AMPERE

Assessment of Climate Change Mitigation Pathways and Evaluation of the Robustness of Mitigation Cost Estimates

Project N° 265139

Report on potential co-benefits of mitigation for Europe

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Executive Summary

This task (5.5) within the AMPERE project aims at evaluating potential economic costs and benefits arising from different timing configurations for climate policies ultimately aiming at stabilisation of climate change within the current century. In addressing the issues involved in such analysis it is important to use models that explicitly incorporate endogenous mechanisms for technical change, productivity improvements and R&D allocation to different sectors, activities and technologies. Two economic models within the AMPERE project are equipped with such mechanisms: the GEM-E3-RD world model and the NEMESIS model for EU countries. GEM-E3-RD is a general equilibrium model of the type that has been used extensively for measuring the economic implications of different policy measures. The specific version in question is distinguished for its endogenous learning mechanisms (both learning by research and learning by doing) and the micro-economic details explicitly addressed concerning the uptake of a number of technologies relevant to the climate change issue as well as their production and international trade in them. The model is serviced to run to the year 2050. NEMESIS is a macro-econometric model serviced to run only until 2030. The version of the model used in the task includes an endogenous technological change module, where technological change is driven by process innovation as well as quality innovation. This results from sector-specific R&D investments but also from knowledge externalities in the form of spillovers. Together they increase knowledge stock that leads to further innovations.

The analysis was carried out by means of evaluation of a number of scenarios. The Reference scenario represents a situation where climate policy is limited to current commitments of the different countries and regions of the world (e.g. renewable and nuclear expansion targets, emissions intensity targets, etc.). This clearly does not tackle the climate change issue. On the contrary, it renders eventual attempts at mitigation in the second half of the century much more difficult if not virtually unrealistic. The EU, which so far has been most active in pushing the agenda for stronger climate action in the world arena, is faced with an important dilemma: Does it undertake immediately a strong effort towards decarbonisation of the EU energy system in the hope that other countries will eventually join or does it delay such action until an international consensus has been reached?

In exploring this question alternative scenarios have been evaluated. The EU Alone scenario assumes that such a unilateral action is taken and the world fails to follow suit before 2050. In that case according to GEM-E3-RD results the EU incurs a cost equivalent to 0.51% of cumulative reference GDP in the period 2010-2050 and the climate change issue remains virtually unaffected. Delaying action until 2030 and supposing that by that date the EU and the rest of the world jointly start strong climate action leads to an even higher cost for the EU, equivalent to 0.6% of cumulative EU GDP, due to the stronger EU

decarbonisation effort after 2030 (reflected in higher carbon prices) and to the depressive effect of mitigation action on global GDP that implies lower global demand for EU exports. The corresponding loss for the rest of the world is of the order of 1%. On the other hand, if the EU undertakes early action and the world joins it after 2030 the cost to the EU is drastically diminished to the equivalent of 0.2% cumulatively due to the increased exports of clean energy technologies and the prolonged decarbonisation period. Clearly the desirability of early EU action depends crucially on the probability attached to the world joining in the medium term. It is conceivable that such a probability increases if the EU sets the example and demonstrates that the costs involved are not inordinate.

The results above depend to a considerable extent on the issue of technology dynamics. The GEM-E3 model has been enlarged to incorporate such dynamics for a number of key technological options in pursuit of decarbonisation, such as wind, photovoltaics, CCS, electric vehicles, advanced energy equipment and biofuels. Early action sets into motion R&D effort on such clean energy technologies which combines with economies of scale and other learning by doing obtained by drastically increased uptake within the EU leading to reductions in costs. Such reductions can to some extent (subject to technological spillovers) be appropriated by EU industries leading to increased market shares which can be particularly important if world markets also grow very rapidly as a result of strong climate mitigation policies.

The most important among these technological options is electric vehicles. According to the GEM-E3-RD model results, their deployment is an essential ingredient of decarbonisation as they tackle the issue in the important road transport sector which is not amenable to many other options. The EU already enjoys a comparative advantage in vehicle construction and is well poised to take advantage of an early start in the construction of electric vehicles. Another decarbonisation option that can generate a large market under appropriate policy conditions concerns CCS. Here most of the potential is to be found outside the EU and especially in large emerging economies such as China and India. The CCS option is by no means an immediate possibility. However an early start could also produce competitive advantage with large possibilities for export expansion. Photovoltaics also offer some possibilities for building an early advantage in a market with a large potential in the developing world. On the other hand, wind turbine related technologies are relatively mature with few possibilities for improvement and therefore offer a less fertile ground for export expansion. In terms of biofuels, the EU is not well placed to become an exporter of this energy vector as it is a high-cost producer requiring subsidies for domestic production.

The NEMESIS model addressed the question by running similar scenarios. The major difference concerns the time horizon (since NEMESIS only runs to 2030). In order to be able to contribute to the analysis, NEMESIS had to consider a policy delay only to the year

2020. In general, the shorter horizon means that expected impacts are considerably weaker. In terms of macroeconomic impacts, the delayed action scenario, as is the case with GEM-E3-RD, produces the strongest negative impact (-0.36% of GDP in 2030 compared to reference) as the achievement of the EU carbon budget in this scenario implies a stronger decarbonisation effort between 2020 and 2030. For the EU alone scenario the GDP loss compared to the reference is -0.22% in 2030 which is comparable to the case of the first mover scenario (-0.2%). In the first mover scenario, the European sectors producing carbon free technologies benefit from increased experience and innovation compared to the rest of the World. In this scenario more than 110.000 new jobs are created in sectors producing the decarbonisation technologies compared to the EU alone scenario resulting from competitive advantage in the emission reduction technologies.

1 Introduction

In the last two decades climate change has emerged as one of the great global policy challenges. In the last UNFCCC[1] conferences of parties, held in Copenhagen, Cancun, Durban and Doha, most countries made pledges to reduce their GHG[2] emissions (or GHG emissions intensity of GDP) by 2020. However, the emission pledges made by the major carbon emitting economies are not binding and not ambitious; even if these pledges are actually achieved, they do not lead to the necessary GHG atmospheric concentrations that are consistent with a 50% probability of limiting the global average temperature increase to 2°C compared to pre-industrial levels, as defined by the IPCC Fourth Assessment Report [39]. As a result, emphasis has shifted from global cooperative action against climate change to regional climate action and to the integration of other policy priorities, such as energy security, reduction of hydrocarbon import bill, RES development, avoidance of external costs (air pollution, human health, etc.) and economic development policies.

The EU leads the global effort for climate change mitigation, as it has adopted a target to reduce its GHG emissions by 20% relative to the 1990 levels until 2020 as part of its Energy and Climate package [12]. The region has already established the worlds' largest emissions trading system (EU-ETS) and has implemented a number of additional climate policies at national level, key among which is the GHG Effort Sharing Decision [13] that establishes binding annual GHG emission targets for non-ETS sectors for the EU Member States in the period 2013 to 2020. The European Commission in 2013 has adopted the Green Paper on "A 2030 framework for climate and energy policies" [40] that launched a public consultation with the aim to extend to 2030 the current legislative 2020 framework and to set specific targets for GHG emissions reduction, energy savings and RES deployment for 2030. Furthermore, the European Union confirmed its long-term objective to reduce its GHG emissions by 80-95% compared to 1990 levels by 2050 [9]; the trajectory of such emissions should allow keeping global average temperature below 2°C provided that strong emission reducing policies and targets are also adopted worldwide [14]. Consequently, the study essentially focuses on the EU as an obvious candidate for first mover climate action.

A central concern for the EU policy makers is what would be the macro-economic implications for the EU in case that it unilaterally adopts strong decarbonisation policies without an international agreement for GHG mitigation in place. The objective of this study is to explore whether the European economy can get first mover advantages, at least partially for some sectors, by pursuing ambitious emission reduction targets earlier than

[1] United Nations Framework Convention on Climate Change
[2] Greenhouse Gases

other regions or whether it would be preferable that the EU waits until 2030 to synchronize GHG mitigation actions with the rest of the world.

The study presents a model based evaluation (conducted within the AMPERE project) of the impacts of incomplete regional participation in the GHG emission reduction effort for the EU region and aims to quantify the First Mover Advantages that the EU economy can get in the context of fragmented international carbon markets. The key research question of the model-based analysis concerns the economic risks and benefits faced by the EU in case that it unilaterally adopts a stringent pioneering decarbonisation policy in line with the EU Roadmap emission reduction targets [5, 9] without a global emission reduction agreement in place. The objective of the study is to examine the conditions under which the EU can get First Mover Advantage (in terms of positive growth, employment and balance of trade outcomes) by pursuing ambitious pioneering climate action. Such key conditions refer to the potential for technology-driven productivity gains, technological learning through R&D investments, model assumptions regarding the recycling scheme for carbon revenues and the treatment of intellectual innovation rights, the engagement of world regions to a global GHG mitigation objective and the possibility for spillover effects (global diffusion of innovation).

For this purpose, the GEM-E3 and NEMESIS macro-economic models have quantified a series of scenarios that assume lack of international cooperation for GHG mitigation and first mover climate action for the EU. The two models are well-established tools with an extensive previous record in mitigation cost studies for the European Commission and other stakeholders. The models are well-suited to perform this type of analysis as they represent comprehensively the sectoral structure of the economy and account for the complex interactions between the energy system and the overall economy. The GEM-E3 and NEMESIS models can handle scenarios that assume different levels of regional climate policy intensity, incomplete carbon markets at the global scale and can simulate various accompanying macro-economic policies, such as alternative schemes for the recycling of revenues from carbon allowance auctioning. Despite their differences in terms of economic methodology, as GEM-E3 is a dynamic recursive Computable General Equilibrium (CGE) model and NEMESIS is a macro-econometric neo-Keynesian model, the models can be used in conjunction to each other in order to evaluate similarities and differences in their projections and derive robust conclusions that are useful for energy and climate policy makers.

The models are enhanced with a bottom-up representation of the energy system including a large portfolio of emission reduction technological options, such as RES in power generation and final energy demand sectors, nuclear, transport electrification, advanced energy equipment, biofuels for transport, CCS for electricity production and industrial processes and bottom-up modelling of energy efficiency policies and measures.

Endogenous technical progress has been incorporated in the models both in the form of learning through experience (LbD) and learning by research (LbR). Both models include an endogenous R&D module and can therefore quantify technology-driven productivity gains for each economic sector, technological learning due to increased R&D stock and spillover effects regarding global diffusion of innovation for low and zero carbon energy technologies. The models can also simulate public and/or private support for R&D innovation capital and subsidies for R&D directed to specific energy technologies (such as RES technologies or electric vehicles). Growth in the models is endogenous in the sense that technological progress which generates long-term growth is endogenous and depends on R&D investments undertaken by rational, profit-maximising economic agents.

2 Methodology

The study presents results of two macro-economic models for the EU that participate in the AMPERE Work Package 5 (WP5) analysis, namely GEM-E3 and NEMESIS. The models represent comprehensively the sectoral structure of the economy but have a rather limited technological representation of the energy system compared to partial equilibrium energy system models, like PRIMES, POLES or typical MARKAL/TIMES models.

2.1 Description of the participating models

2.1.1 The GEM-E3-RD model

GEM-E3 [1] is a global, multi-region, recursive dynamic computable general equilibrium (CGE) model that covers the interactions between the economy, the energy system and the environment and provides quantitative results until 2050 in five-year steps. It is especially designed to evaluate energy and environmental policies, in particular CO_2 emission reduction policies. GEM-E3 covers the entire economy and can evaluate consistently the effects of policies on national accounts, investment, consumption, public finance, foreign trade and employment for the various economic sectors and agents across countries. It has been widely used by the European Commission, mainly for climate and energy policies but also for the Single Market Act, the Lisbon Agenda, tax reforms, and employment policies.

In the standard version, the GEM-E3 model includes the 28 Member States of the European Union and all major non-European countries in a disaggregated manner while the remaining countries are aggregated into regions. The model covers all production sectors (aggregated to 38) and institutional agents of the economy (firms, households, government). Table 1 and Table 2 present the sectors and the regions identified in the version of GEM-E3 used for the current study (GEM-E3-RD). The GEM-E3-RD model simultaneously computes the equilibrium prices of goods, services, labour and capital that simultaneously clear all markets under the Walras law (global closure). It formulates separately the supply or demand behavior of the economic agents which are considered to optimize individually their objectives while market derived prices guarantee global equilibrium.

Code	Sector	Code	Sector
01	Agriculture	20	Ethanol
02	Wheat, Cereal Grains, Sugar cane, sugar beet	21	Bio-Diesel
03	Oil Seeds	22	Coal fired power generation
04	Coal	23	Oil fired power generation
05	Crude Oil	24	Gas fired power generation
06	Oil	25	Nuclear power generation
07	Gas	26	Biomass power generation
08	Electricity supply	27	Hydro-electric production
09	Ferrous and non ferrous metals	28	Wind power generation
10	Chemical Products	29	PV power generation
11	Other energy intensive	30	CCS Coal power generation
12	Electric Goods	31	CCS Gas power generation
13	Transport equipment	32	R&D services
14	Other Equipment Goods	33	Production of Wind
15	Consumer Goods Industries	34	Production of PV
16	Construction	35	Production of CCS
17	Transport	36	Production of Electric Vehicles
18	Market Services	37	Production of Advanced Equipment in Household energy appliances
19	Non Market Services	38	Dwellings

Table 1 : GEM-E3-RD Sectors

Code	Region
EU28	Current 28 members of EU
NOAM	North America (USA and Canada)
CHN	China (incl. Hong Kong)
WPAC	OECD Western Pacific (Japan, S. Korea, Australia and New Zealand)
ENEXP	Energy Exporters (Middle East, North Africa and CIS)
ROW	Rest of the World countries (including India)

Table 2: GEM-E3-RD Regions

The regions of the model are linked through endogenous bilateral trade (following the Armington specification). The labour market is modelled following the efficiency wages approach which allows for non-voluntary unemployment and flexibility in wages. The model is able to compare the welfare effects of various environmental instruments, such as carbon taxes, auctioning, various forms of pollution permits and command-and-control policy in the context of climate and energy policies. It is also possible to consider various ways of recycling of carbon revenues.

The model includes a bottom-up representation of power generation technologies and calculates endogenously the energy-related emissions of carbon dioxide (CO_2) per economic sector. There are three main mechanisms of emission reduction explicitly specified in the model: (i) substitution between fuels and between energy and non-energy inputs, (ii) emission reduction due to the decline in production and consumption, and (iii) purchasing of energy efficiency and emissions abatement equipment.

GEM-E3 has been further developed to include an induced technology progress mechanism representing endogenous growth through innovation (endogenous R&D) and the distinct representation of clean energy technologies and their global trade. Specifically, in order to improve the representation of the energy system restructuring as required to meet the stringent emission reduction targets imposed, the model has been extended into the following domains:

- **Power generation**: The CES aggregate production function has been replaced by a set of production functions which explicitly represent competition among the main power generation technologies (coal, oil, gas, nuclear, wind, biomass, solar, hydro, CCS coal and CCS gas). The unit costs of the technologies depend on both learning by doing and learning by research effects. The power generation mix is dynamically calibrated to reproduce results from more specialized partial equilibrium energy system model, like PRIMES for the EU and POLES or PROMETHEUS for the other regions of the world.
- **Biofuels:** The agriculture sector has been split into sectors producing feedstock for food and other purposes, and sectors producing feedstock for biofuels. The model distinguishes ethanol and biodiesel, which are further disaggregated into conventional and advanced technologies.
- **Electric vehicles and advanced energy equipment:** The model of energy demand for households has been extended to separately represent the choice of electric and plug-in hybrid cars competing with conventional cars. A similar extension is also introduced for advanced energy-saving equipment which compete with conventional heating and cooling equipment to satisfy energy demand of households.

- **Energy efficiency investment:** Energy savings in all sectors are modelled through a non-linear cost supply curve which links the marginal cost of energy savings with the cumulative savings potential for each country/region of the model. Firms and households are modelled to have the possibility to invest in energy savings, instead of other expenditures, which leads to higher energy productivity. The effect of cumulative savings on energy productivity exhibits diminishing returns to scale. Investments in energy efficiency improvement are incited by high carbon prices but can be also driven by specific energy efficiency promoting policies which are simulated as a system of white certificates issued by the state which, under budget neutrality, collects revenues from auctioning white certificates and finances the energy efficiency investments. The total amount spent on energy savings is adjusted so as to mimic energy efficiency improvement by sector projected with the technologically-rich PRIMES model for the EU countries.
- The **carbon price** is determined endogenously at an economy-wide level so as to meet the given emission reduction target in each scenario for each region identified in the model, assuming that state revenues arising from the ETS carbon pricing are recycled back to the economy under a specific scheme.

In order to model the First Mover Advantage issue, which is the main focus of the current study, the following model extensions have been developed.

- The equipment production sectors were split to separately represent production of the following low and zero-carbon energy technologies: photovoltaic, wind, CCS (Carbon Capture and Storage) technologies, electric vehicles and advanced energy-saving equipment. The new production sectors were consistently introduced in all Input-Output tables, the investment matrices and the bilateral trade matrix of the model.
- Learning by doing curves were introduced for the clean energy technologies and also for the production of ethanol and biodiesel; the learning curves were modelled as to increase total factor productivity in the sectors producing the corresponding goods. Therefore, economic sectors that use the new products will see lower prices for these products as a result of learning gains.
- The causality is then as follows: Emission reduction targets (or cumulative carbon budget) are imposed as targets (model constraints) in the regions of the GEM-E3-RD model. This implies a non-zero carbon price which leads to higher use of low and zero-carbon energy technologies. The latter is further facilitated by structural changes (i.e. change in share parameters of CES functions calibrated to reproduce PRIMES or PROMETHEUS model projections). The higher demand for the new low carbon energy products implies more learning, hence bigger productivity gains. This further implies lower costs for the users of the new products. In case such learning

progress takes place only in one region (e.g. in the EU), this region gains a higher market share in global trade for these technologies as the other regions experience smaller cost reducing benefits.

2.1.2 The NEMESIS model

NEMESIS [2] is a comprehensive recursive dynamic macro-econometric Neo-Keynesian modelling system estimated for the 27 members of the European Union and can provide forecasts up to 2030 with annual resolution. NEMESIS is based on detailed sectoral models for the 27 members of the EU. Each model starts from an economic framework which is linked to an energy/environment module. The construction of the macro-economic pathway established by the NEMESIS model could be viewed as a "hybrid" approach, i.e. "bottom-up" forces resulting from sectoral dynamics and interactions and "top-down" ones coming from the macro-economic level (labour force, international context, financial aspects, etc.). The sectoral interactions come not only from input/output matrixes but also from more innovative exchange matrix: knowledge spillovers matrix based on patent data and R&D investments. The NEMESIS model is "econometric", implying that equations are not directly derived from the traditional optimality conditions (like in a general equilibrium model) even if the agents' behaviour is implicitly governed by utility or profit maximization. Instead, the equations are behavioural relations estimated econometrically over historical samples.

On the supply side, NEMESIS distinguishes 30 economic sectors. Table 3 presents the sectors identified in the NEMESIS model. Each sector is modelled with a representative firm that takes its production decisions given its expectations on production capacity expansion and input prices. Firms' behaviour includes very innovative features grounded on new growth theories, principally endogenous R&D decisions that allow firms to improve their process productivity and product quality. Production in the different sectors is represented with CES functions with five production factors: capital, low skilled labour, high skilled labour, energy and materials. Interdependencies between sectors and countries are modelled with a collection of convert matrices, which describe the exchanges of intermediate goods, of capital goods and of knowledge in terms of technological spillovers, and the description of substitutions between consumption goods by a very detailed consumption module. Furthermore, the energy/environment module computes the primary and final energy demand (through CES functions) for ten different energy products and the corresponding CO_2 energy related emissions.

Code	Sector	Code	Sector
1	Agriculture	16	Food, Drink & Tobacco
2	Other extractions	17	Textiles, Clothing & Footwear
3	Oil & Gas Extraction	18	Paper & Printing Products
4	Gas distribution	19	Rubber and Plastic
5	Refined oil, Coke and nuclear fuels	20	Other manufacturing
6	Electricity	21	Construction
7	Water supply	22	Distribution, sales, trade
8	Ferrous& Non Ferrous Metals	23	Lodging & Catering
9	Non Metallic Minerals	24	Inland Transport
10	Chemicals	25	Sea & Air Transport
11	Metal Products	26	Other Transport
12	Machinery	27	Communication
13	Office Machines	28	Bank, Finance & Insurance
14	Electrical Goods	29	Other Market Services
15	Transport Equipment	30	Non Market Services

Table 3 : Economic Sectors represented in the NEMESIS model

On the demand side, the aggregate consumption of the representative household depends on current income and population structure. Consistent with the other behavioural equations of the model, the disaggregated consumption module is based on the assumption that equilibrium exists in the long term, but rigidities are evident in the short term which prevent immediate adjustment to the long-term equilibrium solution. Total consumption of households is indirectly affected by 27 different consumption sub-functions through their impact on relative prices and total income, to which demographic changes are added.

NEMESIS treats external trade as if it takes place through two channels: intra-EU, and extra-EU trade. The intra-EU and extra-EU export equations can be separated into two components, namely income and prices. The income effect is captured by a variable representing economic activity in the rest of the EU for intra-EU trade and a variable representing economic activity in the rest of the world for extra-EU trade. In each of the two equations (intra- and extra-EU trade) two sources of price impacts are modelled. The intra-EU trade is determined by the relative price of exports for the exporting EU country and the price of exports in other EU countries. For extra-EU trade, impacts of prices come through the price of exports for the exporting country, and a rest-of-the-world price variable. The latter is provided by the GEM-E3-RD model for all scenarios, countries and economic sectors. The stock of innovations (R&D stock) in a country is also included in the export equations in order to capture the role of innovation in trade performance and structural competitiveness.

Beyond economic indicators like GDP, balance of trade, consumption, investment, employment and revenues, the NEMESIS energy/environment module gives detailed results for energy demand by product and sector, the power generation mix and the related CO_2 and GHG emissions. The model can also quantify several social indicators like employment by sector and by skills, unemployment rate by skills, etc. by incorporating detailed data on population and working force. NEMESIS can be used to quantify short and medium-term economic and industrial projections, analyse Business As Usual (BAU) scenarios and long-term structural economic changes, research and innovation policies, energy supply and demand policies, climate policies and more generally sustainable development. NEMESIS is usually used to study BAU scenarios as well as alternative scenarios for the EU in order to quantify future economic, energy, environmental and societal challenges (projections of sectoral employment, short and medium-term GDP growth, long-term economic restructuring, etc). It is also used for policy assessment in terms of research and innovation (such as Horizon 2020, Framework Programme 7, 3% R&D to GDP ratio objective by 2020) and climate and energy policies (EU Energy and Climate package by 2020, EU climate change mitigation policies, nuclear phasing-out in France, etc).

2.2 Learning by doing

The endogenisation of technical change in applied energy-economy integrated assessment models is modelled with the learning curve concept. Traditional technology dynamics has long recognised the importance of learning by experience in the improvement of the cost and technical performance of technologies (Arrow, [24]). An abundant literature exists on the learning curve itself and on the factors that are not explicitly dealt with by the concept of learning curve. The technological learning is usually decomposed in two components, namely learning through experience and learning by research. The learning by doing or experience curve has been studied extensively. It represents technical progress as a function of some cumulative experience indicator. Stiglitz [42] assumes that the increase in productivity through learning by doing is a positive function of the capital intensity of production. One should note that this type of productivity growth is not embodied in machinery and equipment, but it is not strictly disembodied either, since it needs the machinery and equipment as the object of learning. According to Lieberman [16], a typical empirical study of the learning process, learning is found to be a function of cumulative investment, while the analysis suggests that in industries for which the learning curve is an important factor, the nature of competition depends critically on information diffusion. Similarly Christensen [20] uses the cumulative capacity as a measure of the knowledge accumulation occurring during the manufacturing and use of one technology.

In the GEM-E3-RD model, technology progress is explicitly represented in the production function endogenously, depending on cumulative capacity of technologies, R&D expenditure by the private and public sector, spillover effects through trade and purchases of intermediate inputs and learning by doing. Endogeneity of technical change has been identified as a crucial aspect of modelling energy system transformations (Kahouli-Brahmi [17] and Kouvaritakis et al. [18]). In [21] Leimbach et al highlight the importance of RES technological learning for the regional mitigation cost estimates using the hybrid energy-economy model REMIND-R. In the GEM-E3-RD model, the learning curves are endogenous and measure how much the costs of a given energy technology will be reduced due to its increased adoption.

Since learning by doing exhibits increasing returns to scale it was not fully endogenised in the GEM-E3-RD model as a fully endogenous specification could lead to non-convexity and convergence problems. GEM-E3-RD assumes that the agents (in our case power producing sectors, energy equipment and vehicle manufacturers) are not aware of the learning by doing effect prior to their decision to select the optimal production factor mix in a given year. The cost reduction occurs once their investment decision is made. It is assumed that the gains from the learning effect occur with one period lag which in the case of GEM-E3-RD means over a five year period. In the GEM-E3-RD setup, technological progress is incorporated in power producing sectors and in sectors that produce advanced energy technologies (Table 4).

Power generation technologies	Advanced energy technologies
Equipment for Wind power gen.	Equipment for Electric Vehicles
Photovoltaic systems	Equipment for Advanced heating and Cooking and Electric appliances
Equipment for Coal with CCS	Production of Ethanol
Equipment for Gas with CCS	Production of Biodiesel

Table 4 : GEM-E3-RD activities with learning by doing effects

The learning or experience curve describes the quantitative relationship between output or capacity growth with cost reductions of energy technologies. The common mathematical formulation used to represent the learning curve is by using an exponential function of the form:

$$C = C_0 \cdot CSales^{-lr} \quad (1)$$

where C is the cost per unit of production, $CSales$ represents the cumulative sales (cumulative output), C_0 is the cost of the first unit produced and lr is the learning elasticity (or experience parameter) which defines the slope of the learning curve of each technology. The learning effect is then measured in terms of percentage cost reduction for each doubling of the cumulative capacity, output or production:

$$LRE = 1 - 2^{-lr} \quad (2)$$

where LRE represents the learning rate that indicates the cost reduction achieved for every doubling of the cumulative capacity or output. Estimates of the learning rates of energy technologies provided by different studies vary, in some cases significantly. A rather comprehensive review of historical learning rates for energy and GHG emissions related sectors can be found in Jamasb [19].

2.3 Learning by Research

It is widely recognised that technological change through learning by research and induced innovation will play an important role in reducing global GHG at a smaller negative impact on economic growth. R&D can contribute directly to technological improvement especially for energy technologies that are in early stages of development and commercial uptake; thus it is clear that R&D must figure explicitly in the technology dynamics specification.

A substantial empirical literature examining the issue of endogenous innovation through R&D in energy-economy models has already emerged. Gerlagh and Kuik [22] use a static general equilibrium model to analyze the effect of endogenous technical change and international technology diffusion on carbon leakage. Kemfert [23] attempts to account for international technology spillovers across countries via capital flows in a general equilibrium integrated assessment model. Nordhaus [25] introduces endogenous technological learning in a global model of the economics of global warming and examines the implications of induced technological change through R&D for optimal climate policy. Goulder and Mathai [26] used both theoretical and numerical models to examine the impacts of learning by doing and learning by research on the optimal design of emission reduction policies. They showed that the presence of induced technological change for zero-carbon energy technologies lowers the time profile of optimal carbon taxes and reduces the costs of reaching the predefined CO_2 atmospheric concentration levels. Study [27] explores how international knowledge flows affect the dynamics of the R&D sector and the main economic and environmental variables; the focus is on energy efficiency improvements, which is considered to be one of the most important emission reduction strategies, and the model-based analysis performed showed that international knowledge spillovers tend to increase free-riding incentives and decrease the investments in energy R&D, especially in high income countries where international knowledge flows crowd out domestic R&D efforts, while the overall mitigation cost remain largely unaffected.

The GEM-E3-RD model version used in the present study incorporates an endogenous R&D module that determines the R&D expenditures of the private and public sector for all economic sectors. Table 5 presents the GEM-E3-RD economic sectors that undertake R&D expenditures.

Sector	Sector
Agriculture	Ethanol
Wheat, Cereal Grains, Sugar cane, sugar beet	Bio-Diesel
Oil Seeds	R&D services
Coal	Production of Wind
Oil	Production of PV
Gas	Production of CCS
Electricity supply	Production of Electric Vehicles
Ferrous and non ferrous metals	Production of Advanced Equipment in Household energy appliances
Consumer Goods Industries	Chemical Products
Construction	Other energy intensive
Transport	Electric Goods
Market Services	Transport equipment
Non Market Services	Other Equipment Goods

Table 5: GEM-E3-RD activities that undertake R&D expenditures

The basic modelling idea is the incorporation of the knowledge production function that determines the generation of new innovation endogenously in the model. The output production function is the standard KLEM production function extended to account for the impacts of endogenous technology innovation. A discrete R&D sector is modelled in order to produce innovation for each activity in the model (Figure 1). The R&D sector is modelled separately and provides services to firms, households and government (public R&D).

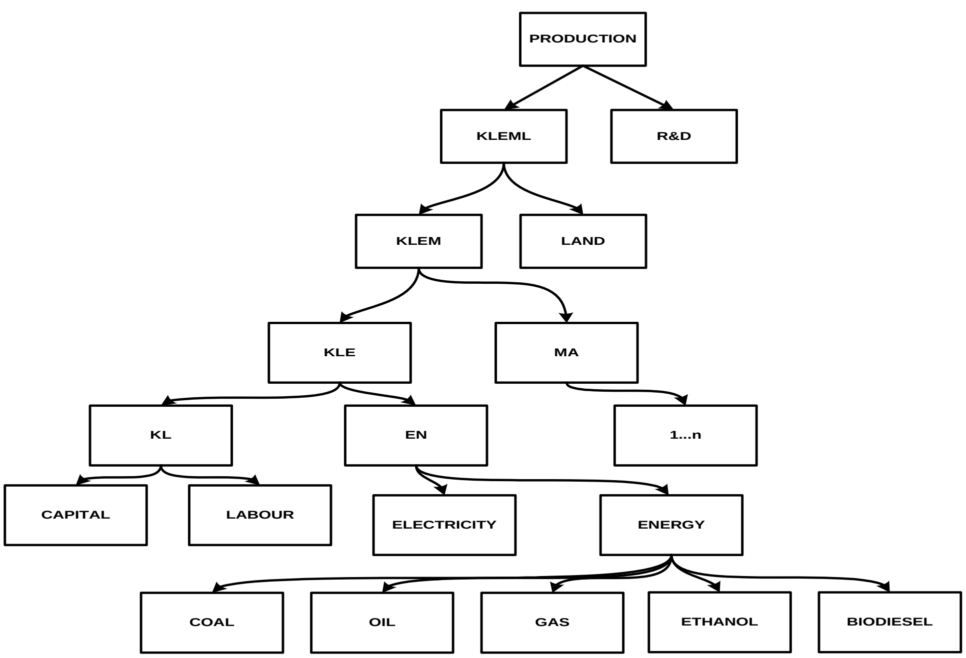


Figure 1: Decision tree of producer in the GEM-E3-RD model

The cost structure of the R&D sector (that is presented in Table 6) is based on the cost structure of other business services of GTAP[3] and the level of R&D supply is calibrated to data extracted from the ANBERD database. The R&D expenditures by branch are based on the results of the CLIMATECOST[4] EC research project.

Production factor	% Share in output
Firms (Intermediate demand)	16
Capital	33
Labour	51

Table 6: Structure of R&D supply in the GEM-E3-RD model

The R&D expenditures by sector are translated into innovation according to the semi endogenous growth approach of Jones [30, 31], that identifies both spill-over and fishing out effects[5]. The international spill-over effects are captured through endogenous bilateral trade flows represented in the model. Each sector buys services from the R&D sector in order to innovate and that leads to a reduction of its production costs and consequently an increase in the competitiveness of the sector. The new sectors incorporated in GEM-E3-RD (Wind, PV, CCS, Electric Vehicles, Advanced Household energy equipment) are generally characterised by high capital costs, but at the same time they have a considerable potential for cost reductions compared to the average production of conventional power generation, transport equipment and other Equipment Goods.

The demand for innovation is endogenous in the model and is derived from the solution of the firms' inter-temporal cost minimisation problem. Innovation through R&D is assumed to affect positively the productivity of labour, energy and electricity, but requires increased expenditure. The decision of a firm to purchase innovation applies to the new capital vintage. The relative prices of the production factors, including R&D price, drive the incentive for innovation. Once the total R&D budget is decided by the firms then it is split into R&D for specific production factors, namely capital, labour, energy, electricity and materials. "Knowledge" in a specific sector arises from the R&D investments in the sector but also from knowledge externalities in the form of spillovers. These knowledge spillovers come from R&D investments realised in others sectors of the domestic economy and from the same sector or other sectors of foreign economies. All these flows are weighted by knowledge spillovers matrices, based on patent data and bilateral trade.

[3] GTAP database, v.7, 2011

[4] Details of the project can be found in: http://www.climatecost.cc/

[5] Fishing out effects are evident when the rate of R&D innovation decreases with the level of cumulative R&D stock (knowledge).

In order to quantify the effects of R&D in the reduction of the production cost, the learning curve is extended to include the accumulated stock of knowledge. The generalised equation used to model the two factor learning curve (TFLC) concept for the new clean energy producing sectors is:

$$C = C_0 * CSales^{-a} * RDSTOCK^{-b} \quad (3)$$

where C is the cost per unit of production, $CSales$ represents the cumulative sales (cumulative output), C_0 is the cost of the first unit produced, a is the elasticity for learning by doing mechanism and b is the elasticity for the learning through innovation mechanism. Table 7 below provides estimates by Ton van Dril & van Tilburg [29] for the cost reduction of power generation technologies achieved through learning by doing and through learning by research.

Power producing technologies	One factor learning rate	Learning rate (LBD)	Learning rate (R&D)
Coal fired	0.05-0.07	0.06-0.11	0.04-0.05
Gas Combined Cycle	0.1-0.15	0.11-0.24	0.01-0.02
New Nuclear	0.04-0.07	0.04	0.02
Wind power	0.08-0.15	0.12-0.16	0.06-0.07
Solar PV	0.18-0.28	0.19-0.25	0.1

Table 7: Learning rate estimates for selected power producing technologies

For the transport sector, Weiss et al. [28] find the following learning rates (Table 8) for each type of vehicle (conventional, hybrid, electric).

Type of vehicle	Learning rate	
	Price differential	**Cumulative production**
Conventional		0.42 ± 0.27
Hybrid	0.23 ± 0.05	0.07 ± 0.02
Electric		0.17

Table 8: Learning rates for vehicle types

The GEM-E3-RD model includes international spillovers based on international patent matrices and inter-sectoral spillovers. The model takes into account the indirect productivity effects induced by the purchases of efficient intermediate goods. In the standard model version, spillovers are assumed to come free, i.e. there is no extra cost in absorbing the knowledge produced abroad. Spillovers in the energy sector relate mainly to the equipment manufacturing industry (i.e. equipment for power generation, transport equipment). When a region acts unilaterally to reduce GHG emissions and therefore increases R&D expenditures directed to low and zero-carbon energy technologies gains an advantage in global trade of these technologies, as in other regions of the world imported R&D energy intensive goods compete with domestically produced goods.

The NEMESIS model incorporates a detailed R&D module that calculates endogenously R&D expenditure in all economic sectors of the model and their impact on productivity and costs of technologies [2]. The variable that plays a critical role in the endogenisation of technical progress is assumed to be "Knowledge" that arises from R&D stock which is calculated by equation 4 (general form). "Knowledge" is not determined only by the sector's R&D stock but also by knowledge spillovers stemming from other sectors and other regions/ countries.

$$RDSTOCK_t = RDSTOCK_{t-1} * (1 - d) + RD_{t-x} \quad (4)$$

The NEMESIS model considers two types of innovation through R&D investments, namely process innovation (that increases the global productivity of the production factors) and product innovation (that is considered as quality improvement). The two types of innovation act differently on the overall economic performance. Process innovation increases the global productivity of factors, thus increasing product supply and reducing the unit production cost, and therefore the product price. This price reduction leads to increased demand, which depends on the demand price elasticity. Econometric time-series estimates reveal that this elasticity is generally lower than one for each sector, and thus for the whole economy and as a result process innovation reduces the use of factors as the effects of supply outweigh the effects of demand. Product innovation acts like an increase in efficiency per volume unit and increases demand for units of efficiency. Volume production is only maintained if the increase in demand for the new efficiency is just equal to the increase in efficiency due to innovation. In general, product innovation more than compensates for the fall in factor usage due to the process innovation. Consequently, R&D leads simultaneously to an increase in GDP and in the use of factors.

Technical change is assumed to result both from investment decisions for new equipment goods and machinery and from investments in R&D based innovations that modify the rate and the direction of technical change. In every production sector innovation through increased R&D investment is incorporated in the CES specification of production. The firms can increase the quality of their products, and the productivity of their inputs, by investing in R&D activities and by buying certain amounts of innovations from the R&D sectors.

The firms benefit from positive knowledge spillovers from R&D activities in other production sectors, but also from other countries and from public laboratories. They have also negative knowledge spillovers from their past innovations (fishing-out effect), as in Jones [30].

R&D expenditures are realized by private firms and by public universities and research centres. In NEMESIS, x (that represents the lag between the time that the R&D is performed and the time that the knowledge is added to the stock of knowledge) is set to one year for private R&D investments and to three years for public R&D. In each country, the knowledge in a sector is the sum of the past R&D efforts realized in the production sector, by national and foreign firms (intra-sectoral spillover), the past R&D efforts realized in other production sectors (inter-sectoral knowledge), R&D externalities coming from the public sector of the country (that are beneficial for the sector) and R&D externalities from public laboratories in foreign countries (that benefit the sector).

2.4 First Mover Advantage

In general, First Mover Advantage (FMAs) is defined as the benefits gained by an economic agent from taking/gaining early market share in a nascent market. Typically, FMAs were considered in terms of the ability of pioneering firms to earn positive economic profits (e.g. Lieberman and Montgomery [35]). Beise [33] argues that the globally successful innovations have commonly been introduced first in one country or region before being adopted internationally. Countries that first adopt a successful innovation can be described as lead markets (for example Denmark is considered as a lead market for wind turbines). A lead market is the origin of the diffusion of innovation, as in this market the demand for the new technology is higher than in other regions of the world, thus the firms can grow and realise cost and quality advantages and/ or technological leadership. According to Ragwitz et al [34], the potential of countries to become market leaders in a specific technology depends on:

- **Lead Market Capability**: Competition is not only driven by price differentials but also by quality differentiation (especially for the knowledge-intensive goods)
- **Large potential for technological learning** and high innovation dynamics
- **Demand side is important:** A demand which is oriented towards innovations and firmly supports new technologies benefits a country in becoming a lead market
- Innovation-friendly regulation and **subsidies for R&D investments**

The model-based analysis aims to investigate the conditions that enable the EU region to reap economic benefits (in terms of increased employment, exports, GDP or welfare) as a result of its strong pioneering GHG mitigation action. The decarbonisation scenarios for the EU generally involve substitution of imported fossil fuels by domestically produced goods and services, which are used to improve energy efficiency and implement RES and other emission reduction technologies. The decarbonisation scenarios also imply more rapid capital turnover in all sectors, ranging from domestic appliances, investments to improve the energy and transport related infrastructure to power generation capital. Depending on accompanying macroeconomic policies and the support for innovation capital, the emission reduction process can trigger acceleration of technology progress in many sectors of the economy, including the equipment goods industries, construction and the market services sectors. The new activity and the technology progress may exert positive effects on the balance of trade, economic growth and employment, depending on similar development expected to take place later in other regions of the world and the spillover effects for low and zero carbon energy technologies. Such positive effects can be intensified by directing part of the revenues from auctions and carbon taxes to remove market distortions, for example in the labour market and social security contributions, or to support innovation through increased R&D investments in clean energy technologies.

First mover advantage in the current study is meant as the possible trade and GDP growth benefits stemming from EU leadership in technologies required to implement the transition to a low carbon emitting economy. It is assumed that the technological learning achieved by the early entrant (first mover) provides cost advantages which allow maintaining the leadership in global markets for the low and zero carbon technologies. The diffusion of technology to other regions of the world diminishes the first mover advantages over time. Non-linear learning curves relate unit investment costs with total cumulative production volumes by type of technology. When a technology is deployed in a single region of the model, the magnitude of cost reductions depends on the region's market volume; cost reductions are obviously more pronounced when the technology is deployed globally. However, the European internal market is sufficiently large and unified and can thus achieve a large part of the learning potential of the RES and other emission reduction technologies. As zero carbon emitting energy technologies are assumed to experience cost reductions at a sector rather than at the firm level, the issues of monopoly rents from innovation are not addressed by the models [32].

Low and zero carbon emitting energy technologies (wind, photovoltaics, CCS technologies, electric and plug-in hybrid vehicles and advanced energy efficient household equipment) have a large potential of cost reduction if developed at a large scale. Early movers in these industries would achieve economies of scale and enjoy the benefits of clustering research centres, manufacturers and suppliers that form a critical mass in support of continued growth in the above mentioned sectors. The cost reduction of clean energy technologies depends on their total cumulative volume of production and hence it is induced by the stringency of climate policies (high carbon taxes). Technical change is a result of both high R&D investments and economies of scale due to the mass production of the necessary equipment in the decarbonisation context. Technological learning for zero carbon energy technologies reduces the overall cost for achieving the predefined emission reduction objectives, compared to a case without technical change [32]. The EU aims to spur innovation and deployment of clean energy technologies in order to gain high global market shares and become the leading exporter of these technologies. The latter drives the current EU policy ambition to be a first mover in climate change mitigation policies.

The advantages that the EU economy can get by pursuing stringent pioneering climate action have been widely studied in recent years. Some studies suggest that unilaterally committing to higher emissions reduction targets might pay off under certain conditions leading to GDP, employment and exports increase relative to the reference levels. Study [34] focused on the strong benefits for the EU economy (especially in terms of increase in exports) arising from the adoption of RES promoting policies. Capros et al [32] use the GEM-E3 model to analyse the FMA in EU and they show that if the EU has to meet the decarbonisation carbon budget, then it is beneficial to start the emission reduction effort (and not wait for a global agreement) irrespectively of whether or not the rest of the world will later adopt decarbonisation policies. They also found that getting an advantage in global trade of clean energy technologies depends on the speed of technology diffusion in the rest of the world.

A study by the Climate Group [36] used the E3MG macro-econometric model and showed that the EU GDP will increase by 1.4% and 1.1 million extra jobs will be created by 2020 (compared to the Reference scenario) if the EU acts unilaterally to achieve a 30% GHG emission reduction target by 2020. Jochem et al. [37] assessed the economic impacts of the imposition of a 40% GHG emissions reduction target by 2020 relative to 1990 levels in Germany. The study concluded that this target could result in at least 500,000 additional jobs in 2020 (and 900,000 in 2030) and an increase of €70bn in German GDP, while requiring additional net investments of €30bn per year. Boyd [38] (based on a survey of key Chinese government documents and Chinese academic articles) concludes that three ideas underpin China's new energy and climate policy: energy security, concern over environmental impacts and the desire to gain a competitive first-mover advantage in "strategic emerging industries", key among which are renewable energy, energy efficiency technologies, electric vehicles and other low-carbon energy technologies.

3 Scenarios Specification

3.1 General characteristics of the scenarios

The study involves comparisons of model results for the EU region for a sequence of four scenarios with the objective to quantify the conditions that enable the EU to get First Mover Advantages in the case of fragmented global climate action. The four scenarios examined in the analysis include:

- ***The Reference Scenario (Ref)*** that assumes continuation of fragmentation in regional climate policies; The regions/countries implement the low end of their Copenhagen-Cancun pledges and the targets for RES deployment up to 2020 and continue to improve their carbon intensity of GDP in the period 2020-2050 at rates comparable to their action in the period 2005-2020. Specific assumptions for the EU reference climate policies are presented in section 3.3.1. This scenario is generally consistent with the moderate climate policy reference scenario implemented by the global models in the AMPERE project [10] and the Reference scenario of the EU Energy Roadmap 2050 [5].

- ***The 450 ppm global mitigation scenario with delayed climate action until 2030 (450delay),*** where a cumulative global carbon budget (consistent with keeping the GHG atmospheric concentration below 450 ppm until the end of the 21st century) is imposed as a constraint in the models in the period 2030 to 2050. Before 2030, the models follow the reference scenario climate policy assumptions. All technological decarbonisation options are available and are used according to cost optimality. The EU region meets the carbon budget of the period 2010 to 2050 as specified in the EU Roadmap 2050 [9].
- ***The EU Alone decarbonisation scenario (EU-alone***), where the EU is assumed to unilaterally adopt stringent emission reduction action in the period 2015-2050 in line with the EU Roadmap targets (80% reduction in GHG emissions by 2050 compared to 1990 levels), while the rest of the world implements the climate policies and measures of the Reference scenario.
- ***The EU as a First Mover in climate policy until 2030 (EUFMA),*** which assumes that the other world regions join the stringent unilateral EU decarbonisation action (in line with the EU Roadmap 2050 targets) in 2030. The scenario also assumes that the global carbon budget of the 450 ppm target is met in the period up to 2050.

The table below summarises the main specifications of the series of scenarios.

Scenario Type	Scenario name	Global Target	EU target by 2050	Regions	Climate policy until 2030	Climate Policy in the period 2030-2050
Reference policy	**Ref**	None	Reference policies	All	Derived from regional reference climate targets	
Delayed 450 ppm climate action	**450delay**	450 ppm	EU Roadmap targets	All	All regions follow the reference scenario	EU Roadmap, others consistent with the 450 ppm global target
EU alone scenario	**EU-alone**	None	EU Roadmap targets	EU as a front runner	EU follows the Roadmap, others the reference scenario until 2050	
EU as a First Mover	**EUFMA**	450 ppm	EU Roadmap targets	EU front runner, others follow	EU Roadmap, others reference	EU Roadmap, others consistent with the 450 ppm global target

Table 9: Specifications of scenarios examined

The key research and policy related questions that will be answered by the model results from the set of scenarios are:

1. What would be the macroeconomic cost for the EU for acting unilaterally (following the Roadmap targets) in the period until 2050, while the rest of the world only implements the Copenhagen-Cancun pledges? What are the long-term implications on the overall economic activity, employment, sectoral production and on the EU's external balance of trade?
2. What would be the macroeconomic costs and benefits for the EU if the rest of the world adopts strong decarbonisation policies as required for reaching the 450 ppm global GHG mitigation targets in line with the EU's strong decarbonisation action?
3. What are the conditions that enable the EU to get first mover advantages in the context of incomplete carbon markets at the global scale? What are the potential co-benefits of early decarbonisation action for Europe in terms of positive GDP growth, higher employment, increased exports and international competitiveness in the global trade of clean energy technologies?
4. Would it be preferable for the EU to wait until 2030 and to synchronize emission reduction actions with the rest of the world? Is it beneficial for the EU to start the decarbonisation effort unilaterally irrespectively of whether or not the rest of the world will later adopt decarbonisation policies?

3.2 Main Scenario assumptions

3.2.1 Model harmonisation

Population and economic growth assumptions, which are the main socio-economic drivers of carbon emissions and energy demand, are harmonised in the two macro-economic models that participate in the current analysis (GEM-E3-RD and NEMESIS) so as to increase comparability of results. Population projections are based on the medium fertility variant of the 2010 version of the UN World Population Prospects (United Nations 2010 [3]). The country-level data from this source are aggregated to correspond to the GEM-E3-RD model regions. The series of scenarios examined project a continuous (but declining rate of) population growth throughout the period 2010 to 2100. The world population is projected to increase from 6.8 billion people in 2010 to 9.3 billion in 2050 and to 10.3 billion people by the end of the century. India is projected to be the most populated country with nearly 1.7 billion inhabitants in 2050 surpassing China after 2020. Table 10 shows the population projections used for the regions of the GEM-E3-RD model in the period 2010 to 2050.

Population in GEM-E3-RD regions (in millions)					
	2010	**2020**	**2030**	**2040**	**2050**
World	**6896**	**7657**	**8321**	**8874**	**9306**
EU28	504	515	520	519	516
NOAM	348	378	405	429	451
CHN	1349	1396	1402	1371	1306

WPAC	202	205	203	198	193
ENEXP	656	725	781	827	863
ROW	3837	4438	5010	5530	5977

Table 10: Population projections in GEM-E3-RD regions until 2050

The harmonization of economic activity for the reference scenario is based on a methodology developed for the RoSE project[6] which establishes GDP via a growth accounting method [4]. Medium population growth, medium total factor productivity growth and fast convergence among world regions are the main assumptions driving the GDP projections for all parts of the world. This leads to a nearly four-fold increase of gross world product in constant MER terms (constant $2005) between 2005 and 2050. Table 11 presents the GDP growth assumptions used for the Reference scenario in GEM-E3-RD regions. These macro-economic assumptions are consistent with the GDP projections used in the AMPERE model inter-comparison [10].

The GDP trajectory is applied to all regions identified in the GEM-E3-RD model in the moderate climate policy reference scenario. In the GEM-E3-RD model, the imposition of climate policies and targets in the different scenarios leads to a change in GDP compared to the reference case.

Average annual growth of GDP in GEM-E3-RD regions (in %p.a.)					
	2005-2010	**2010-2020**	**2020-2030**	**2030-2040**	**2040-2050**
World	1.9	3.6	3.1	2.7	2.4
EU28	0.9	2.0	1.8	1.6	1.4
NOAM	0.6	2.4	1.9	1.9	1.8
WPAC	0.3	2.4	1.7	1.2	1.1
CHN	9.5	9.4	5.7	3.1	2.4
ENEXP	3.9	4.6	3.5	2.9	1.9
ROW	4.4	5.4	5.0	4.5	4.0

Table 11: Reference scenario GDP projections in GEM-E3-RD regions until 2050 (average annual growth of GDP)

GDP of the EU in the reference scenario is calibrated to the macroeconomic projections already adopted by the European Commission and DG-ENER in 2010. Population and GDP projections are harmonised with the 2009 "Ageing report" of the European Commission[7]. In their medium–fertility variant, the UN projections for the population of EU match the Ageing Report of the European Commission very well.

[6] Available at: http://www.rose-project.org/

[7] Available at: http://ec.europa.eu/economy_finance/publications/publication14992_en.pdf

3.2.2 Treatment of carbon tax revenues

The results of the macro-economic models depend on assumptions about the use of public revenues from the imposition of a tax on GHG emissions (recycling scheme). Each model is allowed to select the optimal revenues recycling scheme (in terms of minimization of the impact on overall economic activity), following the specifications below:

- Revenues should be recycled inside the region where the tax is imposed
- Revenues recycling schemes must not change between the series of scenarios.
- Revenues recycling schemes adopted by the models should reflect the least cost mitigation strategy.

The GEM-E3-RD model assumes that the carbon revenues are recycled back to households as lump-sum transfers because this scheme minimizes impacts on welfare. NEMESIS assumes that a part of the carbon revenues is used to reduce labour costs through the decrease of social security contributions (distributed in proportion to the social contributions of each sector but without transfer between member states) and the rest is recycled to households through lump sum transfers.

3.3 Scenario definition

In the last four UN international climate conferences, it was agreed that the long-term objective should be to limit global temperature increase to 2°C compared to the pre-industrial levels [7, 8]. There exists a scientific consensus on the fact that idealised climate policies (i.e. full flexibility as to when and where to reduce emissions, based on emissions budgets and global participation) would lead to the least global mitigation costs [43]. However, the recent slow progress in international negotiations shows that a global concerted action to reduce GHG emissions is not politically realistic in the near term. The series of scenarios are designed with the purpose to quantify the macro-economic consequences for the EU in case that the region acts as a first mover in climate policy and to explore the First Mover Advantages that the EU economy can get in the case that other regions also adopt strong mitigation policies after 2030.

3.3.1 The Reference scenario

The Reference (Ref) is the scenario that provides the basis for evaluating all other scenarios in terms of economic activity and welfare implications. The reference scenario projects sustained economic growth at a global scale. In this scenario, a continuous regional fragmentation of climate policies and a stalling in international climate policy negotiations is assumed, while world regions are locked into their current level of emissions reduction policies and measures throughout the 21st century. The scenario includes the implementation of the low end of unconditional Copenhagen-Cancun pledges for the major carbon-emitting economies. In the period up to 2020, explicit climate targets are introduced in the models in the form of emission (or emissions intensity) reduction commitments, share of RES in power generation (or in gross final energy demand) and capacity expansion targets for renewable and nuclear energy in each region of the world.

After 2020, regions are assumed to sustain the level of CO_2 (or GHG) intensity improvement at a rate that is roughly consistent with their pre-2020 action or slightly strengthened for regions without ambitious climate targets until 2020. Emission (and emissions intensity) reduction targets are implemented by imposing a regionally specific carbon tax that leads to their achievement (i.e. it acts as a policy instrument). Table 12 presents the analytical specifications of GHG emissions reduction and renewable expansion targets for the major carbon-emitting economies in the reference scenario; these countries/regions jointly represented more than 70% of the global GHG emissions in 2005.

Region	GHG emissions reduction in 2005-2020	GHG intensity reduction in 2005-2020	RES share in power generation in 2020	Installed RES capacity targets in 2020	Installed nuclear capacity in 2020	GHG annual intensity improvement after 2020
EU-27	-15.0%	N/A	20.0%[8]	N/A	N/A	3.0%
China	N/A	-40%	25.0%	Wind: 200 GW, Solar PV: 50 GW	41 GW	3.3%
India	N/A	-20%	N/A	Wind: 20 GW, Solar PV: 10 GW	20 GW	3.3%
Japan	-1.0%	N/A	N/A	Wind: 5 GW, Solar PV: 28 GW	N/A	2.2%
USA	-5.0%	N/A	13.0%	N/A	N/A	2.5%
Russia	27.0%	N/A	4.5%	N/A	34 GW	2.6%
Australia	-13.0%	N/A	10.0%	N/A	N/A	3.0%
Brazil	-18% (from BAU)	N/A	N/A	N/A	N/A	2.7%
Latin America	-15% (from BAU)	N/A	N/A	N/A	N/A	2.1%
Canada	-5.0%	N/A	13.0%	N/A	N/A	2.4%

Table 12: Regional climate targets in the AMPERE reference scenario

The Reference scenario (Ref) reflects to a large extent the main energy and climate policy assumptions of the Reference scenario of the European Commission as specified in the Energy Roadmap 2050 [5]. The Reference scenario assumes the full implementation of the EU's already adopted energy and climate policies by 2020. The scenario assumes the operation of the EU-ETS carbon market until 2050 with linearly decreasing allowances and the inclusion of a series of directives on energy efficiency, car regulations and air pollution in the member-state legislations. More specifically after 2020 the scenario assumes a linear annual reduction of the ETS cap (-1.74% per annum), no additional policies for energy

[8] in gross final energy demand

efficiency and RES penetration, limited electrification of the transport sector and non-ETS GHG emissions to remain below the cap specified for 2020. Table 13 presents the key energy and climate policies assumed in the Reference scenario for the EU.

a.	Full implementation of the EU Climate and Energy package for 2020
b.	Inclusion of the labelling and the buildings directives
c.	Gradual implementation of the Eco-design Framework Directive and the associated regulations
d.	Completion of the internal energy market (full implementation of the 2nd Internal Market Package by 2010 and 3rd Internal Market Package by 2015 is assumed)
e.	Implementation of the EU ETS directive. ETS legislation is assumed to continue to 2050 with allowances decreasing throughout the time period. ETS is the main driver for the continued emission reductions beyond 2020
f.	GHG Effort Sharing Decision (ESD). Member states targets for non-ETS sectors are achieved by 2020. After 2020, stability but not strengthening of the policy is assumed
g.	Regulation on CO_2 standards for vehicles as pertaining over time in the current legislation (emission limits introduced for new passenger cars and for new heavy-duty vehicles)
h.	Strong national RES support policies (in line with the RES directive), including feed-in tariffs, subsidies, green certificates and quota systems as specified by member state and anticipated to strengthen where necessary to meet the 2020 RES targets. After 2020, no additional RES promoting policies are assumed.

Table 13: Key energy and climate policies assumed in the Reference scenario for the EU

The GEM-E3-RD and NEMESIS models satisfy the predefined CO_2 emission reductions for the EU by imposing a carbon price that increases the cost of fossil fuel use. The non-CO_2 GHG emissions represented in each model are priced with the same carbon prices as CO_2 emissions. The EU climate policies included in the Reference scenario until 2020 are also assumed to apply in the decarbonisation scenarios. Table 14 summarises the main emission reduction and RES deployment targets for the EU for the Reference scenario until 2050.

EU Target	Reference scenario
GHG emissions (compared to 2005)	-15% by 2020
RES share in gross final energy demand	20% by 2020
Post 2020 targets	GHG intensity: -3% p.a. until 2050

Table 14: EU energy and climate targets in the reference scenario

3.3.2 The 450 ppm mitigation scenario with delayed climate action until 2030

The 450 ppm mitigation scenario with delayed action until 2030 (450delay) aims to achieve the stabilisation of atmospheric concentrations of GHGs at the level of 450 ppm of CO_2-eq. by the end of the century. In the AMPERE project, the models use the cumulative carbon budget for the period 2000 to 2050 as the long-term target/constraint. This target is implemented with the imposition of a globally harmonized carbon tax. It has been argued that cumulative CO_2 emissions until 2100 are a good proxy for radiative forcing (Meinshausen et al., 2009, reference [6]).

The GEM-E3-RD model uses the global carbon budget of 1300 Gtn. of CO_2 in the period 2000 to 2050 as specified in the AMPERE study[9] [10, 11]. All regions follow the reference scenario climate policies in the period 2010-2030. The climate change mitigation target is implemented by imposing the cumulative CO_2 emissions budget[10] on top of the climate policies and RES capacity expansion targets assumed in the moderate climate policy reference scenario after 2030. The historic carbon emissions of the decade 2000 to 2010 and the reference emissions in the period 2010 to 2030 are subtracted from the overall carbon budget in order to calculate the remaining global emissions that are imposed as a constraint on GEM-E3-RD in the period 2030 to 2050.

The EU adopts the Roadmap targets after 2030, i.e. the Roadmap carbon budget is imposed as a constraint on cumulative EU carbon emissions in the period 2010-2050. As a result of delays in increasing the stringency of mitigation effort before 2030, the emission reductions in the 2030-2050 period required to meet the overall carbon budget are larger compared to the non-delaying optimal decarbonisation scenario as specified in the EU Roadmap [9]. As a result marginal abatement costs (carbon prices) are projected to be higher compared to the non-delaying scenario after 2030.

A globally harmonized carbon tax ensuring full "when and where" flexibility of emissions reduction is imposed on non-EU regions after 2030 on top of climate policies assumed for the reference scenario. No emissions trading, banking and borrowing is allowed. The model adopts the optimal GHG emissions reduction trajectory in the period after 2030. All mitigation options are available and optimistic technical progress is considered regarding the emission reduction technologies, especially for RES and CCS in power generation and batteries used in electric and plug-in hybrid vehicles. The GEM-E3-RD model decides on the cost optimal mix of different emission reduction technologies, including energy efficiency improvement in all sectors.

The NEMESIS model is not able to define the optimal global pathway of GHG emission reductions as it includes only the EU region. In order to overcome this limitation, NEMESIS

[9] GEM-E3 does not include emissions from Land Use, Land Use Change and Forestry sector.
[10] The carbon budget is imposed on CO_2 emissions from fossil fuel combustion and industrial processes.

imposed as a constraint the average CO_2 emission reductions for the EU arising from results of the global energy-economy models used in AMPERE for the 450 ppm global mitigation scenario [10]. Only the models that have an exact representation of EU are included in computing the average[11].

The NEMESIS model that runs until 2030 implemented the scenario in the following way: The reference scenario is followed until 2020 in all EU countries. In the decade 2020-2030 climate policy intensity in the EU increases so as to ensure that the cumulative carbon budget of 72 Gtn. (in line with the EU Low Carbon Roadmap [9]) is met in the period 2010 to 2030. The Rest of the World also increases its mitigation efforts after 2020 in order to meet the CO_2 budget of 680 Gtn. of CO_2 (computed as the median of models in the AMPERE 450 ppm global GHG mitigation scenario) in the period 2010-2030. The reaction of the Rest of the world is provided by GEM-E3-RD to NEMESIS. The GEM-E3-RD and NEMESIS models use the CO_2 price that emerges from the imposition of the cumulative carbon budget constraint to price the non-CO_2 emissions represented in each model.

3.3.3 The EU alone scenario

The EU Alone scenario assumes that the EU-28 region unilaterally follows strong decarbonisation policies in line with the EU Roadmap [9] in the period 2010 to 2050, while Rest of the World implements the moderate energy and climate policies assumed in the Reference scenario (Table 12). Specifications about the treatment of non-CO_2 GHGs and carbon revenues recycling schemes remain unchanged from the 450 ppm global delayed mitigation scenario (450delay).

The EU Alone scenario explores the stakes for the EU of adopting the Roadmap without an international climate agreement in place. This constitutes a very important concern for European policy makers especially with regard to energy intensive industries like metals and chemicals [41]. Especially in the context of adopting a legislative framework and explicit ambitious climate targets for 2030 [40], it is of special interest to quantify the macro-economic costs incurred for the EU in case that it adopts the Roadmap emission reduction targets, while the rest of the world only implements the low-end of Copenhagen-Cancun pledges.

The study essentially focuses on the EU region as an obvious candidate for pioneering strong climate action. The EU leads the global climate effort, as it has already adopted specific emissions reduction targets for 2020, has implemented a number of energy and climate policies (including the establishment of the EU ETS system) and has confirmed the long term objective to reduced GHG emissions by at least 80% in 2050 [9]. In the EU Alone scenario, the EU-28 region is assumed to unilaterally follow the Roadmap decarbonisation

[11] The GCAM, IMACLIM and MESSAGE models that include Turkey in the EU are excluded from the calculations as their results for the EU region are not comparable to other models.

pathway by 2050, i.e. the 80% reduction target in GHG emissions in the period 1990-2050 and the equivalent carbon budget are imposed as constraints in the models. Carbon emissions might deviate from the Reference scenario in 2020, as the EU adopts more stringent decarbonisation action in the first modelling year after 2012. The cumulative carbon budget for the EU region is assumed to be the same with the 450delay scenario.

On the other hand, regions outside the EU follow the moderate climate policy Reference scenario and do not intensify their efforts until 2050. Consequently, carbon prices and other energy and climate policies are the same as in the Reference case. The unilateral EU decarbonisation action decreases the effectiveness of the climate policy, because of carbon leakage. Carbon leakage is defined by IPCC [39] as "The part of emissions reductions in abating countries that may be offset by an increase of the emissions in the non-abating countries". There are two main channels through which carbon leakage occurs, namely: the **energy channel** (increase of energy consumption in non-abating countries induced by lower international fossil fuel prices due to emission reduction, hence lower fossil fuel consumption, in the carbon abating regions) and **the industry channel** (energy intensive production partly shifts from countries applying emission reduction policies to countries that do not, due to different relative costs induced by carbon prices). The unilateral EU climate action can also lead to higher learning of clean energy technologies and regions outside the EU can take advantage of technological spillovers. Consequently, the evolution of the energy and economic system in non-EU regions is not fixed to the Reference levels, as the unilateral EU action impacts the global economy and the associated GHG emissions in divergent ways as analysed above.

3.3.4 The EU acts as a First Mover in climate policies until 2030

In the EU as a First Mover scenario (EUFMA) the EU region is assumed to successfully motivate other parts of the world to join an ambitious climate policy regime after 2030. The EUFMA scenario investigates the conditions that enable the EU to get First Mover Advantages (FMAs) in the context of asymmetric global climate policies.

In the period 2010 to 2030, the EU region unilaterally follows strong decarbonisation policies in line with the EU Roadmap, while the Rest of the World only implements the Reference climate policies. In the period after 2030, all regions increase their efforts to reduce GHG emissions with the objective to achieve the stabilisation of atmospheric concentrations of GHGs at the level of 450 ppm of CO_2-eq. by the end of the century.

The definition of this scenario (and the respective model results) is identical to the EU Alone scenario in the period 2010 to 2030. After 2030, the EU continues the implementation of the Roadmap emission reduction targets, while other world regions abandon the moderate climate policy reference scenario and follow the 450 ppm global mitigation pathway. In particular, in non-EU regions a globally harmonised carbon price is imposed in the 2030-2050 period in order to ensure that the global carbon budget of 1300

Gtn of CO_2 in the 2000-2050 period is met[12]. The global and the EU carbon budgets are the same as in the 450delay scenario in order to increase comparability of model results for the different scenarios.

As in the previous scenarios, all emission reduction technologies are available and the models are free to decide on the cost-optimal mix of RES, CCS, nuclear, transport electrification and energy efficiency improvement in order to accomplish the mitigation target.

The NEMESIS model follows the emission reduction target (as specified in the EU Roadmap) from the first modelling year after 2010 and ensures that the cumulative carbon budget of 72 Gtn. will be met in the EU in the period 2010 to 2030. The rest of the world follows the moderate climate policy reference scenario until 2020. In the decade 2020-2030, world regions increase their mitigation efforts in order to meet the cumulative carbon budget of 680 Gtn. of CO_2[13] in the period 2010-2030. The reaction of the Rest of the world to the EU's first mover climate action is provided by GEM-E3-RD.

The scenario assumes that regions outside the EU have to meet the overall targeted carbon budget of the 2000-2050 period despite pursuing strong mitigation actions only after 2030; this leads to higher stringency of their emission reduction effort in the period 2030 to 2050. This scenario is used to quantify the potential FMAs of early decarbonisation action for Europe in terms of positive GDP growth, higher employment in specific sectors and increased international competitiveness in the global trade of clean energy technologies.

4 GEM-E3-RD results

The report introduces briefly the Reference scenario constructed using the updated and enhanced model versions with endogenous R&D and endogenous technology learning mechanisms. The Reference scenario takes a very cautious view with regard to future developments of the global energy-economy system and especially with regard to the future climate policy (section 4.1). The reference scenario is used as the benchmark against which various policy cases are compared in order to derive analytical model-based conclusions. In sections 4.2, 4.3 and 4.4 a detailed comparison of the alternative scenarios with the Reference is carried out with regard to their impacts on the overall economy, carbon emissions, energy system restructuring and trade of clean energy technologies.

[12] The historic CO_2 emissions in the 2000-2010 period and the reference carbon emissions in the 2010-2030 period are subtracted from the global carbon budget that is imposed in the period 2030 to 2050.
[13] The same global carbon budget as in the 450 ppm delayed mitigation action scenario (AM5FM2) is applied.

4.1 The Reference scenario

4.1.1 Energy and carbon emissions projections

Several regions in the world have adopted some type of climate policy by 2012 and pledged to reduce their GHG emissions (or emission intensity of GDP) by 2020. In addition, targets to support the deployment of zero-carbon energy sources have been implemented in a number of countries. The Reference scenario tries to capture a situation of regionally fragmented climate action based on existing or planned policies and to conceptualize a continued stalemate in international climate negotiations where countries continue with their currently pursued or slightly strengthened rates of emissions intensity improvement throughout the 21st century. Table 15 presents the regional and global CO_2 emissions in the period 2010 to 2050 as projected by the GEM-E3-RD model in the Reference scenario.

Reference CO_2 emissions in GEM-E3-RD regions (in Gtn. of CO_2-eq.)						
	2010	**2020**	**2030**	**2040**	**2050**	**Cumulative 2010-2050**
World	29.4	36.1	43.2	47.2	45.5	**1655**
EU28	3.8	3.3	3.1	2.7	2.3	**121**
NOAM	6.4	6.1	5.7	5.3	4.1	**222**
WPAC	2.1	1.9	1.8	1.6	1.2	**70**
CHN	6.6	10.4	13.6	14.0	12.2	**478**
ENEXP	4.5	5.3	6.0	6.5	6.6	**236**
ROW	6.0	9.1	13.0	17.1	19.1	**527**

Table 15: Reference CO_2 emissions in the period 2010-2050 in GEM-E3-RD

GEM-E3-RD shows that global carbon emissions increase from 29.4 Gtn of CO_2-eq in 2010 to 47.2 Gtn. in 2040 in the reference scenario. After 2040 global carbon emissions are projected to follow a declining path as a result of the introduction of more ambitious climate policies and targets in all regions and the deceleration in GDP growth, especially in China. Cumulative global carbon emissions in the period 2000 to 2050 are projected to amount to 1920 Gtn. of CO_2; thus they substantially exceed the cumulative 450 ppm carbon budget (1300 Gtn). Therefore, the moderate climate policy Reference scenario is clearly inconsistent with the goal of long-term climate stabilization [10, 11].

Emissions in developing and less developed regions (Energy exporters, Rest of the World) are projected to increase steadily as a result of continuing economic growth, increased urbanization and rising standards of living. Chinese carbon emissions more than double between 2010 and 2030, while a relative stabilisation is projected for the decade 2030 to 2040 and a decline in the period after 2040. The latter is the result of the strong deceleration in GDP growth, the relative deindustrialisation of the Chinese economy (reduction of the share of industrial value added in GDP) and the Chinese energy and climate policies that encourage the use of natural gas to substitute for coal, envisage a strong promotion of RES development and aim at a large reduction of carbon intensity per unit of economic output. In the EU, emissions decrease sharply throughout the period 2010 to 2050 as a result of the ambitious energy and climate policies assumed in the Reference scenario. Emissions in other developed economies (like USA, Canada Japan and Australia) are also projected to follow a declining trajectory in the period 2010-2050.

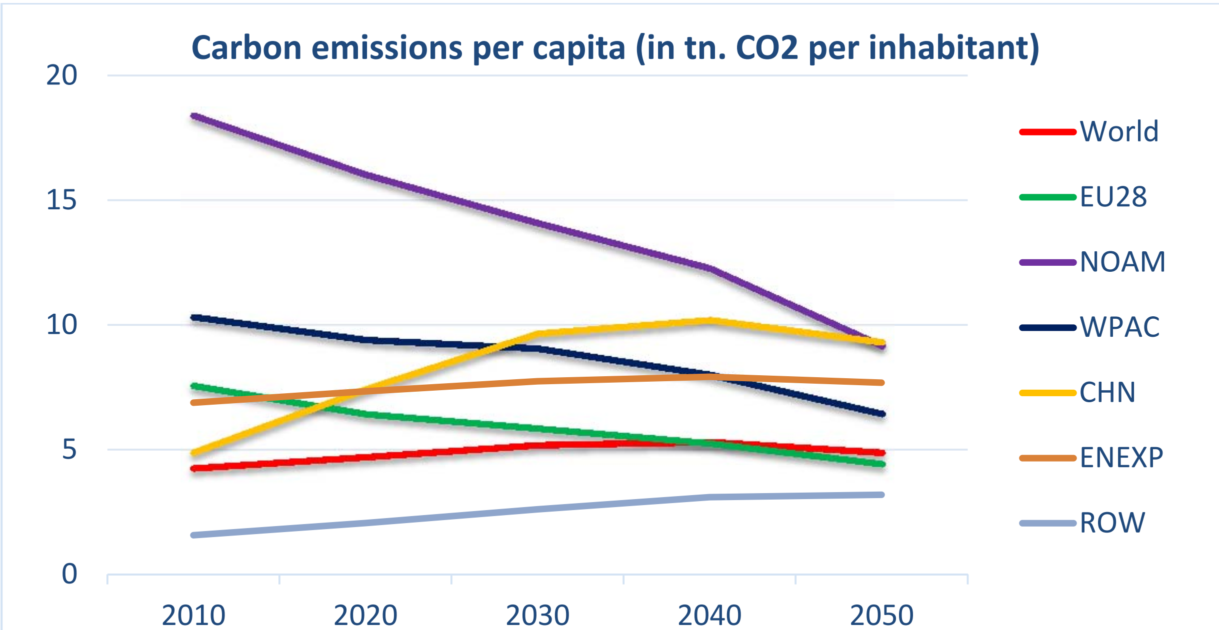


Figure 2: Evolution of CO_2 emissions per capita by region in the GEM-E3-RD Reference scenario

Figure 2 depicts the evolution of carbon emissions per capita in the reference scenario in GEM-E3-RD regions in the period 2010-2050. The global average CO_2 emissions per capita are projected to increase from 4.3 tn CO_2/inhabitant in 2010 to 5.3 tn CO_2/inhabitant in 2040 before declining to 4.9 tn CO_2/inhabitant by 2050. The most prosperous regions of the world (North America, OECD Pacific and the EU) register reductions in emissions per capita throughout the period 2010 to 2050. These are very pronounced for the EU-28 region reaching 4.4 tn CO_2/inhabitant in 2050 which is even below the global 2050 average. North America also experiences a sharp decline over the period 2010-2050 but still emits more than 9 tn CO_2/inhabitant in 2050. In the OECD Pacific region carbon emissions per capita are projected to decrease by 38% over the projection period. China registers a dramatic increase (albeit moderated compared to the recent past) until 2030 and even reaches US levels by 2050, because of its high GDP growth and the massive use of coal to satisfy increasing energy requirements. In Energy Exporters, emissions per capita increase over the projection period and reach 7.7 tn CO_2/inhabitant in 2050, which is consistent with increased motorisation and natural gas demand in Middle East and North Africa and high heating requirements in Former Soviet Union. Emissions per capita almost double in the rest of the world region mainly because of high GDP growth, although they remain at a relatively low level (3.2 tn CO_2/inhabitant) even in 2050.

The RES deployment, energy savings and emission reduction targets imposed in the moderate climate policy reference scenario together with the upward trend projected for prices of internationally traded fossil fuels (coal, oil and gas) lead to accelerated energy efficiency improvement in all regions in the decade 2010-2020. After 2020 energy intensity of GDP continues to decline albeit at a decelerated pace compared to the 2010-2020 period (Table 16). Global energy intensity of GDP is projected to decline by 1.5% per annum in the period 2010 to 2050; higher rates are projected for regions with strong reference climate policies (like EU and North America) and in regions with high energy efficiency potential (like China and Energy Exporters).

	2005-2010	2010-2020	2020-2030	2030-2040	2040-2050	2010-2050
World	0.0	-1.9	-1.4	-1.3	-1.3	***-1.5***
EU28	-0.2	-2.5	-1.9	-1.7	-1.7	***-1.9***
NOAM	0.4	-2.6	-2.2	-2.3	-3.0	***-2.5***
WPAC	0.5	-2.5	-1.5	-1.5	-1.3	***-1.7***
CHN	-3.6	-3.4	-2.4	-1.8	-1.7	***-2.3***
ENEXP	-1.2	-2.6	-1.9	-1.7	-1.3	***-1.9***
ROW	-1.1	-1.3	-1.0	-1.0	-1.0	***-1.1***

Table 16: Evolution of final energy intensity of GDP in GEM-E3-RD regions (% change p.a.)

The reference climate policies imply the imposition of a non-zero carbon price in model regions so as to satisfy the specified emission reduction targets. Carbon prices increase the cost for using fossil fuels which combined with increases in international fossil fuel prices and technological progress assumed for low and zero carbon energy technologies leads to massive penetration of RES technologies in the power generation mix, as they become increasingly competitive with the fossil fuel based options (Figure 3). Global share of RES doubles in the projection period (from 19.2% in 2005 to 39% in 2050). The RES share is projected to be even higher in EU and amounts to 52.7% in 2050 due to the ambitious RES promoting policies assumed for the region. Massive RES penetration in the power generation mix is also projected for regions outside the EU; The RES share is projected to amount to 43% in Rest of the world, 37% in North America and OECD Pacific and 31% in China in 2050. RES global production mix in 2050 consists of hydro (that accounts for 35% of total RES), wind (25%), biomass (19%) and solar technologies (21%). Wind and solar are found to be the most rapidly emerging RES technologies as the wind share in global RES electricity production increases from 1.7% in 2010 to nearly 10% in 2050 and solar power generation amounts to nearly 8.5% of global power requirements in 2050.

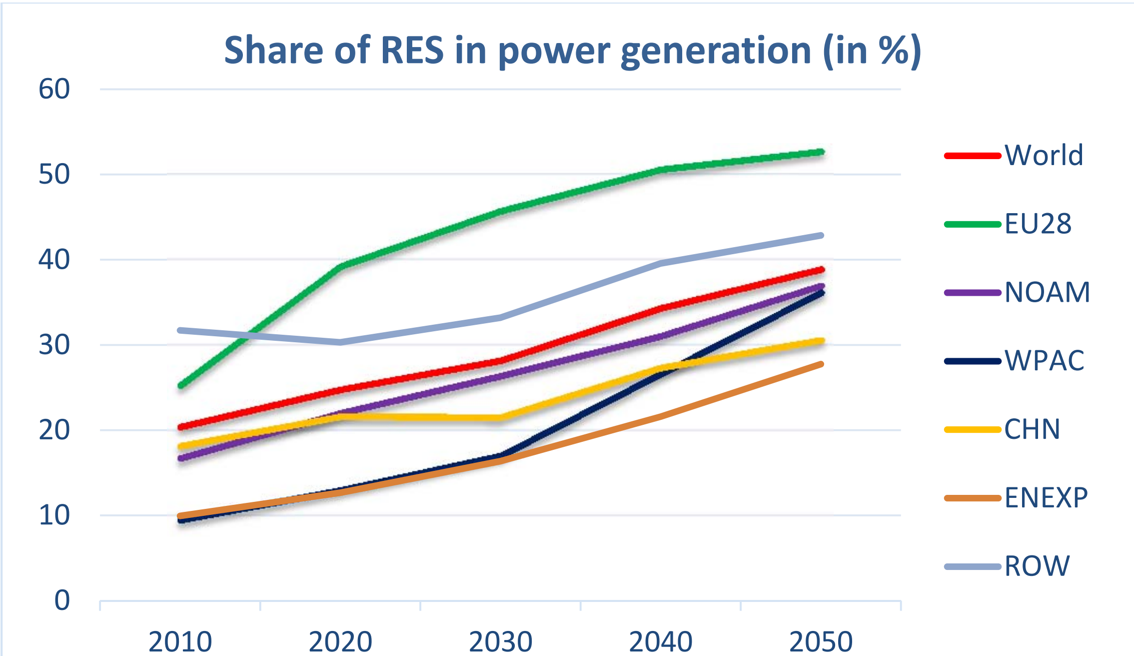


Figure 3: Evolution of RES share in power generation in the GEM-E3-RD Reference scenario

While in regions like Energy Exporters and Rest of the World emission and RES targets assumed in the Reference scenario are not found to be particularly ambitious, in the developed OECD regions stringent emission reduction targets imply high carbon prices in the medium term (until 2030). Carbon prices in EU ETS sectors increase sharply after 2020 and reach nearly 100 \$05/tn. CO_2 in 2050 due to the reference scenario assumption for linear annual reduction of the EU ETS cap(-1.74% per annum). GEM-E3-RD shows that the Chinese energy and climate targets are not particularly ambitious until 2020 due to the high GDP growth assumed. However, after 2030 the GEM-E3-RD model finds it increasingly difficult to meet the 3.3% annual improvement in GHG intensity of GDP target thus leading to a high carbon price that reaches 73 \$05/tn. CO_2 in 2050 (Table 17).

Carbon price in $2005/tn. of CO2				
	2020	**2030**	**2040**	**2050**
World	7.5	10.4	15.5	25.6
EU28 (ETS)	21.1	47.9	71.5	98.6
NOAM	17.7	17.5	17.3	17.1
WPAC	17.0	22.6	30.0	38.4
CHN	5.3	14.4	32.2	73.1
ENEXP	2.6	2.6	2.6	2.6
ROW	2.5	2.5	2.5	2.4

Table 17: Carbon prices in GEM-E3-RD regions

4.1.2 The clean energy producing sectors

The current section concentrates on the new sectors that have been introduced in the GEM-E3-RD model, namely low and zero carbon power generation technologies (wind, solar, CCS, biomass), alternative transport fuels (ethanol, biodiesel), electrification of transport (electric and plug-in hybrid vehicles) and advanced equipment in household energy appliances that leads to energy savings. In particular, this section establishes the benchmark for the prospects of EU energy technology producing sectors in a world context and under assumptions that provide only a limited stimulus for the markets addressed by such sectors.

Wind power generation

Among renewable energy forms, wind power is a relatively mature option. It has rather limited potential for drastic reduction in costs with a possible exception of off-shore applications, where some improvements are expected in terms of economies of scale. On the other hand, wind power has reached a point where it is often competitive even without special assistance or a high carbon value reflecting a vigorous climate policy. It is therefore expected to expand substantially even under the conditions of the reference scenario, which incorporates a modest GHG emission reduction effort in the world.

For the EU, the reference scenario implies the maintenance of the market for wind equipment at high levels in the period 2010 to 2040, due to the large deployment of wind power that goes from 4.5% in 2010 to 22% in 2040 with respect to meeting EU power requirements. Beyond 2040 there are clear signs of saturation of the penetration of wind in power generation and this translates to a decline in the market for such equipment as it becomes increasingly directed towards replacement. The world market for wind turbines is expected to grow vigorously until 2040 as GEM-E3-RD shows that 9% of global power needs will be produced from wind turbines in that year (from 1.7% in 2010). After 2040, the Rest of the World market marks a pronounced decline for reasons similar to those applying to Europe. The share of the EU in world cumulative sales between 2010 and 2050 is projected to be a substantial 40%, while North America accounts for 21%.

In general the reference implies a stable competitive position of the EU in the wind generator market after increase in market share during the current decade. The decline in the share of EU market in the world does mean, however, that producers in the rest of the world become increasingly important in meeting demand requirements for this technology.

	2010	2020	2030	2040	2050	Cumulative 2011-2050
EU Domestic demand in bn. $2004	28	26	20	22	15	977
RoW Domestic demand in bn. $2004	29	47	65	85	51	2510
World Market in bn. $2004	56	73	85	107	67	3487

Share of EU demand met by domestic production	96	97	97	97	97	97
Share of EU exports in RoW demand	13	16	17	17	21	17
Share of EU in global production	54	45	36	33	38	40

Table 18: Production of Wind power

Photovoltaics

Options for photovoltaic generation have experienced dramatic reduction in costs in recent years and perspective technological analysis suggests that there is further scope for improvement arising both from additional Research and Development and learning by experience especially in terms of economies of scale. On the other hand, photovoltaics remain highly dependent on specific supports like feed-in tariffs, a dependence which is projected to diminish but not entirely disappear even by the end of the projection period. Consequently, deployment will still take place to the extent that policy support allows it.

The reference scenario assumes that such support in the EU is forthcoming. There is a rapid growth in the market between 2010 and 2040 and a stabilisation between 2040 and 2050 due to the onset of some saturation effects. The Rest of the World (non-EU regions) experiences an even more rapid growth between 2010 and 2040, in part due to starting from a very low base. In this period, developing countries increase their share in total PV power generation in the world from a mere 1.2% to 74%.

Regarding the importance of the photovoltaic market, it is worth noting that by 2050, although its contribution to world power generation is projected to be 8.4% compared to 10% for wind, in economic terms the photovoltaic producing sector stands 87% above wind cumulatively. This of course comes as a result of the much higher value added that characterizes photovoltaic production on a GW to GW basis.

	2010	2020	2030	2040	2050	Cumulative 2011-2050
EU Domestic demand in bn. $2004	8	14	25	31	31	946
RoW Domestic demand in bn. $2004	8	56	125	248	191	5571
World Market in bn. $2004	15	70	150	279	223	6517
Share of EU demand met by domestic production[14]	97	96	96	96	96	96
Share of EU exports in RoW demand	21	25	23	23	20	23
Share of EU in global production	58	39	35	31	31	33

[14] The shares reported are model results and overstate the EU's position even for 2010 when already Chinese imports exceeded the 3% suggested for all imports by the number reported. On the other hand, anti-dumping measures are already in place effectively protecting the EU industry.

Table 19: Production of Photovoltaics

The reference implies an increase in EU competitive advantage in the near term, a stabilisation in the 2020s and a subsequent erosion beyond 2030. This erosion is in line with recent experience concerning Chinese imports that were deemed to constitute dumping and have provoked anti-dumping action at EU level in the form of import tariffs to protect domestic producers from unfair competition. This end of period erosion will reflect the strong likelihood that technological spillovers and learning by doing in countries like China, India, Brazil and other emerging economies will result in fast reductions in costs in these countries that also benefit from lower labour costs. This reduction in competiveness together with a slow growth in domestic market mean that according to the reference the EU PV industry, which accounts for 58% of world markets in 2010, drops to just 31% in 2050.

CCS technologies

CCS is not a meaningful power generation option before 2030 primarily because of technological immaturity and public acceptability concerns with regard to sequestration of large volumes of CO_2 underground. Thus CCS deployment depends on high carbon prices and public acceptability. In the reference case significant shares of CCS in total power generation are registered for the EU and China at the very end of the projection period. By 2050 CCS accounts for 11.6% of power requirements in EU28 (6.3% coal-based and 5.3% gas-based) and 16% in China (11% coal-based and 5% gas-based). The high percentages in China reflect the fact that CCS offers a cost-effective means for China to meet its reference scenario long-term emission intensity reduction requirements. In the rest of the world, CCS deployment is more modest accounting for 6.8% of total power generation in 2050.

In the reference scenario the EU enjoys a first mover advantage with regard to this cluster of technologies. Even though the EU domestic market by 2050 only represents 9%, the share of EU industry in the global market remains nearly 50%.

	2010	2020	2030	2040	2050	Cumulative 2011-2050
EU Domestic demand in bn. $2004	0	0	3	13	54	431
RoW Domestic demand in bn. $2004	0	0	1	76	528	2942
World Market in bn. $2004	0	0	4	88	582	3373
Share of EU demand met by domestic production				91	89	89
Share of EU exports in RoW demand				40	40	41
Share of EU in global production				47	44	48

Table 20: Production of CCS technologies

Electric and plug-in hybrid vehicles

GEM-E3-RD covers explicitly plug-in hybrid vehicles and pure electric ones. The key technological development on which their future depends concerns the capacity and vehicle range of batteries together with speed of recharging. Large scale deployment also depends on the development of adequate recharging infrastructure which is likely only in the context of delivered efforts to promote such vehicles. Electric vehicles (EVs) provide an option for considerably increasing energy efficiency in road transport, while at the same time enabling decarbonisation of this sector on condition that carbon-free power generation is achieved. Given that road transport is a large GHG emitting sector, EVs offer a credible decarbonisation option in the context of a strong climate mitigation policy. On the other hand, the reference scenario only assumes incremental policies towards such mitigation. Consequently, the penetration of EVs in vehicle stocks to the horizon of 2050 is rather limited: 19% in the EU assuming strong policy incentives in terms of energy efficiency targets beyond 2030 and 10% in the rest of the world.

Apart from the EU, high penetration rates of EVs and PHEVs are achieved mostly in developed economies, like North America and OECD Pacific, with the efforts of local auto manufacturers constituting the essential background for the evolution of the conditions for take-off such as the creation of an appropriate infrastructure. In the above context, the EU according to the reference constitutes an important market in world terms in an industry that expands much less than its potential. The low penetration rates notwithstanding, the potential market for electric and plug-in hybrid vehicles is huge. This is clearly a case where a fist mover action of the EU could confer major benefits that are explored in the scenario EUFMA.

	2010	2020	2030	2040	2050	Cumulative 2011-2050
EU Domestic demand in bn. $2004	0	4	24	81	161	1915
RoW Domestic demand in bn. $2004	0	9	53	166	321	3938
World Market in bn. $2004	0	13	77	247	482	5853
Share of EU demand met by domestic production			93	94	94	94
Share of EU exports in RoW demand			21	26	27	26
Share of EU in global production			43	48	49	48

Table 21: Production of electric and plug-in vehicles

Advanced equipment in household energy appliances

This technological category is derived from the PRIMES energy system model that distinguishes various appliance categories like heaters, washing machines, refrigerators, cookers, cooling devices etc., between a standard and an advanced version. The advanced version is characterized by a higher efficiency but at the same time has higher cost. The EU has pioneered a system of classifying appliances according to efficiency and imposing increasingly ambitious standards for new equipment sales. Consequently, according to the reference scenario, the EU represents the 38% of global demand cumulatively since EU policies assumed in the moderate climate policy reference scenario can take the form of efficiency requirements for household equipment. The uptake of such technologies in the rest of the world occurs with a lag and concerns primarily the most developed regions of the world (North America and OECD Pacific). The technologies involved represent very high standards of efficiency. Consequently, the inter-regional trade of these high-end technologies does not develop fast. The EU builds some competitive advantage between 2030 and 2050.

	2020	2030	2040	2050	Cumulative 2011-2050
EU Domestic demand in bn. $2004	21	34	44	54	1307
RoW Domestic demand in bn. $2004	27	51	74	114	2164
World Market in bn. $2004	48	85	118	168	3471
Share of EU demand met by domestic production	95	95	96	96	95
Share of EU exports in RoW demand	6	9	12	14	11
Share of EU in global production	44	43	43	41	43

Table 22: Production of advanced energy appliances for households

Biofuels

Biofuels constitute an alternative way of substituting away from oil in the transport sector. Unlike electric cars, they are characterised by current use in a number of regions/countries like the EU, Brazil and North America. The EU is assumed to implement a policy to the horizon of 2020 of providing 10% of the energy used in the transport sector by renewable sources. Biofuels in the form of ethanol and biodiesel figure high as a means of achieving this objective. On the other hand, the reference case does not assume that this policy is intensified beyond 2020. Given improvements in energy efficiency of vehicles especially with the introduction of electric vehicles, biofuels' use in the EU is projected to decline slightly despite the introduction of biokerosene in aviation fuels. This policy assumption is in line with current concerns about competition of biofuel production with food production. In the rest of the world and more particularly in North America and Latin America, high biofuel use is projected even beyond 2020 as a response to high oil prices. Growth in biofuel use is markedly higher for biodiesel rather than ethanol. This is due to a large extent to the introduction of lignocellulosic biomass (advanced biofuels) that does not compete with food production. By 2050 biodiesel mostly from lignocellulosic feedstock accounts for 66% of world biofuel production. In the EU, imports take an increasing share in ethanol demand in the period 2020 to 2050. On the other hand, biodiesel and biokerosene production is maintained as part of the Common Agricultural Policy.

	2010	2020	2030	2040	2050	Cumulative 2011-2050
EU Domestic demand in bn. $2004	4	7	7	6	6	254
RoW Domestic demand in bn. $2004	36	52	66	83	97	2712
World Market in bn. $2004	41	59	73	89	103	2965
Share of EU demand met by domestic production	89	88	84	79	70	82
Share of EU exports in RoW demand	0	0	0	0	0	0
Share of EU in global production	9	11	8	5	4	7

Table 23: Production of ethanol

	2010	2020	2030	2040	2050	Cumulative 2011-2050
EU Domestic demand in bn. $2004	17	27	28	26	25	1017
RoW Domestic demand in bn. $2004	22	54	83	122	176	3647
World Market in bn. $2004	39	82	111	148	201	4664
Share of EU demand met by domestic production	99	98	97	95	93	96
Share of EU exports in RoW demand	0	0	0	0	0	0
Share of EU in global production	42	33	25	17	12	22

Table 24: Production of biodiesel

4.2 The EU alone decarbonisation scenario

The EU Alone decarbonisation scenario assumes that the EU unilaterally adopts the EU Roadmap [9] in the first modelling year after 2012 while non-EU regions implement the energy and climate policies assumed in the moderate climate policy Reference scenario. The EU Alone scenario conceptualizes a situation of pioneering EU decarbonisation action without a global climate agreement in place and aims to quantify the potential risks and benefits for the EU economy. The scenario assumes that the EU pursues strong emission reduction policies so as to meet the required cumulative EU Roadmap carbon budget in the period 2010-2050.

4.2.1 The energy system transformation in the EU

According to the Energy Roadmap 2050 [5] , the decarbonisation of the EU energy system can be achieved by combining a series of options, including energy efficiency improvement, high RES penetration, utilization of nuclear and CCS technologies and substitution away from carbon intensive fossil fuels (especially coal and oil). Another important option is the massive electrification of transport that is accompanied by the timely development of the necessary recharging infrastructure and the rapid improvement in technical-economic characteristics of batteries.

Energy Efficiency

Energy efficiency improvement is considered as an important decarbonisation option because saving energy implies by definition lower carbon emissions in both energy demand and supply sectors. Energy efficiency gains lead to lower energy requirements and thus lower development of supply-oriented decarbonisation options. The improvement of energy efficiency in most cases implies high up-front investments (e.g. investments for the insulation of buildings, for the purchase of more efficient equipment etc.) and money savings over a prolonged period of time (because of lower energy consumption enabled by the efficient equipment). The most common barriers for consumers to invest in energy efficiency improvement are the uncertainty that surrounds the evolution of energy prices, the incomplete knowledge about new energy savings technologies, the consumers' reluctance to bear high up-front costs (implying high subjective discount rates of energy consumers) and the lack of infrastructure development; for example market penetration of efficient electric vehicles highly depends on the existence of battery recharging infrastructure. Public policy intervention can remove the market and non-market barriers for the implementation of investments related to energy efficiency. This intervention can take the form of regulations for large energy utilities, support to manufacturers of energy-saving technologies, imposition of minimum efficiency standards or implementation of a subsidization scheme directed to final energy consumers.

Energy savings in all sectors are modelled in GEM-E3-RD through a non-linear cost supply curve which links marginal cost of savings with cumulative savings potential in each sector. Firms and households are assumed to have the possibility to spend in energy savings, instead of other expenditures, which implies higher energy productivity; the effect of cumulative energy savings on energy productivity exhibits diminishing returns to scale. The total amount of money spent on energy savings is adjusted so as to mimic energy efficiency improvement by sector as projected by the PRIMES model.

Figure 4 depicts the energy intensity of GDP in the EU-28 region in the reference and in the EU Alone decarbonisation scenarios. The GEM-E3-RD model confirms that demand side restructuring is necessary for the EU in order to meet its ambitious emission reduction targets. Even the reference case shows an important decoupling of final energy demand from GDP growth; the final energy intensity indicator (final energy demand per unit of GDP) decreases by 50% in the period 2010 to 2050. Energy intensity of GDP decreases even more in the EU Alone decarbonisation scenario (-60% in the period 2010-2050) induced by higher carbon prices in the EU and energy efficiency promoting policies.

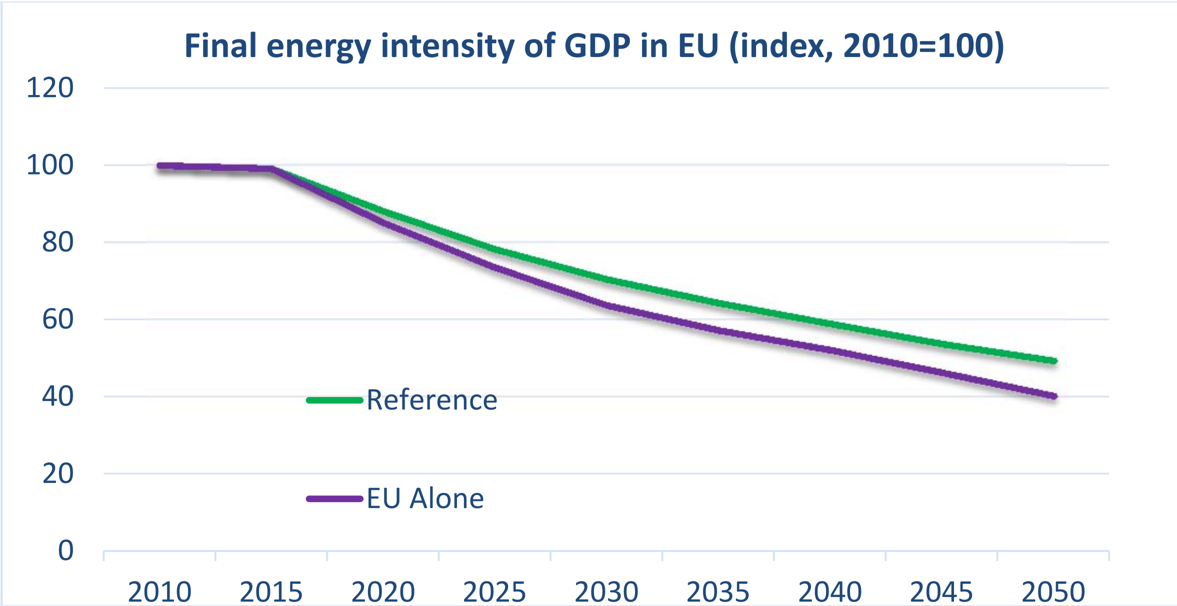


Figure 4: Evolution of energy intensity of GDP in EU in the period 2010 to 2050

The substitution of fossil fuels like oil and coal that are characterized by high carbon intensity and low transformation efficiency in power generation and in final energy demand sectors with natural gas leads to lower energy consumption and to lower carbon emissions. Natural gas can also provide the flexibility and back-up capacity needed in the case of high deployment of intermittent RES technologies in the power generation sector.

<u>RES penetration</u>

The large scale deployment of carbon-free energy sources (like RES) leads directly to lower carbon emissions, as they substitute for fossil fuels in power generation and in final energy demand sectors. RES technologies are characterised by very high theoretical technical potential, but RES costs are highly non-linear, i.e. they tend to increase sharply when RES production approaches the potential limit.

The biomass and waste energy resources have the advantage of being dispatchable, but their deployment is constrained by future availability of primary resources (biomass feedstocks) and by environmental EU regulations. The hydro-electric EU potential has already been tapped to a large extent and the further development of hydro-electricity is limited. As a result, intermittent RES technologies, like wind and solar, have to be deployed massively in the decarbonisation context. High deployment of intermittent RES requires increasing amounts of flexible and controllable generation (usually using gas combined cycle) in order to meet increasing ramping, reserve and flexibility requirements. Electricity storage techniques (besides hydro pumping that has a limited potential in the EU) are expensive and cumbersome to develop, while high investments are required in transmission and distribution grids in order to enable the penetration of highly decentralised RES technologies, like rooftop photovoltaics and small scale wind stations. The high learning potential for the RES power generation technologies (especially for photovoltaics) can at least partly offset the additional grid and storage costs incurred by large intermittent RES deployment.

The macroeconomic models that participate in the current study lack the spatial representation that is required in order to represent in detail stochastic intermittent RES electricity production. They also do not include the power grid in sufficient detail and follow rather simple approaches for modelling the additional grid investments required for high penetration of intermittent RES. Figure 5 presents the share of RES in EU power generation in the Reference and in the EU Alone decarbonisation scenario as projected by GEM-E3-RD. The model projects that the share of RES in electricity production increases considerably during the forecast period even in the reference scenario. The EU Alone decarbonisation scenario leads to an increase in RES penetration in EU power generation (relative to the reference) mainly after 2020. The GEM-E3-RD model shows that the RES share increases from 52.7% in the reference scenario to 60.3% in the EU-alone scenario in 2050. This result is in line with the "Diversified Supply technologies"[15] scenario of the EU Energy Roadmap [5] in which RES share is projected to reach 60% by 2050.

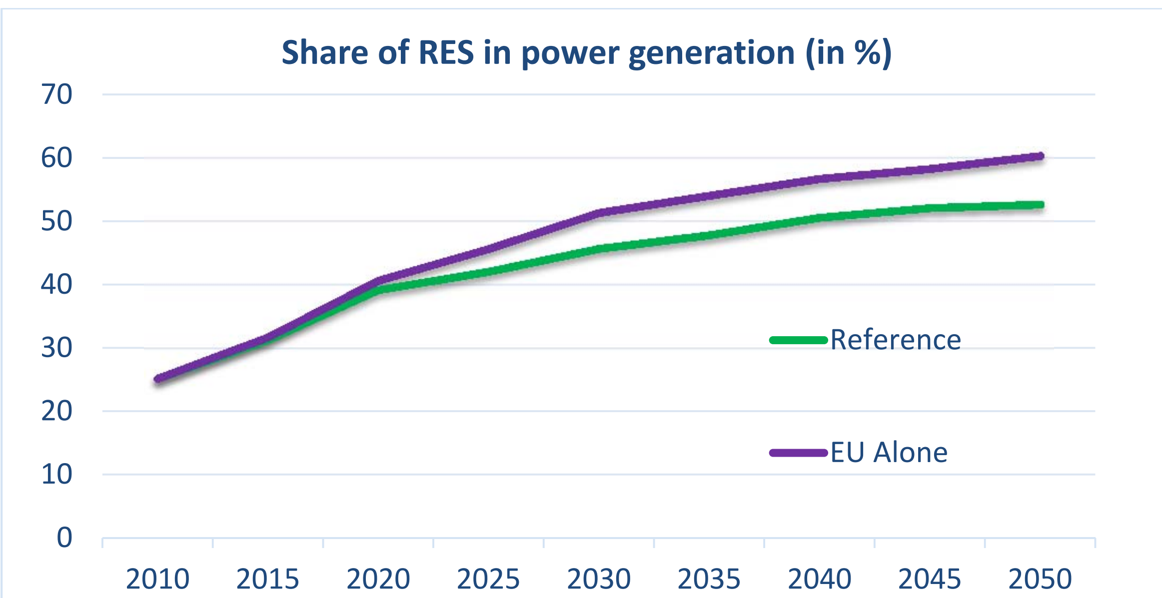


Figure 5: Share of RES in EU power generation

[15] The "Diversified Supply Technologies" scenario shows a decarbonisation pathway for the EU (in line with the 80% GHG emissions reduction target by 2050) where all emission reduction options are available and are used according to cost optimality.

Electrification of final energy mix (including mobility electrification)

The proportion of final energy demand that is covered by electricity has been increasing in recent years in the EU as demand shifts towards more sophisticated and less consuming energy uses, the penetration of electrical appliances in the residential and services sector increases constantly and electrical industrial processes substitute for fossil-fuel based ones. Electricity is characterized by very high efficiency and zero carbon emissions at the point of use in the final energy demand sectors. The GEM-E3-RD model shows that decarbonising power generation and allowing electricity to substitute for fossil fuels in inflexible final energy uses like transport (which otherwise would be rather inflexible in terms of reducing emissions) is a cost-effective decarbonisation strategy.

Apart from the stationary energy uses that are already increasingly electrified, electrification of transport is considered a crucial element of the EU decarbonisation strategy. The penetration of electric vehicles (both pure electric and plug-in hybrids) in the transport sector depends on the improvement in the technical and economic characteristics of batteries, on the development of recharging infrastructure and on the uptake of electric vehicles by consumers. The three elements depend on each other. Consumers are going to purchase electric vehicles only under the certainty of the availability of recharging infrastructure. The latter will only develop if there is a substantial improvement in the technical and economic characteristics of batteries that will lead to the market uptake of electric vehicles by EU consumers. The EU Alone scenario assumes uptake of electric vehicles by consumers facilitated by timely development of battery recharging infrastructure. Electromobility is projected to emerge gradually after 2020 and start reaching maturity conditions after 2035. It is therefore a long process which requires stable regulations and continuous development of infrastructure so as to provide positive anticipation signals both to consumers and to technology providers.

Table 25 shows that the reference climate policies lead to modest penetration of plug-in hybrid vehicles in EU car stocks; by 2050 they represent 13.9% of the EU passenger cars. Electric vehicles represent a niche market even by 2050 (5% share in EU vehicle fleet). The increased emission reduction effort leads to higher penetration of both plug-in hybrids and pure electric vehicles already in the medium term. In 2050 the share of electric and plug-in hybrid vehicles is projected to exceed 61% in the EU, while the share of conventional oil-fuelled cars is only 38.4% (while in the reference it exceeds 81%).

Share of electric and plug-in hybrids in EU car stocks (in %)

Vehicle type	*Scenario*	2020	2030	2040	2050
Plug-in hybrids	*Reference*	0.3	1.9	7.0	13.9
Plug-in hybrids	*EU Alone decarb.*	0.5	4.7	18.7	33.8
Electric vehicles	*Reference*	0.1	0.7	2.5	5.0
Electric vehicles	*EU Alone decarb.*	0.4	3.9	15.2	27.8

Table 25: Transport electrification in the EU Alone decarbonisation scenario

Development of nuclear and CCS technologies

Nuclear power is a carbon-free power source that is fully dispatchable and can economically accommodate base load electricity demand which is important for achieving affordable electricity prices to EU energy intensive industries. On the other hand, nuclear power raises acceptability concerns in many European countries. Maintaining until 2050 a nuclear capacity amounting to roughly the current 132 GW is considered as a serious challenge by many policy makers and energy analysts. The costs and the public acceptance of nuclear have been significantly affected in the aftermath of the nuclear accident in Fukushima in March 2011. Several EU countries have excluded nuclear from their energy mix (Austria, Cyprus, Denmark, Estonia, Greece, Ireland, Italy, Latvia, Luxembourg, Croatia, Malta and Portugal) and others start early decommissioning, while a series of new nuclear projects planned over a long period of time in eastern European countries are financially challenged today mainly due to increased capital costs for new nuclear investments [15].

Under these circumstances, it is possible to see only a relatively modest nuclear development in the EU even under a strict decarbonisation regime. GEM-E3-RD calibrates nuclear development taking into account firmly adopted plans for decommissioning, extension of nuclear plants' lifetime, refurbishment investment and investments in new nuclear power plants in the EU.

Electricity production in EU (in TWh)						
		2010	**2020**	**2030**	**2040**	**2050**
Nuclear	**Reference**	818	727	715	821	940
Nuclear	**EU Alone**	818	728	716	884	1107
CCS	**Reference**	0	0	10	105	479
CCS	**EU Alone**	0	21	191	319	598

Table 26: Power generation from nuclear and CCS technologies in EU

GEM-E3-RD shows that nuclear deployment in the EU is identical in the reference and in EU alone decarbonisation scenario in the period 2010 to 2030 (Table 26). After 2030, the model shows a modest increase in nuclear-based power generation due to increasing emission reduction effort in the EU Alone scenario. By the end of the projection period, the share of nuclear in EU power needs reaches 24.2% in the decarbonisation scenario (higher than the 22.7% share projected in the reference).

CCS technologies can capture up to 99% of carbon emissions from fossil fuel based power generation. They are fully dispatchable and can satisfy base and medium load electricity demand. However, underground storage of CO_2 raises public acceptability concerns in several EU countries. The failure of licensing storage facilities in some EU countries following attempts to set up pilot CCS plants is indicative of the situation. Very few pilot CCS plants are ongoing projects, far below expectations some years ago. The process is not hampered by technology performance or costs expectations of the capturing technology but clearly by gloomy prospects of licensing and operating large underground CO_2 storage areas in Europe. GEM-E3-RD captures the storage development difficulty by assuming high costs or steep cost-supply curves for underground storage of carbon dioxide.

The GEM-E3-RD model shows that CCS technologies have to be deployed after 2030 even in the moderate climate policy reference scenario in the EU due to the assumed emission reduction targets (Table 26). The share of CCS in power generation is projected to reach 11.6% in 2050 in the reference scenario. The high carbon prices in the EU Alone decarbonisation scenario lead to higher deployment of CCS technologies in combination with coal and gas-based power generation that substitute for fossil-fuel power generation without CCS. The model shows that CCS power generation increases by 25% in 2050 relative to the reference scenario.

The combination of CCS technologies with biomass can lead to negative CO_2 emissions (net carbon removal from the atmosphere). High upfront investment costs and uncertain technical performance combined with increasing sustainability concerns with regard to biomass feedstock mean that the massive commercialization of this technology is highly unlikely in the horizon of 2050. Consequently, the current model-based analysis does not include the option of integrated biomass gasification with CCS.

4.2.2 Projections for clean energy technologies

With regard to the clean energy technologies, the scenario leaves the rest of the world virtually unaffected from its reference situation. On the other hand, demand for these technologies in the EU increases and EU industry satisfies the bulk of this demand. Increased R&D in these technologies and larger volumes of production lead to an EU gain in competitive advantage for some of these technologies which is translated into an increase in exports to the rest of the world. This is particularly pronounced in the case of electric and plug-in hybrid vehicles where European exports account for 54% of rest of the world demand compared to only 26% in the reference scenario. This represents additional sales abroad of the order of 1222 bn. $04 cumulatively.

Important gains in competitiveness are also registered in CCS technologies which are developed in the EU earlier and more extensively enabling a gain of market share in the period beyond 2030 when some CCS introduction is projected for the rest of the world. EU exports account for 53% of the rest of the world demand instead of 41% in the reference which translates to a gain of 308 bn. $04 cumulatively by 2050. More important in terms of global sales are the gains obtained in competitiveness for the photovoltaics industry. The scenario implies a big increase in R&D directed towards this technology in the period to

2030. The share of cumulative EU exports in Rest of the world demand for photovoltaics increases from 23% in the reference to 32% in the EU Alone decarbonisation scenario, which represents 501 bn. $04 cumulatively until 2050.

Competitiveness gains are much less pronounced for the remaining technologies. The scope for additional learning for wind technologies is much more limited and consequently there is only a small gain in export markets and most of the increase of the European industry can be accounted by the increase in domestic demand for wind turbines. Domestic demand is also the key driver for the increase in biodiesel and biokerosene based on lignocellulosic biomass. Exports do not occur because despite some improvement, as the EU production remains uncompetitive compared to some other regions in the world.

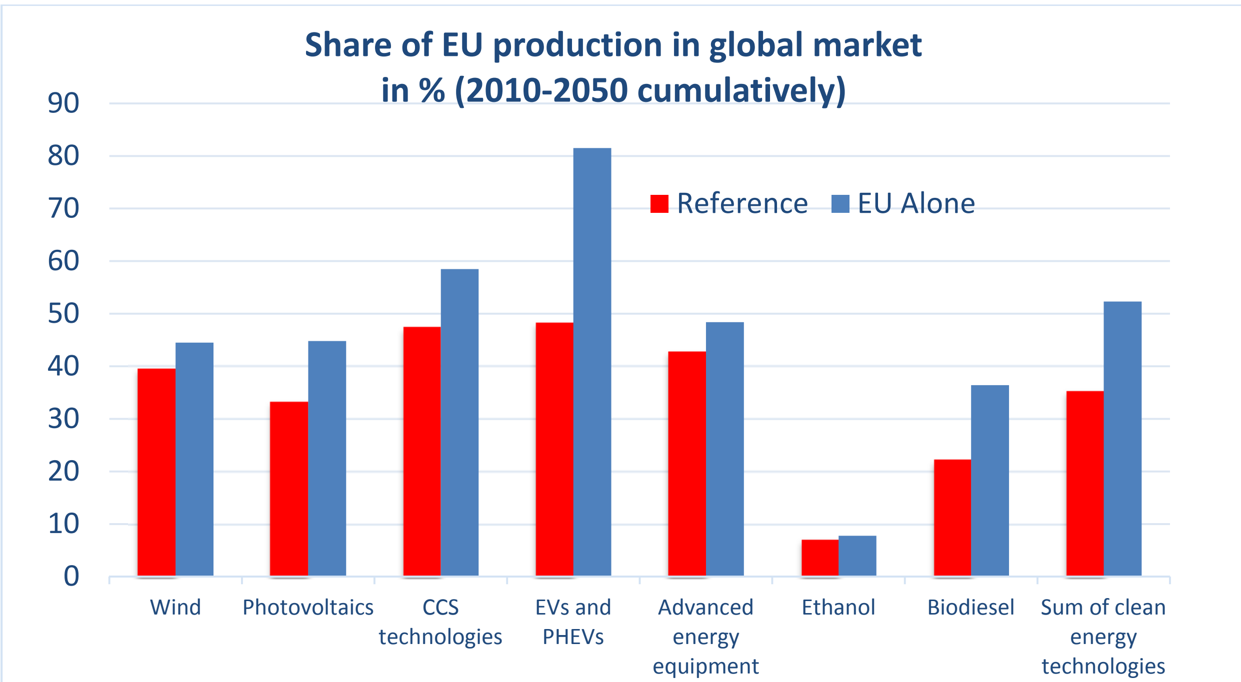


Figure 6: Share of EU in global market of clean energy technologies

The mitigation scenario with delayed action until 2030 (450delay scenario) assumes that the cumulative global carbon budget (consistent with keeping the GHG atmospheric concentration below 450 ppm until the end of the 21st century) is imposed as a constraint in the models in the period 2030 to 2050. Before 2030, all world regions follow the reference scenario climate policy assumptions. All technological decarbonisation options are available and are used according to cost optimality after 2030 in order to meet the carbon budget target. The EU region meets the carbon budget of the period 2010 to 2050 as specified in the EU Roadmap [9].

4.2.3 Global CO_2 emissions outlook

The 450delay scenario assumes the imposition of strong climate policies after 2030 in all regions of the world. Delayed climate action leads to very stringent decarbonisation effort in the period 2030 to 2050 in order to comply with the global carbon budget of 1300 Gtn of CO_2 in the period 2000-2050. After several iterations performed with the GEM-E3-RD model, the global carbon budget is not met. As a result the assumptions of the scenario are somewhat relaxed: climate policies are partly introduced from 2025 onwards and global carbon emissions amount to 1400 Gtn of CO_2 in the period 2000 to 2050 (100 Gtn of CO_2 higher than the carbon budget target).

Global carbon emissions are projected to be reduced by 71% in the 450 ppm delayed mitigation scenario compared to the reference in 2050 (Figure 7). The model results show that regional reductions of carbon emissions are in the same order of magnitude ranging from 63% in China and OECD Pacific to 80% in North America and Energy Exporters. The reduction of global cumulative emissions in the period 2010 to 2050 is projected to amount to 32% compared to the reference scenario, while in the Rest of the World region the decline is even stronger (39%) due to the weak climate policies assumed for this region in the reference scenario. Furthermore, the model results show that the carbon price is more effective in reducing emissions in countries which are inefficient in terms of energy and carbon intensity, such as the rest of the world; thus the same level of carbon price implies larger rates of decrease of carbon emissions in the 450delay scenario compared to the reference in rest of the world than in the EU or the OECD Pacific region.

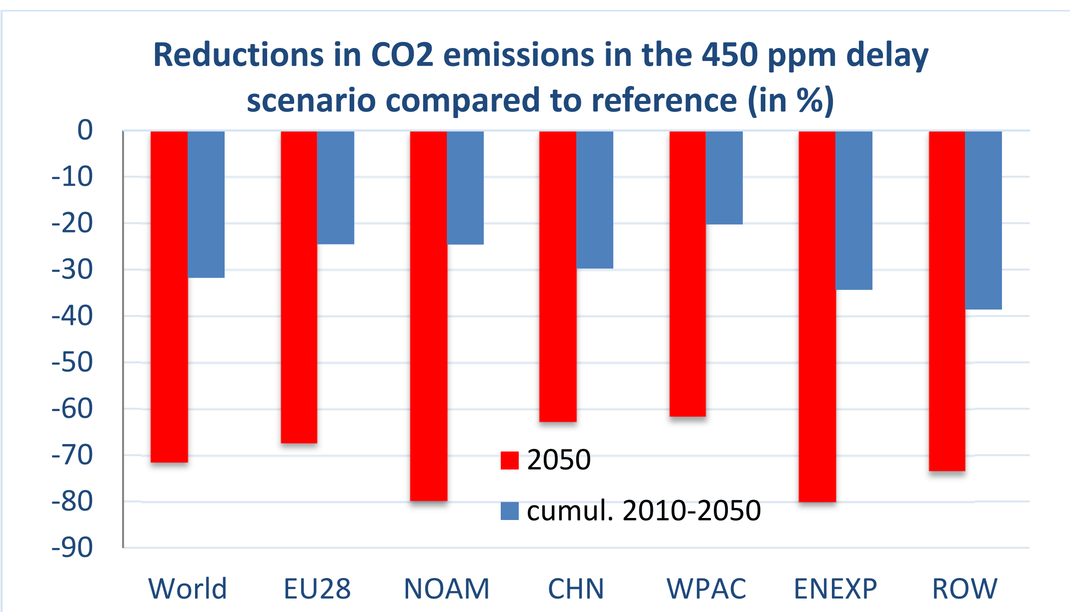


Figure 7: Reduction in carbon emissions in GEM-E3-RD regions compared to the reference

4.2.4 The global energy system transformation

Achieving the stringent GHG mitigation target by 2050 requires major changes in the global energy system. An important characteristic of the energy sector is its long-lived capital stock, with lifetimes for infrastructure and energy conversion facilities (including power plants) of 20–40 years and sometimes longer. Lack of near term decarbonisation policies adds to the transformation challenge by increasing the inertia of the energy system due to additional lock-in of fossil-intensive infrastructures until 2030.

The increased emission reduction effort after 2030 requires both demand-side restructuring (energy efficiency improvements) and the substitution of fossil fuels by low-carbon alternatives, such as renewables, nuclear and CCS technologies. Figure 8 depicts RES shares in power generation in GEM-E3-RD regions in the 450 ppm scenario relative to the reference in 2050. The model results confirm that the global mitigation effort implies higher deployment of RES to satisfy increasing electricity requirements in all regions. Nearly 50% of global electricity is projected to be produced from RES in 2050. Intermittent RES (wind and solar) account for 24% of global power generation in 2050, thus requiring additional investments for smart grids, electricity storage and balance capacity.

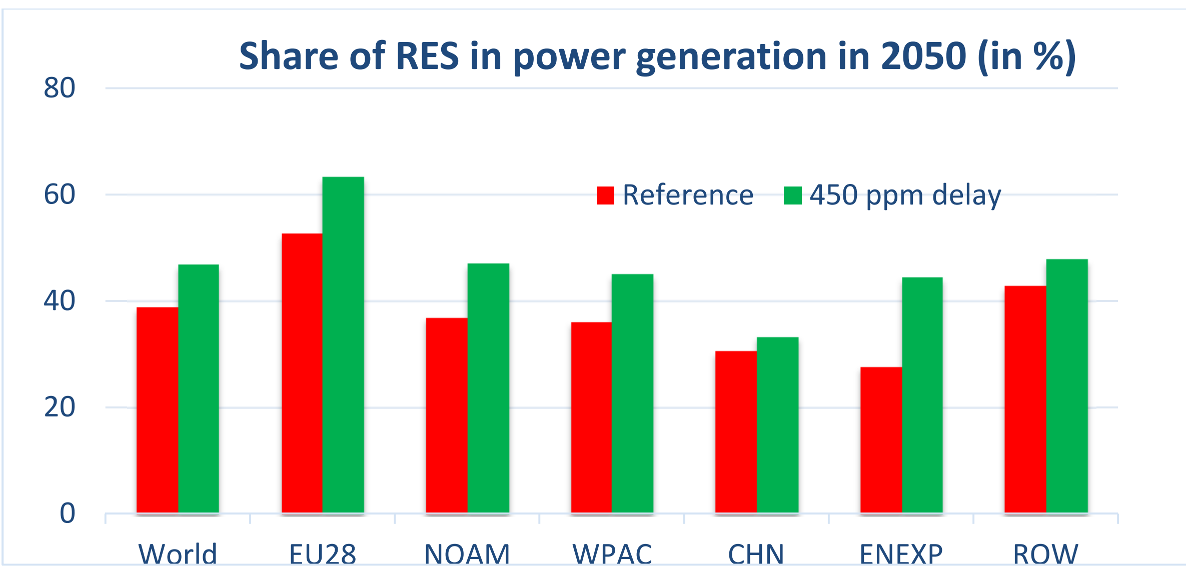


Figure 8: Share of RES in power generation in 2050

Accelerated energy efficiency improvement is considered an important decarbonisation option as saving energy implies by definition lower carbon emissions in both energy demand and supply sectors. The GEM-E3-RD model confirms the importance of demand-side restructuring and projects that energy intensity of GDP in the delayed global mitigation scenario declines by 2.5% annually in the period 2010 to 2050 thus exceeding the annual improvement of 1.5% projected in the reference scenario. The model shows that the highest potential for further energy efficiency improvement (relative to the reference scenario) is found in China, North America and Energy Exporters, while the potential is limited in the OECD Pacific region.

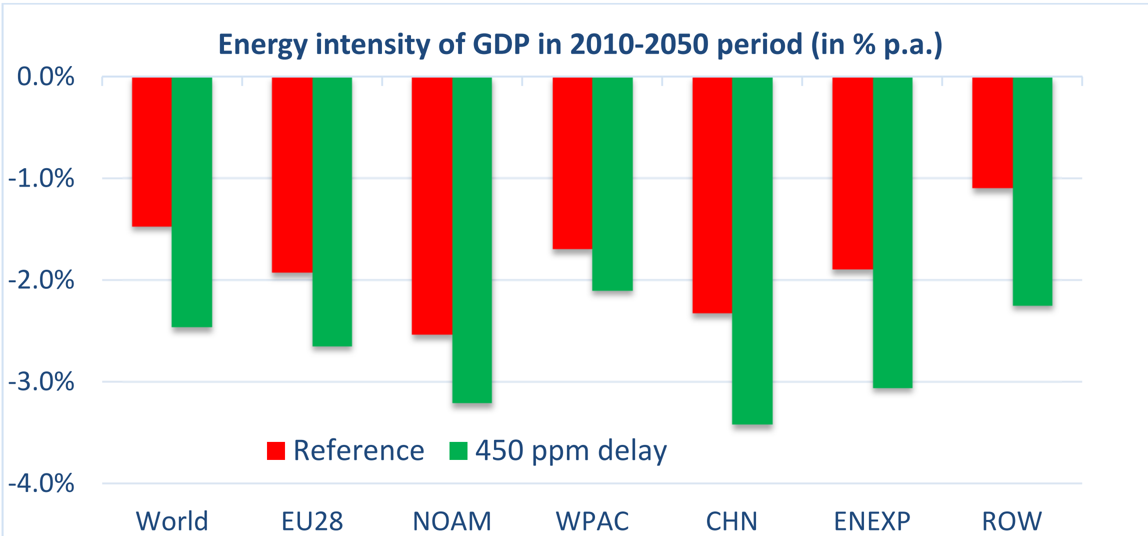


Figure 9: Annual improvement in energy intensity of GDP

According to the GEM-E3-RD model, the 450 ppm delayed mitigation scenario implies an almost fully decarbonised power generation sector by 2050. RES electricity covers nearly 50% of global power needs in 2050; thus the other low carbon power generation technologies (nuclear and CCS) cover the remaining 50%. Nuclear power is projected to increase above reference levels after 2030 and reaches 17% in world electricity production by 2050 (Table 27). The impact of the accelerated global emission reduction effort after 2030 on nuclear deployment is modest due to constraints of political nature imposed in the model (i.e. countries excluding nuclear from their energy mix), lack of public acceptance, long construction time for nuclear power plants and the limited cost reduction of nuclear power in contrast to RES and CCS technologies. On the other hand, GEM-E3-RD shows a rapid development of CCS substituting for conventional fossil-fuel based power plants after 2030. CCS technologies are projected to cover more than 33% of global power requirements in 2050, while in China CCS share reaches 46%.

World Electricity production (in TWh)						
		2010	**2020**	**2030**	**2040**	**2050**
Nuclear	Reference	2344	2976	3604	4298	7315
Nuclear	450 ppm delay	2344	2976	3612	4675	7824
Nuclear	***% Share in 450 delay***	**13.4**	**12.7**	**12.4**	**13.4**	**16.8**
CCS	Reference	0	0	10	245	3745
CCS	450 ppm delay	0	0	176	6975	15545
CCS	***% Share in 450 delay***	**0.0**	**0.0**	**0.6**	**20.6**	**33.3**

Table 27: World deployment of nuclear and CCS technologies

An important element of the global mitigation effort is transport electrification. The share of plug-in hybrid and pure electric vehicles in world passenger car stock is projected to reach 62.5% in 2050, while in the reference scenario the share is only 10.9%. Penetration of electric vehicles is projected to be particularly high in regions with rapidly increasing passenger car stock and large vehicle markets (like China, Energy exporters and rest of the world). The massive penetration of electric cars is accompanied by the timely development of battery recharging infrastructure and the rapid improvement in technical and economic characteristics of batteries.

Share of electric and plug-in hybrids in car stocks in 2050 (in %)		
	Reference	**450 mitigation action**
World	**10.9**	**62.5**
EU28	19.0	58.7
NOAM	14.8	59.2
WPAC	15.4	56.8
CHN	13.1	71.5
ENEXP	3.6	62.6
ROW	7.4	63.0

Table 28: Transport electrification in the 450 ppm global mitigation scenario

4.2.5 Projections for clean energy technologies

The severity of the climate action beyond 2030 has a marked impact on the markets for clean technologies (Table 29). The reference scenario already implies a sizeable industry for wind and photovoltaics and therefore the impact of the scenario in their case is more modest. Biodiesel sees a major increase especially as the additional mitigation takes place beyond 2030 when lignocellulosic options are widely available. The latter explains the insignificant impact of the scenario on ethanol production. On the other hand, the major impact occurs in the CCS technologies and especially in electric and plug-in hybrid vehicles. This is due to the fact that such technologies are deployed very modestly in the reference case but become essential in the context of the delayed mitigation action scenario. Unlike the EU Alone scenario, EU industry does not develop the same degree of competitiveness (it gains 30% share in RoW demand for CCS technologies and 25% for electric vehicles in the delayed action scenario compared to 53% and 54% respectively in the EU alone case).

	Delayed mitigation	Reference	% diff. from reference
Wind	4780	3487	37%
Photovoltaics	9218	6517	41%
CCS technologies	7363	3373	118%
EVs and PHEVs	26268	5853	349%
Ethanol	3036	2965	2%

Biodiesel	7830	4664	68%
New clean energy technologies	**58494**	**26859**	**118%**

Table 29: Global market for clean energy technologies in bn $04 in 2010-2050 cumulatively

4.3 The EU acts as a first mover until 2030

In this scenario, the EU region is assumed to act as a first mover in climate policies until 2030 and to successfully motivate other parts of the world to join an ambitious climate policy regime after 2030. In the period 2010 to 2030, the EU pursues ambitious emission reduction policies, along the pathway defined in the EU Roadmap [9] while other world regions adopt the energy and climate policies assumed in the moderate policy Reference scenario. After 2030 the rest of the world joins the EU decarbonisation effort with the target to limit the global average temperature increase to 2°C compared to pre-industrial levels. The global carbon budget as defined in the delayed mitigation scenario (450delay) is imposed as a constraint in world cumulative emissions in the period 2010 to 2050.

The scenario conceptualizes a situation of pioneering EU decarbonisation action without a global climate agreement in place and aims to quantify the potential risks and benefits for the EU economy. In the context of induced technology progress (through learning by doing and learning by research), the EU achieves before 2030 a significant part of the cost reduction potential for clean energy technologies. It is assumed that the European market is sufficiently large and unified to allow for achieving a large part of the learning potential of clean energy technologies that have a high potential of cost reduction if developed at a large scale as a result of R&D and economies of scale in mass production. After 2030, and while the spillover effects of innovation towards the non-EU regions are still moderate, the EU has a cost advantage over the other regions for the low and zero carbon energy technologies, which are increasingly demanded by the non EU regions during the period post 2030. The cost advantage of the EU is assumed to be gradually eroded and vanish towards the end of the projection horizon.

4.3.1 Projections for clean energy technologies

In the First Mover Advantage scenario, the EU is motivated to invest in R&D in the clean energy technologies early in the forecasting period (to 2030) and at the same time take advantage of a faster growing EU market enabling the consolidation of economies of scale and other learning by doing advantages. It is therefore well poised to gain market share in the rest of the world at the time when according to the scenario world markets start expanding very rapidly as the rest of the world joins in the decarbonisation effort.

It is worth pointing out here that in both decarbonisation scenarios the world market for the clean technology categories considered in the new version of GEM-E3-RD assumes a far from insignificant size. Cumulatively over the period 2010-2050 for the world, these categories represent a production value of around 62 trillion $04 which is equivalent to 1.6% of cumulative GDP. Their relative importance is even greater if the final year of the forecast is considered (2.4% of GDP for 2050). For the EU, the weight of these industries is even greater. They account for 2.6% of cumulative 2010-2050 GDP in the delayed action scenario and 3.1% in the first mover scenario. The difference between the two scenarios is mainly explained by the higher exports that characterise the first mover scenario. In the latter scenario in 2050 the clean technologies account for 18.5% of EU exports into the rest of the world.

		2020	2030	2040	2050	Cumulative share 2010-2050	Cumulative production (in constant bn $04)
Wind	**All delay**	45	30	33	39	38	4780
	EU as first mover	47	25	33	42	38	4789
Photovoltaics	**All delay**	39	41	35	34	37	9218
	EU as first mover	43	39	41	40	40	9073
CCS technologies	**All delay**	67	39	30	33	33	7363
	EU as first mover	72	49	35	38	41	7424
EVs and PHEVs	**All delay**	38	35	39	41	40	26268
	EU as first mover	56	53	51	48	52	27346
Advanced household energy equipment	**All delay**	44	44	44	44	43	3339
	EU as first mover	44	46	46	47	52	3418
Ethanol	**All delay**	10	11	9	8	8	3036
	EU as first mover	10	11	9	8	8	3037
Biodiesel	**All delay**	35	33	28	25	26	7830
	EU as first mover	35	33	29	24	26	7848
Sum of clean energy technologies	**All delay**	35	36	35	36	35	61833
	EU as first mover	38	41	43	42	42	62935

Table 30: Share of EU production in global clean energy technologies market (in %)

Within the group of industries considered here, manufacturing of electric vehicles and plug-in hybrids is particularly important accounting for 42-43% of the total. Vehicle manufacturing is a sector where the EU already enjoys a comparative advantage in world trade and is therefore in a good position to profit from this potentially huge market. Figure 10 below showing the EU production coverage of the rest of the world market serves as an illustration of the way the model reacts to the First Mover Advantages. The impact is relatively small in 2025 when the EU industry is concentrating on building the domestic market. By 2030 and as the world also starts engaging in electrification of road transport, the EU gains a major slice taking advantage of its early start. Beyond that year, the advantage starts eroding due to spillover effects (productivity improvements obtained through R&D and learning by doing start being absorbed by EU competitors). This erosion notwithstanding the market in the period 2030-2050 expands rapidly and the EU maintains an advantage even in the latter year arising from a consolidation of its market position in previous years.

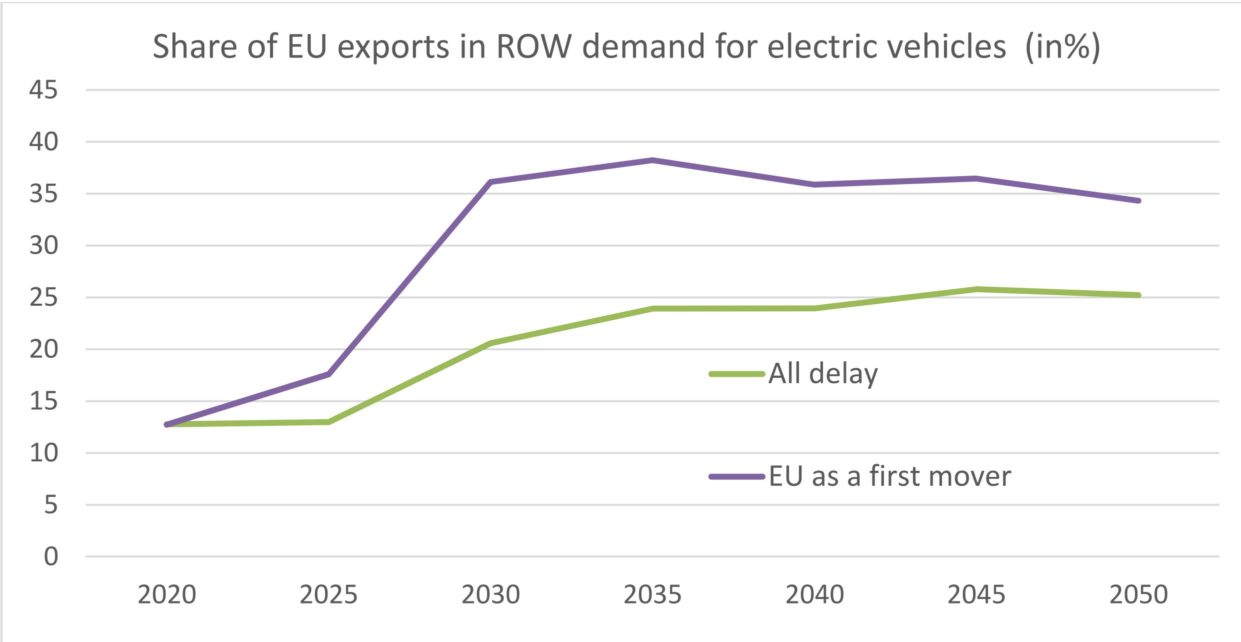


Figure 10: Share of EU exports in ROW demand for electric vehicles (in %)

A similar picture emerges for other technology groups such as CCS, advanced household energy equipment and photovoltaics. The relative maturity of the wind technologies and the large share already enjoyed by the EU in this market mean that the impact of the First mover scenario on the EU wind turbine producing industry is very small. In all scenarios the EU undertakes no exports of biofuels to the Rest of the world as this industry is not competitive at world level and is maintained in Europe by means of subsidies.

4.4 Macroeconomic implications of the scenarios

4.4.1 The EU Alone decarbonisation scenario

The EU Alone decarbonisation scenario implies high carbon prices in the EU that reach 121 \$05/tn CO_2 in 2030 and 509 \$05/tn CO_2 in 2050. Carbon pricing induces changes in the economy driven by substitution away from fossil fuels and lower energy consumption per unit of GDP. These changes are costly and energy services[16] become more expensive in all

[16] Useful energy services delivered by using purchased energy commodities and equipment as well as energy saving capital at the user's premises, plant or vehicle.

sectors. The increased costs of energy services imply lower purchasing power of private income and thus lower demand and higher prices in the supply of goods and services that further reduce demand in the EU. As a response to increasing energy costs, the macro-economic models simulate substitution of fossil fuels (that are usually imported in EU) by other domestically produced energy technologies (zero carbon technologies and energy savings equipment) that are capital intensive. The additional investment in clean energy technologies increases demand for goods and services that are needed to produce the energy efficient equipment, the clean power plants and for insulating buildings.

Higher investments required for the restructuring of the energy system put stresses on the capital market which leads to higher requirements for total savings, hence both for domestic savings and external capital flows. At the same time, the trade balance is driven towards a deficit compared to the reference scenario due to the higher prices in the EU. The combined effect of the capital and trade balances is likely to show a trend towards a deficit in the current account under decarbonisation conditions relative to the reference. If such a deficit is possible (as in the NEMESIS macro-econometric neo-Keynesian model) then the EU would benefit from higher capital inflows coming from other regions which would of course ease emission reduction effort by avoiding adjustments in current account that have restrictive effects on the EU economy and the capital balance. However this situation implies incomparability of macroeconomic results under the decarbonisation conditions relative to the reference. In reality, even if such relaxation through the current account balance can be observed during a short time period, it is unlikely to last over a prolonged period of time. Feedback reactions and adjustments would take place sooner or later. The GEM-E3-RD model adjusts the real interest rate (basic lending rate) by region so as to obtain in all scenarios the same current account as a percentage of GDP as in the reference case. The decarbonisation conditions imply a trend towards a negative imbalance of the current account in EU; therefore higher interest rates would be required compared to the reference in order to rebalance the current account to reference scenario percentages with respect to GDP. An increase in the real interest rate leads to higher savings, lower private consumption and lower investment under capital mobility conditions ("crowding-out" investment effects).

Under the influence of high carbon prices, the prices of domestic goods increase in the EU alone decarbonisation scenario which undermines EU competitiveness. This loss of competitiveness drives an increase in imports, while lower domestic demand, driven by higher unit costs tends to decrease imports compared to the reference scenario. Exports tend to decrease because of higher domestic prices in the EU compared to the Reference scenario. On the other hand, induced technological progress for low and zero carbon energy technologies leads to increased competitiveness of EU in global markets for these technologies. This effect is projected to be relatively small in magnitude in the EU Alone decarbonisation scenario as the rest of the world does not pursue additional (from the reference scenario) emissions reduction effort and thus non-EU markets for wind, photovoltaics, CCS and electric vehicles do not change significantly relative to the reference scenario.

The model-based simulations in this study show that the net effect of decarbonisation on EU GDP is negative compared to the Reference scenario, because of higher production costs which depress demand (Table 31). Even if the EU undertakes domestically the required investments, the corresponding activity is not found sufficiently high to offset the activity depressing effects stemming from higher costs and prices. The GEM-E3-RD model shows that GDP decreases by 0.51% in the EU Alone decarbonisation scenario compared to the reference in the period 2011-2050 in cumulative terms; cumulative GDP losses amount to 4374 bn. $. Investments are projected to increase by 0.15% in cumulative terms compared to the reference scenario as a result of additional investments in low and zero carbon energy technologies. Exports are projected to be 0.5% lower in the period 2011 to 2050 due to high carbon prices that undermine EU competitiveness in global markets. On the other hand, GEM-E3-RD shows that the impact of the accelerated decarbonisation effort on EU employment is insignificant (0.01% cumulatively in the period 2011-2050). This is the result of two opposite trends: (i) GDP reduction that implies lower employment relative to the reference scenario and (ii) high labour intensity of the clean energy producing sectors; e.g. employment per TWh of electricity produced is six times higher for photovoltaics compared to conventional coal-fired power plants.

Changes from the reference scenario in EU (in %)			
	2030	**2050**	**Cumulative 2011-2050**
Gross Domestic Product	-0.28	-1.13	**-0.51**
Investment	0.73	-0.28	**0.15**
Private Consumption	-0.55	-1.52	**-0.77**
Exports	-1.05	0.00	**-0.53**
Imports	-0.10	1.10	**0.28**
Employment	0.02	0.00	**0.01**

Table 31: EU Macroeconomic projections of GEM-E3-RD

The rest of the world also encounters GDP losses, to a far lesser extent than the EU, as demand stemming from the EU decreases, relative to the Reference (Table 32). The loss in EU demand implies also a (marginal) reduction in exports of other regions to the EU. The EU Alone decarbonisation scenario implies more expensive EU exports to other regions (relative to the Reference) that lead to higher production costs hence lower private consumption in non-EU regions.

Changes from reference scenario in non-EU regions (in %)			
	2030	2050	Cumulative 2011-2050
Gross Domestic Product	0.00	-0.05	-0.02
Investment	-0.01	-0.02	-0.03
Private Consumption	-0.03	-0.07	-0.03
Employment	0.00	0.01	**0.00**

Table 32: Macroeconomic projections of GEM-E3-RD for non-EU regions

The cumulative losses of equivalent variation of welfare[17] for the EU are estimated equal to 868 bn. $2004, over the period 2011-2050, in the EU alone decarbonisation scenario. The induced technological progress assumed in the EU Alone decarbonisation scenario (through endogenous learning by doing and learning by research mechanisms) tends to mitigate GDP losses relative to the Reference case. Technological progress discussed in sections 2.2 and 2.3 exerts beneficial effects to the domestic economy through the reduction of unit energy service costs, thanks to decreasing costs of low and zero carbon energy technologies, and so by reducing the cost differences from conventional technologies. As a result, smaller effects on the general level of domestic prices are obtained, hence smaller losses in EU competitiveness and in domestic production relative to imports.

4.4.2 The 450 delayed mitigation scenario

In this scenario, the EU synchronises ambitious climate action with the rest of the world. The economic effects in the period before 2025 are negligible, as all regions follow the reference climate policies until 2025. The economic consequences start to show from 2030 onwards when stringent decarbonisation targets are imposed in all regions. The 450 ppm delayed action scenario assumes that the carbon budget target is imposed globally and as a result the same level of carbon price is applied in all regions (with the exception of EU in which the Roadmap carbon budget is imposed). The imposition of a global constraint on cumulative carbon emissions has clear economic benefits. The globally harmonised carbon prices (i.e. equal marginal emission abatement costs across regions and sectors) lead to optimal global mitigation costs, as it is most cost-efficient to exploit the cheapest emission reduction options in all regions and all sectors at the margin. The carbon price increases sharply relative to the reference scenario after 2030 in all regions. The carbon price in EU reaches 850 $05/tn. CO2 in 2050, while in non-EU regions it reaches 400$05/tn. CO2 in 2050.

[17] Hicksian equivalent variation is a money metric utility measure and represents the amount of income that should be given or taken away to the consumer in the reference case in order to attain the scenario utility. A negative equivalent variation indicates a cost to the consumer.

Global GDP is lower by 1.7% in 2050 relative to the Reference projection, and also lower by 0.9% in cumulative terms over the entire projection period (Table 33). The GDP losses are due to the higher cost of the decarbonised energy services, compared to the conventional way energy services are produced in the Reference scenario. Including the induced technology progress plays a great role in maintaining domestic demand as decarbonisation costs are lower. The technological progress also helps preserving employment.

GDP losses for the EU are higher in the scenario where all regions act later than in the scenario where the EU acts unilaterally. The GDP losses amount to 5137 bn.$ in cumulative terms in the former scenario in the period 2010 to 2050, while in the EU Alone decarbonisation scenario they are projected to amount to 4374 bn.$ cumulatively. The increased losses for the EU are primarily due to the depressive effect on global GDP because the EU bears the consequences of the global increase of costs and of the global reduction in demand in the context of the global GHG mitigation scenario that reduces global demand for EU exports. Another reason is related to the shorter time in which the EU has to meet the decarbonisation carbon budget compared to the scenario where the EU acts alone from 2015 onwards. Energy savings as well as the substitutions in demand and in energy production need to be more intensive resulting in much higher carbon values in the period 2030-2050, as the EU acts after 2030 in the delayed global mitigation scenario. This implies higher strains on primary production factors, in particular on the capital market, which aggravates unit production costs, thus adding on depressive effects on domestic demand. Consequently, the delay in EU climate action has adverse consequences on the EU cost for complying with the given carbon budget.

Investments in non-EU regions are projected to increase by 0.6% cumulatively in the period 2011-2050 as a result of the substitution of fossil fuels with domestically produced energy technologies (zero carbon technologies and energy savings equipment) that are more capital and labour intensive relative to conventional fossil fuel-based ones. On the other hand, higher investments required for the restructuring of the energy system put stresses on the capital market which leads to higher requirements for total savings. As in the EU Alone case, the model adjusts the real interest rate by region so as to obtain the same current account as a percentage of GDP as in the reference case. As the decarbonisation conditions imply a trend towards a negative imbalance of the current account, higher interest rates would be required in order to rebalance the current account to reference scenario percentages of GDP leading to higher savings and lower private consumption (that is projected to decline by 1.6% cumulatively in non-EU regions).

% Changes from the reference scenario						
	EU			Non-EU regions		
	2030	2050	Cumulative 2011-2050	2030	2050	Cumulative 2011-2050
Gross Domestic Product	-0.01	-1.48	**-0.60**	-0.28	-1.73	**-0.95**
Investment	2.34	-0.92	**0.13**	3.43	-0.96	**0.63**
Private Consumption	-0.62	-2.63	**-1.16**	-1.54	-2.21	**-1.60**
Exports	1.53	-1.29	**-0.23**	1.40	-3.31	**-1.00**
Imports	1.78	-2.40	**-0.46**	2.05	0.60	**0.96**
Employment	0.03	0.00	**0.01**	0.02	0.00	**0.01**

Table 33: Macroeconomic impacts of the 450 ppm delayed mitigation scenario

As all regions of the world simultaneously perform strong emissions reduction (relative to the Reference scenario) the impacts owing to relative competitiveness in foreign trade are relatively small. The model results show that the induced technology progress implies higher exports by developed countries to developing regions. The exports of North America and OECD Pacific are projected to increase from their reference levels (by 0.9% and 0.3% respectively in the period 2010 to 2050 cumulatively). This also leads to lower cumulative GDP losses in developed regions as the global imposition of the same carbon price trajectory implies a higher relative increase in the prices of developing regions thus undermining their competitiveness in international markets. The model results show that the Delayed mitigation scenario leads to larger GDP losses in developing economies (China, Energy Exporters and Rest of the World) relative to the developed. This is the result of the weak reference climate policies assumed in developing regions and the high energy and carbon intensity of developing economies. The highest GDP losses are projected for the Energy Exporters region (2.13% cumulative GDP reduction from reference in the period 2010 to 2050) due to the reduced oil and gas revenues as a result of the lower global fossil fuel demand and the lower international prices relative to the reference scenario.

Global GDP is lower by 0.87% in cumulative terms over the entire projection period in the Delayed mitigation scenario compared to the Reference scenario. This corresponds to 0.04 percentage points lower average annual rate of growth of global GDP in the period 2010 to 2050. In terms of equivalent variation of welfare, the scenario leads to global losses of 7067 bn. $ in the period 2010 to 2050 in cumulative terms. In all regions the impact of the delayed mitigation scenario on employment is relatively small in the period 2010 to 2050.

% Cumulative Changes from the reference (2011-2050 period)							
	EU28	CHN	NOAM	WPAC	ENEXP	ROW	WORLD
GDP	-0.60	-1.43	-0.27	-0.35	-2.13	-1.19	-0.87
Investment	0.13	-0.10	0.97	0.24	1.85	0.75	0.53

Priv. Cons.	-1.16	-2.17	-0.76	-0.72	-3.01	-2.11	-1.51
Exports	-0.23	-0.08	0.88	0.27	-2.75	0.18	-
Imports	-0.46	1.25	0.22	0.23	0.44	-0.19	-
Employment	0.01	0.00	0.00	0.00	0.02	-0.01	0.01

Table 34: Regional Macroeconomic impacts of the 450 ppm delayed mitigation scenario

4.4.3 The First Mover Advantage scenario

The results of the First Mover scenario show clear economic benefits for the EU compared to the delayed action until 2030 scenario stemming from the fact that action toward the decarbonisation target starts earlier and is spread over a prolonged period of time. The induced technology progress also plays a considerable role in reducing the decarbonisation costs and in alleviating the negative impacts on the economy provided that the EU uses the internal market to capture a considerable part of the learning potential of clean energy technologies, such as the solar, wind, CCS, electric vehicles and advanced household energy equipment.

The numerical model-based results show that the cumulative amount saved by the EU because of not delaying climate action is equal to 3416 bn. $04 (in terms of cumulative GDP in the period 2010 to 2050), despite the fact that the non EU regions do not join the effort until 2030. In a sense, this benefit from not delaying the climate actions is a first-mover advantage[18]. A similar benefit is found also looking at equivalent variation of welfare: gains of 605 bn. $ cumulatively for the EU and 477 bn. $ for the world relative to the scenario where all regions act later. The causes are primarily the reduced cost of decarbonisation of the EU owing to delivering the given carbon budget over a longer period of time and the induced technological progress of low and zero carbon energy technologies.

Looking at the time profile of the impact of the First mover scenario it is worth noting that for the EU the early period before the rest of the world joins in the effort marks an increase in investment in the EU, a modest drop in private consumption and a more pronounced reduction in exports with minimal impacts on imports and employment. The situation changes sharply in 2030: investment remains buoyant but exports and imports peak up sharply with a weaker effect on private consumption. Moving towards the end of the forecast horizon, the depressing effects associated with strong climate action, that were discussed in the previous sections involving the EU Alone and delayed action scenarios, come into play resulting in lower consumption and investments and an increasingly more pronounced impact on GDP. Exports on the other hand buoyed by increasing EU market shares for the new clean energy technologies as discussed in section 4.4.

[18] Obviously an important caveat of the analysis is that this benefit is valid only if we assume a finite time horizon (until 2050) and the same global and EU carbon budget in both scenarios.

Changes from the Reference scenario (in %)					
	2025	2030	2040	2050	Cumulative 2011-2050
Gross Domestic Product	-0.08	0.00	-0.26	-0.72	**-0.20**
Investment	0.64	0.71	-0.41	-0.77	**-0.02**
Private Consumption	-0.27	-0.16	-0.85	-1.64	**-0.61**
Exports	-0.56	2.46	1.98	1.29	**1.37**
Imports	-0.02	2.63	0.02	-0.91	**0.38**
Employment	0.02	0.03	0.01	0.00	**0.02**

Table 35: Macroeconomic impacts of the First mover scenario relative to the reference for the EU

% Changes from reference, cumulative (2011-2050)			
	First Mover	All delay	EU Alone
Gross Domestic Product	-0.20	-0.60	-0.51
Investment	-0.02	0.13	0.15
Private Consumption	-0.61	-1.16	-0.77
Exports	1.37	-0.23	-0.53
Imports	0.38	-0.46	0.28
Employment	0.02	0.01	0.01

Table 36: Macroeconomic impacts of the series of scenarios for the EU

For the rest of the world the picture remains similar to the delayed action scenario with the exception of a differential impact on imports and exports (which are both higher in the first mover scenario) directly attributable to the impact of the scenario on the EU.

% Changes from reference, cumulative (2011-2050)			
	First Mover	All delay	EU Alone
Gross Domestic Product	-0.97	-0.95	-0.02
Investment	0.64	0.63	-0.03
Private Consumption	-1.63	-1.60	-0.03
Exports	-0.21	-1.00	0.25
Imports	2.13	0.96	0.13
Employment	0.01	0.01	0.00

Table 37: Macroeconomic impacts of the series of scenarios for non-EU regions

5 The NEMESIS model results

5.1 Scenarios specification and implementation with the NEMESIS model

The NEMESIS model[19] is a macro-economic model covering EU-27 countries, and in the current State of the art, the rest of the world is left exogenous. The simulation horizon is 2030[20] with annual steps. The next sections describe the framework for the implementation of the AMPERE Task 5.5 scenarios in the model according to the model restrictions.

5.1.1 AMPERE scenarios

The scenarios specification for the NEMESIS model can be summarised as follows (see section 3 of the report for details):

Scenarios	GHG mitigation policy in EU	GHG mitigation policy in the RoW
"Reference scenario"	• 2010-2020: -20% compared to 1990 • 2020-2030: -1.74%/year in EU-ETS sectors and no additional policy in non EU-ETS sectors	• 2010-2030: weak climate policies
"Delayed action scenario"	• 2010-2020: idem Reference • 2020-2030: EU Roadmap (72 Gtn of CO_2 budget between 2010 and 2030)	• 2010-2020: idem Reference • 2020-2030: median AMPERE 450 ppm scenario (680 Gtn of CO_2 budget between 2010 and 2030)
"EU alone scenario"	• 2010-2030: EU Roadmap (72 Gtn of CO_2 budget between 2010 and 2030)	• 2010-2030: idem Reference
"First mover scenario"	• 2010-2030: EU Roadmap (72 Gtn of CO_2 budget between 2010 and 2030)	• 2010-2020: idem Reference • 2020-2030: median AMPERE 450 ppm scenario (680 Gtn of CO_2 budget between 2010 and 2030)

Table 38: Overview of GHG emissions mitigation assumption for the decarbonisation scenarios

5.1.2 Implementation of the scenarios with the NEMESIS model

NEMESIS specific features

In all the decarbonisation scenarios, a similar recycling scheme for the carbon tax revenues is used. The revenues of carbon tax are recycled through:

- lump sum to households equivalent to the carbon tax paid and,
- lower social contribution for firms in proportion of the labour cost.

[19] http://goo.gl/5dJ9c and (Zagamé, et al., 2010).

[20] Extension up to 2050 is ongoing. Nevertheless it was not possible to extent the time horizon for the AMPERE project. The difficulties come from energy technology after 2030. Before 2030, there is few uncertainty about economic valuable energy technology but, after 2030, electricity generation technologies (back-up technologies, CSS, nuclear, etc.) as well as transportation technologies are uncertain and then the valuation of their cost is more speculative.

There is no transfer between households and firms. Despite the fact that the tax credit on social contribution is implemented as a reduction of the employers' social contribution rate, some transfers between sectors can occur, as labour intensive sectors will be favoured when compared to energy intensive ones. As a consequence, the carbon cost could be not totally compensated for a specific sector or, at the opposite end, could be overcompensated.

The version of the NEMESIS model used to assess these scenarios includes an endogenous technological change module. The NEMESIS model has track records in the assessment of European and national innovation policies (Brécard, et al., 2006) [45], (Zagamé, et al., 2012) [2] or (EC, 2013) [46]. Briefly, the technological change in NEMESIS is driven by process innovation as well as quality innovation. The former improves the production process by reducing input cost whereas the latter increases the quality of goods perceived by consumers/users. The innovation within a sector results from its own R&D investments but also from knowledge externalities. These knowledge spillovers come from R&D investments realised in others sectors of the domestic economy, from the same sector in foreign economies and from others sectors in foreign economies. All these flows are weighted by knowledge spillovers matrices, based on patent data and trade flows. The spillovers together with R&D investments of the considered sector increase the knowledge stock of the sector that generates new innovations[21].

The Rest of the World

The geographical coverage of the NEMESIS model (EU-27), does not allow the worldwide coverage of the decarbonisation scenarios. In order to overcome this pitfall, GEM-E3-RD results are used (Capros, et al., 2010) [1] to change the "general context" in which the EU economy performs and to include feedbacks from the rest of the World. The following indicators are used:

1. GDP in the Rest of the World divided into 5 regions
2. Sectorial import prices for the EU-27 divided into 16 sectors

Furthermore, in the GEM-E3-RD model the GHG emissions mitigation policies in the Rest of the World start in 2030 and not in 2020 as in NEMESIS. To consider the feedbacks from the rest of the World, the GEM-E3 results in 2030 and 2040 are used in the NEMESIS scenarios, as expected reaction of the Rest of the World, in 2020 and 2030 respectively. Table 39 and Table 40 summarise the GEM-E3-RD results used as inputs for the NEMESIS model.

The GEM-E3-RD results for the Rest of the World, up to 2040, are relatively similar in delayed action scenario and the first mover scenario. So in the NEMESIS model, the impact of the Rest of the World between these scenarios is very weak.

[21] Further details can be found in (Brécard, et al., 2006) or (Zagamé, et al., 2010).

	Delayed action		EU Alone		First Mover	
GDP	2030	2040	2030	2040	2030	2040
North-America	-0.03%	-0.44%	-0.01%	-0.05%	-0.06%	-0.48%
Japan, Korea, Australia, New Zealand	-0.03%	-0.60%	-0.01%	-0.06%	-0.05%	-0.72%
China	-0.50%	-2.96%	0.00%	-0.04%	-0.50%	-2.97%
Energy Exporters	-1.02%	-3.10%	0.06%	0.03%	-0.99%	-3.27%
Rest of the World	-0.29%	-1.80%	0.00%	-0.03%	-0.29%	-1.76%

Source: GEM-E3-RD

Table 39: GDP change in decarbonisation scenarios (% w.r.t. reference scenario)

	Delayed action		EU Alone		First Mover	
Import prices	**2030**	**2040**	**2030**	**2040**	**2030**	**2040**
Agriculture	-0.5%	4.3%	-0.8%	-1.9%	-0.9%	-2.1%
Coal	2.2%	6.3%	0.2%	0.2%	2.1%	5.8%
Oil	5.4%	25.6%	0.1%	-0.2%	5.1%	25.0%
Gas	6.3%	31.0%	0.1%	0.0%	6.0%	30.4%
Electricity supply	23.5%	40.7%	0.2%	0.1%	22.9%	40.1%
Ferrous and non-ferrous metals	4.8%	12.3%	0.2%	0.2%	4.6%	11.8%
Chemical Products	3.7%	9.9%	0.2%	0.1%	3.5%	9.3%
Other energy intensive	3.7%	10.8%	0.2%	0.2%	3.5%	10.3%
Electric Goods	1.1%	2.9%	0.2%	0.2%	1.0%	2.5%
Transport equipment	2.5%	6.2%	0.9%	1.0%	2.4%	5.2%
Other Equipment Goods	1.6%	5.0%	0.2%	0.2%	1.6%	4.6%
Consumer Goods Industries	0.9%	3.9%	0.0%	-0.2%	0.7%	2.2%
Construction	1.4%	4.2%	0.2%	0.1%	1.2%	3.5%
Transport	2.7%	10.6%	0.2%	0.2%	2.4%	9.8%
Market Services	0.4%	0.7%	0.2%	0.1%	0.2%	0.2%
Non Market Services	0.6%	2.1%	0.2%	0.2%	0.4%	1.6%

Source: GEM-E3-RD

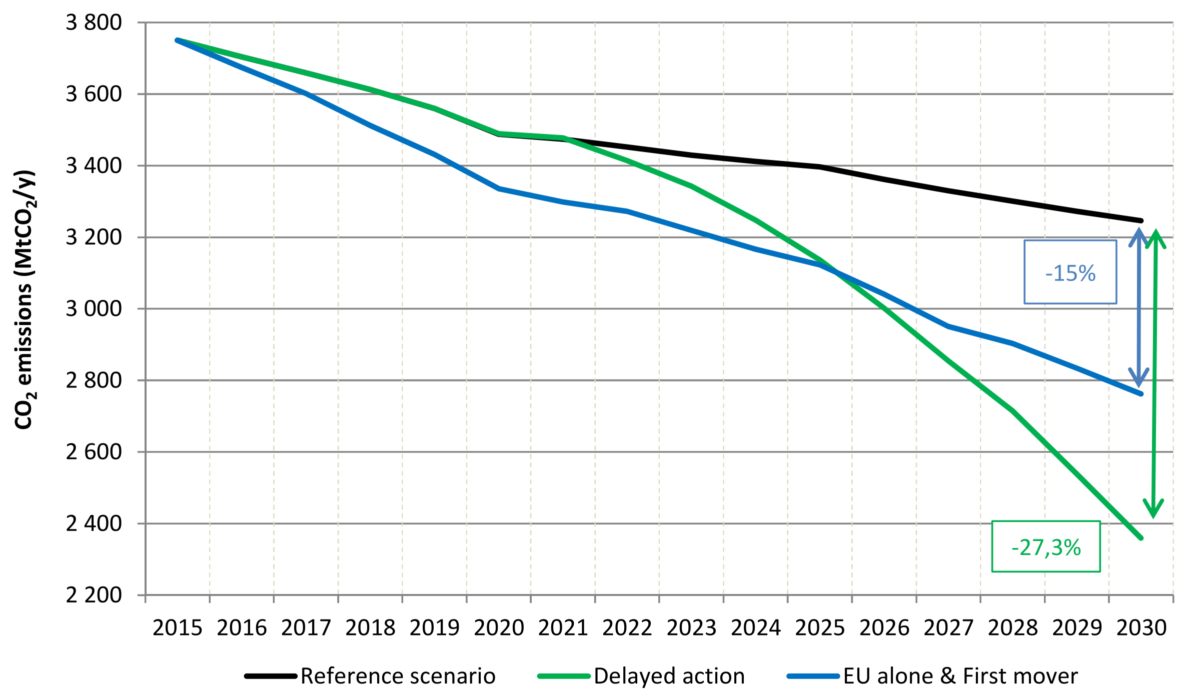
Table 40: Change in sectorial import prices for EU28 in decarbonisation scenarios (% w.r.t. reference scenario)

5.2 GHG emissions reduction

In the decarbonisation scenarios, the European GHG budget is constrained at 72 Gt between 2010 and 2030, i.e. in line with the EU Roadmap (EC, 2011) [9][22]. But the GHG emissions mitigation policies do not start at the same period: they start from 2010 in the EU alone scenario and in the first mover scenario and from 2020 in the delayed action scenario. At the end of the period, the decarbonisation will be smoother in the EU alone scenario and the first mover scenario than in the delayed action scenario in order to reach

[22] We focus on CO_2 emissions instead of GHG emissions, as non-CO_2 emissions reduction is similar in all decarbonisation scenarios.

the same carbon budget. Figure 11 displays the CO2 emissions reduction trajectory for the four scenarios. Due to the delayed action in the 450 delay scenario, the overall GHG emissions mitigation effort should be done between 2020 and 2030 in order to reach the total 2010-2030 carbon budget. The CO_2 emissions in the delayed action scenario are thus 12% lower in 2030 than in the EU alone and first mover scenarios with 2.36 Gtn. of CO_2 in the delayed action scenario against 2.76 Gt. in the non-delaying scenarios.



Source: NEMESIS

Figure 11: EU CO2 emissions in the series of scenarios (in MtCO2/y)

Thus, the CO_2 budget in delayed action scenario should be reduced by 3.3 Gt between 2025 and 2030 whereas it should decrease about 2.3 Gt in the EU alone and the first mover scenarios, in which one third of the CO_2 reduction effort compared to the reference scenario is already achieved before 2025 (see Table 41). These different trajectories of CO_2 reduction are also visible in the change of energy mix as well as in the cost of the GHG emissions reduction scenarios.

		2010-2025	2025-2030	2010-2030
Reference scenario	**CO_2 budget**	54.8	19.9	74.7
Delayed action scenario	**CO_2 budget**	54.5	16.6	71.1
	CO_2 reduction from ref	*0.3*	*3.3*	*3.6*
EU alone scenario*	**CO_2 budget**	53.5	17.6	71.1
	CO_2 reduction from ref	*1.3*	*2.3*	*3.6*

**: similar to fist mover scenario*

Source: NEMESIS

Table 41: EU CO2 budget in the series of scenarios (in Gtn. CO2)

5.3 Energy system transformation

The reduction of the CO_2 emissions in the decarbonisation scenarios can be achieved by (i) an increase in energy efficiency (i.e. a decrease in energy consumption per unit of GDP), (ii) a substitution between sources of energy (i.e. change in the energy mix) and (iii) a reduction of energy needs (i.e. change in economic activity). In the NEMESIS model, the repartition between these three channels in the decarbonisation scenarios is presented in Table 42. The main decarbonisation effort in NEMESIS comes from energy efficiency investments with nearly two thirds (64%) in the delayed action scenarios and 80% in the EU alone and first mover scenarios. Changes in the energy mix are also an important source of CO_2 emissions reduction with 35% in the delayed action scenario and 20% in the two others scenarios.

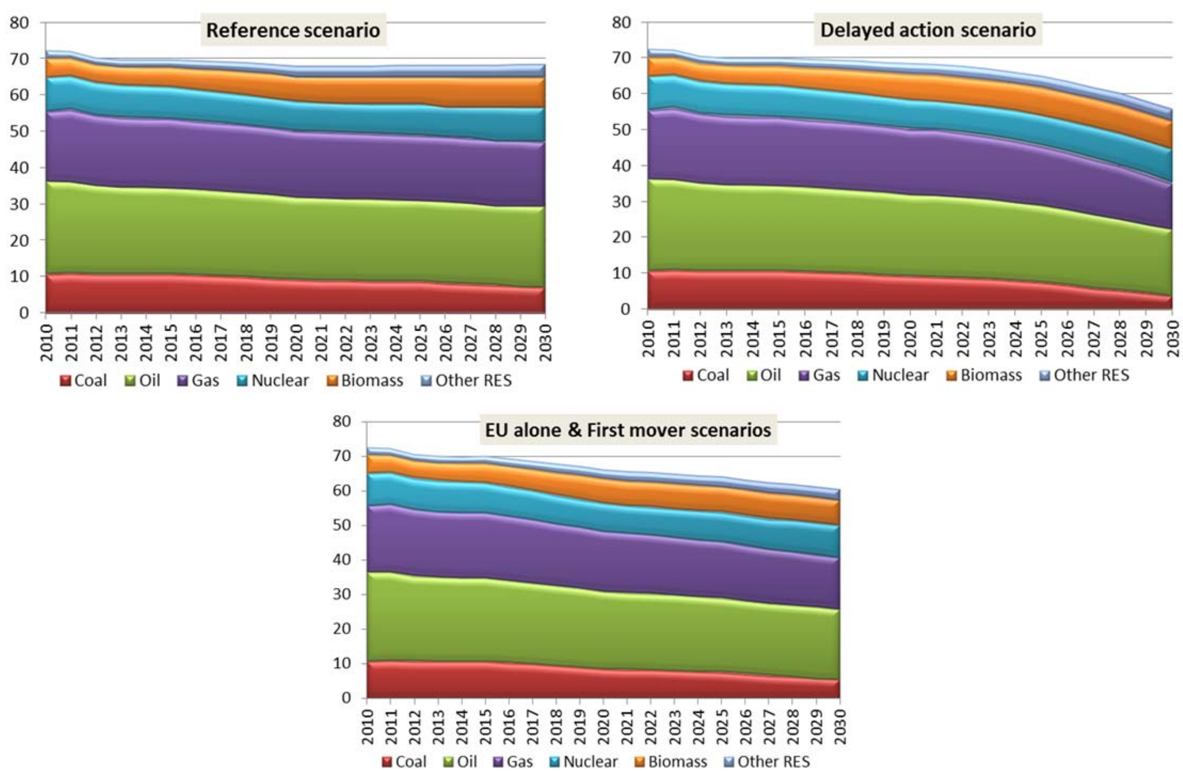
When the decarbonisation is smooth, energy saving investments are the most cost effective strategy to reduce CO_2 emissions. Indeed, the energy efficiency improvement requires important investments in the short term but it produces a flow of energy saving all along their lifetime which could have positive income effects in the long run. Furthermore, energy efficiency could be achieved by all sectors such as tertiary or residential sectors, with thermal isolation or renovation of buildings. At last, the energy efficiency investments reduce the need for decarbonisation of the energy supply, by reducing demand for energy.

When annual CO_2 emissions reduction effort is stronger, as in the delayed action scenario, the flow of energy saving from energy efficiency investments is not sufficient to achieve the mitigation target. In this case, more costly GHG emissions mitigation strategies should complete the energy efficiency investments, such as the decarbonisation of the power generation sector. Contrary to the energy saving investments, the decarbonisation of the power generation sector implies additional costs at long as well as at short-term. The carbon free technologies for power generation are more expensive than CO_2 emitting ones (based on fossil fuels) even if their cost could be alleviated by higher technological progress in the decarbonisation scenario than in the reference scenario.

	Delayed action scenario			EU alone scenario			First mover scenario		
	GDP	CO_2 intensity	Energy intensity	GDP	CO_2 intensity	Energy intensity	GDP	CO_2 intensity	Energy intensity
2020	0.0%	0.0%	0.0%	0.4%	27.3%	72.3%	-1.6%	27.1%	74.5%
2030	1.1%	35.3%	63.6%	1.3%	20.5%	78.1%	1.2%	19.9%	78.9%

Source: NEMESIS

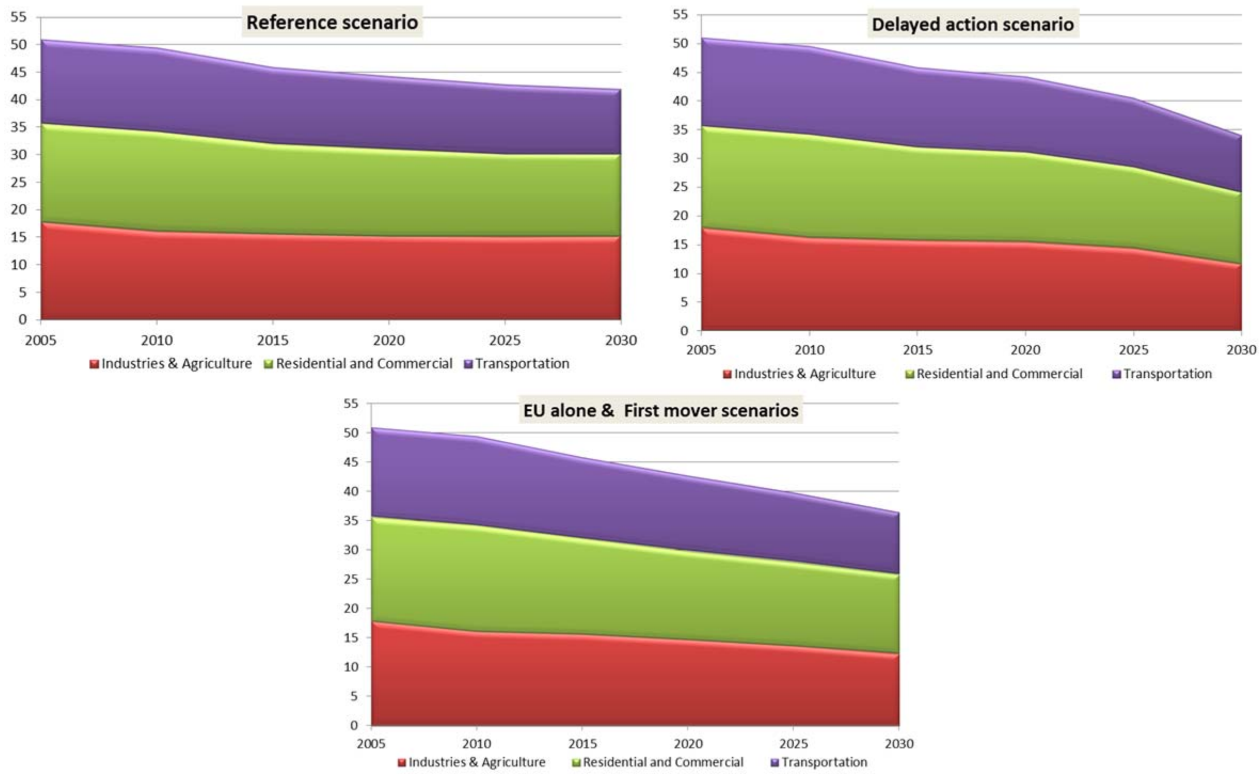
Table 42: Decomposition of EU CO2 emissions reduction in the decarbonisation scenarios (%)



Source: NEMESIS

Figure 12: Primary energy by product in EU (EJ/y)

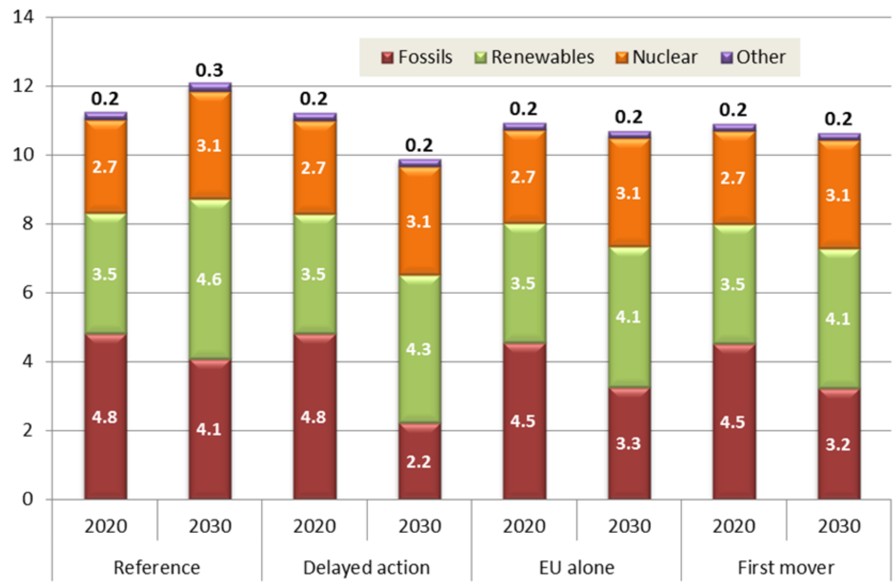
The evolution of primary energy consumption in the decarbonisation scenarios confirms the previous results (Figure 12). The primary energy consumption decreases by 12.8 EJ in 2030 in the delayed action scenario and by 8.3 EJ in the EU alone and First mover scenarios, compared to the reference scenario. In the former, the fossil energy consumption is reduced by 12 EJ in 2030 with -3.4 EJ for coal, -3.6 EJ for oil and -4.9 EJ for gas. In the smoother decarbonisation scenarios, fossil energy consumption declines by 6.7 EJ in 2030 with -1.5 EJ for coal, -2.3 EJ for oil and -2.9 EJ for gas. Thus the share of fossil energy in the total EU primary energy consumption is about 63% in delayed action scenario and 67% in EU alone and First mover scenarios whereas it was about 70% in reference scenario in 2030. The biomass energy consumption decreases slightly in the decarbonisation scenarios due to the strong improvement of energy efficiency in the decarbonisation scenarios and to the assumption of fixed nuclear power generation up to 2030 compared to the reference scenario.



Source: NEMESIS

Figure 13: Final energy consumption in EU (EJ/y)

The CO2 reduction effort takes place in all the economic sectors in the decarbonisation scenarios (Figure 13). In 2030, the reduction of the final energy consumption in “residential & tertiary” sector as well as in “transportation” sector is about 10% in the EU alone and the First mover scenarios compared to the reference scenario and the decrease of the final energy consumption is about 16% in delayed action scenario compared to reference scenario. In 2030, the reduction of the final energy consumption in the “industry and agriculture” sector is bigger with -18% in the EU alone and the First mover scenarios and -24% in the delayed action scenario with respect to the reference scenario. Most of the CO2 emissions reduction in the decarbonisation scenarios comes from the decarbonisation of the power generation mix. The CO2 emissions in the power generation sector are reduced by almost 50% in the delayed action scenario and reach 525 Mt in 2030; they are 20% lower in the other scenarios (790 Mt).

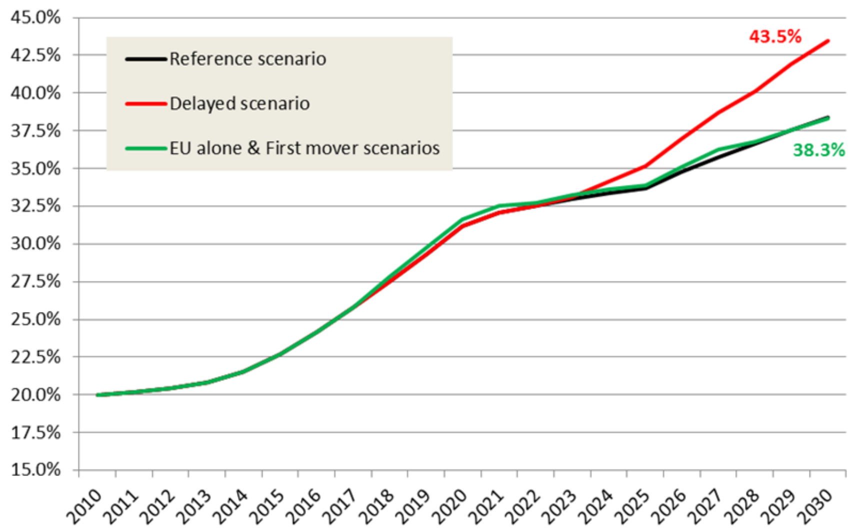


Source: NEMESIS

Figure 14: Power generation mix in EU (EJ/y)

In the power generation sector, the reduction of CO_2 emissions is a combination of lower demand for electricity (-2.2 EJ in the delayed action scenario and -1.4 EJ in EU alone and First mover scenarios compared to the reference scenario in 2030) and a change in the power generation mix (Figure 14)[23]. In 2030, fossil energy in the power generation represents 2.2 EJ in the delayed action scenario and 3.3 EJ in the two other decarbonisation scenarios. Thus, as the share of nuclear power generation is assumed to be fixed, the deployment of the RES in the power generation is limited. The share of RES in power generation in 2020 is slightly higher in the non-delayed scenarios than in the reference scenario. In 2030, this share reaches a similar level relative to the reference scenario, with 38.3% (Figure 15). However, the relatively weaker reduction of electricity demand in the delayed action scenario and the stronger CO_2 emissions reduction, push the share of renewable energy to 43.5% in this scenario in 2030. The main RES contributor is the wind energy with more than 50% of total RES in power generation in 2030. Hydro energy remains an important renewable source in the power generation sector in 2030 with almost 30% whereas the contribution of solar energy raises significantly to nearly 10% in delayed action scenario in 2030.

[23] In the NEMESIS model, the electrification of the transport sector is a very limited option of decarbonisation up to 2030. It is assumed that the required infrastructures for a large expansion of the electrification of the transportation sector are not available before 2030.



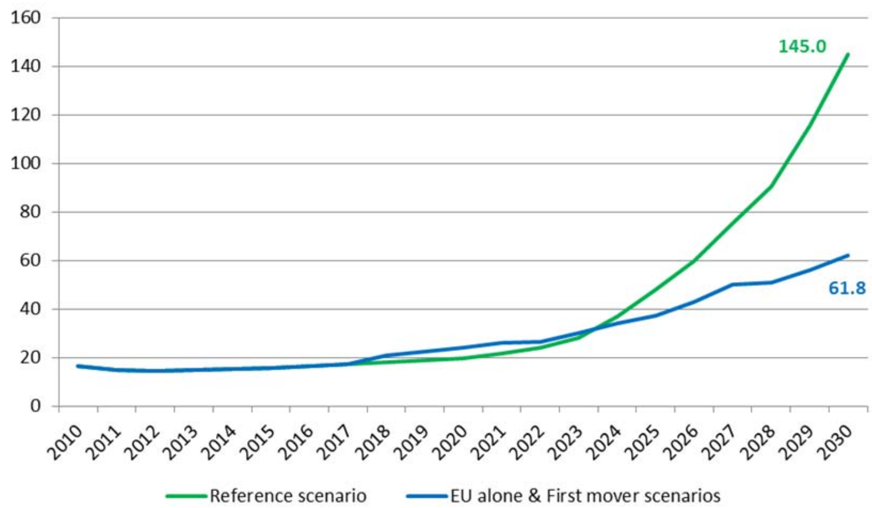
Source: NEMESIS

Figure 15: Share of RES in power generation in EU (%)

5.3.1 Carbon price

The unique economic instrument to meet the carbon budget, in these decarbonisation scenarios, is the carbon price. It increases the cost of fossil energy accessibility and thus changes the relative prices between energy sources. With the revenues impacts, these changes in the relative price of the different sources of energy modify the choice of economic agents. In these scenarios, the carbon price is recycled by a lump sum to households compensating their tax expenditures and by lowering social contribution of firms.

The carbon abatement cost is increasing with the CO_2 emissions reduction effort and the marginal abatement cost is also increasing with CO_2 emissions reduction effort (Figure 16). Thus, the carbon price in the delayed action scenario, where the CO_2 emissions reduction effort is the strongest, reaches 145 \$US05/t CO_2 in 2030. In the smoother decarbonisation scenarios the carbon price is lower and reaches 61.8 \$US05/t in 2030.



Source: NEMESIS

Figure 16: Carbon price in EU (US$05/tn. CO_2)

5.3.2 GDP and components

The carbon price increases the cost of energy services as well as the production cost of domestic goods compared to foreign ones. It also impacts households' income insomuch as the substitution between goods and between energy sources is not perfect. Finally, the firms' revenues are modified by the increase in the carbon price through two channels: (i) their production costs are higher and (ii) the labour intensive sectors are favoured compared to energy intensive sectors due to the recycling scheme assumed (lowering of social contribution).

In the delayed action scenario, where the CO_2 reduction effort is the strongest in 2030, the GDP loss is about -0.35% at the end of the period compared to the reference scenario (Table 43). In the smoother decarbonisation scenario, the GDP losses are lower with respectively -0.22% and -0.20% in EU alone and First Mover compared to the reference scenario.

	Delayed action	EU alone scenario	First mover scenario
GDP (% change from reference)	-0.36%	-0.22%	-0.20%

Table 43: GDP losses in EU in 2030 (% w.r.t reference scenario)

In the decarbonisation scenarios, the economic mechanisms behind these results can be highlighted by decomposing the GDP changes into contribution of GDP components to these GDP changes (Figure 17). The comparison of the delayed action and the first mover scenarios with the reference scenario allows the analysis of the decarbonisation effects as well as the impacts of the delayed action in EU.

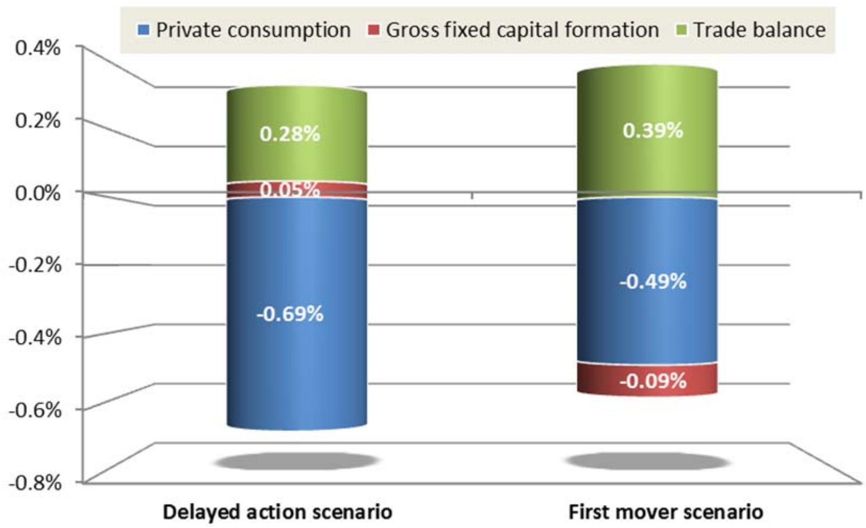
	Delayed action scenario		First mover scenario	
	2020	**2030**	**2020**	**2030**
GDP	0.10%	-0.35%	0.07%	-0.20%
Private final consumption	0.00%	-1.11%	-0.08%	-0.78%
Gross fixed capital formation	0.09%	0.17%	0.11%	-0.41%
Trade balance	1.76%	6.47%	1.83%	9.14%

Source: NEMESIS

Table 44: GDP and GDP components change in EU (% w.r.t the reference scenario)

In the delayed action scenario, the GDP loss in 2030 is about 0.36% compared to the reference scenario with -0.7 pt of GDP due to the fall of private final consumption, +0.05 pt of GDP for GFCF (Gross Fixed Capital Formation) and +0.3 pt of GDP from trade balance. In the smoother decarbonisation scenario, the loss of GDP due to private final consumption is lower with -0.5 pt in 2030, the GFCF contributes negatively of about -0.1 pt, whereas the trade balance has a positive impact of 0.4 pt of GDP. The decarbonisation of the European economy implies a reduction of the households' final consumption. Despite the recycling scheme of the carbon tax, the raise of the energy prices and the domestic goods prices penalise the households by reducing their purchasing power. The impact on GFCF is relatively moderated despite the slowdown of the European economic activity. The investments in energy saving and energy carbon free technologies compensate the fall of investments in other economic sectors. Furthermore, the combination of labour cost reduction (through lower social contribution) and the mitigation policies implemented in the Rest of the World allow an enhancement of external balance.

The economic impacts of the delayed action are not negligible, as the difference in GDP losses incurred for the EU between the delayed action scenario and the smoother decarbonisation scenario is about -0.15% i.e. two thirds of the GDP loss in the first mover scenario GDP compared to the reference scenario. Indeed, the higher carbon price in the delayed action scenario penalises the European economy by reducing households' final consumption (-0.2 pt of GDP compared to first mover scenario) and by deteriorating the European competitiveness (-0.1 pt of GDP). In the delayed action scenario, the domestic goods are more expensive because of the higher energy prices.



Source: NEMESIS

Figure 17: Contribution of GDP components to GDP change in EU (pt of GDP compared to reference scenario)

5.3.3 Economic performance and innovation

In addition, the R&D investments, which allow the alleviation of the decarbonisation in the decarbonisation scenarios, do not reach their full potential effects in the delayed action scenario. Indeed, despite stronger R&D investments in cleaner energy sources and energy efficient technologies, (+50 bn €05 and +31 bn €05 compared to the reference scenario in the delayed action and first mover scenarios respectively), the period for innovation remains too short in the delayed action scenario to be fully productive.

R&D investments are important drivers of the economic impact in the decarbonisation scenarios. In the delayed action scenario more than 50 bn €05 are invested in research activities between 2010 and 2030, compared to the reference scenario. These expenditures are invested at almost 90% by industries (i.e. 28 bn €05) and especially in the industries where energy technologies are manufactured (i.e. “chemicals” for biofuels and electricity storage, “metal products” for isolation and lightening, “industrial machines” for wind energy, “electronic goods” for solar energy or “equipment transport” for energy efficiency in transportation sector)[24]. Indeed, between 2010 and 2030, the total additional investments in R&D in these sectors is about 23 bn €05, i.e. almost 75% of the additional investments in R&D in the first mover scenario (Table 45). These research investments allow the reduction of the decarbonisation cost by lowering energy technologies cost and

[24] See (Le Hir, et al., 2013) for a detail presentation of sectorial knowledge flows in energy technologies.

especially for carbon free power generation technologies as well as energy saving technologies. The process innovation in these sectors allows the EU to produce the decarbonisation technologies at a lower cost, favouring their development as a cost effective decarbonisation option. The research investments, thus moderate the price increases and their economic consequences. Subsequently, they enhance the opportunities for exportations of the corresponding technologies.

M €05	2020	2025	2030
Total	**1 439.7**	**12 466.3**	**31 297.4**
Total industries	1 342.4	11 214.3	28 008.2
of which			
- Chemicals	*382.9*	*3 155.9*	*8 292.0*
- Metal products	*15.0*	*181.7*	*443.4*
- Agriculture & Industrial machines	*48.6*	*806.7*	*2 040.6*
- Electronical and Optical equipment	*110.9*	*1 652.8*	*4 232.2*
- Transport equipment	*293.9*	*3 240.1*	*7 934.5*

Source: NEMESIS

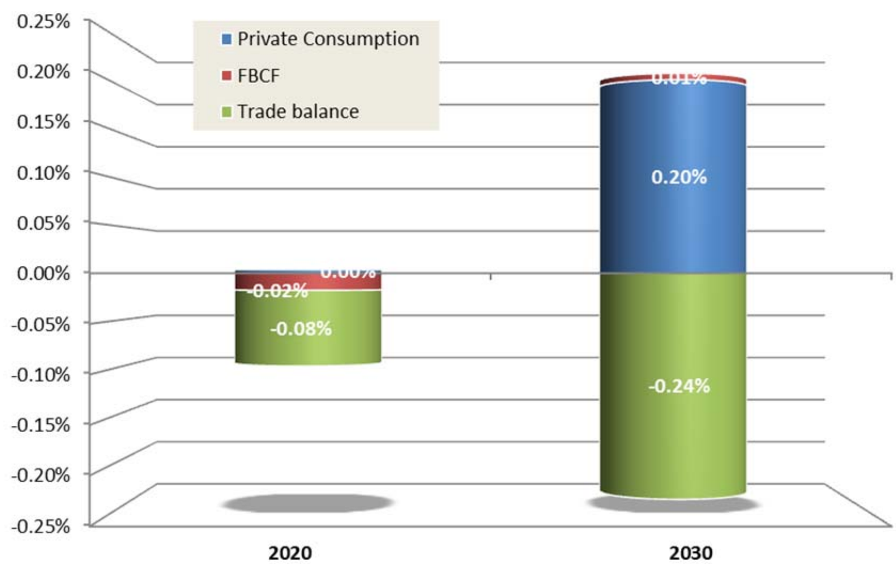
Table 45: Cumulative additional EU R&D investments in the first mover scenario compared to the reference scenario (in M €05)

5.3.4 First mover advantage

Finally, despite the absence of the modelling of the Rest of the World and the weak technological representation in the NEMESIS model, some insights on the first mover advantage can be drawn by comparing the EU alone scenario and the first mover scenario.

The implementation of mitigation policies in the rest of the World from 2020, in the first mover scenario, implies an increase in import prices for EU and as well as a weaker economic activity in the rest of the World. The increase of foreign goods prices compared to domestic goods favours the European economy in the first mover scenario compared to EU alone scenario. Nevertheless, as domestic and foreign goods are imperfect substitutes, the consumer price index is higher when the rest of the World enters in the global GHG emissions mitigation policies. At the opposite, the relative price of EU domestic goods compared to foreign ones is lower in the first mover scenario and thus it allows the improvement of the European competitiveness in the first mover scenario compared to the EU alone scenario from 2020. Thus, it favours the European exports. These competitiveness effects are reinforced by R&D investments realised in European industries. However, there is no assumption about the reaction of the Rest of the World in terms of research investments. The Rest of the World will probably also launch into the innovation competition for decarbonisation technologies.

Figure 18 confirms these economic mechanisms. The contribution of the private final consumption to the change of GDP in the EU alone scenario is positive with 0.2 pt of GDP in 2030 compared to first mover scenario resulting from the lower general inflation in this scenario. At the opposite end, the trade balance in the EU provides a negative contribution to GDP change in the EU alone scenario compared to first mover scenario, with -0.24 pt of GDP. Thus, the cumulative effect of each components to GDP change is about -0.02 pt in the EU alone scenario compared to the first mover scenario. The economic negative impacts are then slightly higher when EU acts alone for its decarbonisation than when the rest of the World follows the GHG emissions mitigation. It can be explain by an enhancement of its competitiveness which comes from (i) the raise of the foreign goods prices and (ii) the technological advantage acquired by the EU in the decarbonisation technologies.



Source: NEMESIS

Figure 18: EU GDP components contribution to EU GDP change, EU alone scenario vs first mover scenario (in GDP pt)

This European technological advantage acquired in the decarbonisation technologies during the first period increases the chances of the European Union to be a major player from 2020. It allows then the creation of new jobs in the sectors producing these technologies. In the first mover scenario, European employment is slightly higher than in the EU alone scenario, as nearly 200.000 jobs are created in the European economy in 2030 in the first mover scenario compared to the EU alone scenario.

	2020	2025	2030
Total	**250.7**	**300.4**	**193.2**
Total industries	136.7	197.1	168.9

of which			
- Chemicals	*11.3*	*24.5*	*27.6*
- Metal products	*19.1*	*38.9*	*41.6*
- Agriculture & Industrial machines	*10.8*	*16.8*	*13.6*
- Electronical and Optical equipment	*7.0*	*9.7*	*9.5*
- Transport equipment	*10.2*	*18.5*	*18.2*

Source: NEMESIS

Table 46: Change in EU employment in the first mover scenario compared to the EU alone scenario (in thousand)

At the end of the period, almost 90% of European the employment is created in the industrial sectors, with +170.000 jobs in 2030. The main sectors creating new jobs, in the EU first mover scenario compared to EU alone scenarios, are sectors identified as energy technologies producer and especially decarbonisation technology producer. Among the 193.000 jobs created in the EU first mover scenario, 27.600 are in "Chemicals", 41.600 in "Metal products", 13.600 in "Agricultural and Industrial machines", 9.500 in "Electronical and optical equipment" and 18.200 in "Transports equipment". Thus, almost 60%, i.e. 110.000 jobs are created in sectors producing the decarbonisation technologies.

6 Conclusions

6.1 Analysis with the GEM-E3-RD model

The aim of the quantitative projections conducted within the AMPERE project is to analyse the macroeconomic costs and benefits for the EU as a first mover in climate change mitigation and identify the possible First Mover Advantages that the EU economy can get. A general equilibrium approach is followed using the GEM-E3-RD global model enhanced with endogenous R&D mechanisms. A series of scenarios have been quantified, which are compared with the Reference projection to 2050.

The Reference scenario represents a situation where climate policy is limited to current commitments of the different countries and regions of the world (e.g. renewable and nuclear expansion targets, emissions intensity targets, etc.). This clearly does not tackle the climate change issue. On the contrary, it renders eventual attempts at mitigation in the second half of the century much more difficult if not virtually unrealistic [44]. The EU, which so far has been most active in pushing the agenda for stronger climate action in the world arena, is faced with an important dilemma: Does it undertake immediately a strong effort towards decarbonisation of the EU energy system in the hope that other countries will eventually join or does it delay such action until an international consensus has been reached?

In exploring this question a number of scenarios using the GEM-E3-RD model have been evaluated. The EU Alone scenario assumes that such a unilateral action is taken and the world fails to follow suit before 2050. In that case according to model results the EU incurs a cost equivalent to 0.51% of cumulative reference GDP in the period 2010-2050 and the climate change issue remains virtually unaffected. Delaying action until 2030 and supposing that by that date the EU and the rest of the world jointly start strong climate action leads to an even higher cost for the EU, equivalent to 0.6% of cumulative EU GDP, due to the stronger EU decarbonisation effort after 2030 (reflected in higher carbon prices) and to the depressive effect of mitigation action on global GDP that implies lower global demand for EU exports. The corresponding loss for the rest of the world is of the order of 1%. On the other hand, if the EU undertakes early action and the world joins it after 2030 the cost to the EU is drastically diminished to the equivalent of 0.2% cumulatively due to the increased exports of clean energy technologies and the prolonged decarbonisation period. Clearly the desirability of early EU action depends crucially on the probability attached to the world joining in the medium term. It is conceivable that such a probability increases if the EU sets the example and demonstrates that the costs involved are not inordinate.

The results above depend to a considerable extent on the issue of technology dynamics. The GEM-E3 model has been enlarged to incorporate such dynamics for a number of key technological options in pursuit of decarbonisation, such as wind, photovoltaics, CCS, electric vehicles, advanced energy equipment and biofuels. Early action sets into motion R&D effort on such clean energy technologies which combines with economies of scale and other learning by doing obtained by drastically increased uptake within the EU leading to reductions in costs. Such reductions can to some extent (subject to technological spillovers) be appropriated by EU industries leading to increased market shares which can be particularly important if world markets also grow very rapidly as a result of strong climate mitigation policies.

The most important among these technological options is electric vehicles (pure electric and plug-in hybrids). According to model results, their deployment is an essential ingredient of decarbonisation as they tackle the issue in the important road transport sector which is not amenable to many other options. The EU already enjoys a comparative advantage in vehicle construction and is well poised to take advantage of an early start in the construction of electric vehicles. Another decarbonisation option that can generate a large market under appropriate policy conditions concerns CCS. Here most of the potential is to be found outside the EU and especially in large emerging economies such as China and India. The CCS option is by no means an immediate possibility. However an early start could also produce competitive advantage with large possibilities for export expansion. Photovoltaics also offer big possibilities for building an early advantage in a market with a large potential in the developing world. On the other hand, wind turbine related technologies are relatively mature with few possibilities for improvement and therefore offer a less fertile ground for export expansion. Biofuels also constitute an option with modest prospects for decarbonisation of the transport sector, but the EU is not well placed to become an exporter of this energy vector as it is a high-cost producer requiring subsidies for domestic production.

6.2 Analysis with the NEMESIS model

The decarbonisation scenarios implemented in the NEMESIS model up to 2030 aim to assess different options in GHG emissions mitigation policies in the EU but also in the rest of the World. As the NEMESIS model is a European model which only covers EU-27 countries, the rest of the World has been considered through GEM-E3-RD results in order to (i) assess the change in addressed demand from the rest of the World and (ii) assess the change in production cost in the rest of the World. In the EU, the carbon budget between 2010 and 2030 is constrained at 72 Gt. In the EU alone and the first mover scenarios, this budget could be reached between 2010 and 2030, whereas in the delayed action scenario, it is reached between 2020 and 2030. Finally, between the EU alone scenario and the First mover scenario, the difference comes from the rest of the World which engages in EU GHG emissions mitigation policies in 2020 in the first mover scenario whereas only the EU realises decarbonisation policies in the EU alone scenario.

The CO_2 emissions reduction is mainly achieved by energy efficiency gains and at a lesser extent by changes in the energy mix. Nevertheless, in the delayed action scenario, the stronger CO_2 emissions reduction between 2020 and 2030 limits the feasibility of strong investments in energy efficiency technologies. Therefore, the share of GHG emissions reduction arising from changes in energy mix (carbon intensity of energy) is higher in the delayed action scenario than in the smoother decarbonisation scenarios. Energy efficiency investments allow carbon emissions reduction in all sectors and help the decarbonisation of the supply by reducing the demand for CO_2 emitting energy. But, the GHG emissions mitigation effort is relatively strong in the power generation sector which, in addition to a lower electricity demand compared to the reference scenario, substitutes CO_2 emitting technologies with renewable energy sources. Thus, in the delayed action scenario, the share of RES in the EU power generation sector reaches 43.5% in 2030 mainly driven by onshore and offshore wind and solar energy.

In terms of macroeconomic impacts, the delayed action scenario, as is the case with GEM-E3-RD, produces the strongest negative impact (-0.36% of GDP in 2030 compared to reference) as the achievement of the EU carbon budget in this scenario implies a stronger decarbonisation effort between 2020 and 2030. This strong increase of the cost of the energy services penalises the households' purchasing power as well as the European competitiveness with the rest of the World.

In the EU alone and the first mover decarbonisation scenarios, the EU carbon price increases progressively to reach 61.8 $US05 in 2030. It allows to the European industries to invest in R&D as well as to reap the benefit of the innovation induced by these R&D investments. Furthermore, the cost of the decarbonisation technologies is reduced as a result of accelerated learning by doing and learning by research. In the first mover scenario, the European sectors producing carbon free technologies benefit from increased experience and innovation compared to the rest of the World. In this scenario more than 110.000 new jobs are created in sectors producing the decarbonisation technologies compared to the EU alone scenario resulting from competitive advantage in the emission reduction technologies.

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