuclear in the power production at a global level is relatively low which explains that a phase out has moderate impact at a global level. However, at a national scale, costs can be more significant given the share of nuclear, in particular in countries such as France where nuclear provides 80% of total electricity production or in countries which strongly depend on fossil fuels and/or does not having good RES potentials.

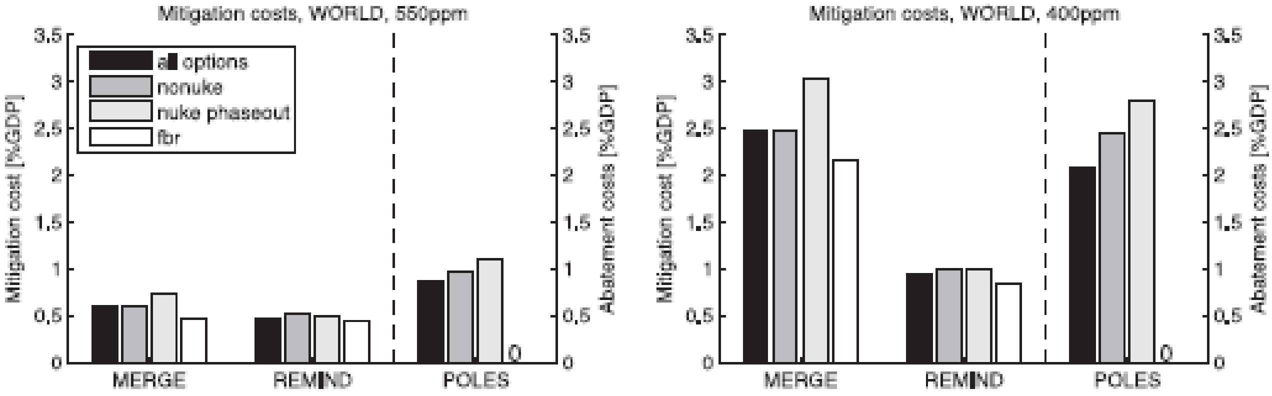

Figure 15 Global mitigation Costs given different Nuclear Options for 550ppm (left) and 400ppm (right) in the ADAM project (Source ADAM project, Edenhofer et al., 2010)

Transport

In all scenarios, the increase of mobility in absolute terms and associated energy demand on the long term is largely driven by the developing countries. For instance, in baseline scenarios, according to ReMIND and IMACLIM, energy demand for transport will grow respectively by a factor of 4.5 to 6 up to 2100. Fossil fuels will remain the main energy carrier of transport although as oil will become increasingly scarce, alternatives fuels will keep on playing an important role, in particular coal to liquid or biomass to liquid (after 2030) (RECIPE project, Luderer et al., 2012).

Climate policies in most scenarios involve fuel switching (increase of market share of biofuels and electric cars) and the reduction of oil demand. For instance, Energy [R]evolution scenario believes that electric cars can seriously enter the transport sector (Greenpeace, 2012). Electric vehicles will play an even more important role in improving energy efficiency in transport and substituting for fossil fuels. According to Greenpeace scenarios, in 2030, electricity will provide 12% of the transport sector’s total energy demand in the Energy [R]evolution, while in 2050 the share will be 44%, replacing gasoline and diesel. According to Energy Technology Perspective (IEA, 2012) by 2050, electricity use in the transport sector amounts to 11% of overall electricity demand.

However, other scenarios (RECIPE, IMACLIM-R and WITCH) consider electric or hydrogen cars as the most promising technology options for decarbonization of the transport sector. Some models in particular REMIND-R also point out the role of biomass liquefaction in combination with CCS as another key long term option for transport. In that case, there is no reduction of energy demand in the transport sector compared to the baseline. The bulk of the demand-side reductions of final energy are offset by efficiency losses due the large-scale deployment of CCS (RECIPE project, Luderer et al., 2012).

Another way to increase energy efficiency is reducing demand for mobility as an energy service (e.g., by substituting travel with teleconferencing or encouraging higher urban density in order to limit commuting) and shifting demand for mobility to public transportation (e.g., trains and buses). This is however a complex issue as non-coordinated types of policies (national, regional and sectoral), impact cities at the European level (Laconte, 2008).

Overall, scenarios more or less combine both future conventional and advanced transportation system put forward in the GEA pathways (Figure 16). Either the system remains conventional, relying predominantly on liquid fuels (including some oil), biofuels, liquefied natural gas, and potentially the direct use of biogas and natural gas. This represents the least discontinuity from current trends in terms of both end-use technologies and fuel supply and distribution infrastructure. In contrast, an advanced transportation system involves a more fundamental transformation, requiring largely new infrastructure systems in the case of hydrogen fuel cell vehicles, or new uses for existing infrastructure in the case of plug-in hybrids or fully electric vehicles. However, only one study (Waisman et al., 2012) captures location and infrastructure constraints (residential areas, work centers, transport infrastructures, urban policies aimed at limiting urban sprawl) which impact basic needs of households in the model.

It is important to note that the transport sector is confronted with high inertias due to the life time of infrastructures. In the models in which oil continues to be used extensively, it is in fact still used for transport at the end of the century and is the major source for the remaining CO2 emissions.

Only one model based on RECIPE findings (Waisman et al., 2012) tries to assess the role of infrastructure policy introduced as complementary measures of carbon pricing to decrease the emission intensity of the transport sector.

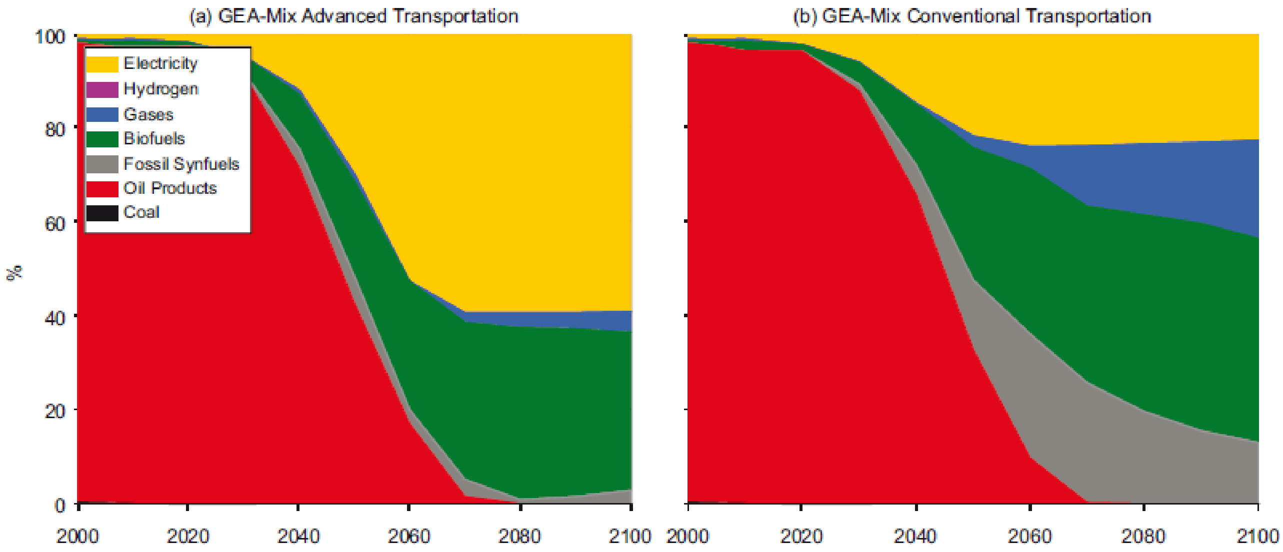

Figure 16 Development of global final energy fuel shares in the transportation sector under Advanced and Conventional assumptions for the GEA mix pathways group (Source: IIASA, 2012)

Building sector

According to the ETP report, in the Baseline scenario, global final energy demand in building sector increases by 60% between 2007 and 2050 (ETP, 2010). Total energy demand in the buildings sector increases from 2 759 Mtoe in 2007 to 4 407 Mtoe in 2050 in the Baseline scenario. The residential sector accounts for 59% of this growth and the service sector for around 41%. In baseline scenario, the energy mix of this sector is dominated by natural gas or to a lesser extent by coal. Non-biomass renewables use (predominantly solar) still only represents 2% of the sector's energy consumption in 2050. In the BLUE Map scenario (ETP, 2010), energy consumption in the buildings sector is reduced by around one-third of the Baseline scenario level in 2050. Energy consumption in 2050 is only 5% higher than in 2007. The energy consumption of fossil fuels declines significantly. Solar grows the most, accounting for 11% of total energy consumption in the building sector. Its widespread deployment for water heating (30% to 60% of useful demand depending on the region) and, to a lesser extent, space heating (10% to 35% of useful demand depending on the region) helps to improve the efficiency of energy use in the buildings sector.

In Greenpeace (2008) scenarios, any new building are equipped with either heat pumps, renewable heating, or solar thermal hot water. Energy primary demand decreases or remains stable. Under the Energy [R]evolution scenario the overall primary energy demand will be reduced by 40% in 2050 compared to the Reference scenario. In this projection almost the entire global electricity supply, including the majority of the energy used in buildings, would come from renewable energy sources. As already written RES achieve by 41% by 2030 and by 94% by 2050 under the Energy [R]evolution scenario. Some scenarios project after 2050 the penetration of biomass in combination with CCS, both for heating purposes (RECIPE; Luderer et al., 2012). This shift will certainly entail a more significant rate of retrofitting, currently of 2%/yr.

Industry

At a global level, the industry sector currently accounts for around 30 % of the primary energy demand and a similar share of energy-related CO2 emissions[45]. In the absence of climate policies, both primary energy demand and emissions are projected to increase, more than double by 2100 in the RECIPE scenarios. Fossil fuel use will continue to dominate, in particular coal, but its share in the energy primary demand will decline.

Under climate policies, scenarios also show that the decarbonization of the industry sector is linked to the decarbonization of the power sector generation as electricity penetrates more in the energy mix of the industry sector. The shift comes after 2040 in Europe according to the RECIPE scenarios.

"The major emission reduction strategy is thus the replacement of old capital vintages with more efficient equipment, largely run with electricity as a secondary energy carrier" (Edenhofer et al., 2009). According to the RECIPE scenarios, steel, cement[46] and pulp and paper industries have the largest mitigation potentials within the industry sector, in particular in developing countries.

Moreover, the sector is characterized by significant possibilities for energy efficiency. For instance the Energy [R]evolution scenario saves 40% more energy per $ GDP than the Reference case. According to ETP2012 scenarios fossil fuels share of final energy use will reduce to 57% in the BLUE low-demand scenario and to 55% in the BLUE high-demand scenario. In the short term perspective, IEA (2012) predicts that in the 450ppm Scenario the share in industrial energy demand of fossil fuels drops to 53% in 2035, from 61% in 2008.

In the absence of an integrated global carbon pricing regime, asymmetric carbon prices across world regions are likely to persist. Hence, they entail risk of carbon leakage for a few industry sectors (cement, iron and steel, aluminium, refineries and fertilizers). Carbon leakage refers to increases in GHG emissions in the one part of the world (e.g. out of Annex I countries), which could occur following the implementation of a climate policy limited to other part of the world (e.g. EU27). Carbon leakage can result from the worldwide drop in price of hydrocarbons, which results from the reduction in demand for these products due to climate policy or the potential loss of market shares in the industry of the country where climate policies

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[45] CO2 emissions from industry arise from three sources: i) the use of fossil fuels for energy ii) non-energy uses of fossil fuels in chemical processing and metal smelting; and iii) non-fossil fuel sources (cement for instance)

[46] On mitigation option in the cement production is the use of blended cement (with less clinker)

are applied unilaterally due to an asymmetric increase in costs (Sijm et al., 2004). CGE model estimates of the size of carbon leakage vary considerably. They range between 2 percent and 21 percent (Gerlagh and Kuik, 2007). Indeed, other factors like transport costs, product differentiation, investment costs and trade volumes need to be considered to make a assess of the leakage costs and carbon leakage can be offset by spillovers (i.e. reductions in emissions in the rest of the world) as technology and climate policies spread (Sijm et al., 2004; Gerlagh and Kuik, 2007, EU Commission, 2008). In terms of policy instruments, carbon leakage could be tackled through border adjustments, free allowances for industries at risk or investment support for efficiency improvements. Although border adjustment measures are more cost effective, they are likely to be not compatible with the WTO rules (Boehringer et al., 2011).

Agriculture/biomass/land use

Depending on IAMs, different types of biomass are incorporated : “energy crops” and waste (maize, sugarcane and woods) for 1st generation biofuels and 2nd generation liquid fuel. They are used for transport (biomass to liquid, biomass to gas, biodiesel…) and other uses (direct use, combined heat and power (CHP), electricity, H2).

Bioenergy is supposed to play a significant role in long term stabilization pathway, in particular combined with CCS. Strong bioenergy growth is observed in models in the medium term from; 45 EJ in 2005 to 80–140 EJ by 2050 in the GEA pathways based on the analysis carried out by Van Vuuren et al. (2009) with the IMAGE model during the ADAM project.

Interactions concerning food demand, biomass energy and forest at the global scale are also subject to growing interest, especially regarding indirect land-use changes (Searchinger et al., 2008) and the consequences for food prices of agrofuel production and forest preservation (Baier et al., 2009; Tokgoz and Elobeid, 2006; Wise et al., 2009). Agricultural intensification mechanisms are viewed as a key driver to bridge conflicts on land-use (van Vuuren et al., 2009). However, only the IMAGE model in the GEA and ADAM projects has an explicit representation of land use[47], most models use generally exogenous land use emissions trajectories.

Section 6 will point out more closely the limits of these findings, in particular regarding energy security issues.

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[47] However, a drawback of the model is that economic development is treated as an exogenous driver. Hence changes in the energy sector and in land use are decoupled from changes in GDP.

4.2 The LCS vision is achievable under modeling technological options

The previous section has pointed out that new technologies and technological change are expected to play a key role in the long-term transition of the global energy supply. The third IPCC report still concluded that "renewable energies can provide up to 35% of the primary energy for less than 50$/t CO2"[48]. Following Pacala and Socolow (2004), Fisher et al. (2007), these results have been summarized in a persuasive argument that the decision making community has used to a large extent assuming that all relevant technologies are at hand to reach low carbon stabilization objectives:

"The range of stabilization levels assessed can be achieved by deployment of a portfolio of technologies that are currently available and those that are expected to be commercialized in coming decades. This assumes that appropriate and effective incentives are in place for development, acquisition, deployment and diffusion of technologies and for addressing related barriers" (IPCC, 2007, WGIII, Summary for policy-makers, p.18, §19).

Long term scenarios analyzed in the survey show that low stabilization is feasible through a wider portfolio of technologies. This section focuses more precisely on the deployment of one key technology which has been integrated in modeling exercises to comply with stringent carbon targets

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[48] GIEC, 2007, WG III, SPM, §10, p. 13. The Four Assessment Report of IPCC reports that greenhouse gas emissions can be reduced by about 30-50% at costs below 100$/tCO2 based on an assessment of both bottom up and top down studies.

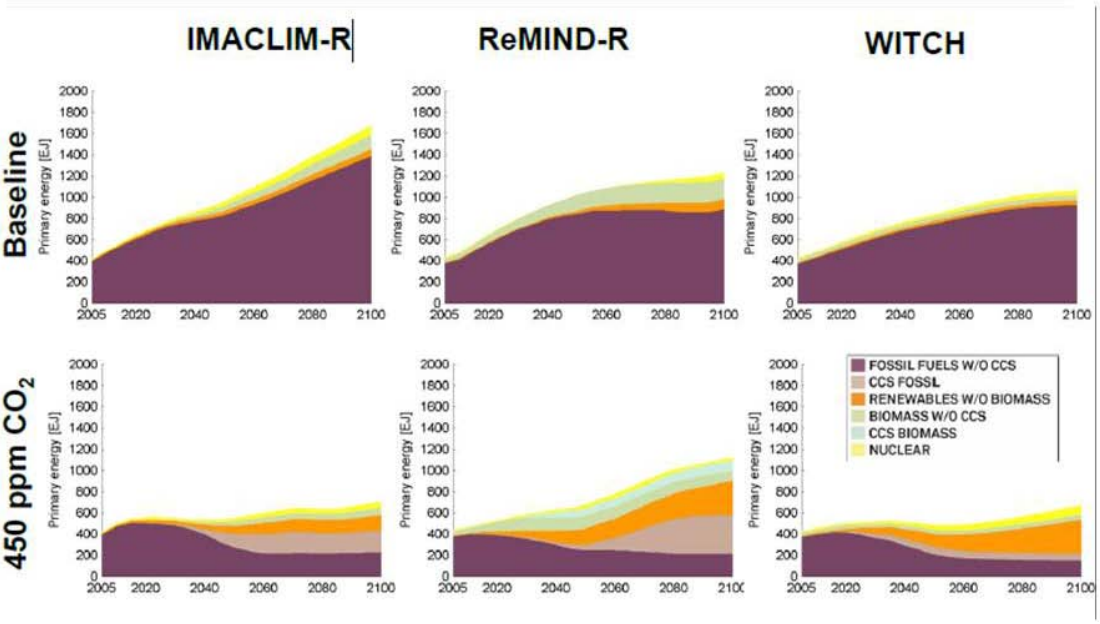

Figure 17 Energy system transformation in the RECIPE project in the 450ppm scenario compared to the baseline (Source: RECIPE Project, Kriegler et al., 2009)

To achieve the lowest reduction target of 450ppm CO2-eq models show that negative emissions (e.g. CCS biomass) can be necessary. To reach the 400 and 450 ppm concentration targets, an overshoot, or peaking of concentration is assumed: concentrations first increase to 480 ppm and 510 ppm before stabilizing at 400 and 450 ppm, respectively. Indeed, in models this requires a large-scale deployment of technological options, particularly CCS options e.g. biomass plants equipped with sequestration systems which have been identified as a very promising option. CO_2 is removed from the atmosphere through photosynthesis as vegetation grows. Stored carbon eventually returns to the atmosphere when biomass decomposes, and this carbon can be sequestered in the very long term either by cutting and burying the grown biomass (Metzger and Benford, 2001) or by combining energy production from biomass and carbon capture and storage (called BECCS). Over the last three years, a majority of IAMs have yet incorporated BECCS technologies to achieve very low carbon concentration targets. All models (MERGE, ReMIND, POLES, TIMER) excepting E3MG include it in the ADAM project and mostly in the EMF22 project(Figure 18).The availability of BECCS to provide negative emissions is necessary in particular with regards to stringent reduction emissions targets. [49]

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[49] In policy scenarios, REMIND-R, use extensively BECCS as an option to generate transport fuels. IMACLIM-R, by contrast, which in 2008 did not include BECCS emphasizes that one major mitigation option in the transport sector is the deployment of plug-in hybrid vehicles, resulting in considerable efficiency gains and a shift from non-electric to electric energy demand.

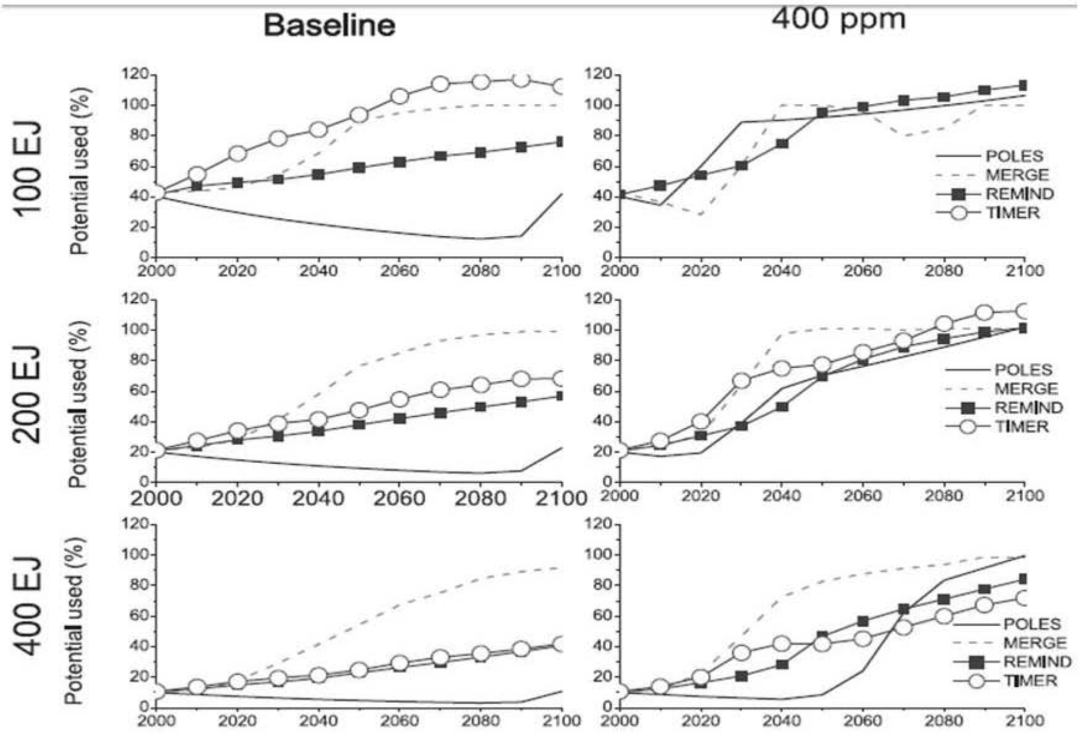

Figure 18 Biomass potential use across Models and for Different Potentials, in the Baseline and 400ppm Scenarios (Source: ADAM Project, Van Vuuren et al., 2010)

Hence, only one model with BECCS in the EMF22 exercise was unable to represent the overshoot 450ppmCO2-eq case with a global action (full participation of countries in terms of emission reductions)[50] . Optimist assumptions about the development of BECCS technologies by 2050 raise several issues in terms of cost-effectiveness biomass availability and more broadly about the legitimacy of the 2°C target[51]. These points will be discussed in section 6.

Another key technology challenge highlighted by scenarios is the development of smart grids and supergrids for renewable power generation. Smart grids are supposed to improve energy savings and facilitate the integration of renewables in a more decentralized production system by optimizing production and demand usually incorporating energy storage. In particular, the successful implementation of smart

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[50] Nevertheless, only two models were able to produce the most stringent scenarios (450ppmCO2-e case: not-to-exceed with full participation and overshoot with delayed participation).

[51] It is out of the scope of this survey to discuss the latter point. We can nevertheless notice that models are forced to embark ambitious technical assumptions which may limit their use as policy tool.

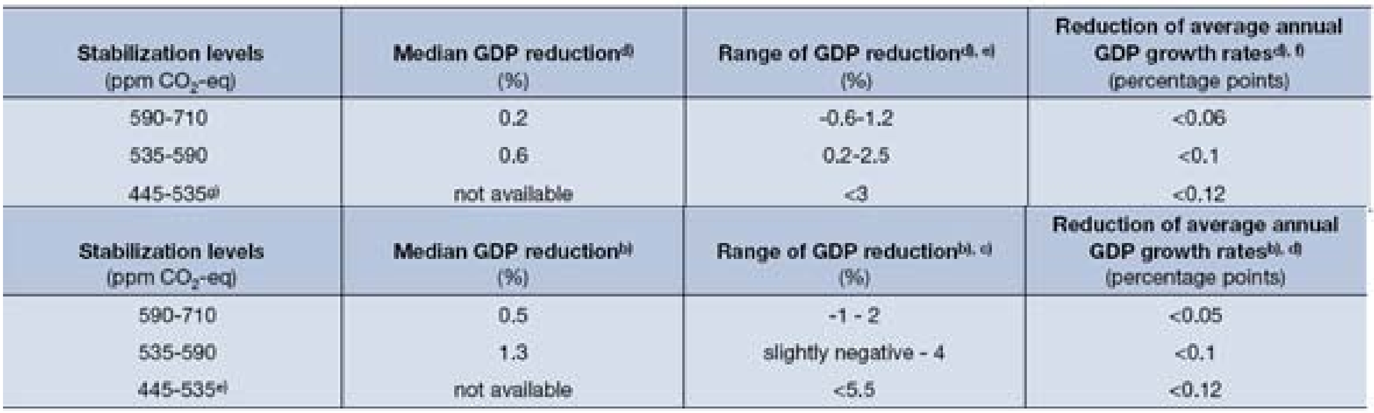
grids is vital for the advanced Energy [R]evolution in the Greenpeace scenarios (Greenpeace, 2010, 2012)[52].

Finally, to achieve an economically attractive growth of renewable energy sources requires a balanced and timely mobilization of all technologies . This depends on "technical potentials, actual costs, cost reduction potentials and technical maturity" (Tavoni et al., 2012) but also on social acceptance. This point is crucial for efficient and effective energy transformation in Europe and globally.

4.3 A transition associated with moderate average global costs

Macroeconomic results have been extensively analyzed because of their high political roles in the debates over combating climate change. The Stern Report disseminated to a large audience the conclusions of the fourth IPCC report (AR4) relating on emission cost reductions.

Table **10** provided in the Summary for Policy Makers from the IPCC AR4 summarizes the range of global costs found in literature of scenarios for different stabilization targets. This shows that on average, the most severe target (445-535ppm CO2-eq corresponding more or less to the 2°C target) would cost 3% of the world GDP in 2030 and less than 5% in 2050, i.e. 0.1 on the yearly average growth rate. In other words, the world GDP in 2050 would only be reached in 2052 with the most commonly hypothesis assumed. These are supposed to be macro-economic costs. Recent modeling exercises also emphasize moderate global mitigation cost.



Stabilization levels (ppm CO_2-eq)	Median GDP reduction[d)] (%)	Range of GDP reduction[d, e)] (%)	Reduction of average annual GDP growth rates[d, f)] (percentage points)
590-710	0.2	-0.6-1.2	<0.06
535-590	0.6	0.2-2.5	<0.1
445-535[g)]	not available	<3	<0.12

Stabilization levels (ppm CO_2-eq)	Median GDP reduction[b)] (%)	Range of GDP reduction[b), c)] (%)	Reduction of average annual GDP growth rates[b), d)] (percentage points)
590-710	0.5	-1 - 2	<0.05
535-590	1.3	slightly negative - 4	<0.1
445-535[e)]	not available	<5.5	<0.12

Table 10 Global macroeconomic costs of GHG reduction until 2030 (superior table) and 2050 (inferior table), without taking into account gains on avoided damages (source: IPCC, 2007).

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[52] In addition to RES, other technologies not considered in the surveyed scenarios could be integrated in smart grids. For instance, small micro-reactors fueled by gas micro-reactors could be used by consumers, mainly in urban areas.

Strachan et al. (2008), with MARKALMACRO model, conclude that a 80% reduction target in 2050 compared to 1990 level leads to GDP losses lower than 2.2%, depending on the size of the climate coalition. Barker et al (2008) find, for a 50% global emissions reduction scenario in 2050 compared to 1990, a slight GDP gain compared to the reference scenario owing to the combined effects of induced technical change and the economic spillover from energy efficiency investments. The ADAM project concludes that losses of GDP vary from about 0.9% to 2.5% by 2100 relative to the baseline, compared to a range of 0.5 to 0.9% in case of the 550ppm scenario. The global costs for all scenarios reported are in the lower to medium range compared to the values given in the IPCC AR4[53]. It is important to note that there is still confusion in some modeling exercises, in particular in the ADAM project, between technical costs (provided by partial equilibrium models such as Markal or Poles) and GDP losses (provided by optimization and CGE model).

Modeling exercises also provide investment costs. Contrary to GDP costs, this is a partial equilibrium measure i.e. it does not take into account the interactions between the described system and the rest of the economy. It consist in the variation, compared to a scenario without carbon constraint of the investment cost or total life-time cost of the technical systems (power generation plants, vehicle fleet, cement) chosen to respect a carbon constraint at the scale of a company, sector or group of sectors. Bottom up models are more designed to calculate such costs.

In terms of *net additional investment costs* associated with *low carbon* development to 2030 this spans a range from $US 400 to 1200 billion / yr.[54] The IPCC Special Report on Renewable Energy estimates the global *cumulative* investment in renewable electricity sources alone by 2030 to vary between about $3 trillion (in a ‘business as usual’ case) to up to $ 12 trillion (for a 2 °C case). The IEA’s WEO in 2010 estimated an overall investment cost to 2030 of a 2°C scenario at US $ 18 trillion; the New Policies scenario of the subsequent WEO (2012) estimated US$17trn global investment for the power sector to 2035.[55] If compared against

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[53] Low stabilization of CO2 emissions is found to be achievable, at moderate costs, in all models used if the full range of technologies is available, all regions participate in emission reduction and effective policy instruments are applied.

[54] These are respectively UNFCCC ($380bn in 2030), IEA ($808bn/yr average during the 2020s), and McKinsey ($1215 bn/yr, average over 2026-2030).

[55] The IPCC SSRN report estimates cumulative investment in renewable energy for power generation at between $US 2850 bn (reference scenario IEA) and $US 12280 bn (450ppm target IEA 2009) to 2030. The IEA’s World Energy Outlook (2010) projected total system investment costs to 2030 at $18trn for a scenario consistent with a 2°C world; the 2012

global GDP , currently around \$70 trillion a year and expected to rise to eg. \$100 trillion during the 2020s then this implies redirecting close to 1% of global GDP to transform the power sector alone.

To be achieved, this ambitious carbon targets will also depend on the timing of actions.

4.4 The three flexibilities

The recent modeling exercises assess the feasibility of achieving ambitious long term emission reduction targets. This is complex as it combines the issue related to:

- the design of climate architecture (“The Where flexibility”- which country will join a climate coalition) ,
- the time profile of emissions reduction i.e. “The When Flexibility” (when should emissions have to be reduced to remain below a chosen stabilization or target?) and
- the way to reduce emissions (CO2 only or all GHG gases; the “what flexibility”).

In particular, EMF22[56] explored the interactions between three factors that influence long term pathways: the long term target, the type of international climate cooperation, and under what conditions targets might be temporarily exceeded. Different types of climate coalitions are taken into account given two main emission targets 450ppm CO2-eq and even 550ppm CO2-eq[57]. The main conclusion of the study is that without early and full participation of major emitters, concentrations may exceed these ambitious targets. Short term flexibility in terms of climate commitments provides the ability to temporarily exceed, or overshoot, long term targets. It may make some of the more stringent long term climate limitation goals more achievable and lessen the impacts of failure to achieve a comprehensive approach (Figure 19). But these pathways come at a cost. Scenarios in the RECIPE project show for instance that a delay of mitigation action until 2020 may increase global costs by 70% (the cost of delayed action was not assessed in EMF22). The 450ppm CO2-eq

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analysis warned that 2°C was slipping out of reach and instead focused on a New Policies scenario, in which power sector investments alone totaled 16,9 trillion USD to 2035.

[56] Conversely, in the ADAM project, all models assume global participation in climate policy in the near-term and shift technology transfer across regions.

[57] The study assesses full participation of countries to a climate agreement and delayed participation scenarios in which the BASIC countries adopt climate policies at different points.

was also infeasible in a scenario with delayed action of main emitters in 2030 (no overshoot tested).

In the RECIPE project, models were unable to find a numerical solution had a global agreement is delayed after 2030 as shown in Table 11 (scenario delay 2030).

In general, several factors play in favour of an early action[58]:

- The uncertainty on future economic settings (growth, rate of innovation, reserves and prices of fossil fuels…) combined with the inertia of technical systems encourage to act more and earlier to maintain a range of options in case of bad surprises;
- Induce technical change by incentive instruments and/or by direct efforts of R&D (Goulder and Mathai, 2002 ; Manne and Richels, 2004b), in contrast with the older vision of an autonomous technical progress which involves to wait while postponing too early efforts;
- Emerging countries offer windows of opportunity to long term emissions abatements during periods of high level of long-lived investment in infrastructure and productive capital (Shalizi and Lecocq, 2009);
- Early mitigation action could bring a side effect benefit, that is a lower inflationary pressure on the world fossil fuel markets and offer an insurance against sharp oil rises (Rozenberg et al., 2010).

Conversely, delayed action ensures that equipment is not renewed prematurely and hence limits the extra costs of an untimely energy transition (Hammitt et al., 2002, Wigley et al., 1996).

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[58] Intense debates relative to the right time profile of efforts have occurred in the 90's, especially between supporters of early starting abatement versus progressive action. Indeed, the intertemporal flexibility for allocating emission reductions for the same carbon budget could affect near-term mitigation costs by postponing emission reductions -and the "Where Flexibility" - emissions should be cut down in those places where it is the cheapest to do so as their impact is independent from their geographical origin.

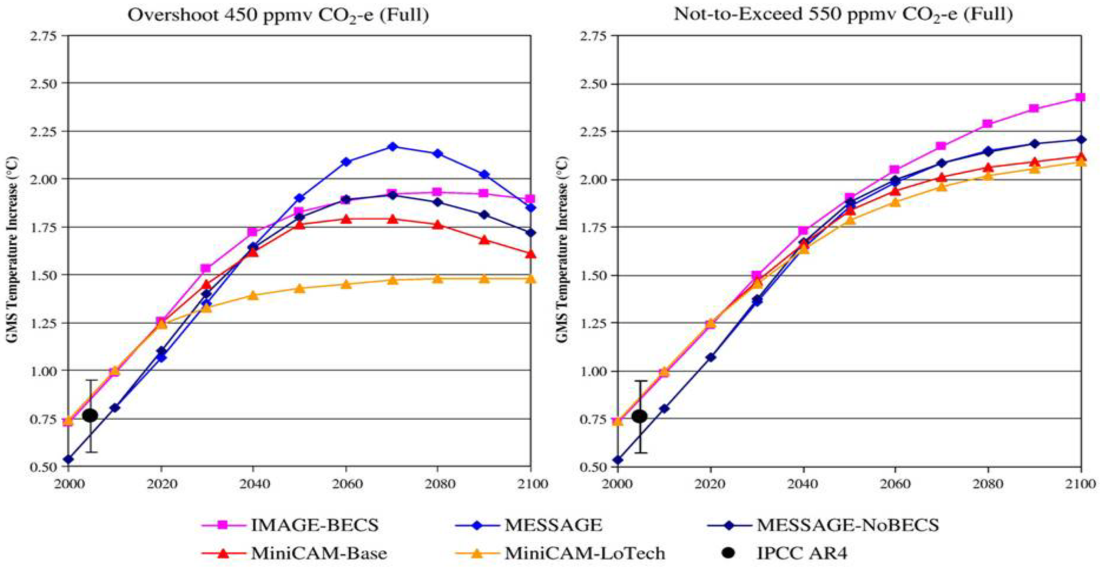
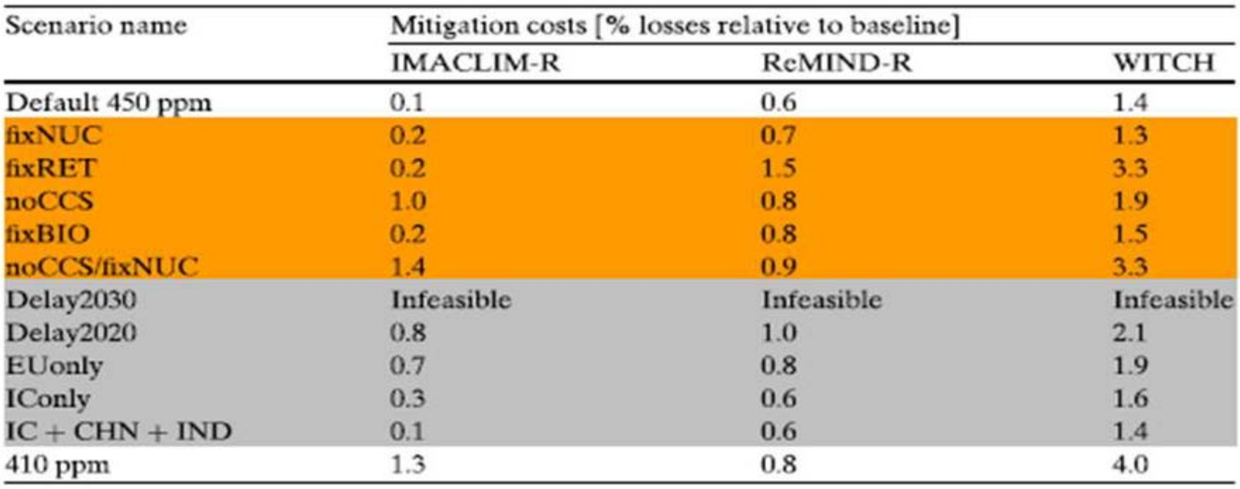


Figure 19 Transient temperature increase in the overshoot 450 ppmv CO2-e and not-to exceed 550 ppmv CO2-e scenarios, both under full participation and with a climate sensitivity of 3 °C from selected models (IMAGE MESSAGE, and MiniCAM). (Source: EMF22, Clarke et al., 2009)



Scenario name	Mitigation costs [% losses relative to baseline]		
	IMACLIM-R	ReMIND-R	WITCH
Default 450 ppm	0.1	0.6	1.4
fixNUC	0.2	0.7	1.3
fixRET	0.2	1.5	3.3
noCCS	1.0	0.8	1.9
fixBIO	0.2	0.8	1.5
noCCS/fixNUC	1.4	0.9	3.3
Delay2030	Infeasible	Infeasible	Infeasible
Delay2020	0.8	1.0	2.1
EUonly	0.7	0.8	1.9
ICOnly	0.3	0.6	1.6
IC + CHN + IND	0.1	0.6	1.4
410 ppm	1.3	0.8	4.0

Table 11 The global cost of mitigation policies (Source: RECIPE Project Luderer et al., 2012).

IAMs are quite optimistic regarding the timing and the global costs of the transition toward a LCS despite ambitious targets (2°C). Next section gives specific regional insights before analyzing the increasing gap between models results and real issues at stakes in the transition toward a LCS, in particular linked to energy security issues.

Many studies (Reilly et al., 2004 ; EMF 21, Weyant et al., 2006; Van Vuuren et al., 2006;) showed that both the price of carbon and the global mitigation costs could be significantly reduced if all GHG gases were taken into account, and not only CO2 (what we call the what flexibility). For example, Van Vuuren et al. (2006) analyze the results from the eighteen models from EMF-21 study and that, for a given radiative forcing target, carbon prices are on average reduced by 30 to 60%, and the global macroeconomic costs (GDP losses compared to a scenario without climate policies) by 30 to 40%.

Consequently, recent modeling exercises confirm the diagnosis of the last IPCC report: a broad portfolio of technologies will be needed to achieve the transition towards a low carbon society, with a specific emphasis on CCS combined with biomass to reach very low carbon trajectories, at a moderate cost if a global agreement comes soon. The RECIPE project shows indeed that if the international community agrees to start climate mitigation policy immediately, and if the full portfolio of low-carbon technologies represented in the models is available, stabilizing global CO2 emissions at 450 ppm by 2100 can be achieved at costs of 0.1% to 1.4% of aggregated global macro-economic consumption (Luderer et al., 2012). However, the conditions for achieving the 2°C targets by models are really ambitious and seem a little bit unrealistic given the current setting of international climate negotiations, hung to a potential global agreement in 2015.

5. Regional perspectives

As explored in the previous section, scenarios feature meaningful energy system in 2050 and 2100 from today when integrating energy and carbon constraints. Figure 20 highlights the huge efforts required for different regions of the world to comply with the 2°C target. This is all the more important as the bulk of the infrastructures in developing countries will be built in the coming decades. Current distinctions between low- and higher-income countries will also become largely obsolete given the catch up trends in productivity and economic growth. This section analyzes how the carbon and energy constraints affect key regions in selected scenarios, including: the EU, the US and two emerging giants: China and India.

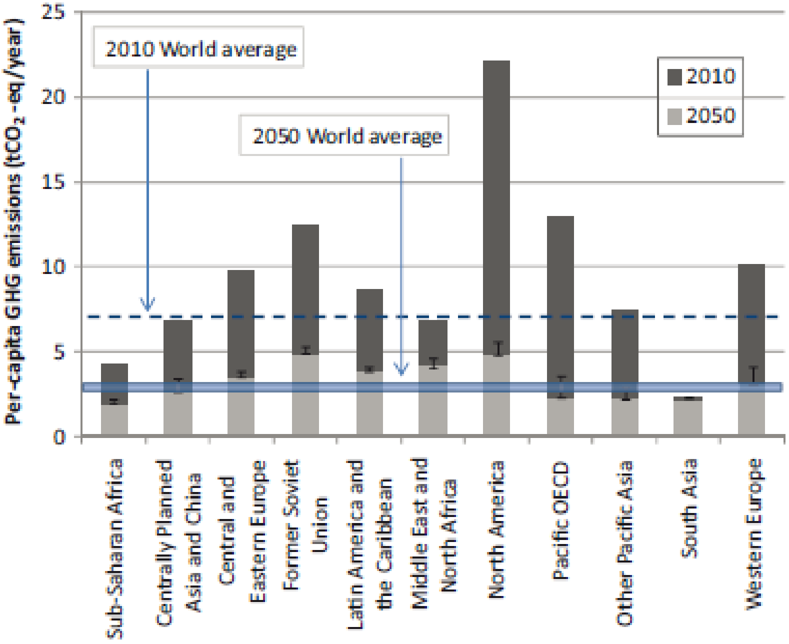


Figure 20 Regional per capita GHG emissions. The upper section from the thick blue line indicated per capita emissions reduction between 2010 and 2050 corresponding to the 2°C target objective (Source: GEA, IIASA, 2012)

5.1 OECD countries

Among OECD countries, this section concentrates on the EU and the US. Their energy systems is highly based on fossil fuels but they have different potential energy resources. Over the last ten years, each has implemented specific energy and climate policies in different ways which will impact their respective long term development pathways. This section analyzes how modeling exercises address these issues.

The European Roadmap

Since the early 90’s the EU has been a frontrunner in climate negotiations. The cap and trade system implemented by the European Union (EU ETS) operates since 2005, and covers approximately 45% of European GHG emission. ETS currently is focusing on the energy sector (power and heat plants), energy intensive industrial branches like: iron and steel, non-ferrous, mineral (cement, lime, glass and ceramics), paper mill, chemical, air transport and others, and GHG main gases (it is worth to mention that in ETS pilot phase 2005-2007 the CO2 emissions was only accounted). In 2008, in order to reach the target of climate stabilization at no more than 2°C above pre-industrial levels by the end of this century the EU has adopted stringent mitigation objectives through a climate policy package. They are corresponding to -20% in 2020 and -80 - 95% GHG reductions target in 2050 relative to 1990 level with an option to enforce the 2020 reduction target to -30% if developing countries would commit to similar binding commitments.

The scenarios surveyed are relatively optimistic regarding the technical feasibility for the EU to achieve its ambitious climate objectives, even in the absence of global agreements in the short term.

The European Commission has published firstly a “Roadmap for moving to a competitive low carbon economy by 2050” (March 2011), and then sectorial more deeply analysis known as Energy Roadmap 2050 (December 2011), providing guidance on how the EU can decarbonize the economy, and in parallel ensure energy supply security and competitiveness. These documents are based on economic modeling and scenario analysis, considering the way and the timing of the EU’s move towards a low carbon economy assuming continued global constraints. Models used to project the evolution in demand and supply sectors are the models POLES for the global energy system modeling and PRIMES for the EU energy system modeling.

The European and Energy Roadmap provides a reference scenario as well as a Current Policy Initiatives Scenario (CPI). For each case, it considers variants on the implementation of climate policies: a Global agreement or Fragmented Actions, and on the deployment of critical technologies or energy carrier (CCS, extended electrification with or without nuclear growth development, deep RES engagement in power sector and/ or strong energy efficiency improvements, etc…).

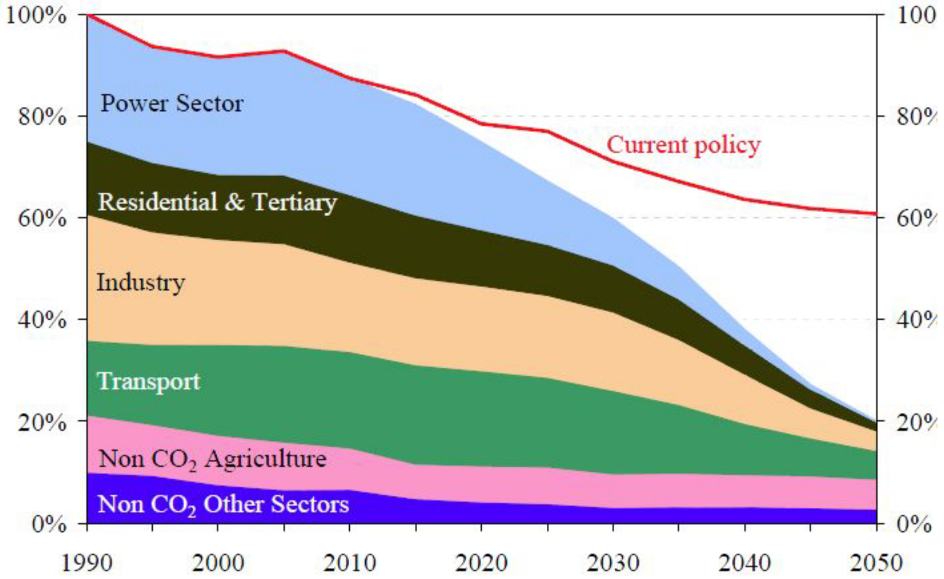


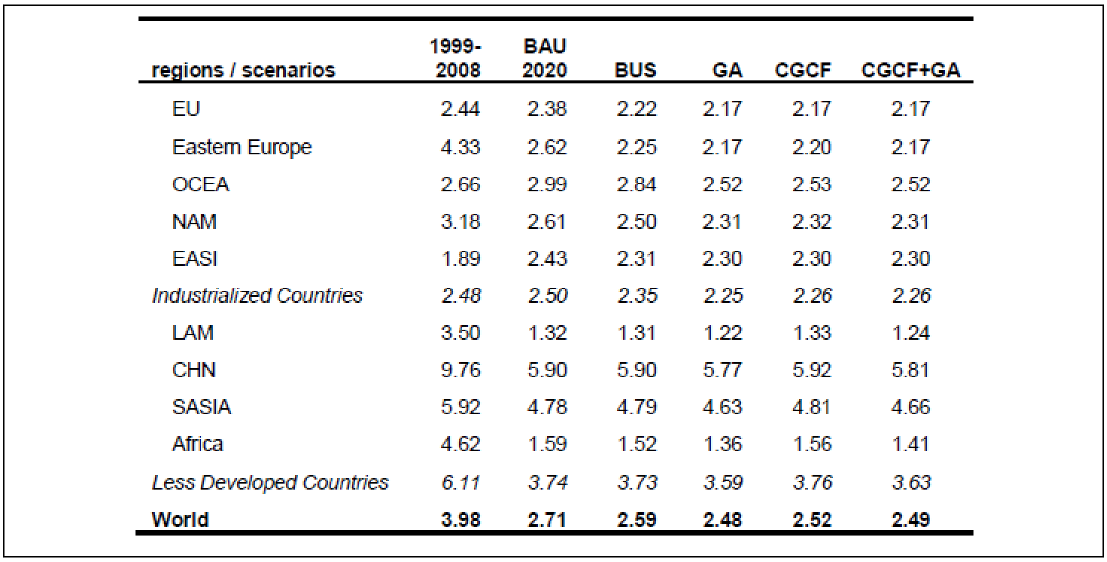
Figure 21 EU GHG emissions towards an 80% domestic reduction (100%=1990) (Source: EU, 2011)

The analysis recommends that the EU should reduce its domestic GHG emissions by 80% below 1990 levels by 2050 and that this target is technically feasible and financially viable using proven technologies if strong incentives (i.e. carbon pricing) exist. Greenpeace (2008, 2012) estimates that current European energy demand can be cut by a range of 30-36% in a cost-effective manner to comply with 78% emission cut in 2050 from 1990 levels for OECD Europe. Beyond this potential a thorough rethinking of energy services is deemed capable of cutting back energy needs by a factor four to ten (Greenpeace, 2008).
The global cost efficient pathway to achieve the 2050 target calls for domestic GHG reductions below 1990 levels of 25% in 2020, 40% in 2030 and 60% in 2040. This would require an additional annual investment of €270 billion for the next 40 years, equivalent to “an additional investment of 1.5% of EU GDP per annum overtaking current investment representing 19% of GDP in 2009. The extent and timing of these GHG reduction targets are differentiated by sector reflecting the different abatement potentials that exist within the EU. The power sector is principally affected (Figure 21), requiring a reduction of its emissions of 93% to 99% by 2050 which is line with what other surveyed scenarios have put forward (Edenhofer et al. 2009, Greenpeace, 2010, 2012). The transport sector requires emissions reduction ranging from 54% to 64%. These results assume the strong penetration of renewables eased by the expansion of smart grids, demand side management (DSM) and storage capacity linked to the increased share of electric vehicles, better grid integration and power generation management.

One of the differences between the different scenarios lays in the electricity demand projections. While the electricity demand increases by 50% between 2005 and 2050 in the baseline scenario and remains stable in the CPI scenario, it grows only by 16 to 31% in the “decarbonization” scenarios.

Although Europe has endorsed a leadership in terms of climate policies, not all regions, in particular the main emitters in emerging countries and the US have implemented similar ambitious policies. Modeling exercises have therefore assessed the impact for Europe of different climate regime architectures. According to (Luderer et al., 2012), even if other regions delay carbon pricing until 2020, Europe will enjoy a first mover advantage when unilaterally implementing climate policy. Europe is better off in this case compared to a scenario in which all world regions, including Europe, delay action until 2020. The benefits of anticipating future emission reductions and redirecting investments early on exceed the costs of higher cumulative emission reduction commitments. Early adjustment of the energy system avoids locking the economy into carbon-intensive investments and R&D, making emission reductions beyond 2020 easier and allowing the EU to sell allowances to other regions once the international carbon market is in place. The recent case of EU and USA reduction scale of GHG and growing competitive advantage thanks to unconventional gas production which lead to cheaper electricity production should be a good warning for the EU low-carbon strategies based on RES[59].

Other studies are less optimistic in the short term (Shinko, 2010, Steininger et al., 2011). By 2020, (Schinko, 2010) shows that whether a global agreement or a *voluntary* Post-2012 agreement of Annex I countries, representing a bottom-up approach scenario based on Copenhagen pledges (BUS scenario entail GDP losses (table 12). Under the BUS scenario assumptions, global GDP decreases near to the 3% relatively to the BAU scenario result. This slowdown in economy activity concerns mainly the ICs region but not only. In the case of a global climate agreement regarding the policy (GA scenario) world GDP « loses » reach 3.5% in 2020 relatively to the BAU scenario. This work has the merit to catch the attention on the short term or transition costs of climate policies which is often underestimated by long term modeling exercises (see section 6 for a more in depth analysis of the way models represent transition dynamics and the interactions with other issues, in particular energy security).



regions / scenarios	1999-2008	BAU 2020	BUS	GA	CGCF	CGCF+GA
EU	2.44	2.38	2.22	2.17	2.17	2.17
Eastern Europe	4.33	2.62	2.25	2.17	2.20	2.17
OCEA	2.66	2.99	2.84	2.52	2.53	2.52
NAM	3.18	2.61	2.50	2.31	2.32	2.31
EASI	1.89	2.43	2.31	2.30	2.30	2.30
Industrialized Countries	*2.48*	*2.50*	*2.35*	*2.25*	*2.26*	*2.26*
LAM	3.50	1.32	1.31	1.22	1.33	1.24
CHN	9.76	5.90	5.90	5.77	5.92	5.81
SASIA	5.92	4.78	4.79	4.63	4.81	4.66
Africa	4.62	1.59	1.52	1.36	1.56	1.41
Less Developed Countries	*6.11*	*3.74*	*3.73*	*3.59*	*3.76*	*3.63*
World	**3.98**	**2.71**	**2.59**	**2.48**	**2.52**	**2.49**

Table 12 Annual average GDP growth rates (2004-2020) for scenarios considered in the Wegener Center for Climate and Global Change project (Source: Schinko, 2010)

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[59] Other studies show that a unilateral reduction emission policies of EU27 has limited environmental effect as it is made up for by stronger carbon leakage (Bosello et al., 2011).

In terms of energy security issues, as pointed out in the next section, the BASICS countries, particularly China and India, will drive most of the increase of energy use in the next decades. This will directly foster tensions on fossil prices although, in the short term, the abundance of unconventional fossil fuel such as shale gas moderates the increases and foster the exports of cheap coal from the US to Europe.

This setting raises the issue for Europe to combine multiple objectives in particular climate policies (20-20-20 objectives), energy security and also competitiveness of its economy. This is a key point of official documents as pointed out by the deliverable D1.1 of the MILESECURE-2050 project, in particular in the Green Paper on a 2030 framework for EU climate change and energy policies (EC, 2013) recently published by the Commission. It states that “the 2030 framework must identify how best to maximize synergies and deal with trade-offs between the objectives of competitiveness, security of energy supply and sustainability” (ibid p3). In terms of policy instruments, it calls to further interconnect energy supplies in different European countries, support significant investments in new and intelligent energy infrastructure, and the diversify Europe's energy supply resources to ensure security of supply and energy efficiency. However, the design of the ETS limits the synergies between climate and energy policies instruments. Indeed, the implementation of both the RES directive (2009/28/EC) in 2011 and Energy Efficiency directive (2012/27/EU) in 2013 has undermined the EU ETS carbon credits (already low as a result of an initial over allocation followed by the economic downturn, and an oversupply of the CER Kyoto credits). Indeed, actors have anticipated the positive impact in terms of GHG emission reductions owing to the perspectives of both energy efficiency and RES progress. Low carbon price therefore limits the investments in the power sector, in particular in RES which require high capitals.

Section 6 provides some insights on the interdependences between climate policy and energy security issues for Europe.

The US energy “Renaissance”?

Recent projections for the US insist on the “Renaissance” of the US energy sector (IEA, 2012)[60]. Indeed, according to the New Policies Scenarios[61] of the IEA, while the

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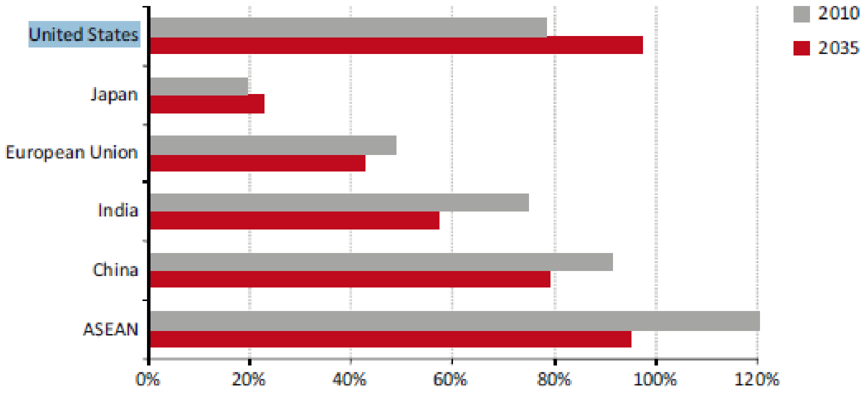
[60] Projections for oil and natural gas production in the OECD have been revised slightly upwards, due to brighter prospects in the United States and Canada (compared to WEO2011).

[61] In these scenarios IEA assumes that from 2015 onwards all investment decisions in the power sector in the United States, Canada and Japan factor in an implicit or “shadow” price for carbon, to take account of the expectation that some form of action will be taken to

US currently imports 20% of its primary energy, thanks to the production of oil, shale gas and bioenergy, the US becomes almost self-sufficient in net-terms by 2035 (Figure 22). Exports of coal, gas and bioenergy help offset (in energy equivalent terms) the declining net imports of oil. Low prices and abundant supply see gas overtake oil around 2030 to become the largest fuel in the energy mix.



Note: Self-sufficiency is calculated as indigenous energy production (including nuclear power) divided by total primary energy demand.

Figure 22 Net energy self-sufficiency in selected countries and regions (Source: IEA, 2012, New Policy Scenario)

Decreasing oil demand is the result in the New Policies Scenarios of more stringent standard in terms of fuel consumption standard (US Corporate Average Fuel Economy, CAFE). Gas use dominates the energy mix (use principally in power generation, industry and also in transport) overtaking coal use owing to cheaper prices and concerns over local air quality and greenhouse-gas emissions (~17% lower in 2035 than in 2010). Furthermore, the share of renewables in total primary energy demand rises to 15%, thanks largely to the continuation of federal policies in favor of renewable electricity production (tax credits) and state renewable portfolio standards. Investments required will be mainly concentrated in the power sector (45% of the total), and more precisely in the development of renewables because of their high capital intensity and relatively low output.

Regarding climate change policies, the US is confronted to a paradoxical setting. Although the deliberations of the Waxman-Markey Bill proposing a US ETS seems so far blocked (Sterk et al., 2009), higher share of gas supply in the energy mix (replacing coal use which is much more carbon intensive), the US may be in a good

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penalize CO2 emissions, although we do not assume that an explicit trading program is introduced position to comply with its non-binding pledges of Copenhagen amounting to a reduction 17% GHG emissions relative to 2005).

Model intercomparison projects explore the impact of long term stringent emission targets on the US. Compared with the EU and Japan, the United States has the highest costs of the three since the US economy is the most carbon intensive (Edenhofer et al., 2010). But its mitigation costs will decrease if they join a climate policy regime alongside other Annex-I countries by 2010 since it benefits from carbon permits.

5.2 The “giants”: India and China

Far ahead of the US, China is the first CO2[62] emitter since 2006 (Olivier et al., 2012) with an average growth rate of its emissions of 10% per year over the last decade (World Bank, 2012). Chinese emissions growth is due to the combination of rapid economic development and a significant increase of energy intensity of GDP (Raupach et al, 2007) that are mainly driven by industrial demand and coal-fired electric generation (Blanford at al., 2009; IMF, 2008). China has indeed a powerful industry which is mainly based on fossil fuel energy and can rely on significant coal reserves (IEA, 2007). China’s share of world energy demand has risen dramatically and it is the world largest energy consumer since 2011 (BP, 2011, 2013 WRI, 2012, and Figure 23). Nevertheless and despite a spectacular growth rate over the last ten years, this carbon-intensive economy has an income which is still much lower than that of developed countries and has historically less contributed to current greenhouse gas concentrations. This can explain why they are not so enthusiastic to engage in a common and equal mitigation effort, and why they rely on the "common but differentiated responsibilities" principle of the UNFCC (van Ruijven et al., 2012). This also can contribute to explain why despite its huge coal reserves, energy security remains one the primary objective of the government, which continues to secure energy supply by investing in key energy exporters.

Although India’s GDP is inferior and its industry less powerful, Indian current perspectives of development are fuelled by a strong demography (see table section 3.2) and make it progressively a “giant” of the world energy system. India is the fourth main GHG emitter and also the fourth main consumer of energy in the world.

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[62] CO2 emissions from fossil fuel use and industrial processes (cement production)

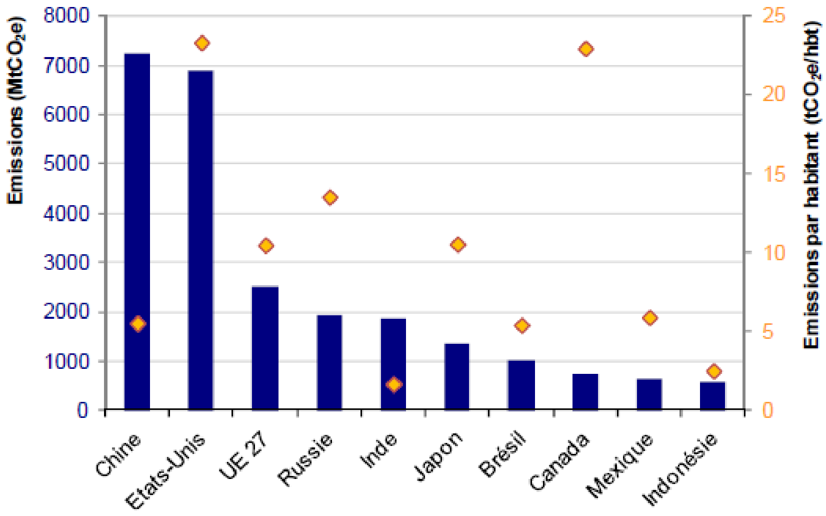


Figure 23 Total Emissions by regions (histogram) and per capita emissions (yellow diamond) (Source: WRI, 2012)

Future projections all agree on the fact that the increase in global energy demand will be mainly driven by emerging economies, in particular by the two giants: India and China.

According to IEA (2007, 2012), China and India would account for more than 45% of the increase in global primary energy demand by 2030, with both countries more than doubling their energy use over that period (the Chinese demand will rise by 60% between 2010 and 2035 according to IEA, 2012) (Figure 24). In this context, China plays a major role in the energy market. As shown in the projections, China could become the world largest energy consumer in 2035 (70-77% more energy than the US) but per capita consumption would be less than half that of the US. As India will know a stronger demography than China (see section 3.2 table 2), the rate of growth in energy consumption in India will be faster than in China (IEA, 2012).

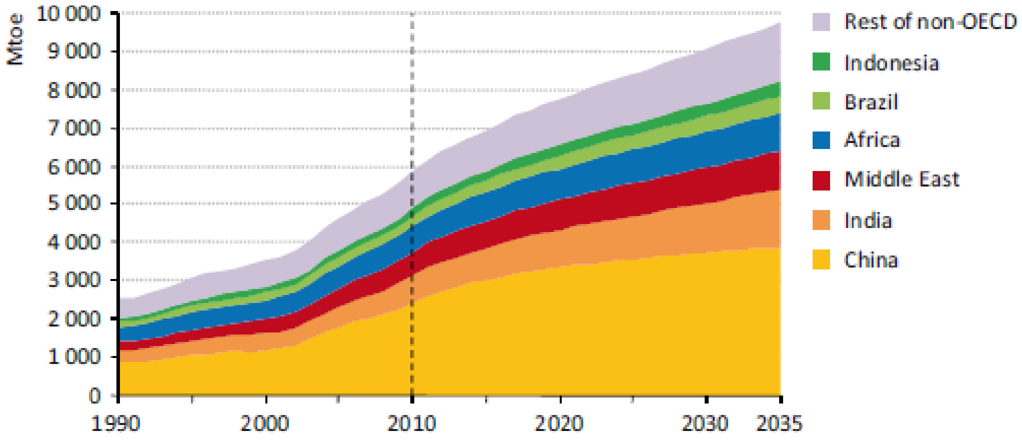


Figure 24 Non-OECD primary energy demand by region (Source: IEA, 2012, New Policies Scenario)

The economic development of the two Giants and more largely of the BASICS (Brazil, South Africa, China and India) will impact energy markets (oil, gas and coal). Figure 25 from IEA (2007) shows for instance that in many baseline scenarios, China will play a major role in the coal demand by 2030 but also in terms of new nuclear capacities and deployment of renewables. These trends have been slightly revised in (IEA, 2012) and they still project China and India as two very energy intensive economies particularly when compared to the rest of OECD countries (e.g. in 2035, the Chinese share of the increase of energy by fuel is projected to be 54% for oil, 49% for coal, 27% for natural gas, 57% of nuclear power and 14% for renewables.)

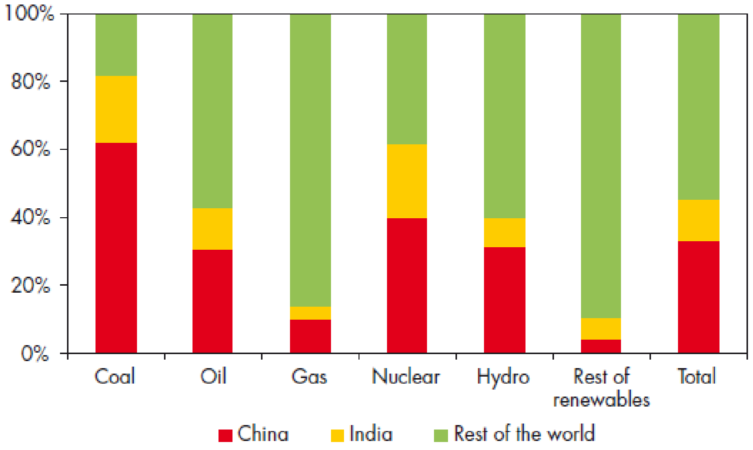


Figure 25 Share of China and India in the Increase in World Primary Energy Demand by fuel in the Reference scenario, 2005-2030 (Source: IEA, 2007)

Indeed, energy mix in both India and China will be dominated by coal in the reference scenario (Figure 26) although its reliance on coal declines in its primary energy use (from 66% to 51% in 2035). The New policy scenario of the IEA (2012) indeed assumes a continuation of provisions in the 12th Five-Year Plan to increase the proportion of natural gas and non-fossil energy in the mix.

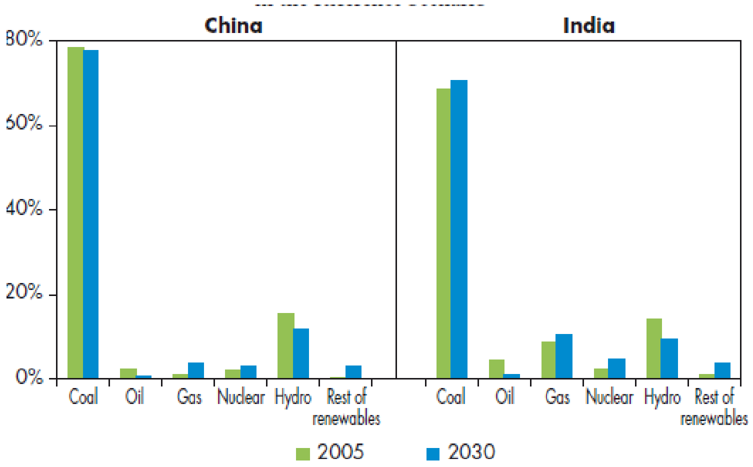
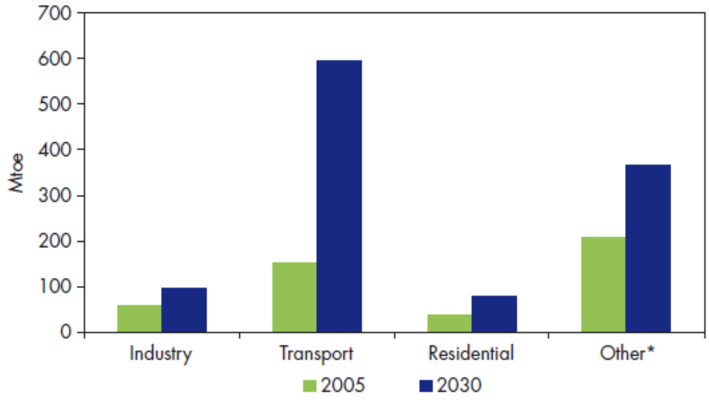


Figure 26 Fuel mix in Power generation in China and India in the Reference scenario (Source: IEA, 2007)

The transport sector will drive most of the demand in oil given the huge prospective in car ownership and use(Figure 27 and Figure 28). At present, only 1 out of 17 Chinese owns a car. Due to a growing middle class, the car fleet in China by 2050 may be 10 times larger than today (Greenpeace, 2012). According to IEA (2012), passenger vehicle ownership per 1000 people in China could climb from around 40 in 2010 to 310 in 2035 demand (It was equal to 4 in 2000 and close to 660 at present in the United States).



* Includes power generation, other energy sector, services, agriculture and non-energy use.

Figure 27 Primary Oil Demand in China and India by Sector in the Reference scenario (Source: IEA, 2007)

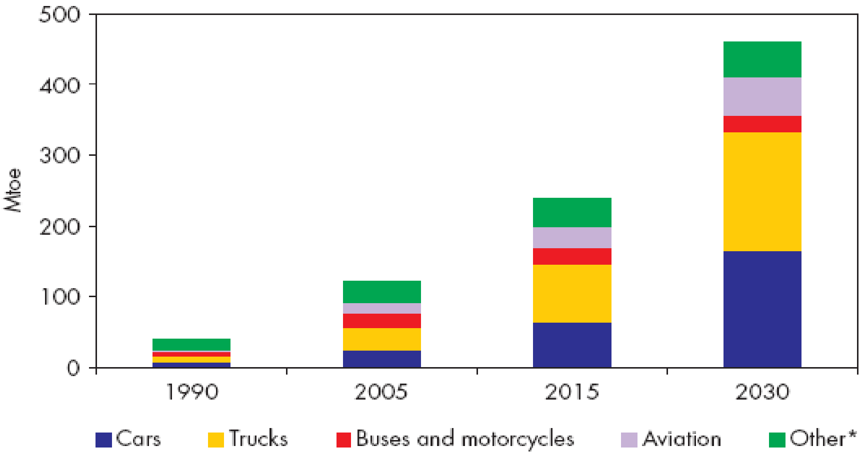


Figure 28 China's transport Energy Demand by Mode in the Reference Scenario (Source: IEA, 2007)

In addition, it is important to notice that India and China are currently at a crossroad as most of their infrastructures (energy, buildings, transportation) will be established in the following two or three decades, causing an important irreversibility effect in terms of GHG accumulation (Figure **29**).

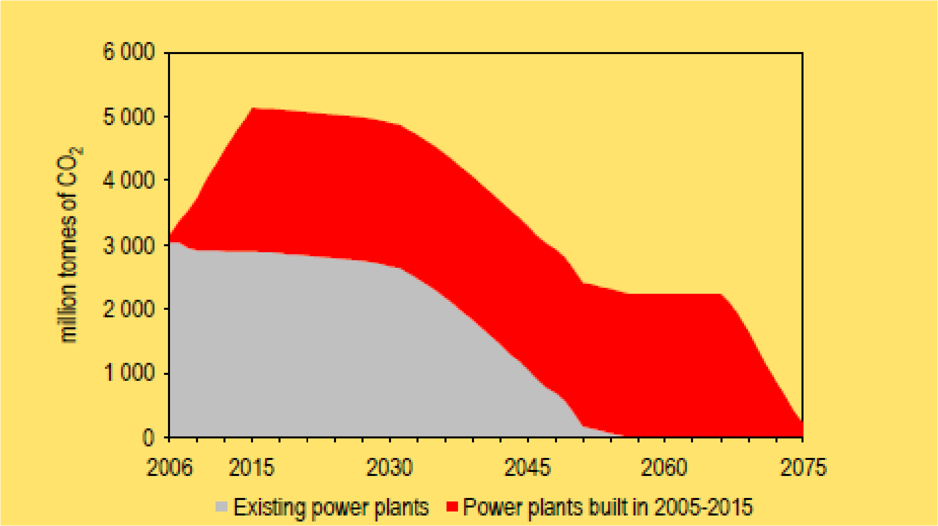


Figure 29 Life time of capacity addition of power plants in China (Source: IEA, 2007)

Low carbon transition pathways for India and China

As part of the Copenhagen Accord (UNFCCC, 2010), emerging countries (in particular China and India) have submitted their reduction pledges the so called "Copenhagen pledges" and action plans for 2020 to the United Nations Framework Convention on Climate Change (UNFCCC) secretariat.

For India, the shift was marked by a voluntary, but conditional, target of reducing emission intensity of GDP by 20% to 25% in 2020 with respect to 2005. One can notice that Indian per capita emissions are very low. In 2008, they were only one-tenth of those of the United States, but also only one-fourth of Chinese per capita emissions. By spurring the development of renewables, the Indian government expects to increase the energy security although the country is currently confronted to a huge deficit in terms of energy infrastructures, causing many disruptions in the power sector.

China pledged to reduce its carbon dioxide emission per unit of GDP by 40-45% by 2020 compared to 2005 levels. In its 12th five year plan, China has confirmed this objective and support ambitious plans in terms of RES development.

The set of scenarios reviewed in this report address either the technological feasibility of the transition or the conditions of the acceptability for China and India to integrate a global agreement with binding commitments. China faces highly emission-intensive growth trajectory in the baseline which requires necessary significant efforts to switch to a low carbon growth trajectory. In their scenario Energy [R] evolution, Greenpeace provides a very optimistic/ambitious vision of the penetration of renewables in the Chinese energy system (Greenpeace, 2012).

Renewables satisfy 35% of China's total heat demand in 2030, 86% in 2050 and 55% of total transport energy is covered by electricity. By 2030 electricity will provide 13% of the transport sector's total energy demand under the Energy [R]evolution scenario. In India as in China, up to 2020, hydro and wind will remain the main contributors of the growing market share. After 2020, the continuing growth of wind will be complemented by electricity from biomass, photovoltaic and solar thermal (CSP) energy.

However, these changes will require strong efforts for China, in particular in a context of stringent carbon constraint. Indeed, China has a high emission-intensive growth trajectory in the baseline and according to the findings of the RECIPE project, it is projected to become a net buyer of emission permits over the 21st century (Edenhofer et al., 2009). Similar findings to the EMF22 project are also stressed out i.e. early participation of China and India will result in significant global cost decreases since much more carbon permit will be available for developed and developing countries (but with higher cost for them).

It is important to notice that these scenarios underestimate the potential costs that the energy transition for these two countries. On the one hand, the spectacular growing of a middle class with consumption styles similar to the one of Western countries spurs energy demand and increases the risk of fossil fuel lock in if the pace of the transition is too slow. On the other hand, higher energy prices owing to tensions around fossil fuel demand will impact dramatically the poorest households which still represents, in particular in India, a large share of the population. These scenarios are centered on the technological feasibility of the transition (even in GEA scenarios which integrate poverty objectives and universal access to energy). They should be complemented by integrating in models of for instance the discrepancies between urban and rural areas, social challenges such as the consequences of the ageing population in China and the lack of a consistent pension system or the persistence of small farmers in India besides highly competitive services. This methodological challenge will be addressed in section 6 of this report in order to better represent the synergies and trade-offs between climate policies and energy security issues.

The overall conclusion from the analyzed sections is that according to scenarios developed in the literature the transition toward a Low Carbon Society given ambitious reduction emissions target is feasible technologically and with moderate costs. However, these pathways are mainly based on debatable assumptions on the development of certain technologies which are far from being mature and competitive. Reaching this goal is possible only if restrictive conditions are satisfied: full and immediate participation of all countries, high degree of flexibility in technical adjustments and the possibility to generate a large amount of negative emissions before 21006 (Krey and Riahi, 2009; van Vuuren et al, 2010). Satisfying simultaneously those conditions imposes to adopt an optimistic vision of the political, technical and behavioral barriers.

Scenarios reviewed also show potential challenges for energy security at the global and regional level. For instance, the higher penetration of RES raises the issues of their integration in the power supply. Indeed, their natural unpredictability and variability over time scales ranging from seconds to years potentially represents an internal stress for the energy system which characterizes one dimension of energy security as put forward in deliverable D1.1. This can “constrain the ease of integration and result in additional system costs, particularly when reaching higher RE shares of electricity, heat or gaseous and liquid fuels” as put forward in (SRREN, 2011). Higher electricity prices entailed in the short term by a carbon price could also affect negatively the poorest households despite energy savings. To what extent Climate policies can provide coherent answers to these issues? Beyond these optimistic visions of long term pathways, next section will point out that a key issue for models is the assessment of the synergies and trade-offs with other key dimensions of the transition, among them energy security issues.

6. A basic vision of transition dynamics for assessing the interactions between climate policies and energy security issues?

6.1 A climate and technology-centric drift

The scientific agenda of the modeling community has been driven by the international climate negotiations since the early 90’s. According to (Hourcade and Shukla, 2013, Hourcade et al., 2007), the economics of climate policy after Rio led to a climate centric paradigm built around the understanding that the Kyoto Protocol implies a world carbon market generating the same carbon price imposed on all the carbon emitters. The perspective of an extended Kyoto Protocol to non-Annex I countries, in particular the BASICS (Brazil, South Africa, India, China), has triggered assessments of potential climate architectures reflecting the three flexibilities mentioned in the previous section. Among the set of scenarios surveyed, EMF22 and RECIPE projects explicitly analyze the impact on long term stabilization targets of differentiated timing of actions among countries. Furthermore, the narrow window of opportunity pointed out by the AR4 in order to comply with a 2°C target echoed the adoption by the EU or the G8 of this ambitious reduction emission objective before being included in International text. As a result, most of modeling exercises have principally focused on the feasibility of climate targets, mainly through a technology centric approach which has put aside the linkages between climate policies and other issues in particular energy security and social impact of energy transition. The GEA pathways in the set of scenarios surveyed represent one noticeable exception complemented by other recent studies conducted with IAMs presented in subsection 4.3.

A feature of this climate centric drift is the belief that a few backstop technologies will make ambitious stabilization targets feasible, including the BECCS which has been recently introduced in most of IAMs to comply with the 2°C target. Low carbon scenarios are based on heroic assumptions in terms of realistic technological deployment. For instance, scenarios of the ADAM project for instance show that for the lowest stabilization target (400 ppm CO2 eq), the use of bio-energy in combination with CCS would amount up to 400 EJ/yr used at its maximum (Van Vuuren et al, 2010)[63]. This result is highly optimistic with respect to the assumptions on potential yields and the availability of lands in the next decades. Impacts on land use competition and biodiversity is debatable since the large scale production of biomass for energy may generate emissions from deforestation and agricultural intensification, and adversely impact food prices (Edenhofer et al., 2010). For instance, based on Haberl et al. (2010) works, (Bibas and Mejean, 2012) shows with assumptions of 149 GJ/ha/year (in a context of “managed forests”), the production of 300 EJ/year of biomass worldwide would require a land area of 2.01 Gha, corresponding to about 15% of total land area. (see also Brunelle, 2012, Souty et al., 2013 for a review on the controversies on land use, land use change and forestry in models and Lambin et Meyfroidt, 2011 for an analysis of the drivers of land availability).

Uncertainties remain also on the technical feasibility of a large scale development of CCS in particular on the size of geological storage capacity and possible leakage from those reservoirs (IPCC, 2005) and the carbon-neutrality of the production of biomass (Farigone et al., 2008; Searchinger et al., 2008). In addition, a social

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[63] All models assume a biomass potential of 200 EJ/yr as a reference, compared to typical estimates in the order of 0-150 EJ/yr for residues and about 100-200 EJ/yr for bio-energy crops (Van Vuuren et al., 2010).

consent on CO2 long distance pipeline transport by densely areas is very sensitive and problematic.

6.2 Second best world or Second best policies?

A complex notion

As the fourth IPCC report (AR4) stresses out:
“Most models use a global least cost approach to mitigation portfolios and with universal emissions trading, assuming transparent markets, no transaction cost, and thus perfect implementation of mitigation measures throughout the 21st century” (IPCC, 2007, Box SPM.3).

Following the caveat of the IPCC AR4 on the limits of first best modeling assessment (as seen in section 3.2 this concerns most of the models used in the set of scenarios surveyed in this report), recent modeling exercises attempt to assess long term low carbon trajectories in so called second best settings. They encompass second-best technology scenarios (ADAM and RECIPE projects) or incomplete climate policy broad countries coverage (EMF22). Second best technology scenarios are assessed more precisely through the option value of delayed penetration of technologies measured by the difference of consumption losses between scenarios with constraints on the technologies and a baseline. Figure 30 pictures the consumption losses among the three models of the RECIPE project given restrictions on the nuclear (FixNuc), biomass (FixBiomass), CCS (Fix CCS), Renewables (FixRenewables) and a combination of no CCS and fixed Nuclear, or not (the scenario 450ppm C&C[64]). In the short term (until 2030), model agree on the fact that the cost of restricting technological options entail limited extra consumption losses compared to the 450ppm scenario (all technologies available) except for the IMACLIM model when CCS and nuclear are constrained. Over the whole period (2005-2100), scenarios with restrictions on the combined deployment of CCS and nuclear and scenarios where only renewables are limited entail extra consumption costs (both in WITCH and REMIND) compared to the 450ppm C&C. Indeed, in WITCH and REMIND, these technologies are key to decarbonize the economy in the long term (in the project, emission reduction efforts are moderate before 2030). Whereas in the IMACLIM model, the impact of restrictions of CCS and nuclear

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[64] C&C or Contraction and Convergence means that every country brings gradually (Contraction) its emissions per capita to a level which is equal for all countries (convergence). C&C rules have been conceived initially by the Global Commons Institute (GCI) in the early 1990s.

combined impact more significantly the economy, even in the short term, given the assumptions of the models relative to the inertias of energy system.

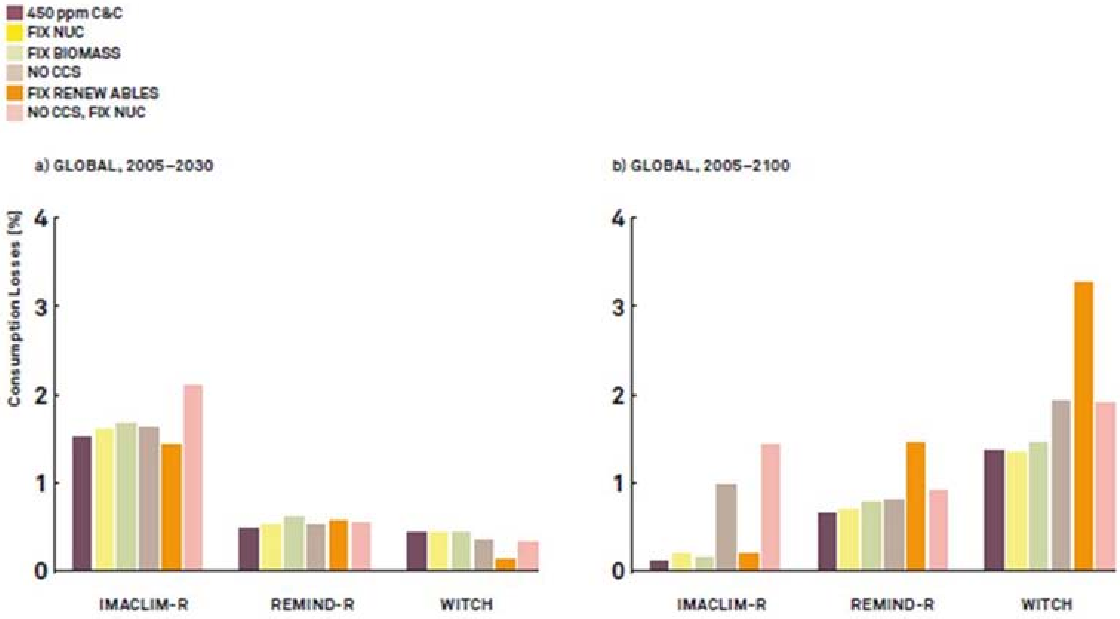

Figure 30 Option values of technologies in terms of consumption losses for scenarios in which the option indicated is foregone (CCS) or limited to BAU levels (all other technologies) for the periods 2005–2030 (a) and 2005–2100 (b) (Source: RECIPE Project, final report, 2009)[65].

Incomplete countries coverage of climate policies are measured by the cost of delayed action of countries in the coming decades. Figure 31 combines the global consumption losses differences relative to baseline for second best technology scenarios and also delayed climate policy in the RECIPE project. Different incomplete climate policy architectures (with the same commitment to 450ppm) are compared to a global regime complying with 450ppm or 410ppm: a delay action of both industrialized countries (IC) and developing countries, the unilateral action of Europe (EUonly), only Industrialized countries commitment and industrialized countries plus China and India. Higher costs compared to the 450ppm scenarios are observed when there is delay action to 2020 and the closest when the main emitters (IC, China and India) commit to climate policies.

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[65] "The economic costs of climate policy are computed by comparing the macro-economic consumption paths that are obtained in the respective policy scenario with the one in the business-as-usual scenario. The difference between these two trajectories determines mitigation costs in each point in time. The mitigation costs are expressed in terms of consumption losses. Consumption is the portion of GDP that is not invested, thus providing utility. To make costs that appear in different points in time comparable – i.e. costs in the far future are valued less than costs at present or in the near future – all costs are converted to net present values. RECIPE used a constant discount rate of 3%. Total mitigation costs are then calculated by summing up these net present values, expressed as a fraction of the net present value of the consumption path that would prevail over the century if no climate measures were implemented" (Edenhofer et al., 2009 box 2-3)

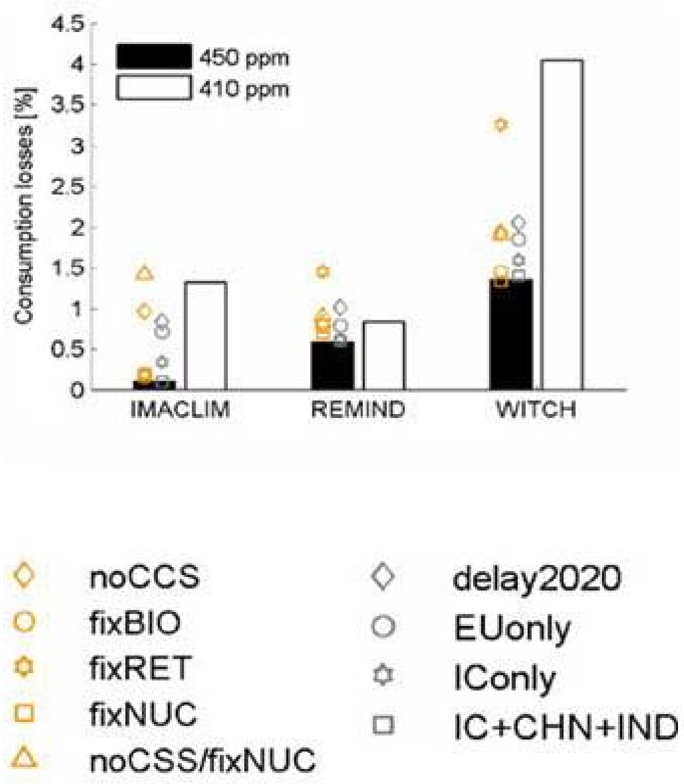

Figure 31 Global welfare losses as consumption differences relative to baseline for the first-best default 450 ppm (*solid*), the 410 ppm (*dashed*) as well as ranges for second best scenarios with limited availability of technologies (*orange shading*) or delayed climate policy (*grey shading*). Aggregated consumption losses (d) are discounted at 3% (Source: Luderer et al., 2012)

However, these analysis reveal a misunderstanding in what modellers call second setting or "second best". Indeed second best policies (delay in technologies availability and action of main emitters) are more frequently addressed by models than in a real second best world characterized by rigidities in the labour market, imperfect expectations, inertia in behaviors and routine (see Guivarch, 2009 for discussion). In the RECIPE project, IMACLIM was the only model to embark in its modeling structure such features whereas ReMIND and WITCH are based on intertemporal optimization approaches. These disequilibrium are however a key point to understand the dynamics of the transition towards a low carbon society and to assess linkages between climate policies and other issues in particular multi-dimension of energy security (technology, economic and social) .

The challenge to represent transitory adjustments

The integration of transitory adjustments in models remains largely unexplored, except for some tools still considered "experimental" in the literature. Indeed, most modelers assume that climate change is a long term issue and underestimate short term and transitory mechanisms. Quantitative assessments poorly integrate them since almost all models are long term equilibrium models, whose "growth engine" is based on the Solow recursive model or the Ramsey intertemporal model (see part 1.1 for a classification of models). These types of models provide and compare equilibrium economic paths and in doing so, however, fail to come to address deviations from equilibrium growth (Solow, 1988).

As a result, mitigation costs on the short term are likely to be underestimated because of the inertia of capital stocks, rigidities of the labor market, and political constraints with respect to carbon tax revenues recycling and reinvestment. Most IAMs hence simply provide full employment trajectories, which neglect the impact of climate policies on the job market. Few models take up the challenge of representing deviations from first best world except for only the hybrid CGE IMACLIM-R (Sassi et al, 2010, Waisman et al., 2012) and the Keynesian sectoral econometric model E3MG (Barker et al, 2006, Barker and Scrieciu, 2009). The IMACLIM-R model shows GDP costs in the short term and long term which differ significantly from those found in a first best economy, because the model captures key features of second- best economies (non-fully flexible labor markets, imperfect competition, adaptive foresight) and represents the inertia of technical systems. In the RECIPE project, the model evaluates the impact of specific measures triggering an early redirection of investments in favor of modal shifts towards public modes, moderation of urban sprawl, and curtailment of the transport intensity of production in addition to a carbon price to limit the lock-in in transport after 2050. Policies combining a carbon price, development of decarbonized infrastructures in the transport sector and reduction of labor taxes on exporting firms reduce transition costs between 2010 and 2030 (expressed in % of global GDP variations between scenarios with emission reduction target and baseline scenarios in the y axis of Figure 32). Indeed they limit fuel consumptions and hence the impact of higher fossil fuel prices. After 2040, the cumulative effect of technical change and the long term impact of early low carbon infrastructures avoid lock in and entail a positive double dividend[66][67] (Waisman et al., 2012 and Figure 32).

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[66] Given the absence of reliable and comprehensive data on the cost of implementing these measures, a redirection of investments at a constant total amount was assumed in the model

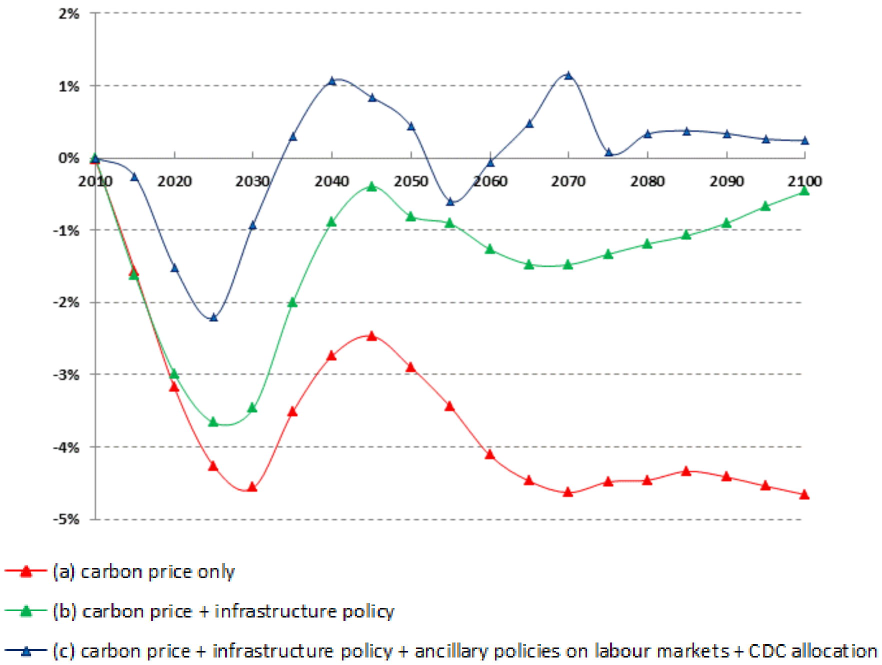

Figure 32 RECIPE model runs reported in: Hourcade, J.C., Shukla, P., 2013. Triggering the low-carbon transition in the aftermath of the global financial crisis. Climate Policy Special Issue Volume 13.

Considering that the transition toward a low carbon society will not be smooth at the global but also at the country level since the transition patterns are complex and characterized by rigidities, that emissions reduction depends not only on the energy system, but also on infrastructures policies at the urban scale, land use policies, fiscal policies… encourage to analyze the potential co-benefits and -offs across different policies.

6.3 Co-benefits and trade-offs between climate policies and energy security

This section concentrates more specifically on the synergies and trade-offs between climate policies and energy security with respect to the objectives of the MILESECURE-2050 project. As put forward in D1.1, energy security is multidimensional[68] and IAM models enable to pursue a "holistic, system wide

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through three main factors: a progressive decoupling of basic mobility, a limitation of investments in road and air infrastructures, and hence a maximum threshold to mobility.

[67] The first dividend is emissions reduction, the second is the positive impact on growth relative to the baseline

[68] "Energy security is a complex issue involving political, economic, socio-cultural, technological and environmental dimensions as well as various considerable threats (Vivoda, 2010; Sovacool et al., 2010; Winzer, 2012)   p 38

integrated assessment" of energy security, in particular by assessing the impacts of "climate mitigation side-effects". Whether they are positive (for instance the penetration of renewables (wind, photovoltaic, geothermal, CSP, biomass) replacing fossils fuel may limit import dependency), they will be called co-benefits or trade-offs.

However, modeling exercises surveyed here principally focus on long term mitigation strategies. Non-climate dimensions and the potential impacts of each of them along other have indeed received much less attention in the research literature. One notable exception among the set of scenarios surveyed are recent studies such as the GEA which shed light on the macro-level implications of climate mitigation for other societal priorities, including energy access, air pollution and its health impacts, water use, energy security, land use requirements and biodiversity preservation.

The GEA assessment

The assessment of potential co-benefits and trade-offs requires first to delineate the diverse dimensions of energy security. These encompass oil volatility, geographical concentration of oil and gas production, vulnerability of energy systems, ageing infrastructures, export vulnerability… GEA considers three dimensions of energy security: sovereignty (relating to geopolitics, power balance in energy trade, and control over energy systems), resilience (ability to respond to disruption), robustness (physical state of infrastructures) and system accuracy following (Cherp et al., 2012). For each dimension, it uses indicators to assess the effect of policies implemented in each pathway.

Firstly, global trade in energy used as a proxy to measure the sovereignty aspects of energy security decreases under the GEA pathways. Indeed, by decreasing energy intensity, ambitious climate policies have the co-benefit to lower oil demand which peaks around 2030. However, gas as a transition fuel, experiences growth to some 30% of global primary energy supply (compared with oil's 36% share today) in 2050, with increasing trade flows and a decrease in the diversity of production. The decline in absolute trade volumes after 2030 is most pronounced in the Advanced Transport GEA-Mix and Efficiency pathways and least prominent in the high demand, supply-dominated GEA transition pathways. In this context, GEA concludes that energy system are supposed to be less likely confronted to disruptions following other studies on this issue (Costantini et al., 2007; Criqui and Mima, 2012; Shukla and Dhar, 2011).

Secondly, the resilience of energy system increases as the sources of energy measured in the GEA pathways by the Shannon-Wiener diversity index (SWDI; see Shannon and Weaver, 1963) become more diverse[69].

The increase in diversity in the transportation sector is particularly significant in the GEA pathways, whereas the improvement is more gradual in the other end-use sectors and in electricity generation.

Thirdly, the reliance on a few exporters countries declines since energy mix are more diverse[70]. This is the case for the OECD countries' energy systems: switch away from fossil fuels, increases in efficiency, and the diversification of transport technologies. Energy security in China and India (which are included in a broader group) is particularly sensitive to the strong energy demand increase in these countries. Energy security improvement in India and China will depend on their ability to make their energy system more diverse and "leapfrog the inherited energy systems inertia of the industrialized world" (IIASA, 2012). Conversely, a risk of global climate mitigation efforts is that such measures may potentially curtail the export revenues of fossil energy producers, thereby decreasing their "demand security"[71].

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[69] The index is calculated as follows:

$SWDI = -\Sigma(pi * \ln(pi))$

where $p\ i$ is the share of primary energy i in total primary energy supply. In the GEA pathways, the global SWDI rises (supply diversification increases) from the current level of 1.6 to 2.0 by 2050, before falling to between 1.3 and 1.6 in the latter half of the century.

[70] The most important energy-exporting region today is the Middle East and North Africa (MEA), with net energy exports of over 52 EJ in 2005, followed by the Former Soviet Union (FSU), which exported about 24 EJ in that year; Latin America and the Caribbean (LAC) and sub-Saharan Africa (AFR) each exported some 11–13 EJ. This point echoes to recent studies conducted with the IMACLIM model.

[71] Waisman et al. (2013) for instance assess the impact of oil producers' strategies on oil prices and OECD growth trajectories. In particular, oil producers may accept lower oil prices so as to maintain oil importers' dependency to oil and benefit from higher long-term revenues in the post-Peak Oil period. Oil importers may implement specific policies such as a carbon tax to secure steady technical change.

An innovative modeling framework to assess the multi-dimensions of energy security

The GEA study improves our understanding of the potential interdependences between climate policies and energy security issues. However, these models are confronted to two main challenges: i) assessing more precisely the impact of climate policies on the entire energy supply chain and the social impacts on households (energy fuel poverty in particular) iii) the structure of the two IAMs IMAGE and MESSAGE only enables to study equilibrated growth pathways, often under perfect foresight assumptions. But an economy with structural debt or unemployment and submitted to volatile energy prices will not react in the same way to environmental shocks or policy intervention as an economy situated on a steady state growth pathway (Sassi et al., 2010). In non-optimal Baselines scenarios, "myopic" people do not anticipate the rise of energy prices and make choices, in particular in terms of equipment, which can be costly when energy prices increase. Representing the rigidities of the economy is a key element as sustainability challenges come primarily from controversies about long term risks which can inhibit their internalization in due time and from the transition costs to adapt to unexpected hazards.

In the following sections, some works conducted by the IMACLIM hybrid modeling architecture to assess the multi-dimensions of energy security are presented. It combines a macroeconomic approach with sectional-engineers views (on oil markets, land use, buildings, transport…) integrated in a modular way through nexus (see Sassi et al., 2010 and Waisman et al., 2012 for a technical description and the annex of this report for a better understanding of hybrid approaches). IMACLIM has the originality to describe an economy with disequilibrium mechanisms triggered by the interplay between inertia, imperfect foresights and "routine" behaviors. This modeling framework enables to better assess the resilience of the energy systems and economies to shocks.

This approach has been applied to the EUFP7 AUGUR project in a context of four main scenarios of global governance by 2030: i) "Multipolar world" where global challenges of climate change, environmental sustainability and energy and food security are addressed at the world level ii) "Reduced government" scenario where both the role of government in the economy and the reliance on international institutions decline iii) "China and US intervention" in which the world is dominated by the US-China accommodation i) "Regionalism" in which a switch from globalization in favor of regional groupings in Asia, Europe and North America occurs.

In the four scenarios, the model projects a steep increase of fossil fuel prices owing to the depletion of resources: this is exacerbated in the regionalized world where there are no efforts to enhance energy efficiency and coordinate them at a global level. In a multipolar world, where climate policies are implemented at a global level, the increase in the next decades is moderated (see Figure 33).

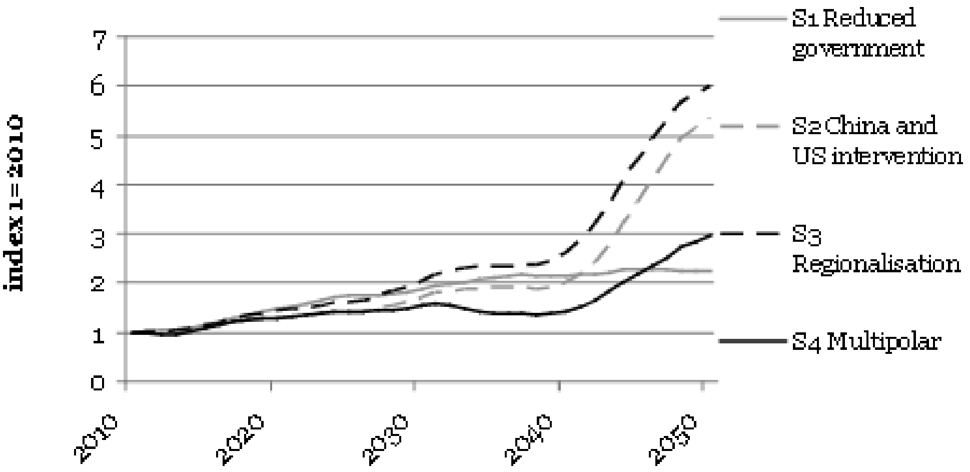


Figure 33 International oil prices pathways (2010-2050) in the four AUGUR scenarios (Source: Guivarch et al., 2012).

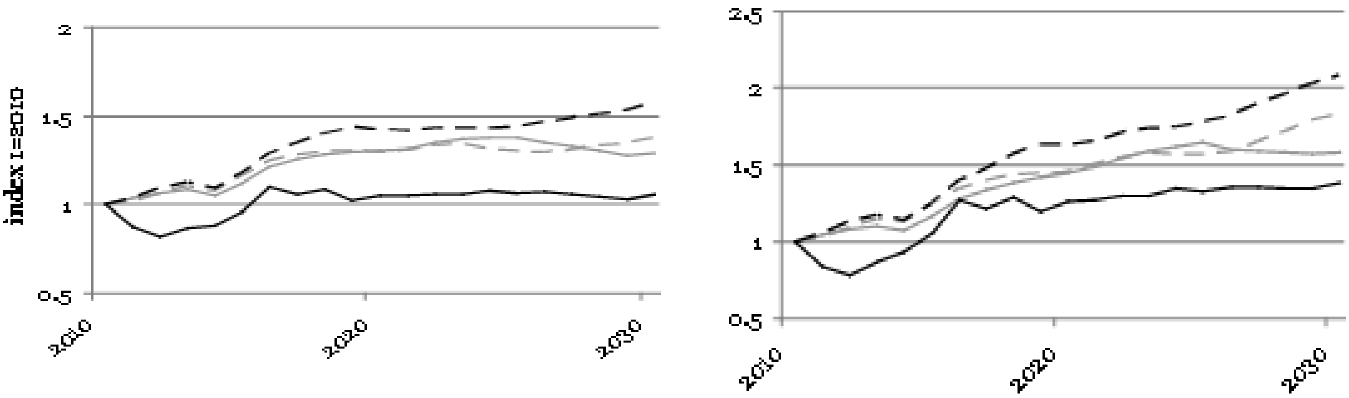
The project analyzes the evolution of two main indicators of energy security: the ratio imports/exports and the share of imports bills in the GDP.

The ratio imports/exports of oil decreases, in particular for Europe, while it increases in a more fragmented world. For Europe, the US, China and India, the share of oil imports bill in GDP increases steeply over 2040-2050 in “Reduced Government”, “China and US intervention” and “Regionalization”, while it does not in the “Multipolar” scenario. This reveals an asymmetric vulnerability to oil price volatility. Indeed, in the two former scenarios, the four energy intensive economies considered (on the supply and demand side) are enclosed in an oil lock-in setting after the peak oil (2020-2030) (see the results relating the share of oil imports for the US, China, India and Europe in Figure 34). Inertias of technical system also increase the negative impacts of oil prices shocks. In the long term (around 2050), these tensions are lessened as economies are forced to reduce fossil fuel energy consumption after a dramatic increase of the energy bill in the short term.

These findings raise several issues:

First, the necessary articulation between short term and long term perspectives. Inertias in the technical systems, behaviors and the institutions make the transformations away from oil consumption and/or away from carbon intensive economies a slow process. Therefore, early redirection of investments towards green infrastructures is required to avoid oil lock-in.

Second, climate change and energy security issues are closely linked. Indeed, the more societies are dependent from fossil fuels, the more difficulties they will have to comply with ambitious reduction GHG emissions targets, in particular to comply with the 2°C objective. Climate policies, by putting a price on carbon, increase the price of fossil fuels, including oil. Therefore they can trigger technical change, structural change and changes in behaviors that improve energy efficiency and leads to substitutions away from fossil fuel, including oil.


Share of oil imports in GDP (Europe)

Share of oil imports in GDP (China)

Share of oil imports in GDP (USA)

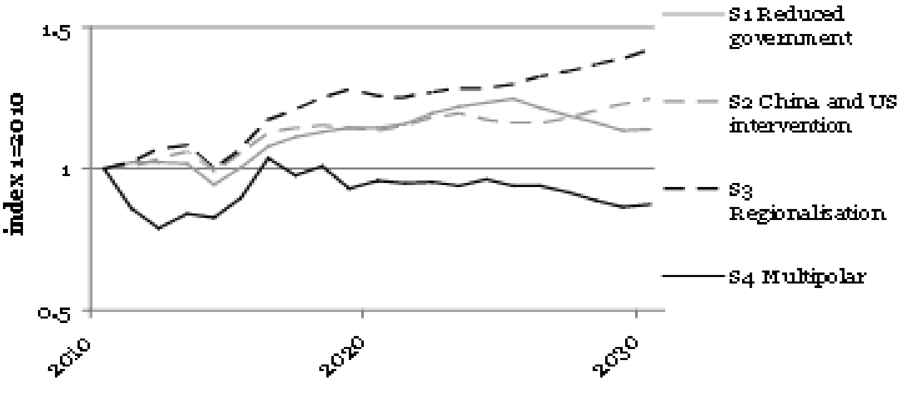


Figure 34 oil imports as a share of GDP for Europe, USA, China and India over 2010-2030 in the four AUGUR scenarios (Source: Guivarch et al., 2012)

Rozenberg et al. (2010) shows with the IMACLIM model how climate policies in addition to their benefits in terms of avoided climate impacts may bring important co-benefits, in terms of resilience to oil scarcity. In a context of imperfect foresights and inertias of infrastructures, the implementation of a carbon price involves more regular increase in energy price and triggers low energy and carbon technologies which prevent from brutal increase in energy prices and economic lock-in. In Figure 35, the histograms in blue covering 450ppm scenarios are shifted to the left, indicating that the mean loss due to oil scarcity is reduced by climate policies.

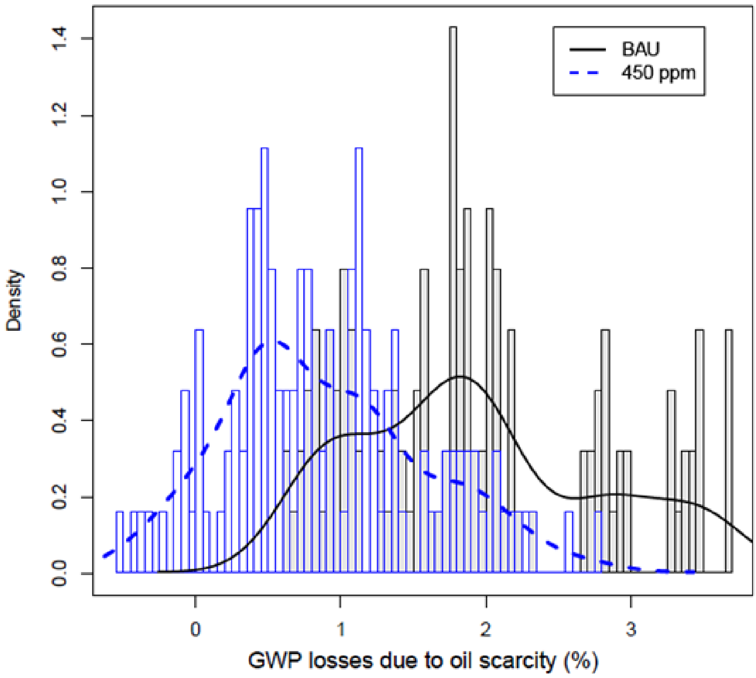


Figure 35 GWP (Global Welfare Production losses) due to oil scarcity (%) (Source: Rozenberg et al., 2010).

Third, energy security is a multidimensional issue which makes key the selection of indicators to understand the synergies and the trade-offs between energy security and other issues, in particular climate change.

In a recent report conducted with the IMACLIM model, Guivarch et al. (2013) follow Sovacoll and Brown (2010), Kruyt et al. (2009) and Chester (2010) and adopt four main types of indicators to assess the interactions between climate policies and the multi-dimension of energy security in Europe:

- Availability and diversification (ratio oil/resources and concentrations of oil imports);
- Dependency and energy efficiency (energy intensity of GDP and rate of energy dependency);

- Cost of energy consumption for the society (ratio energy imports /GDP and the share of households budget allocated to energy purchase);
- Acceptability (nuclear capacity in Europe and wind capacities in Europe). As put forward in D1.1 social acceptance is often taken for granted and frequently disregarded by policy makers.

The study measures with the IMACLIM model how these indicators evolve given the uncertainty around the determinants of future energy systems: population trends and economic growth, cost and potential of low energy technologies (electric vehicle, renewables energy…), coal prices, energy consumption patterns and behaviors, energy efficiency improvement rates etc[72]… Results have been mapped on radar graphs similar to Figure 36[73].

Results point out that there are no easy conclusions about the impact of a climate policy on energy security issues. Climate policies can enhance some indicators of energy security and worsen others depending on the time scale considered, assumptions on key parameters, and specific national conditions.

First, the rate of energy dependency and oil imports are downgraded by a climate policy on the short and middle term (before 2050), but improve, on average, on the long term (after 2050). These trends are driven by two channels: global oil consumption and a reduction of unconventional oil use. On the one hand, climate policies limit the extraction of unconventional oil since the demand decreases. On the other hand, in Europe, the share of fossil fuel in energy imports increases in the short term (around 2030) because carbon price fosters the substitution of coal by gas in the power production[74]. Actors' myopic foresights in the IMACLIM model strengthen this trend which finally increase the energy dependency of Europe. In the long term, the increase share of renewables allows however to reduce imports .

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[72] Europe is one of the 12 regions represented of the model. The database of scenarios combines alternative assumptions on a large number of model parameters (Rozenberg et al., 2012): Natural growth drivers (active population growth, labour productivity growth), Fossil fuel reserves, Speed of induced energy efficiency, Cost and potential of low carbon power generation technologies, Cost and potential of CCS Cost and potential of low carbon end-use technologies. 96 « baseline » scenarios, and 96 corresponding « climate policy » scenarios have been developed.

[73] Some additional comments on Figure 36: the report uses this type of graph (this one is only indicative) to summarize the changes of the value of chosen indicators between the baseline and the climate policies scenario, in Europe. Eight indicators have been reported, two for each dimension of the energy security concept. Rada graphs have been produced for different time scales.

[74] The model assumes that Europe has 200 GToe of coal, corresponding to 9% of world resources. RES are less competitive than gas for power production as carbon price in the short term is relatively low.

Second, households' energy share and imports of energy on GDP are deteriorated by the climate policy in the short run but are then on average improved. The deterioration of household's energy budget is the result of higher energy prices (linked to the implementation of a carbon price) and to the slow adaptation of households' equipment stocks in the short term. Learning by doing process and energy efficiency improvements make this phase transitory.

Third, three indicators are always improved by climate policies (in all scenarios, whatever the time horizon): the ratio of oil production over resources, the energy intensity of GDP and the carbon content of total primary energy supply.

At least, two indicators, nuclear and wind capacities in Europe have more complex long term evolutions. On average, a downgrade in the short term followed by an improvement in the middle term is observed. Nuclear and wind capacities increase in the short term following the implementation of climate policies but decrease in the middle term because of the reduction of power demand.

In the long term, the effect of climate policies is more ambiguous. It depends on the relative substitution effects between power production technologies (plants using fossil fuel with and without CCS, RES, nuclear) and different drivers which influence the power demand: some tend to reduce the effect, such as the improvement of energy efficiency whereas others increase it such as the deployment of EV (Electric vehicles).

This study represents a first attempt to analyze at the European level synergies and trade-offs between climate policies and energy security issues with both an innovative modeling framework (representing the inertias of infrastructures and consumers' behaviors) and a methodology whose objective is to assess the impact of uncertainties around key socio-economic parameters. It has identified the potential conflicts between climate policies and energy security objectives and point out when complementary policies (in particular for households impacted by higher energy prices) are necessary to reconcile both objectives. Further improvements could be conducted in the framework of the MILESECURE-2050 project to apply such a methodology at a country level and also taking into account different climate architectures and specific sectoral policies (urban and labor policies for instance).

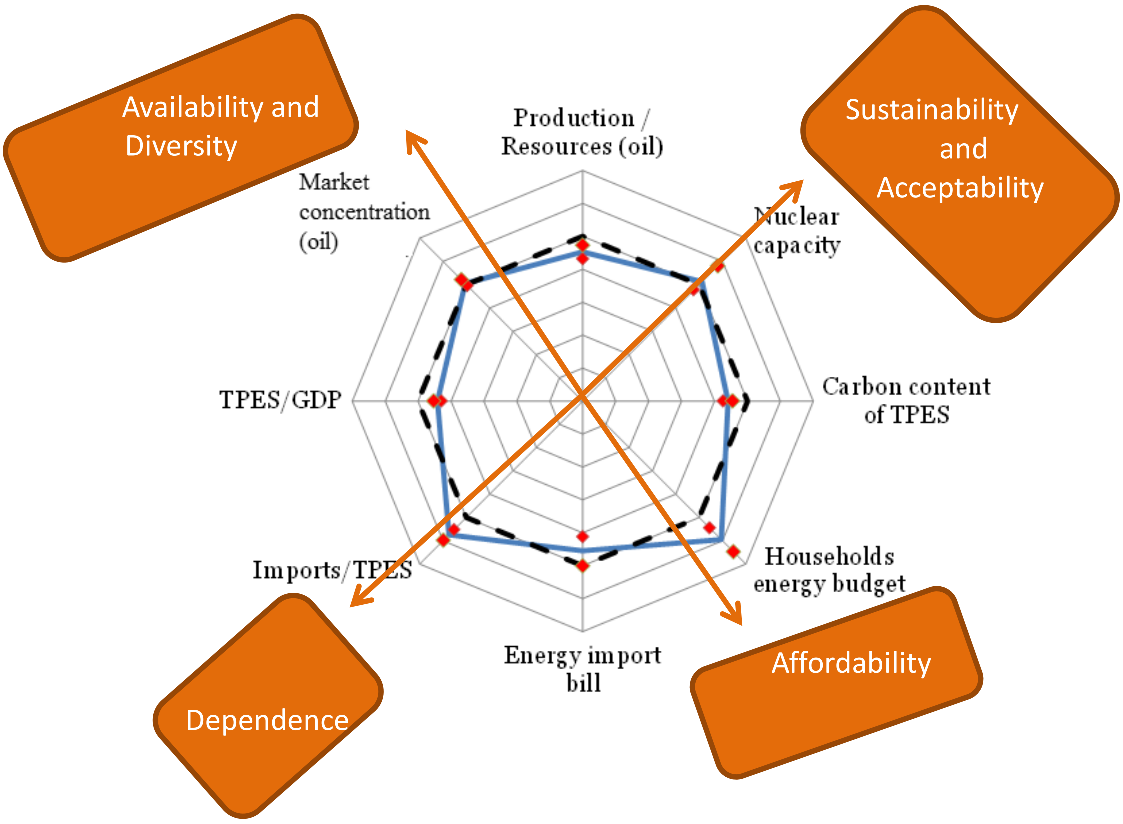

Figure 36 Example of radar graph of the results for each indicator (Source: Guivarch et al., 2013)

7. Conclusions

Over the last 15 years, an increasing amount of studies and quantified results went along with climate change negotiations and energy security issues. Decision makers have requested to modelers for urgent advice on the implementation of policies and domestic measures with the view of the transition toward a low oil dependence and low carbon society (LCD). The set of modeling scenarios surveyed in this report confirms the main findings provided by the fourth IPCC report with respect to the optimism in terms cost of mitigation policies provided that (i) countries commit as early as possible in a global international agreement and (ii) a rapid deployment of key low carbon technologies support by strong public incentives.

This report has also underlined that few scenarios among the set of key modeling exercises surveyed address the potential synergies between climate change and energy security issues. This is partly due to the agenda of international negotiations over centered since the last fifteen years on climate emission reduction targets. Climate talks have progressively come to be structured around the objective of limiting global temperature rise to 2°C above pre-industrial levels impacting research issues in modeling exercises [75]. This has partially put aside the linkages with other development issues, in particular energy security. The evaluation of co-benefits of climate policies is also still submitted to intense debates in the current works of IPCC group III. The question is how should one account and measure for these multiple co-benefits and costs when assessing policies along one dimension, such as climate change and energy security.

Although IAMs have made progress in the integration of different issues, this survey has delineated two main limits of models: a technology centric drift due to the linkage between B-U and T-D models based in most cases on an optimal structure and an overrepresentation of “first best” mechanisms. Regarding the latter point, most important challenges lie in the (i) the assumption of full employment of factors, which hinders to explore partial disequilibrium, unemployment and economic adjustment (ii) the poor representation of behaviors in final consumptions assessments (barriers, anticipations, social norms, social acceptance) (iii) assumptions of balanced economic and capital flows.

It is important to consider that (i) mitigation policies are closely linked to issues including labor policies, urban and land use planning, infrastructures policies and so on (ii) these policies are implemented in non-steady growth pathways and (iii) energy

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[75] For a better understanding of the history of the 2°C target and how it structures the climate debate see Randall., 2010 and Jaeger and Jaeger, 2011

transition is intrinsically a multi-objective goal. This provides for models opportunities to elaborate more comprehensive ways to address the co-benefits and trade-offs between energy security issues and climate policies.

This agenda has been partially set in the perspective of the next AR5 as shown by the GEA pathways and some recent studies. This report proposes preliminary insights based on a quantitative modeling architecture in line with the methodological requirements provided by D1.1, able to assess the multi-dimensionality of energy security and interactions with other policies areas in an “imperfect” world. This innovative framework integrates indeed second best features of the economy: disequilibrium on the labor market, imperfect foresights of energy prices and inertias of the energy systems and infrastructures.

This first set of scenarios show that the assessment of the synergies and trade-offs between climate policies and energy security issues is complex. On the one hand, low carbon trajectories can globally improve energy security issues by enhancing the diversification of the energy supply and gradually switching (depending on internal national context and the stringency of policies) from fossil fuel to renewables produced locally. On the other hand, climate policies can downgrade other indicators in particular high energy costs which directly affect households in the short and medium terms up to 2040 – 2045.

These global and regional findings will have to be completed by a more in depth analysis of the key challenges at the national level in deliverable 1.3 whose aim is to review of European policies and strategies for a low carbon society and their implications on environmental and energy policies. The visions of the transition in the scenarios surveyed can also help frame the elaboration of a macro-regional energy security scenario in task 1.4. At least, the innovative modeling framework presented in the last part of the report provides some features to define a coherent and comprehensive set of energy multi-scale scenarios apt to integrate the results from WP1, 2 and 3 in WP4.

8. Annexes

Annex 1: A brief overview of the history of the models and a presentation of a typology

Different types of models are used for long term GHG emissions trajectories in regional or global prospective modeling exercises (Zhang and Folmer, 1998, IPCC, 2001, chapter 7, Crassous, 2008). They result from works started at the beginning of the seventies, following the *Limits to Growth* report and the oil crisis. Indeed at that time i) growth theoreticians analyzed how the constraints on natural resources would impact economic growth ii) a detailed representation of energy systems was regarded likely to assess oil importers' option to limit energy supply and the potentials provided by nuclear and energy demand control iii) macro-economic models were used to assess the impact of oil shocks and the increase of imported energy.

In the 80's, the common ancestors of current long term prospective models have emerged and their structure has barely evolved (Matarasso, 2003). They can be characterized in two dimensions:

- A main cleavage is between models that are rooted in either a macro-economic tradition (top-down) or in an engineering tradition (bottom up). Bottom up models give the priority to a detailed description of technologies and sectoral systems in order to provide energy services. Part of bottom up models such as Markal, Poles (Criqui et al., 2003), Message (Riahi and Roehrl, 2000) or GCAM (Kim et al, 2006) cover indeed dozens of key technologies with exogenous economic growth trajectories. Bottom up models range from the basic technology databases with relatively simple implementation to models with more information such as Markal (Worrell et al., 2004). They describe the current and future competition for energy technologies in detail, both on the supply side- (the substitution possibilities between primary forms of energy) and demand side (the potential for end-use energy efficiency and fuel substitution). Substitution is based on relative costs, which is in turn driven by factors such as the technology development. Conversely, top down models such as GREEN (Burniaux et al., 1991) and IMAGE (Bouwman et al., 2006) represent macro-economic consistency but encapsulate a limited description of technologies. They describe substitution across different inputs on the basis of historically calibrated factors. Bottom up and Top Down models differ on some critical issues such as the existence of no regret potentials or the importance of macroeconomic feedbacks. This dichotomy has then remained the main criteria to identify models, despite the impossibility to set a strong correlation between streams and the type of results provided (Hourcade and Robinson, 1996). The fact that the distinction between the top down and bottom up approach is not very clear-cut implies that some models could actually be easily included in both categories. The IPCC AR4 report for instance, uses the term top down for nearly all integrated modeling approaches while the term bottom up is used for the assessment of reduction potential based on individual technologies.

- The modeling paradigm adopted. Optimal models assume that agents have perfect foresights and calcule an intertemporal maximized techno-economic trajectory to provide normative scenarios for/encompassing optimal strategies. Optimization leads to a preferred mix of technologies (or allocation of production factors) vis-à-vis a chosen optimization target (e.g lowest costs or maximum private consumption) given certain constraints (e.g tax levels).
- Conversely, in simulation models agents are semi-myopic and gradually adapt to market signals. An alternative is not to use optimization but describe the economy or the energy sector that do not necessarily lead lead to such full equilibrium. Simulation models have a recursive architecture and provide positive/substantive scenarios which assess the economic impact of a specific policy given a presentation of behaviors. Optimization and simulation are both used in top down and bottom up models.

Analyzed through this double analysis grid, the range of conventional models can be summarized in 4+1 main categories as shown in figure 13.

The development of hybrid models and the necessity of a dialogue between engineers and economists

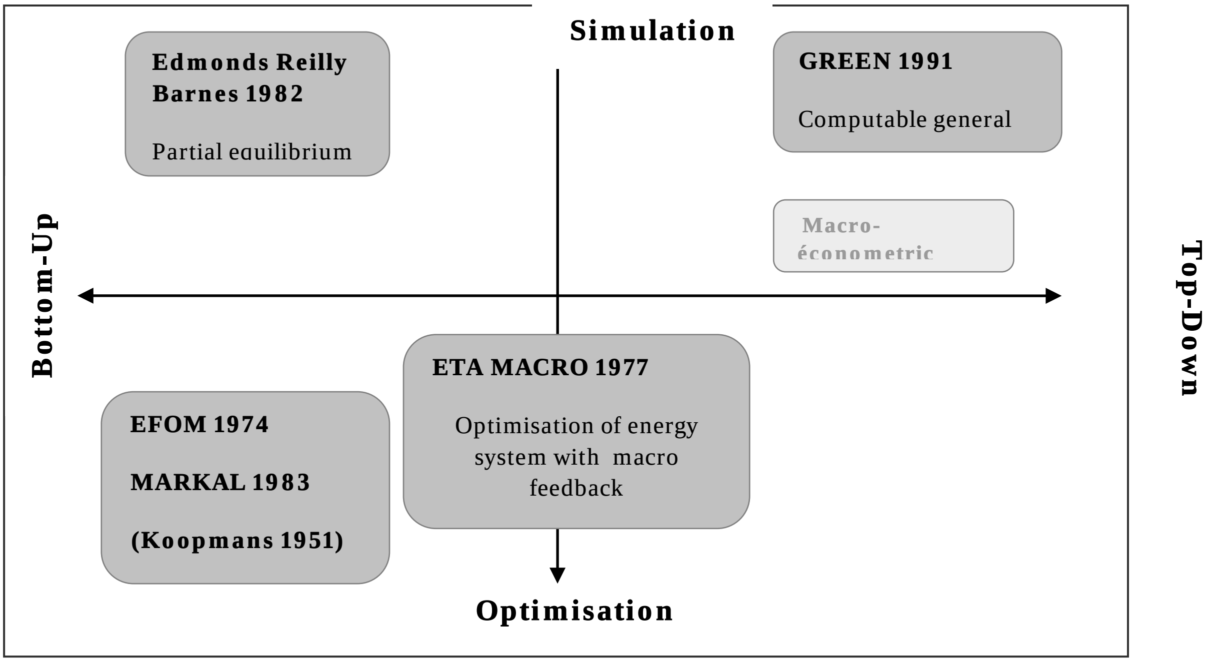
The last one encompasses a new category of hybrid models which has emerged during the last decade. It provides both a detailed description of technologies enclosed into a macro economic framework. It seeks to compensate for the limitations of one approach or the other. Indeed, BU models have been criticized for not providing a realistic portrayal of either microeconomic decision-making by firms and consumers when selecting technologies or the macro-economic feedbacks of different energy pathways and policies in terms of changes in economic structure, productivity and trade that would affect the rate, direction and distribution of economic growth. Conversely, conventional top down models represent technological change as an abstract, aggregate phenomenon.

This approach is well suited to helping policy-makers assess economy-wide price instruments such as taxes and tradable permits, but partially assess the combined effect of these price-based policies with technology-specific policies (Hourcade and Ghersi, 2007). Three main approaches of hybridization exist:

Pseudo-Hybrid Hybrid : this is the case for example of bottom up models completed with compact macroeconomic module, like ETA-MACRO. This does not change the technico-economic nature of the models and does tackle the issue of a lack of description of intersectoral dynamics, international or distributive.

'Soft link' : Böhringer and Rutherford (2006) defines the linking of two preexisting models. For instance, Manne and Rutherford (1994) coupled a general equilibrium model with an energy model. Schäfer and Jacoby (2005) linked the general equilibrium model EPPA with a nexus MARKAL dedicated to the transport sector. Remind-R (Leimbach et al., 2009, Luderer et al, 2010) or Witch (Bossetti et al, 2008) try to display the consistencies of technical systems (production and consumption), the settings in which they are economically viable (highlights the impact of financing and relative price of the capital, labor or land on the relative cost of technologies) and climate policies feedbacks on economic growth given carbon and energy prices variations.

'*Hard link*' : these models are planned to be entirely hybrids (no linking with other models) like for instance the SIMS model de Jaccard and al. (2000) or the E3MG model (Barker et al., 2006).



Main streams of models identified by one or several seminal models

Annex 2 List of tables extracted from Shinko et al., 2010 A CGE Analysis of the Copenhagen Accord from the perspective of less developed countries, University of Graz

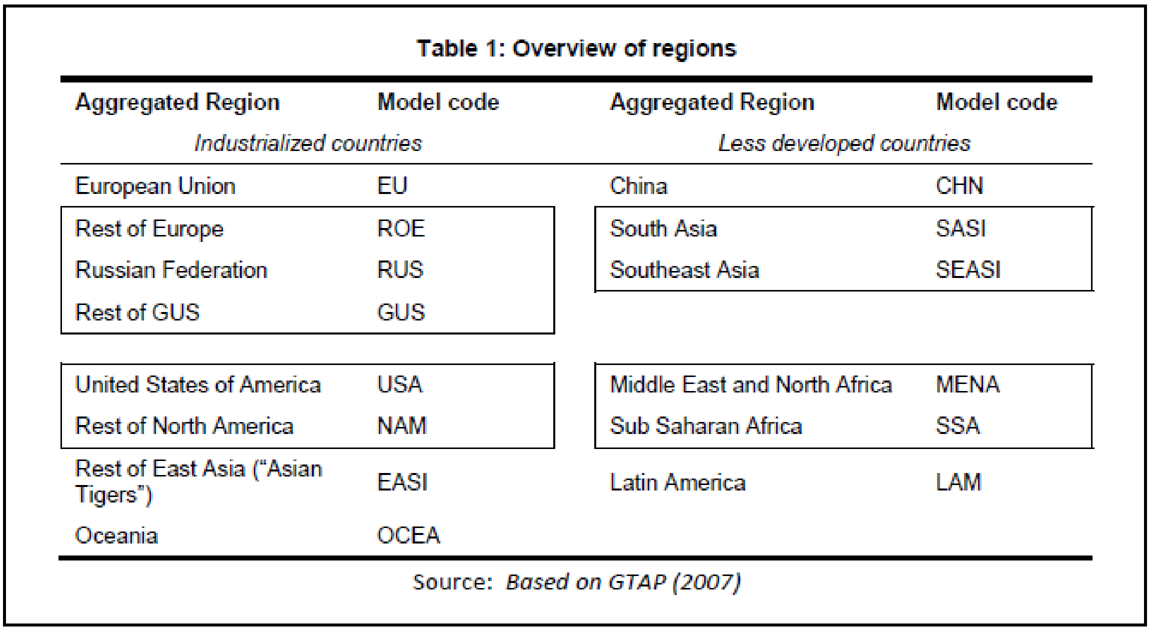


Table 1: Overview of regions

Aggregated Region	Model code	Aggregated Region	Model code
Industrialized countries		*Less developed countries*	
European Union	EU	China	CHN
Rest of Europe	ROE	South Asia	SASI
Russian Federation	RUS	Southeast Asia	SEASI
Rest of GUS	GUS		
United States of America	USA	Middle East and North Africa	MENA
Rest of North America	NAM	Sub Saharan Africa	SSA
Rest of East Asia ("Asian Tigers")	EASI	Latin America	LAM
Oceania	OCEA		

Source: *Based on GTAP (2007)*

World regions examined by Wegener Center for Climate and Global Change (source: Schinko, 2010)

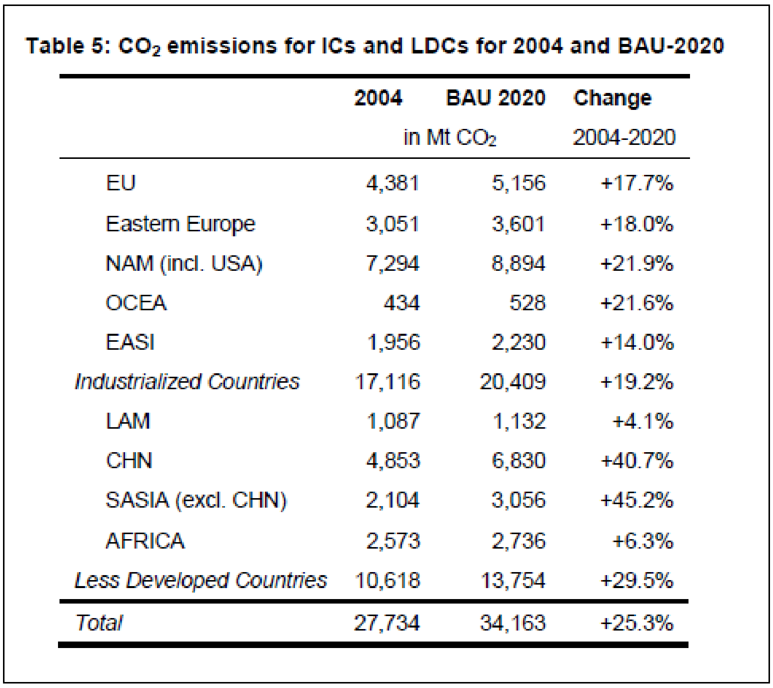


Table 5: CO_2 emissions for ICs and LDCs for 2004 and BAU-2020

	2004	BAU 2020	Change
	in Mt CO_2		2004-2020
EU	4,381	5,156	+17.7%
Eastern Europe	3,051	3,601	+18.0%
NAM (incl. USA)	7,294	8,894	+21.9%
OCEA	434	528	+21.6%
EASI	1,956	2,230	+14.0%
Industrialized Countries	17,116	20,409	+19.2%
LAM	1,087	1,132	+4.1%
CHN	4,853	6,830	+40.7%
SASIA (excl. CHN)	2,104	3,056	+45.2%
AFRICA	2,573	2,736	+6.3%
Less Developed Countries	10,618	13,754	+29.5%
Total	27,734	34,163	+25.3%

Business as Usual scenario assumptions for CO2 emission in Wegener Center for Climate and Global Change project (source: Schinko, 2010)

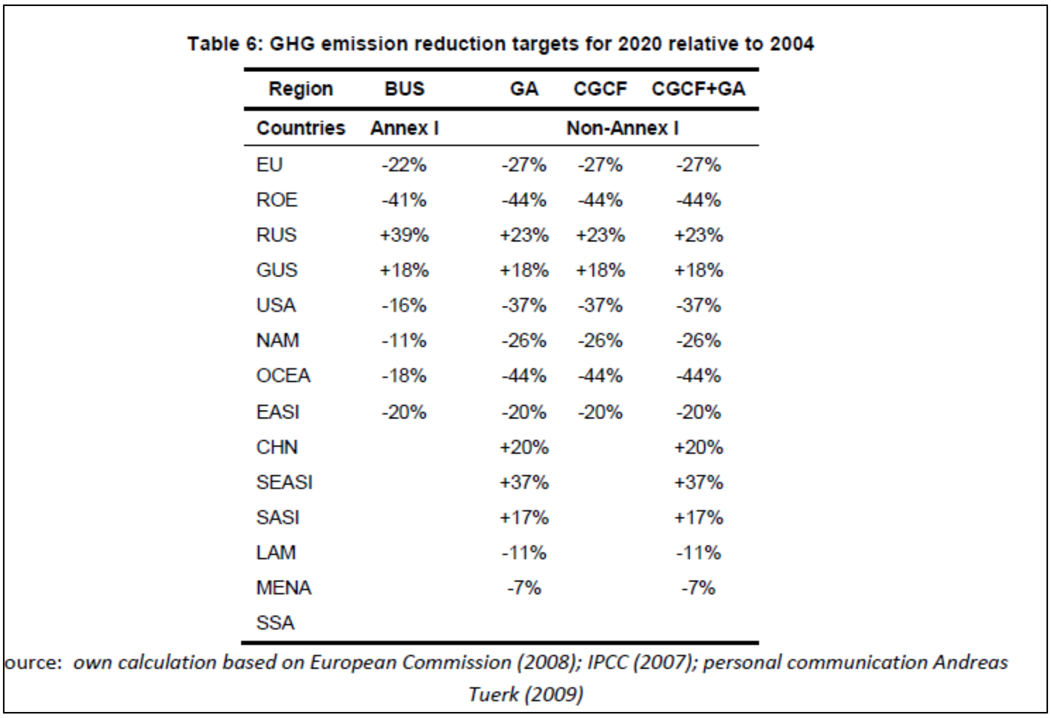


Table 6: GHG emission reduction targets for 2020 relative to 2004

Region	BUS	GA	CGCF	CGCF+GA
Countries	Annex I	Non-Annex I		
EU	-22%	-27%	-27%	-27%
ROE	-41%	-44%	-44%	-44%
RUS	+39%	+23%	+23%	+23%
GUS	+18%	+18%	+18%	+18%
USA	-16%	-37%	-37%	-37%
NAM	-11%	-26%	-26%	-26%
OCEA	-18%	-44%	-44%	-44%
EASI	-20%	-20%	-20%	-20%
CHN		+20%		+20%
SEASI		+37%		+37%
SASI		+17%		+17%
LAM		-11%		-11%
MENA		-7%		-7%
SSA				

ource: *own calculation based on European Commission (2008); IPCC (2007); personal communication Andreas Tuerk (2009)*

Regions GHG emission reduction targets for 2020 under scenarios considered in the Wegener Center for Climate and Global Change project (source: Schinko, 2010)

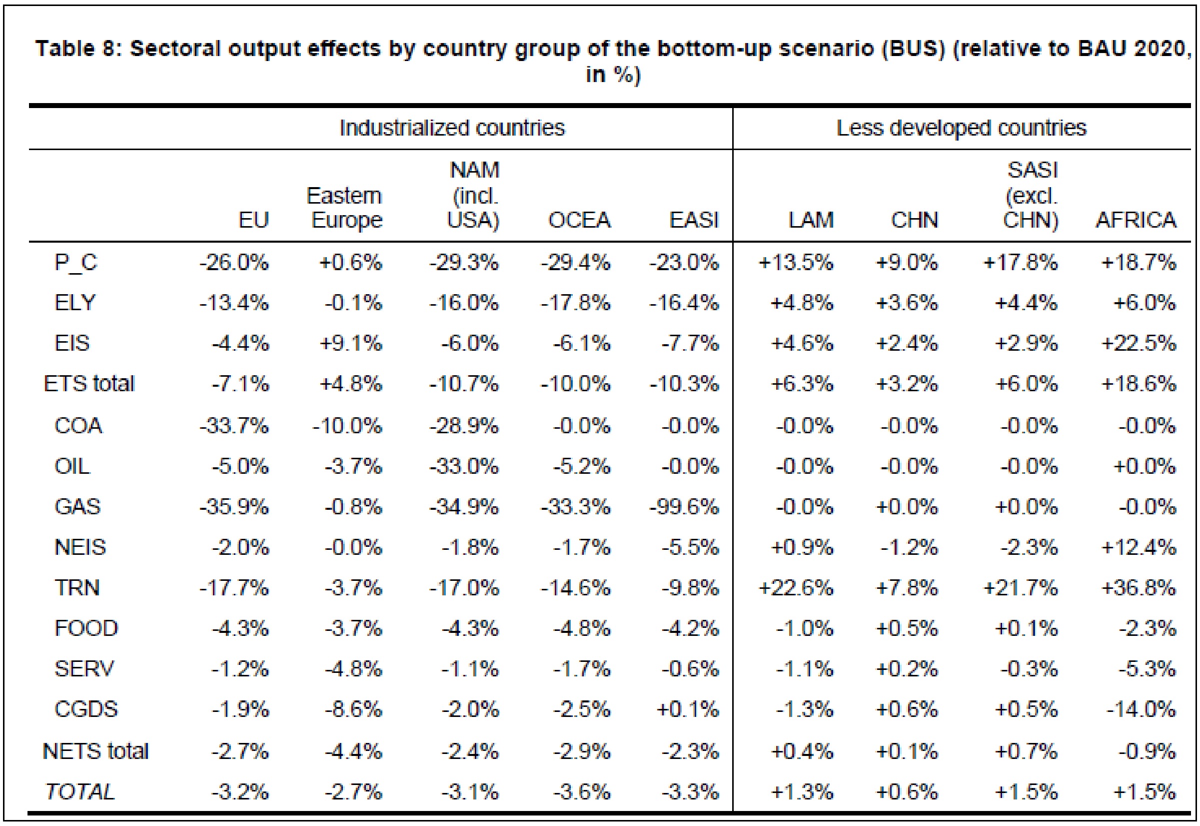


Table 8: Sectoral output effects by country group of the bottom-up scenario (BUS) (relative to BAU 2020, in %)

	Industrialized countries					Less developed countries			
	EU	Eastern Europe	NAM (incl. USA)	OCEA	EASI	LAM	CHN	SASI (excl. CHN)	AFRICA
P_C	-26.0%	+0.6%	-29.3%	-29.4%	-23.0%	+13.5%	+9.0%	+17.8%	+18.7%
ELY	-13.4%	-0.1%	-16.0%	-17.8%	-16.4%	+4.8%	+3.6%	+4.4%	+6.0%
EIS	-4.4%	+9.1%	-6.0%	-6.1%	-7.7%	+4.6%	+2.4%	+2.9%	+22.5%
ETS total	-7.1%	+4.8%	-10.7%	-10.0%	-10.3%	+6.3%	+3.2%	+6.0%	+18.6%
COA	-33.7%	-10.0%	-28.9%	-0.0%	-0.0%	-0.0%	-0.0%	-0.0%	-0.0%
OIL	-5.0%	-3.7%	-33.0%	-5.2%	-0.0%	-0.0%	-0.0%	-0.0%	+0.0%
GAS	-35.9%	-0.8%	-34.9%	-33.3%	-99.6%	-0.0%	+0.0%	+0.0%	-0.0%
NEIS	-2.0%	-0.0%	-1.8%	-1.7%	-5.5%	+0.9%	-1.2%	-2.3%	+12.4%
TRN	-17.7%	-3.7%	-17.0%	-14.6%	-9.8%	+22.6%	+7.8%	+21.7%	+36.8%
FOOD	-4.3%	-3.7%	-4.3%	-4.8%	-4.2%	-1.0%	+0.5%	+0.1%	-2.3%
SERV	-1.2%	-4.8%	-1.1%	-1.7%	-0.6%	-1.1%	+0.2%	-0.3%	-5.3%
CGDS	-1.9%	-8.6%	-2.0%	-2.5%	+0.1%	-1.3%	+0.6%	+0.5%	-14.0%
NETS total	-2.7%	-4.4%	-2.4%	-2.9%	-2.3%	+0.4%	+0.1%	+0.7%	-0.9%
TOTAL	-3.2%	-2.7%	-3.1%	-3.6%	-3.3%	+1.3%	+0.6%	+1.5%	+1.5%

Sectoral output effect for 2020 (BUS scenario) in the Wegener Center for Climate and Global Change project (source: Schinko, 2010)

Review of other case studies in the literature dealing with carbon leakage issue and the cost of climate policies at the European and Global level

Babiker M. (2005), "Climate change policy, market structure, and carbon leakage", ***Journal of International Economics*** **65, pp.421-445**

This article shows that the implementation of emissions reduction under the Kyoto agreement in industrialized countries has led to an increase in global emission.

Boehringer C., C. Fischer, K.E. Rosendahl (2010), "The Global Effects of Subglobal Climate Policies", ***RFF Discussions Paper*** **48, Resources for the Future**

This analysis concludes that the unilateral implementation of climate policy reduces the global level of consumption**.**

Boehringer C., C. Fischer, K.E. Rosendahl (2011), "Cost-Effective Unilateral Climate Policy Design: Size Matters", RFF Discussion Paper 34, Resources for the Future

The efficiency of policies restricting carbon leakage decreases along with the size of the coalition of states implementing mitigation policies. Nevertheless, in case that in a context of global coalition the system of free allowances for the whole energy-consuming production remains, this will inhibit the reduction of carbon leakage.

Bosello F., F. Eboli, R. Parrado, L. Campagnolo, E. Portale (2011), Increasing the EU target on GHG emissions to 30: macro-economic impacts through a CGE analysis, Fondazione Eni Enrico Mattei,

The authors conclude that unilateral European mitigation policies have a reduced environmental efficiency due to a strong carbon leakage. The mitigation costs may decrease significantly by changing "rigid reduction targets" through a more flexible emissions restriction system in order to involve more countries in a climate coalition.

Kąsek L., Kiuila O, Krzysztof Wójtowicz K., Żylicz T. Economic effects of differentiated climate action Uniwersytet Warszawski WNE, Warsaw 2012

The study concludes that unilateral carbon abatement policies can be counter-productive, as a large part of emissions reduced in the EU or other Annex I countries may be offset by an increase in emissions in the rest of the world. More stringent abatement commitments also entail translate welfare losses for Europe. These losses can be mitigated by anti-leakage measures … but this is rather a zero-sum game if the corresponding effects in developing countries region are considered.

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All the scenarios indicate a decreased in global welfare with respect to the Business as usual business scenario by 0.44-0.49%, depending on scenario.

9. Abbreviations

ADAM ADaptation And Mitigation Strategies ;
AR Assessment Report;
BECCS Biomass Energy Carbon Capture Storage;
CGE Computable General Equilibrium;
CES Constant Elasticity of Substitution production function;
CCS Capture and Carbon Storage;
EMF Stanford Energy Modeling Forum;
FSU Former Soviet Union;
IAM Integrated Assessment Model;
IC Industrialized countries;
IPCC Intergovernmental Panel on Climate Change;
LDC Least developed countries
RECIPE Report on Energy and Climate Policy in Europe;
RCP Representative Concentration Pathways
RES Renewables energy Supply
REN Renewables

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