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European decarbonisation pathways under alternative technological and policy choices: A multi-model analysis[1]

Pantelis Caprosa, *, Leonidas Paroussosa, Panagiotis Fragkosa, Stella Tsania, Baptiste Boitierb, Fabian Wagnerc, Sebastian Buschd, Gustav Resch d, Markus Blesle, Johannes Bollenf

[a] National Technical University of Athens, Department of Electrical and Computer Engineering, 9 Iroon Politechniou street, 15773 Zografou Campus, Greece

[b] Université de Paris 1 - « Panthéon-Sorbonne » & SEURECO

[c] International Institute for Applied Systems Analysis, A-2361 Laxenburg, Austria

[d] Energy Economics Group, Vienna University of Technology, Gusshausstrasse 25, 1040 Vienna, Austria

[e] Institute of Energy Economics and the Rational Use of Energy (IER), University Stuttgart, Heßbrühlstr. 49a D-70565 Stuttgart

[f] CPB Netherlands Bureau for Economic Policy Analysis (CPB)

*Corresponding author. Tel.: +0030 210 772 3629; fax: +0030 210 772 3630 (P. Capros)

E-mail address: kapros@central.ntua.gr

Abstract

This paper explores in a systematic manner the required energy system transformations and the associated costs incurred for the EU in order to meet the decarbonisation targets as specified in the EU Roadmap 2050, i.e. the 80% GHG emissions reduction target and the equivalent carbon budget by 2050. Seven large-scale energy-economy models, namely PRIMES, TIMES-PanEu, GEM-E3, NEMESIS, WorldScan, Green-X and GAINS, which have been extensively used in EU climate and energy policy analysis are employed for the simulation and quantification of alternative EU decarbonisation pathways under technological limitations and climate policy delays. The multi-model perspective provides valuable insights for the formulation of robust policies. The model results show that the EU emissions reduction target is feasible with currently known technological options at low costs (lower than 1% of GDP in the period 2015-2050). Models confirm the EU Roadmap priorities for 2050 with regard to accelerated energy efficiency, transport electrification and supply-side restructuring with high RES, CCS and nuclear deployment. Decarbonisation targets are found feasible even in cases with technological limitations regarding CCS and nuclear technologies and delays in transport electrification albeit

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[1] The views expressed are purely those of the author and may not in any circumstances be regarded as stating an official position of the European Commission.

with higher costs. Delaying emission reduction action until 2030 has significant adverse effects on energy system costs and stresses the system capabilities for decarbonisation.

Keywords: EU Decarbonisation pathways, Climate policy delays, Energy Roadmap, EU Energy Policy, Technological limitations

1 Introduction

In 2011 the European Commission in the "Roadmap for moving to a low-carbon economy in 2050" (hereafter Roadmap 2050 [1]) committed to reducing greenhouse gas (GHG) emissions in the European Union by at least 80% in 2050 as compared to 1990 emissions[2]. This initiative was deemed necessary as part of the global GHG mitigation effort to limit average temperature increase to no more than 2°C compared to pre-industrial levels and prevent further climate damages. The Roadmap 2050 was accompanied by the "EU Energy Roadmap 2050" [2] that contains extensive modeling results for a series of decarbonisation scenarios based on the PRIMES energy system model. The EU has also adopted a 20% GHG emissions reduction target for 2020 relative to 1990 as part of its climate and energy package [3], has established the worlds' largest emissions trading system (EU ETS) and has already implemented a series of emission reduction, energy efficiency and RES deployment policies [4]. The European Commission in 2013 has adopted the Green Paper on "A 2030 framework for climate and energy policies" [5] that launched a public consultation with the aim to extend to 2030 the current legislative 2020 framework and to set specific targets[3] for GHG emissions reduction, energy savings and RES deployment for 2030.

The announcement of these goals has triggered a growing interest in the scientific research on the feasibility and the long-term macro-economic implications of climate change mitigation policies and the associated decarbonisation pathways for the EU (see among others Capros et al, [6-7] Graca Carvalho [8] and Hubler and Loschel, 2013 [9]). Recent studies have focused on the comparison of alternative energy-economy models which examine the long term mitigation pathways at global (Luderer et al, 2012 [10]; Clarke et al, 2009 [11]; Kriegler et al [12]; Riahi et al [13]) and EU level (Knopf et al, [14]).

Key questions yet to be addressed regard the alternative strategies towards the achievement of the Roadmap 2050 targets and the cost differentials associated with the alternative mitigation options available. The present paper complements in a novel way the debate by analyzing in a systematic manner the required energy system transformations in order to meet the EU Roadmap 2050 emissions reduction and the carbon budget targets and by quantifying the costs

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[2] GHG emissions include all greenhouse gases covered by the Kyoto protocol.

[3] That can be legally binding

that the EU has to bear when implementing such policies. Towards this end, seven large-scale well established and extensively used in the EU climate and energy policy analysis models, namely PRIMES, TIMES-PanEu , GEM-E3, WorldScan, NEMESIS, Green-X and GAINS, are included in the analysis. An inter-model comparison is undertaken, for the first time to such an extent, with regard to decarbonisation strategies, energy system restructuring, associated costs and further macro-economic implications. The current model-based analysis expands the Roadmap study by quantifying the economic impacts of climate policy failures and technological limitations with a set of energy-economy models. The multi model analysis provides a thorough investigation of the costs of achieving the emissions reduction targets set by the EU and offers valuable insights for the design and formulation of robust energy and climate policies.

The analysis focuses on comparison of results obtained from: *i)* Partial equilibrium energy system models, which are detailed in terms of energy technologies, engineering constraints and simulation of energy markets, but lack closed loop feedback from other sectors of the economy, and *ii)* Macro-economic models which represent comprehensively the articulation of sectors in the macro-economy level and account for the complex interactions between the energy system and the overall economy but have limited technological representation. In this way the analysis further complements the debate on decarbonisation costs by looking at the results of complementary models and by accounting for macroeconomic feedbacks especially in the presence of accompanying climate policies. The analysis extends the assessment of the decarbonisation scenarios described in the EU Energy Roadmap 2050. Additional scenarios considering alternative technological limitations and combination of climate policy and technological failures are simulated and useful conclusions are inferred based on multi-model analysis.

The simulations include the reference scenario which considers all the emission reduction policies already adopted in the EU, a basic least cost decarbonisation scenario for the EU and a set of alternative decarbonisation scenarios. Decarbonisation scenarios are constrained to meet the same carbon budget as the EU Roadmap scenarios. They assume global mitigation action which is consistent with the 450 ppm stabilization target while differ on the assumptions concerning the role of energy efficiency, technological availability and delayed climate action. The alternative decarbonisation scenarios focus on energy efficiency improvements, RES deployment, nuclear power phasing out, non-availability of Carbon Capture and Storage (CCS) technologies and delay of transport electrification. They also consider the implications of not taking any (additional from the reference) climate action before 2030.

Energy efficiency improvement is among the main decarbonisation options, as saving energy implies by definition lower emissions both in demand and supply sectors. Investment in energy efficiency and acquisition of energy efficient equipment constitute capital budgeting decisions which depend on individual discount rates of energy consumers and expectations about future performance of technologies. Energy consumers are usually reluctant to bear high upfront costs, as they implicitly use a high subjective discount rate in capital budgeting decisions that prevents them from selecting the most cost-effective technological options. This is a case where there is scope for public policy intervention (like regulations imposing energy efficiency obligations and minimum standards etc.). Public policies are assumed to be put in place in the decarbonisation scenarios as a means for overcoming these barriers.

Nuclear and CCS are the only carbon free power sources which are fully dispatchable and also can economically accommodate base load demand which is important for achieving affordable electricity prices for energy intensive industries. However, both nuclear and CCS raise acceptability concerns in many European countries. Between 2020 and 2035 the largest part of presently operational nuclear power plants will reach the end of their licenses and will have to be decommissioned unless extension of lifetime is agreed upon. Developing new nuclear sites is very difficult except in few eastern European countries (and few plants in the UK, France, Finland and Sweden). A series of new nuclear projects planned since years are financially challenged today due to public acceptability and cost-related reasons. Several European countries have excluded nuclear energy from their primary energy mix. Underground storage of CO_2 is also challenged in several EU countries. Very few pilot CCS plants are ongoing projects, far below expectations a few years ago. The process is hampered by gloomy prospects of licensing and operating large underground CO_2 storage areas in Europe. Thus a key question is what would be the system resilience and the cost impacts under decarbonisation conditions in the case where nuclear and/or CCS will not be available in the future.

Electrification of transport is considered as a crucial element of decarbonisation strategy as without it transport would have to either undergo major changes, e.g. extreme modal shifts or rely heavily on bio-energy products, thus raising sustainability concerns. The penetration of electric vehicles in the transport sector crucially depends on the improvement in the technical and economic characteristics of batteries, the development of recharging infrastructure and uptake of electric vehicles by consumers. The success of the aforementioned developments is difficult from a policy implementation perspective, as market coordination failures can impede timely and effective development of the recharging infrastructure for alternative transport fuels. Thus assumptions on the timing and the extent of transport electrification are critical for the assessment of the decarbonisation pathways.

The paper aims at addressing a closely related set of research questions on the decarbonisation pathways of the EU. These regard: i) the identification of the characteristics of the optimal emission reduction pathway for the EU, ii) the decarbonisation costs and further macroeconomic implications, iii) the implications of technology failures that challenge the feasibility of the decarbonisation target and increase costs, and iv) the effects of myopia about emissions reduction targets on the energy sector and the EU decarbonisation costs in case of delayed climate action until 2030. Addressing these questions will complement the analysis of the EU Roadmap 2050 and the debate on the implications of alternative decarbonisation pathways for the EU.

The remainder of the paper develops as follows: Section two reviews the alternative models employed and the scenarios simulated. Section three discusses the models' results for the basic decarbonisation scenario. Section four presents the results of the alternative decarbonisation scenarios. Last section concludes.

2 Methods

2.1 Participating Models

A set of well-established models is used in order to analyze the decarbonisation pathways for the EU energy system (Table 1). All models have been extensively used for the analysis of the EU energy and climate policies. Detailed model descriptions and scenario specifications are provided in the companion study [15]. The set of models includes partial equilibrium technology-rich energy system models (PRIMES and TIMES-PanEu), energy models on specific sectors (GAINS and Green-X), comprehensive computable general equilibrium models (GEM-E3 and WorldScan) and one macro-econometric model (NEMESIS). General equilibrium and econometric models are used to assess the macro-economic implications of the EU decarbonisation pathways, while energy system models focus on the impacts of emission reduction policies on energy demand and supply. Energy system models do not include the feedback of GHG emission reduction policies on overall economic activity thus they fail to capture the full economic costs of decarbonisation. However, they identify a wide portfolio of emission reduction technologies and are able to provide detailed results on the required energy system transformations and on the associated energy system costs.

Table 1: Models used in the analysis

Model	Coverage	Model Type	Horizon
PRIMES	Energy system	Energy markets equilibrium	2050
TIMES-PanEu	Energy system	Energy system cost minimization	2050
GEM-E3	All economic sectors	Recursive Computable General Equilibrium	2050
WorldScan	All economic sectors	Recursive Computable General Equilibrium	2050
NEMESIS	All economic sectors	Macro-econometric	2030
Green-X	RES development	Simulation of RES deployment	2030
GAINS	Non-CO_2 GHGs	Marginal abatement cost curves	2050

The differences in model structure, coverage and solution algorithm reflect different choices on how to best approach the analysis of EU decarbonisation pathways. The diversity in model structure and assumptions (e.g. costs of technologies, RES potentials, fossil fuel endowment) allows us to explore a range of possible outcomes and to use the models in a complementary manner. The technological details in the energy sector, the substitutability of energy carriers and the GHGs representation are other key model differences that influence the results presented in the paper.

2.2 Scenario description

Alternative scenarios have been simulated with the models including: i) the reference scenario (AM5S1) that includes all the already firmly decided energy and climate policies in the EU Member States, ii) a basic decarbonisation scenario (AM5S2) with all technological decarbonisation options available and used according to cost optimality; this scenario provides the least cost decarbonisation pathway for the EU, iii) decarbonisation scenarios (AM5S3-AM5S6) under technology limitations assuming nuclear power phasing out, lack of commercially available CCS technologies and delayed transport electrification and iv) decarbonisation scenarios that assume delayed climate action until 2030 (AM5S7-AM5S8). The focus of the study rests with comparisons of the scenarios with the reference case. For the convenience of the reader a detailed analysis of the policy assumptions employed in the reference scenario for the EU is provided in a companion paper [15]. Table 2 provides a summary of the scenarios' specifications.

Scenario AM5S2 assumes that all technological and policy options for GHG emissions reduction are available and that decarbonisation policies are implemented without delays. In this scenario, the models decide freely on the optimal mix of different emission reduction technologies, including energy efficiency improvement in demand sectors. In this process a least cost approach is followed. The overall carbon budget, which is equal to the Roadmap 2050 budget, and the corresponding carbon pricing and other decarbonisation facilitation policies are imposed on top of the Reference climate policies. The main emission reduction options include RES deployment in power generation and final demand sectors[4], development of CCS technologies for power generation and industrial applications, active promotion of strict energy efficiency standards[5] and development of recharging infrastructure as required to facilitate extensive transport electrification. Technical and economic progress for low and zero-carbon technologies beyond AM5S1 is assumed in the context of the (global) decarbonisation scenarios as a result of accelerated learning due to the massive deployment of carbon free technologies.

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[4] RES include wind on-shore and off-shore, photovoltaics, concentrated solar power, biomass and waste, hydro-electricity, marine and geothermal energy for electricity production, bio-fuels for transport purposes as well as solar and biomass, solar thermal and geothermal energy in heating/cooling uses.

[5] Standards for houses, office buildings, appliances, industrial applications, grids and vehicles.

Carbon pricing is assumed to apply to both ETS and non-ETS sectors in order to maximize cost-efficiency. Emission allowances are auctioned to sectors covered by the EU ETS. In the non-ETS sectors carbon prices facilitate decarbonisation, without direct budget effects and without financial transfers between firms and households, as it is assumed that they do not imply direct payments by consumers but only indirect expenditures associated with increased emission reduction effort. Carbon prices are assumed to have equal values for ETS and non-ETS sectors and for all EU member states from 2025 onwards. Since the global emission reduction effort implies a decrease in demand for fossil fuels worldwide models take into account the subsequent decrease in international fossil fuel prices relative to the reference case[6].

Scenarios AM5S3, AM5S4, AM5S5 are variants of AM5S2 assuming low CCS and low nuclear development. They also differ from AM5S2 in assumptions on development of energy efficiency and RES technologies. Scenario AM5S3 assumes that energy efficiency and RES contribute more than in AM5S2 in the overall emission reduction effort, while the deployment of nuclear and CCS technologies is assumed to be limited. Scenario AM5S4 emphasizes the reductions in energy requirements through more stringent implementation of energy efficiency standards. CCS technologies are assumed not to penetrate in the energy mix and nuclear power is gradually phased out. AM5S4 assumes very stringent implementation of the Energy Efficiency Plan[7], difficulties regarding CO_2 storage sites and transportation, and rather negative public perception of nuclear safety. AM5S5 employs identical restrictions to AM5S4 about CCS and nuclear technologies but it focuses on the highest possible RES penetration in the energy mix, mainly in power generation and transport sectors. RES facilitating policies are introduced in addition to the RES policies assumed in AM5S2.

AM5S6 quantifies the impacts of low transport electrification on energy system decarbonisation and on the corresponding costs for the EU. AM5S6 assumes failure in the development of recharging infrastructure and smart metering together with delays in technology progress and cost reduction for batteries. Electrification delays are assumed to result in a relative failure for both plug-in hybrid and pure electric vehicles in penetrating the EU car market until 2050. Scenarios AM5S7 and AM5S8 investigate the consequences of delayed climate action. In scenario AM5S7 the EU and the rest of the world follow the reference scenario without additional GHG mitigation policies until 2030. After 2030, a global agreement to reduce GHG emissions is assumed to be reached. Both EU and other world regions undertake strong emission reducing actions and have to comply with the overall targeted carbon budget cumulatively over the period

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[6] Reductions are projected using the POLES world energy system which calculates endogenously world fossil fuel prices.

[7] Energy Efficiency Plan is implemented through the adoption of specific efficiency measures, such as minimum efficiency requirements for appliances and new buildings, high renovation rates of existing buildings and establishment of energy savings obligations on energy utilities.

2010-2050 as defined in AM5S2 despite acting only after 2030[8]. AM5S8 follows AM5S7 specification, but it assumes that energy efficiency improvements and RES deployment contribute more to the emissions reduction effort in the period 2030-2050, while the development of both nuclear and CCS technologies remains at lower levels as compared to the AM5S7 scenario.

In order to ensure consistency and comparability of model results especially with regard to the main exogenous assumptions influencing the energy system, Reference model results are 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[9].

All decarbonisation scenarios are designed to meet the same carbon budget in the EU in the period 2010-2050, which is consistent with the cumulative emissions as defined in the Roadmap 2050. The models impose emission restrictions for selected years (2020, 2030 and 2050) and ensure consistency with the overall carbon budget in the 2010-2050 period. The macro-economic models (GEM-E3, WorldScan and NEMESIS) which in general have a less detailed energy sector compared to the energy system models have adopted a simple modeling method for accommodating the scenario assumptions, the structural changes such as transport electrification (e.g. by changing technical coefficients) and the mix in power generation (e.g. by calibrating to energy system model projections). WorldScan includes an aggregate representation of the energy system and technological GHG mitigation options and hence it is not the most appropriate model to quantify decarbonisation pathways especially post 2030 (its rigidity regarding the limited use of alternative decarbonisation options leads the model to overestimate the decarbonisation costs after a certain level of emissions reduction). Thus the paper focuses on WorldScan macro-economic results up to 2030.

In all scenarios, the models that include non-CO_2 GHGs[10] use the CO_2 price resulting from the cumulative carbon budget constraint to also price non-CO_2 gases (using 100 years GWPs as provided in IPCC AR4 [16]). The GAINS model, which simulates explicitly a variety of non-CO_2 GHGs emitting activities, uses the carbon price trajectory as derived from the PRIMES model in each scenario.

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[8] Emissions of the period 2010 to 2030 are subtracted from the total carbon budget of the period 2010-2050 and the remaining emissions are imposed as a constraint on cumulative emissions over the period 2030 to 2050. All decarbonisation options are assumed to be available as in the basic decarbonisation scenario.

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

[10] N_2O, CH_4, SF_6 and long-lived halocarbons.

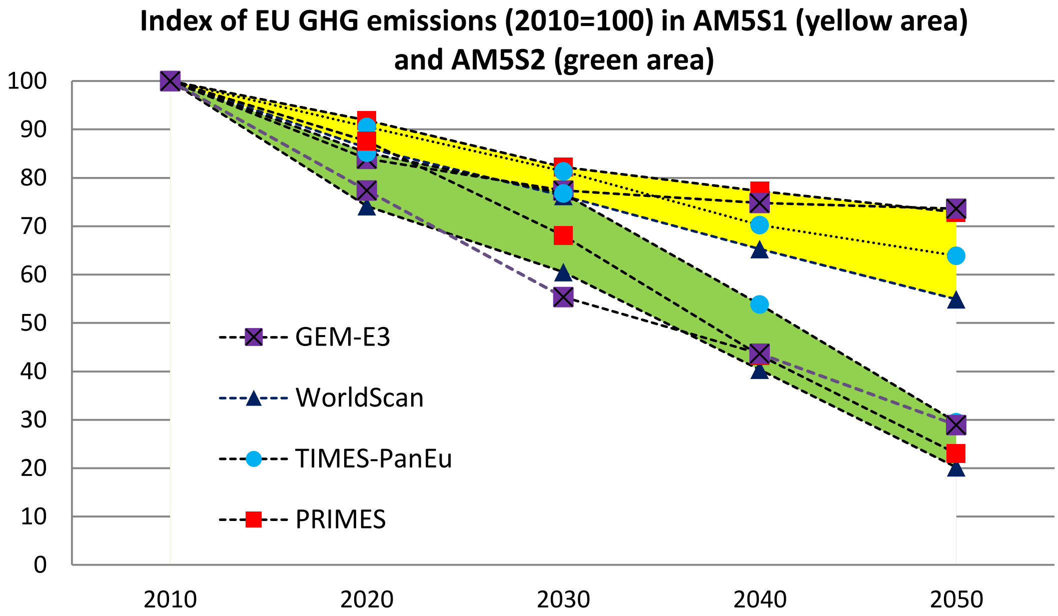
Table 2: Scenario specifications and decarbonisation options

	Reference scenario	Decarbonisation scenarios						
	AM5S1-Reference	**AM5S2**	**AM5S3**	**AM5S4**	**AM5S5**	**AM5S6**	**AM5S7-**	**AM5S8**
Assumptions on EU climate policies and targets	-EU adopted policies up to 2020 (Energy and Climate Policy Package) -After 2020 linear annual reduction of ETS cap (-1.74% p.a.) -No additional RES and EFF policies -Non-ETS emissions remain below the cap specified for 2020	-The Roadmap carbon budget is imposed in 2010-2050 -All emission reduction options are available -Their mix follows least-cost approach	-The Roadmap carbon budget is imposed in 2010-2050 -Higher efficiency and RES compared to AM5S2 - Low CCS and nuclear	-The Roadmap carbon budget is imposed in 2010-2050 -Maximum energy efficiency -No CCS and nuclear phase-out	-The Roadmap carbon budget is imposed in 2010-2050 -Maximum RES deployment - No CCS and nuclear phase-out	-The Roadmap carbon budget is imposed in 2010-2050 - Limited transport electrification	-The Roadmap carbon budget is imposed in 2010-2050 -Delayed climate action until 2030, then all decarbonisation options available	-The Roadmap carbon budget is imposed in 2010-2050 -Delayed climate action until 2030, then no CCS and nuclear phase-out
Assumption on climate policies undertaken by the rest of the world	-Low end of Copenhagen-Cancun pledges until 2020 -No climate policy intensification after 2020 (moderate climate action)	Strong decarbonisation efforts for achieving the 450 ppm stabilisation target	Same as in AM5S2	Same as in AM5S2	Same as in AM5S2	Same as in AM5S2	Delayed action until 2030, then according to the 450 ppm stabilization scenario	
Assumptions on energy efficiency		Optimal	Highest possible	Highest possible	Optimal	Optimal	Optimal, but delayed	Highest possible, but delayed
RES deployment		Optimal	Highest possible	Optimal	Highest possible	Optimal	Optimal, but delayed	Highest possible, but delayed
Nuclear power deployment		Optimal	Low	Phase out	Phase out	Optimal	Optimal, but delayed	Phase out
Deployment of CCS technologies		Optimal	Low	No	No	Optimal	Optimal, but delayed	No
Electrification in transport		Full	Full	Full	Full	No	Full	Full

3 Energy, economic and climate impacts of the basic decarbonisation scenario

In the reference scenario, GHG emissions drop by approximately 40% below the 1990 levels in 2050 according to PRIMES, TIMES-PanEu and GEM-E3 (Figure 1). Thus the reference case represents about half of the effort needed for the EU in order to comply with the decarbonisation target of -80% by 2050. The models find that the optimal decarbonisation pathway leads to a 41% reduction in GHG emissions in 2030 compared to 1990 (median of models). This is in line with Roadmap milestones [1, 2] that envisage a 40-44% GHG emission reduction in 2030 relative to 1990.

Figure 1: EU GHG emissions in the reference and in the basic decarbonisation scenarios



3.1 Allocation of GHG emissions among sectors in 2050

The projected GHG emissions in 2050 differ by model (Table 3). This is mainly because models find different emission reduction pathways as economically efficient; GEM-E3 projects earlier emission reductions relative to PRIMES. Another reason is the different split of emission reduction between CO_2 and non-CO_2 GHG emissions.

All models show that the power generation sector almost fully decarbonises by 2050 not only for reducing emissions in this sector but also for enabling electricity to substitute for fossil fuels in other sectors which are inflexible in reducing emissions otherwise.

Transport sector emissions projected by PRIMES and TIMES-PanEu, represent almost half of total CO_2 emissions remaining in 2050 in AM5S2 indicating the difficulty and the high costs associated with decarbonising the transport sector despite extensive electrification projected by both models. In TIMES-PanEu energy and non-energy related CO_2 emissions from industrial processes are found difficult to reduce without a decline in production levels (industry accounts for 36% of overall CO_2 emissions in 2050). GEM-E3 also shows that the main source of carbon emissions is industrial activities that represent 52% of total CO_2 emissions in 2050. PRIMES shows a significant reduction in carbon emissions from industrial processes where CCS, among other options, is making significant inroads in the long term.

Table 3: EU GHG emissions in AM5S2 scenario in 2050, in Mt of CO_2 equivalent

	PRIMES	TIMES-PanEu	GEM-E3	GAINS
Total GHG emissions	**1103.7**	**1279.7**	**1585.6**	-
CO_2 emissions	**667.4**	**955.4**	**926.7**	-
Electricity production	14.5	57.8	9.3	-
Industry	193.4	344.7	480.2	-
Transportation	317.5	426.4	131.9	-
Residential and commercial	112.7	100.1	277.8	-
Energy branch	29.3	26.4	27.5	-
Non-CO_2 GHGs emissions	**436.3**	**324.3**	**658.9**	**469.6**
N_2O	202.3	207.4	235.6	217.7
CH_4	208.0	116.9	382.0	223.8
F-gases	26.0	-	41.3	28.0

GAINS uses marginal abatement cost curves to derive the most cost-efficient way of reducing non-CO_2 GHG emissions and shows that F-gases have the highest reduction potential compared to methane (CH_4) and nitrous oxide (N_2O). Non-CO_2 emissions in PRIMES and GAINS are similar, as the two models are used in conjunction with each other. GEM-E3 projections regarding N_2O and F-gases emissions are comparable with GAINS in AM5S2 scenario. However, in GEM-E3 there are lower possibilities for cost effective reductions in CH_4 than in GAINS. TIMES-PanEu shows that the optimal solution includes lower non-CO_2 emissions compared to GAINS by 2050.

3.2 Decomposition of the GHG emissions reductions effort

Table 4 presents the decomposition analysis of CO_2 emission reduction in the AM5S2 scenario relative to the reference case based on the Kaya identity for the PRIMES, TIMES-PanEu, NEMESIS, GEM-E3 and WorldScan models for 2030 and 2050. The methodology followed to perform the decomposition analysis is provided in our companion study [15].

PRIMES and NEMESIS results indicate that for 2030 the largest part of CO_2 emission reduction relative to the reference is a result of improvement of the energy intensity of GDP. GEM-E3 and WorldScan show lower energy savings in final demand sectors and thus energy efficiency improvement is lower than in PRIMES and NEMESIS. All models show that the contribution of energy intensity improvement to the overall emission reduction gradually declines after 2030 mainly due to the high energy efficiency improvements already registered in the reference scenario that limit the potential for further low cost efficiency measures in the long term. TIMES-PanEu shows a worsening of overall energy intensity of GDP in 2050 mainly due to the weak further deployment of ambitious energy efficiency measures and the extensive use of less efficient energy forms (i.e. nuclear, CCS, biomass).

PRIMES, TIMES-PanEu and GEM-E3 show that the largest part of the emissions reduction effort until 2050 compared to the reference case is due to changes in carbon intensity of the fossil fuel mix. This is due to the massive penetration of CCS technologies in power generation and in industrial processing after 2030 and the substitution towards natural gas, which penetrates to the detriment of coal and oil in primary energy mix. In 2030, changes in carbon intensity of fossil fuel mix are due to higher use of gas displacing other fossil fuels and not to CCS, which is not emerging before 2030. The extensive use of carbon free energy and the reduction of carbon intensity of the fossil fuel mix are the main factors explaining decarbonisation according to the TIMES-PanEu model projections in 2030 and 2050. PRIMES assumes the implementation of the 20% RES target in gross final energy demand by 2020 already in the reference case and as a result further RES penetration in the decarbonisation scenario is limited in the medium term.

Table 4: Decomposition of CO_2 emissions reductions in the EU in AM5S2 scenario (in %)

	2030					2050		
	PRIMES	**TIMES-PanEu**	**NEMESIS**	**GEM-E3**	**WorldScan**	**PRIMES**	**TIMES-PanEu**	**GEM-E3**
Energy intensity of GDP	57.1	-3.5	61.7	26.2	24.7	22.0	-1.3	17.1
Use of carbon free energy	25.6	57.4	15.1	22.7	-0.5	27.2	44.9	19.9
Change in carbon intensity of fossil fuel mix	17.3	46.1	22.2	48.6	65.1	50.8	56.4	62.5
GDP change	0.0	0.0	1.0	2.5	10.7	0.0	0.0	0.5
SUM	100	100	100	100	100	100	100	100

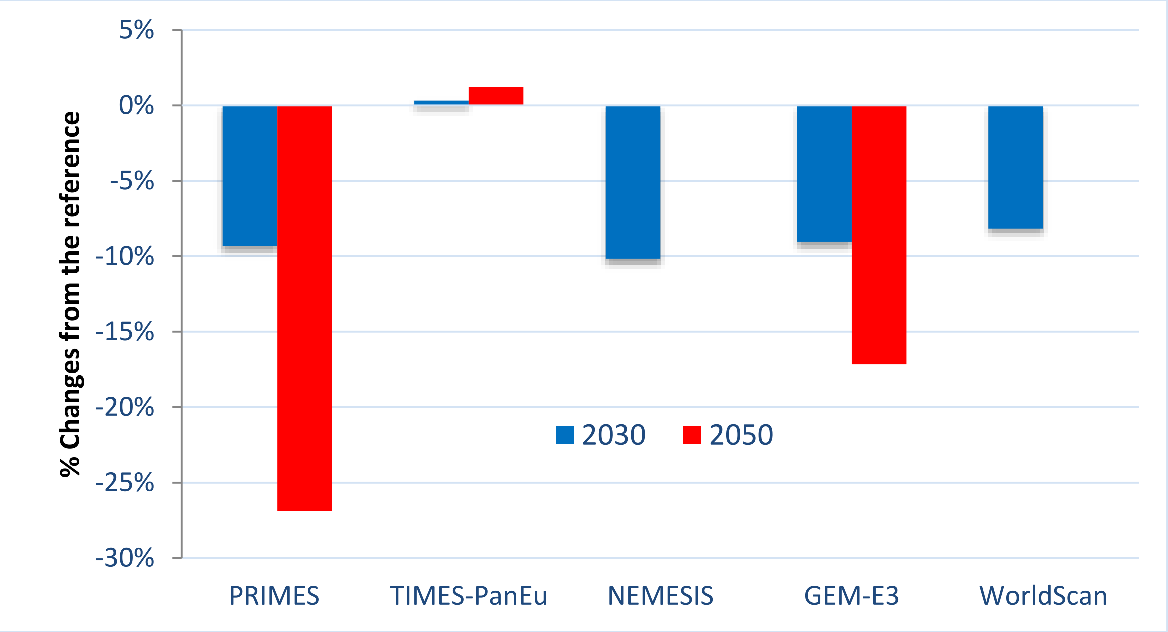
The EU models (excluding TIMES-PanEu) suggest a high contribution of demand-side restructuring (energy efficiency) in the medium term followed by high contribution of carbon-free or low carbon fuel mix on the supply-side in the longer term. GDP feedback effects estimated by GEM-E3 and NEMESIS are rather modest while WorldScan shows that 10% of the emission reduction achieved in 2030 is due to GDP losses.

3.3 Changes in primary and final energy demand

Primary energy demand is projected to be significantly lower in AM5S2 compared to the AM5S1 in all models except TIMES-PanEu (Figure 2). This results from ambitious energy efficiency policies and technological changes. All models show a 10% reduction in primary energy compared to the reference in 2030. The high penetration of energy efficient technologies (like electric vehicles and heat pumps) combined with high renovation rates in buildings and fuel switching in the power generation sector (for example switching from coal to natural gas or wind that are characterized by higher conversion efficiencies) play an important role in the reduction of primary energy demand after 2030. The model assumptions regarding the penetration of the above technologies differ and as a result their primary demand projections vary significantly in the long term.

Decoupling between energy demand and GDP growth is projected by all models both for the reference and the basic decarbonisation scenarios; in the latter the decoupling is significantly stronger. Average annual reduction of final energy intensity of GDP is projected to range between 1.5% and 1.8% in the Reference and 1.7%-2.6% in AM5S2 scenario in the period 2010 to 2050, which is much higher compared to the historical rates of 1.6% p.a. in the 1990-2010 period; thus the models suggest significant intensification of energy efficiency effort as part of the projected decarbonisation pathway.

Figure 2: EU primary energy demand in AM5S2 scenario



All models project significant changes in the shares of energy forms in total primary energy demand in AM5S2 compared to Reference (Figure 3). Zero carbon energy sources[11] see higher shares in the decarbonisation context, as expected. Renewables increase their share in primary energy demand from 9% in 2010 to 22% in 2030 and 42% in 2050, according to both PRIMES and TIMES-PanEu. GEM-E3 projects lower RES shares in total primary energy relative to PRIMES.

PRIMES shows that the nuclear share in primary energy remains relatively constant in the period 2010-2050 whereas it increases from 13.4% in 2010 to 19.3% in 2050 in TIMES-PanEu. This is due to different assumptions about nuclear costs [17] and acceptability[12]. The results of GEM-E3 are also above those of PRIMES. In the context of decarbonisation the nuclear projection is very sensitive to nuclear development limitations applied in the models which are mainly of a political nature.

Lower nuclear deployment in PRIMES (compared to TIMES-PanEu) is compensated by higher use of natural gas. Gas demand is projected to strongly decline in the long term according to TIMES-PanEu. According to PRIMES and GEM-E3 natural gas plays an important role in the medium term, replacing coal in power generation and oil in final energy demand sectors. After 2030, the large-scale deployment of CCS technologies in power generation together with the constantly decreasing gas use without CCS (as a result of high carbon prices) leads to a stabilization of natural gas share in primary energy requirements (around 23% in the period 2030 to 2050).

All models show a continuous reduction of the share of coal in primary energy demand in the context of the decarbonisation scenario, despite the development of CCS after 2030. Models also show a contraction of the predominance of oil in primary energy balance. Oil is increasingly substituted by biofuels and electricity in the transport sector, as this is an effective means for decarbonisation. The degree of reduction of oil demand differs between the two energy models: the higher share of oil in TIMES-PanEu compared to PRIMES is due to lower transport electrification. The macroeconomic models project oil shares similar to PRIMES (28-32% in 2030 and 15-16% in 2050).

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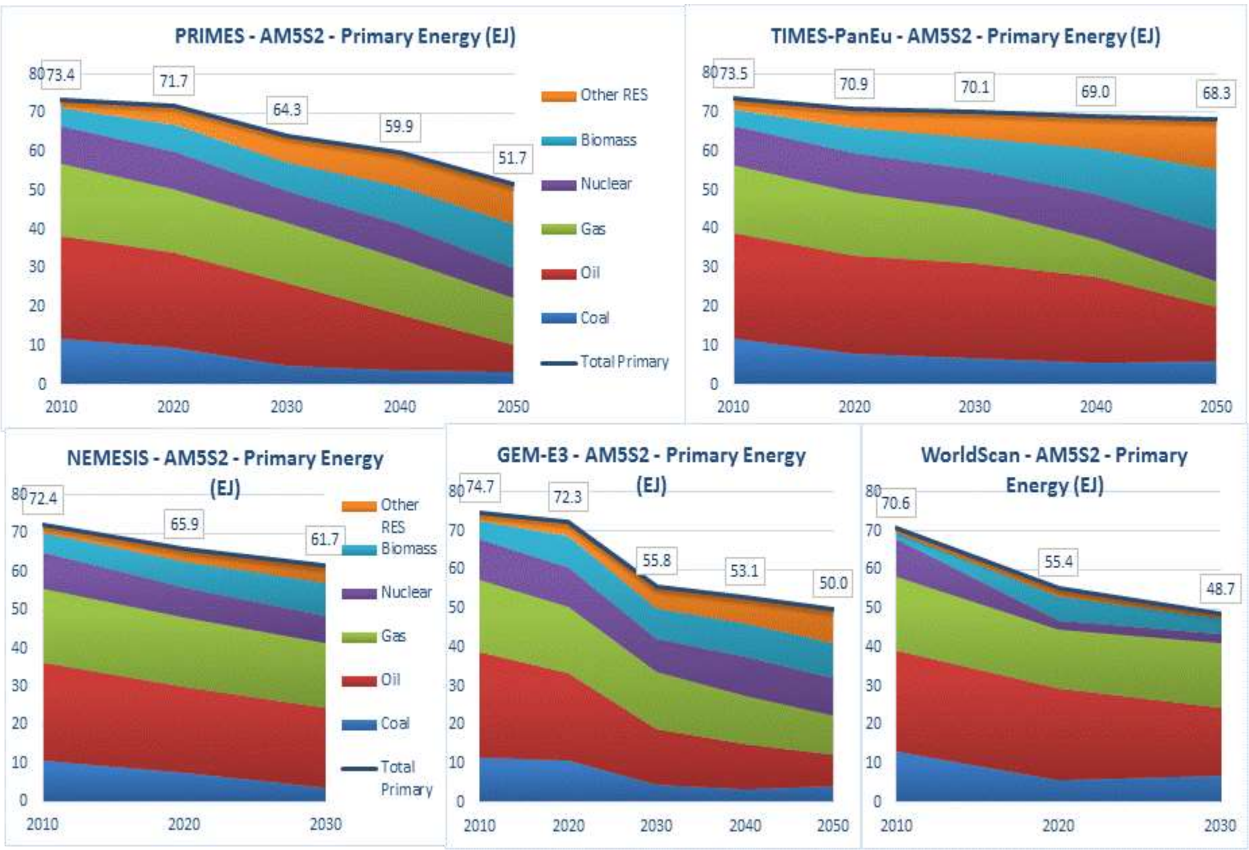
[11] Zero carbon energy sources include biomass (traditional and 2nd generation), non-biomass RES (solar, wind, geothermal, hydro, ocean) and nuclear.

[12] PRIMES assumes that nuclear development has been significantly affected in the aftermath of the nuclear accident in Fukushima in March 2011. Both PRIMES and TIMES-PanEu impose national constraints regarding nuclear, such as countries' decisions not to use nuclear power at all (Austria, Cyprus, Denmark, Estonia, Greece, Ireland, Italy, Latvia, Luxembourg, Malta and Portugal), closure of existing power plants reaching the end of their scheduled life TIMES-PanEu (UK, Belgium, Germany) and implementation of the firmly adopted plans for construction of new nuclear power plants in some EU countries. The differences in nuclear development between PRIMES and TIMES-PanEu models are evident after 2030 and are mainly due to the upward revision of nuclear costs in PRIMES reflecting new initiatives, such as the nuclear stress tests and more stringent safety and waste management regulations which tend to increase the costs for new nuclear plants.

Figure 3: EU primary energy demand in AM5S2 scenario



3.4 Decarbonisation of the power generation sector

The models confirm that decarbonizing power generation and allowing electricity to substitute fossil fuels in inflexible energy uses (mobility[13], heat uses and industrial processing) is a cost-effective decarbonisation strategy. In the decarbonisation scenario total electricity demand increases over time but not above reference levels because the increased electricity demand for transport purposes is compensated by electricity savings using efficient electrical appliances in stationary energy uses. All models show increasing shares of electricity in final energy demand in AM5S2 scenario (Figure 4). Macroeconomic models show higher penetration of electricity in final demand compared to the energy system models. This is probably due to the lack of engineering bottom-up details for the simulation of the energy and power generation system in the macroeconomic models.

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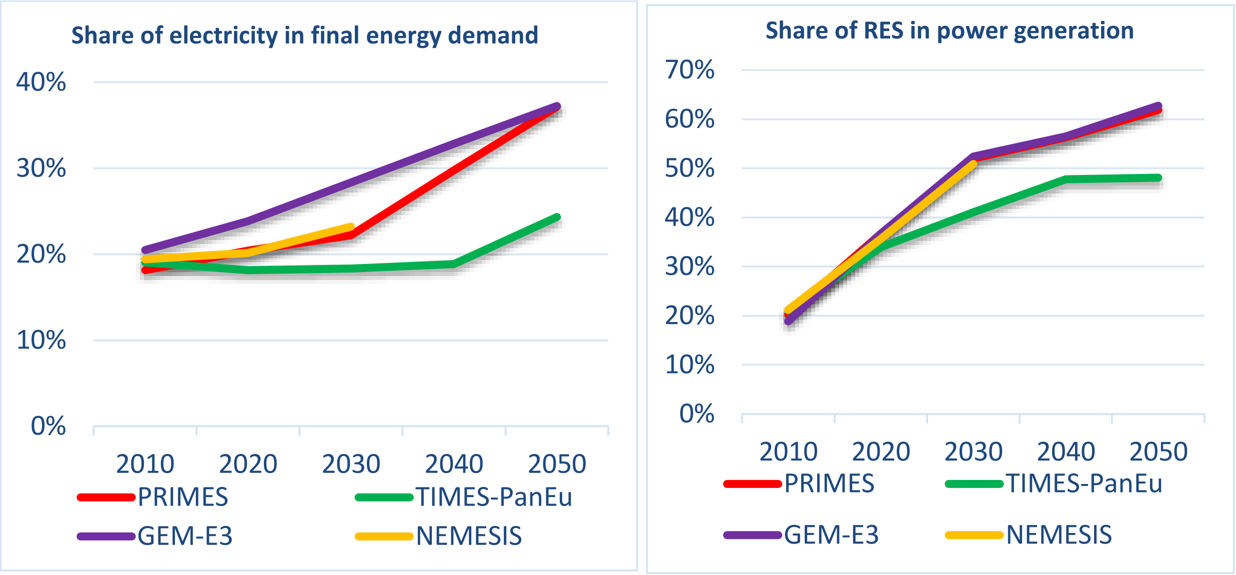
[13] Transport sector is inflexible in reducing oil use; electromobility is attractive in the long term as a decarbonisation option provided that power generation is sufficiently decarbonised.

Figure 4: Electrification of final demand and decarbonisation of electricity production in AM5S2



Decarbonisation of power generation is projected to a significant extent already by 2030. All models project profound changes in the structure of power generation with key role of RES (Figure 4). High ETS carbon prices in the decarbonisation context drive further RES penetration relative to the Reference. The learning process accelerates in the decarbonisation scenario and leads to a reduction of capital costs of RES technologies, mainly for photovoltaics and wind offshore, that facilitates high RES penetration. PRIMES, GEM-E3 and NEMESIS are close to each other in the period 2010-2030. RES share increases to approximately 51-52% by 2030[14]. PRIMES and GEM-E3 results indicate a deceleration in the increase in the RES share in the period after 2030, as specific targets for RES are not included in AM5S2 scenario and the potential for further low-cost RES deployment is limited. RES share reaches 61.7% in 2050 in PRIMES and 62.7% in GEM-E3 in 2050.

TIMES-PanEu shows lower RES shares in electricity production than PRIMES and GEM-E3 in the entire projection period and projects that the share of RES will be lower than 50% even by 2050. The main reason for this is that nuclear energy development is found cheaper than further expanding RES, as TIMES-PanEu assumes a more optimistic evolution of nuclear costs and acceptability relative to PRIMES.

The models show significant penetration of CCS technologies in the power generation sector after 2030. The share of CCS in power generation is projected to be around 20-21% according to PRIMES, TIMES-PanEu and GEM-E3 in 2050; this implies that in 2050 more than 95% of fossil fuel-based power generation (shown in Figure 5) is combined with CCS. All models project oil based

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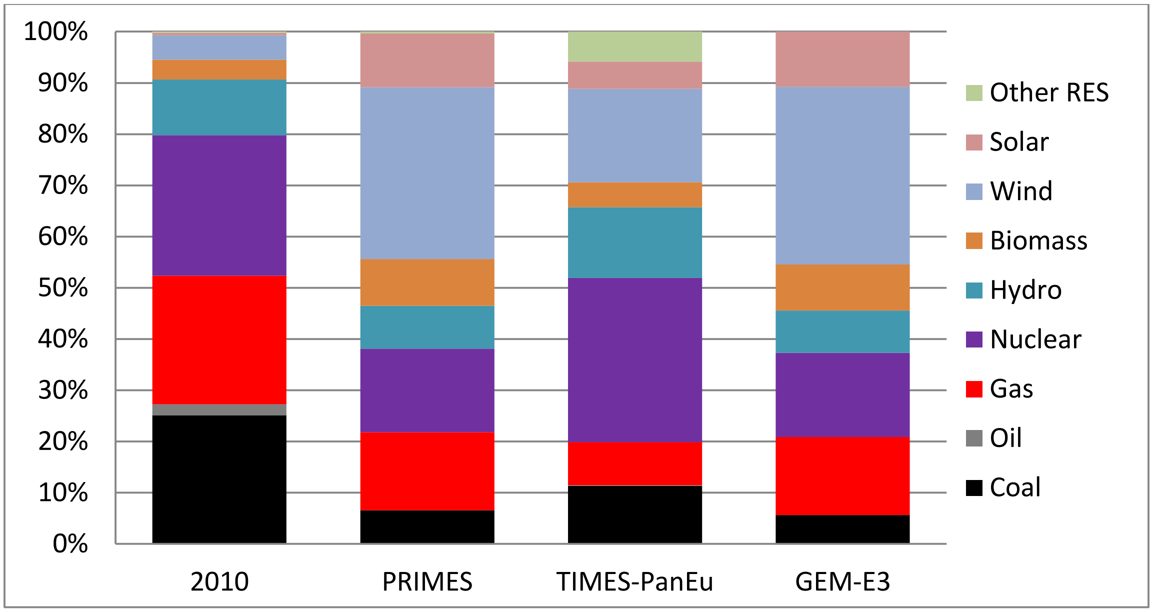
[14] This is in line with the results of the "Diversified Supply Technologies" scenario of the Energy Roadmap 2050, [2].

generation to vanish in the long term, while natural gas maintains a significant share in power generation in the decarbonisation scenario. The energy system models depict an important role for natural gas in the power system with a focus on load balancing and reserve services supporting increasing generation by intermittent RES. The rate of use of gas capacities is projected to decrease from 2010 levels. In 2050, a substantial part of gas generation is based on combined cycle technology equipped with CCS. Detailed model results for the power generation structure and RES penetration in AM5S2 can be found in the companion study [15].

Figure 5: Power generation structure in AM5S2 scenario in 2050



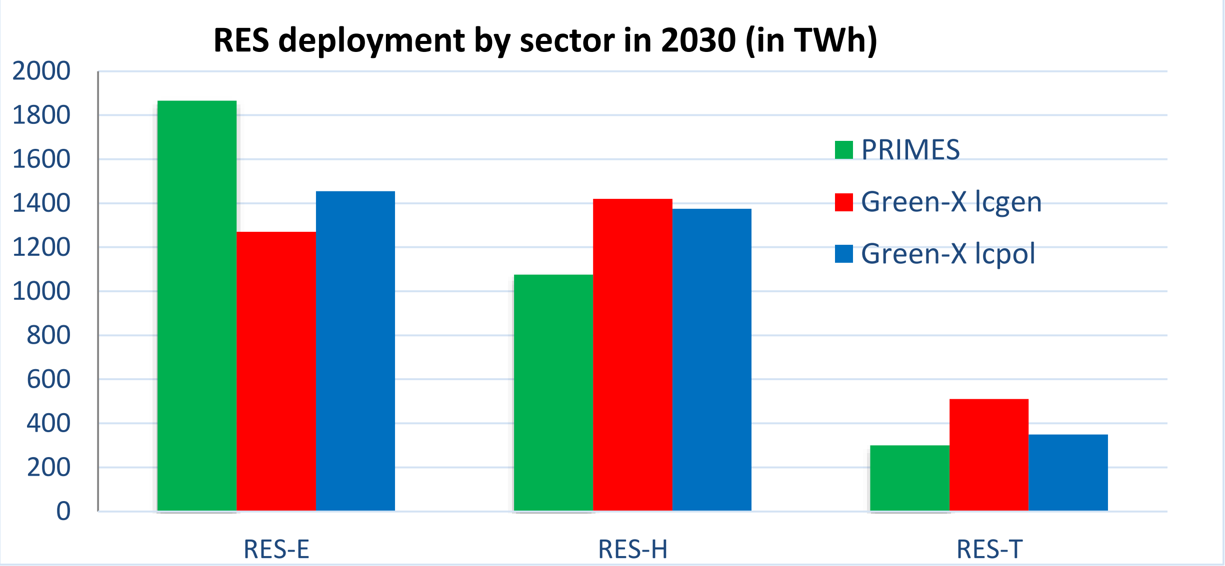
Wind is projected by all models to be the most rapidly increasing source (wind technology is competitive already today for onshore installations) followed by solar, which is assisted by the steady reduction in capital costs of photovoltaics. Hydro generation is limited by available resources and is already today well developed in the EU. Power generation based on biomass and waste energy is projected to develop fast in the medium term and to slow down in the long term because of lack of sufficient biomass feedstock potential in the EU.

3.5 RES penetration (PRIMES and Green-X)

The EU has already adopted autonomous ambitious policy targets for RES deployment (20% share in gross final energy demand by 2020) as part of its Energy and Climate Policy Package [3] and possible RES targets for 2030 are currently under consultation [5]. RES deployment has been further analyzed with Green-X. As the coverage of Green-X is limited to a detailed representation of RES cost-resource curves, the model is calibrated to adapt the total RES production projected by PRIMES, while the choice of the allocation of RES deployment in different technologies, sectors and EU countries is left to the model. In order to reflect the implications of different pathways to reach this target Green-X has been run in two different set-up´s. The first approach (GX-lcgen) assumes a harmonised uniform RES trading scheme in all energy sectors across the EU that gives a strong incentive for the full exploitation of the least-cost options in terms of technologies and site selection, which corresponds to minimising the capital and production costs of the RES portfolio that complies with the overall EU target. In order to incentivise the portfolio from GX-lcgen, some uniform support level tariffication across Europe would need to be in place, which could lead to strong windfall profits of technologies at cheap generation sites. These windfall profits would lead to a redistribution of wealth from producers to consumers and could raise the support expenditures that have to be borne by the consumers. Thus, the second approach (GX-lcpol) provides a more balanced approach that has an emphasis on reducing the RES support costs.

GX-lcgen and GX-lcpol meet the PRIMES RES share in 2030 with GX-lcgen lying much closer to the PRIMES trajectory in the period 2010 to 2030. PRIMES and the Green-X lcgen scenario generally adapt an earlier RES deployment pathway towards the target, while in GX-lcpol the effects of support policies become evident after 2020 when the RES growth rate is comparably steeper. The electricity sector offers more technological options than the heat and transport sectors, while biomass and wind constitute the most important RES options for additional deployment. PRIMES favours RES deployment in the power generation sector (mainly higher deployment of wind technologies), while Green-X puts more emphasis on the heating and transport sectors (solid biomass and biofuels respectively). This is illustrated in the following graph where RES-E, RES-H and RES-T stand for RES deployment in power generation, heating and transport respectively.

Figure 6: RES deployment by sector in AMS2 scenario in year 2030



3.6 The cost of decarbonisation for the EU

Carbon prices are endogenously determined by the models and are used as key drivers for the accomplishment of the emissions reduction objectives. They influence technology choices and the demand behaviour of the energy system agents. Carbon price levels are determined iteratively by the models in order to meet the given carbon budget. All models show increasing carbon prices over time as emissions reduction targets also increase significantly by the end of the projection period (Table 5). Therefore a strongly non-linear marginal abatement cost curve is depicted by the models with strongly increasing marginal costs at emission reduction levels above 60% relative to 1990 emissions. The models register carbon prices that range between 10 and 40 €/tCO_2 for 2020, values close to 100 €/tCO_2 for emission reduction at 60% from 1990 levels (achieved by 2040) and values at much higher levels for the 80% emission reduction achieved in 2050.

PRIMES and TIMES-PanEu projections show similar trajectories of carbon prices until 2040 but they diverge in the last decade. Incremental abatement potential is close to exhaustion according to TIMES-PanEu and so it requires much higher carbon prices in 2040-2050 compared to PRIMES. GEM-E3 registers relatively lower carbon prices than TIMES-PanEu for 2050 as it includes bottom-up formulations mimicking strong energy efficiency improvement and transport electrification which act on top of the effects captured by the constant elasticity of substitution mechanisms.

Table 5: Carbon prices in AM5S2 scenario, in € '05/ tCO_2

	2020	**2030**	**2040**	**2050**
PRIMES	23.7	49.2	95.0	259.9
TIMES-PanEu	41.0	20.8	90.1	565.4
NEMESIS	23.8	60.4		
GEM-E3	10.6	91.4	125.6	243.0
WorldScan	10.0	29.0		

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[15] become more expensive in all 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. As a response to increasing energy costs, the macro-economic models simulate substitution of fossil fuels (that are usually imported in EU) by other energy technologies (zero carbon technologies and energy savings equipment) that are domestically produced and are capital intensive. The additional investment in clean energy

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[15] 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.

technologies increases demand for goods and services that are needed to produce the energy efficient equipment, the clean power plants and for insulating buildings.

The model-based simulations in this paper, in agreement with the literature [9, 10, 11, 12, 14], show that the net effect of decarbonisation on GDP is negative compared to the Reference scenario, because of higher costs which depress demand. Even if the EU builds domestically the required equipment, the corresponding activity is not found sufficiently high to offset the activity depressing effects stemming from higher costs and prices. PRIMES, TIMES-PanEu and GEM-E3 show relatively low cumulative decarbonisation costs for the EU, less than 0.65% of the reference GDP in the period 2015 to 2050 (Figure 7). Cumulative energy system costs are projected by PRIMES and TIMES-PanEu to be less than 0.2 percentage points of GDP higher compared to AM5S1 in 2015-2050. The small costs can be partly attributed to the scenario assumption regarding global participation in the emission reduction effort. In such a global mitigation setting world fossil fuel demand decreases exerting a depressive effect also on international fuel prices[16]. Concerted global climate action reduces decarbonisation costs due to lower EU fossil fuel import prices and due to higher learning for RES technologies induced by their massive global deployment in the GHG mitigation context.

WorldScan projects higher GDP losses than other models (that amount to nearly 1% of the reference GDP by 2030) due to high substitution rigidities and lack of bottom-up mechanisms for the representation of the energy system. NEMESIS shows lower GDP losses compared to GEM-E3 until 2030 due to:

1. The different theoretical foundations of the models (neo-Keynesian vs. General Equilibrium). The model assumptions about the crowding-out of investments, the closure of the markets and the tolerance for current account deficits across the scenarios have an important impact on macro-economic model projections. For a detailed discussion on the GEM-E3 and NEMESIS modelling methodology see Appendix A.
2. Global mitigation effort implies higher costs and depression of demand in the rest of the world, which leads to lower demand for the EU exports and thus reduces EU GDP. GEM-E3 represents endogenously the adverse effects on the EU economy stemming from global climate action whereas in NEMESIS the behavior of non-EU regions is not endogenously projected.

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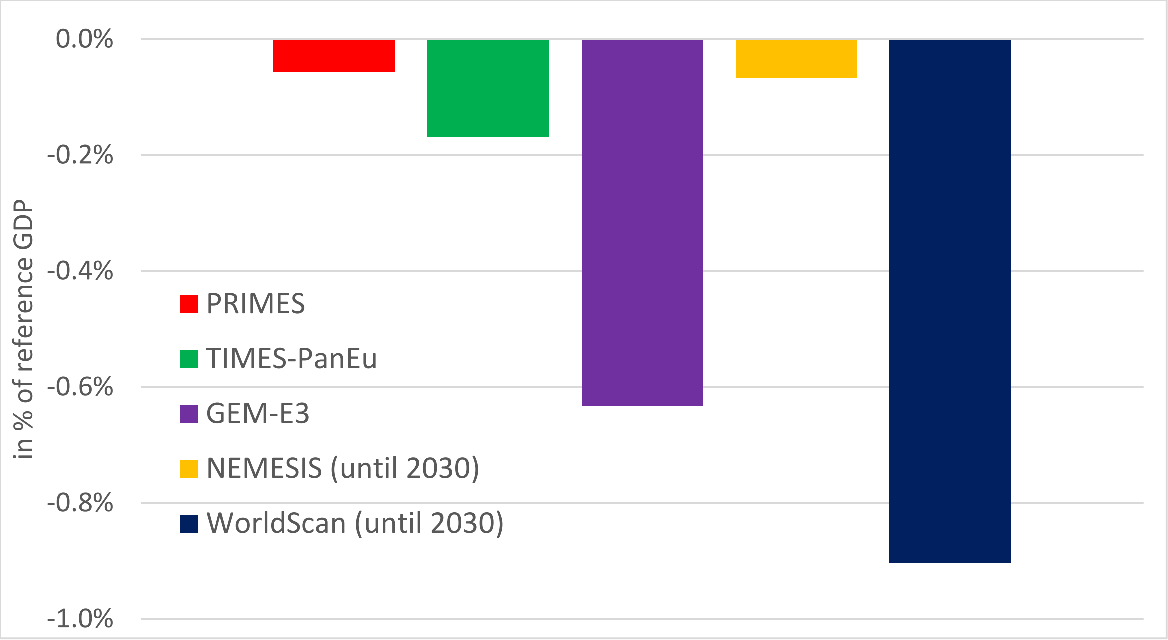
[16] The models assume that the global mitigation effort leads to a 45% reduction in international oil price and 50% in EU gas import price compared to the reference scenario in 2050. These reductions are consistent with the EU Roadmap analysis [1]. However, the assumption about engagement of all world regions in GHG mitigation effort and the depressive effect on international fossil fuel prices is highly uncertain. In the case of unilateral EU climate action, fossil fuel import prices would remain almost unchanged relative to Reference. The drop of fossil fuel prices avoids a cost impact which roughly ranges between 0.7%-0.9% of annual GDP, according to PRIMES, see also [1] and [4].

3. The different recycling scheme of carbon revenues adopted by the models. GEM-E3 assumes that carbon revenues are recycled back to households as lump-sum transfers to support their income loss due to higher energy prices. On the other hand, in NEMESIS carbon revenues are partly used in order to reduce labor costs, through the decrease of social security contributions, and thus exert a positive effect on EU employment.

Figure 7: Cumulative EU decarbonisation costs in AM5S2 scenario (period 2015-2050)



Decarbonisation of the energy system implies shifting demand towards domestically produced goods and services and away from fuel imports. In terms of net effects on GDP, the domestic demand multiplier of zero carbon and energy saving technologies partly compensates for the direct effects of energy costs on GDP. This would lead to net losses of GDP (as projected by the macroeconomic models) to stay at lower levels than the energy system costs as % of GDP as estimated by energy system models. The model results, on the contrary, show higher GDP losses than the energy system costs. There are three explanations for this:

i) Macroeconomic models do not reproduce exactly the energy changes simulated by the energy system models (especially in demand sectors where they have their own mathematical formulations based on aggregate flexible functions such as CES). These functions need to use very high numerical values for elasticities of substitution in order to approximate the substitution flexibility simulated by energy system models in domains such as energy savings and transport electrification. The rigidity of CES implies higher marginal abatement costs, and this is confirmed by the fact that the macroeconomic models generally find higher levels of carbon prices than the energy system models for the same emission abatement.

ii) Decarbonisation implies higher costs and depression of demand also in other regions, which leads to lower demand for EU exports that is detrimental to the EU GDP.

iii) EU imports become more expensive relative to the Reference scenario because of the increases in production costs in other world regions. To the extent that these imported goods are used to produce final goods in the EU, the global GHG mitigation scenario leads to increases in EU production costs, which further compress the EU's domestic demand.

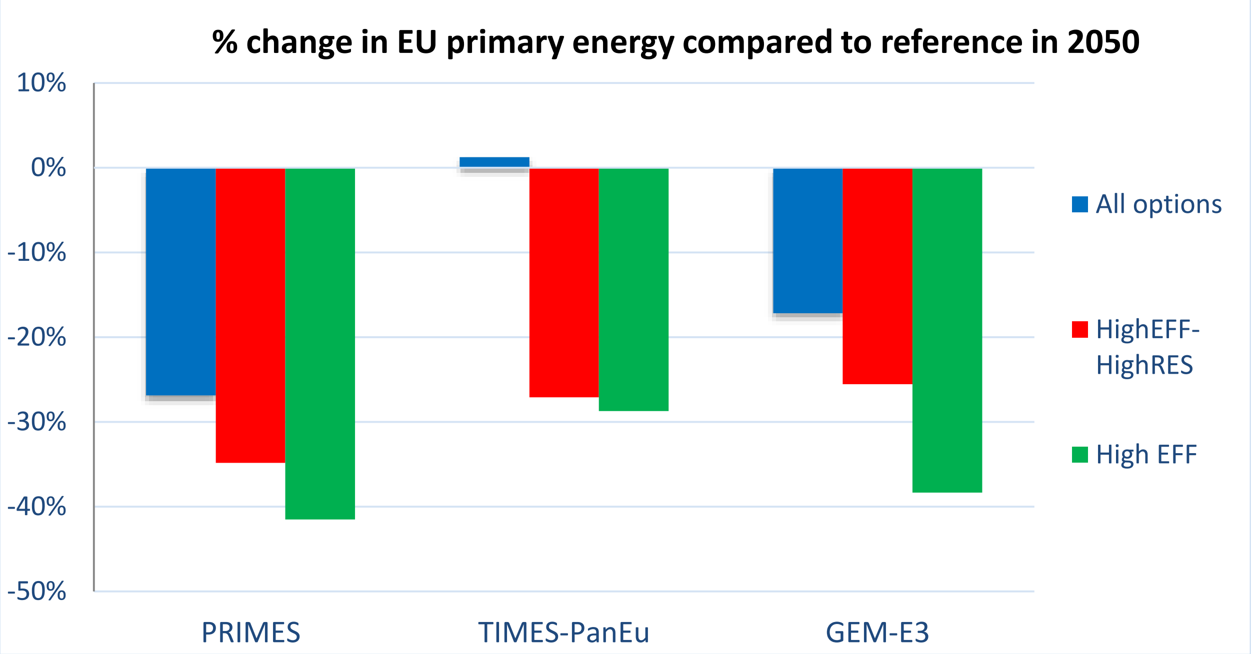
4 Impacts of technological limitations and climate policy delays on the EU decarbonisation effort

Decarbonisation of the energy system in scenario AM5S2 is achieved by combining all options, including energy efficiency gains, higher deployment of RES, extensive transport electrification, development of nuclear power and CCS technologies. The alternative decarbonisation scenarios discussed in this section are designed with the purpose of exploring the impact of limited availability of some of the aforementioned options and possible delays in climate action until 2030. In order to maintain comparability of model results across the scenarios, all decarbonisation cases are designed so as to achieve the same level of cumulative emissions (same carbon budget) equal to the Roadmap carbon budget in the period 2010 to 2050.

4.1 The role of energy efficiency improvements

Scenarios AM5S3 and AM5S4 explore the impacts of high energy efficiency improvements. AM5S3 assumes that the contribution of nuclear and CCS remains at low levels whereas AM5S4 assumes nuclear phase-out and lack of CCS. All models indicate significant amounts of energy efficiency potential which can be exploited in addition to improvements shown in the basic decarbonisation scenario. Primary energy demand can be reduced between 30%-40% in 2050 compared to the reference scenario in AM5S3 and AM5S4 (Figure 8). Final energy intensity of GDP is projected to decline by 68% (median of models) in the period 2010 to 2050 in the High Efficiency scenario. The efficiency potential exploited in AM5S2 is lower because further exploitation is not found to be cost-efficient as cheaper decarbonisation options are available in this scenario, notably nuclear and CCS. The reduction potential of primary energy by 2030 is estimated to range between 12%-18% compared to AM5S1.

Figure 8: Impacts of AM5S2, AM5S3 and AM5S4 scenarios on energy demand



The degree of contribution of energy efficiency improvement to the decarbonisation pathway depends on the cost-effectiveness of energy saving investment and the uncertainty surrounding future energy prices and energy saving technologies that have not reached commercial maturity yet but present high learning potential depending on their choice by consumers. The High Efficiency scenarios (AM5S3 and AM5S4) assume public policy intervention[17] as a means for overcoming barriers (arising from incomplete consumers' information and technology uncertainty) that otherwise would persist if pure carbon pricing strategies were pursued.

In the AM5S3 scenario models show lower carbon prices compared to AM5S2 (Table 6) due to the imposition of energy efficiency policies that allow higher exploitation of the energy savings potential thus leading to lower development of supply-oriented decarbonisation options. On the other hand, carbon prices are considerably higher in AM5S4 due to the lack of nuclear and CCS as these are among the cheapest decarbonisation options in power generation which in this scenario needs to use more expensive emission abatement options. GEM-E3 and TIMES-PanEu show a higher impact of the AM5S4 scenario on carbon prices than PRIMES, because they lack the bottom-up representation of energy efficiency potential details and they also do not explicitly model non-market barriers to energy efficiency. PRIMES includes bottom-up mechanisms to represent energy efficiency policies and explicitly models the removal of non-market barriers in

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[17] That can take the form of campaigns, demonstration projects, support of manufacturers of technology, and regulations (e.g. lighting, car regulations).

the AM5S4 scenario which implies that additional energy efficiency potential is made available at a lower cost.

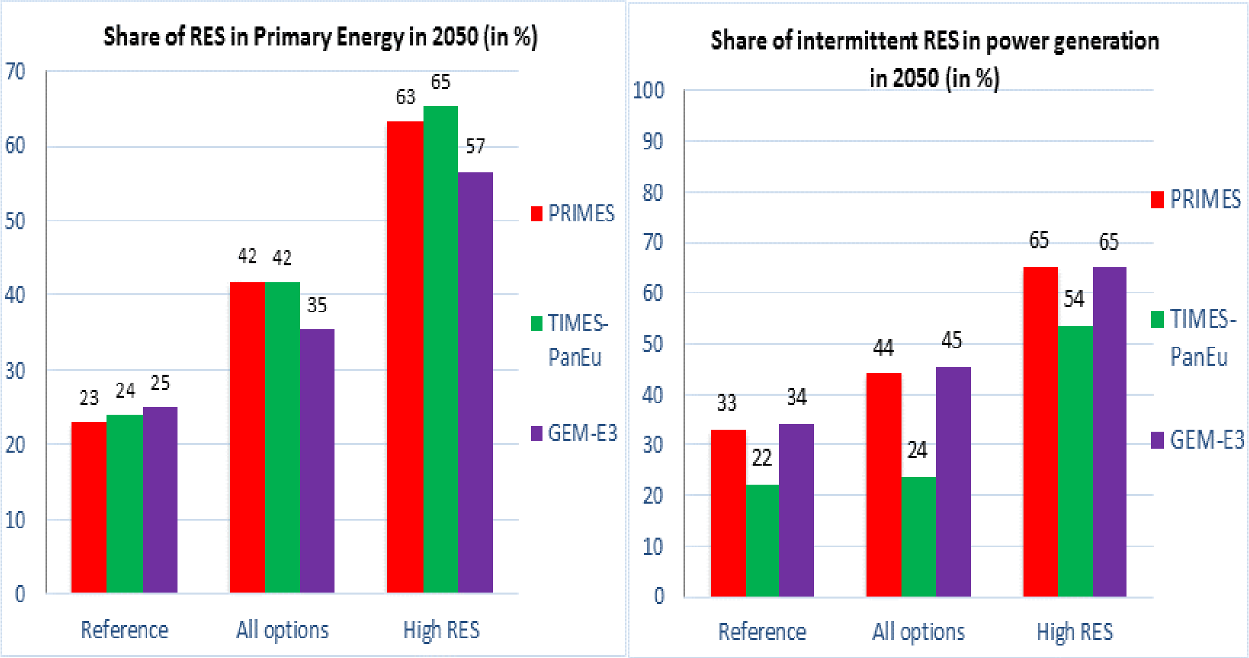
Table 6: Carbon prices in years 2030 and 2050

in Euro 2005/tCO2	2030			2050		
	AM5S2	**AM5S3**	**AM5S4**	**AM5S2**	**AM5S3**	**AM5S4**
PRIMES	49.2	30.3	50	259.9	231.9	354.9
TIMES-PanEu	20.8	97.4	82.3	565.4	251.3	1043.2
NEMESIS	60.4	39.2	39.2	-	-	-
GEM-E3	91.4	64.1	80.4	243.0	210.8	514.7

4.2 The role of RES

Scenarios AM5S3, AM5S4 and AM5S5 project higher development of renewables compared to AM5S2. AM5S3 and AM5S4 imply a reduction in energy demand and so the scope of high development of RES is limited. This contrasts with scenario AM5S5 ("High RES") that assumes higher priority in supporting RES than in supporting energy efficiency. The models show higher RES shares in the AM5S5 case compared to the reference and AM5S2 scenarios; they are projected to reach 57%-65% (across models) of primary energy demand by 2050, while in AM5S2 they amount to 35%-42% (Figure 9).

Figure 9: RES penetration in 2050



The increase takes place mainly in power generation due to limited availability of nuclear and CCS. The share of RES in power generation ranges between 85% and almost 100% in 2050, which is remarkably higher than in the AM5S2 scenario (between 48% and 63%). The almost complete dominance of RES in electricity production is projected to take place mainly post 2030. The share of intermittent RES in power generation reaches high levels, close to 60% by 2050 in the High RES scenario (Figure 9) with high penetration of solar and wind technologies. This underlines that the power generation system, the system services and the grid will have to undergo profound changes in order to comply with decarbonisation requirements in the combined absence of nuclear and CCS. This has tremendous implications on system reliability and requires development of additional resources for storage of electricity, balancing provision by flexible units and long term reserve (from otherwise idle units). Feasibility however is supported by both PRIMES and TIMES-PanEu models that include a detailed simulation of the power system as they take into account the required infrastructure upgrade.

The increased penetration of intermittent RES implies higher power system costs mirrored by increased electricity prices (Table 7). TIMES-PanEu projects higher electricity prices in AM5S3 and AM5S4 compared to AM5S5, which probably is due to higher learning of RES technologies in the latter scenario and to lower impact of fixed costs on electricity prices (as demand for electricity is higher in AM5S5 than in the high efficiency scenarios). In contrast, PRIMES registers bigger increases in electricity prices in the High RES scenario relative to scenarios that assume strong efficiency policies. This reflects high additional storage, balance and grid costs in order to support the increasing intermittent RES penetration.

Table 7: Electricity prices in the EU in the decarbonisation scenarios in 2050

% change from AM5S2	AM5S3	AM5S4	AM5S5
PRIMES	7.6	24.9	35.4
TIMES-PanEu	157.4	179.2	69.7

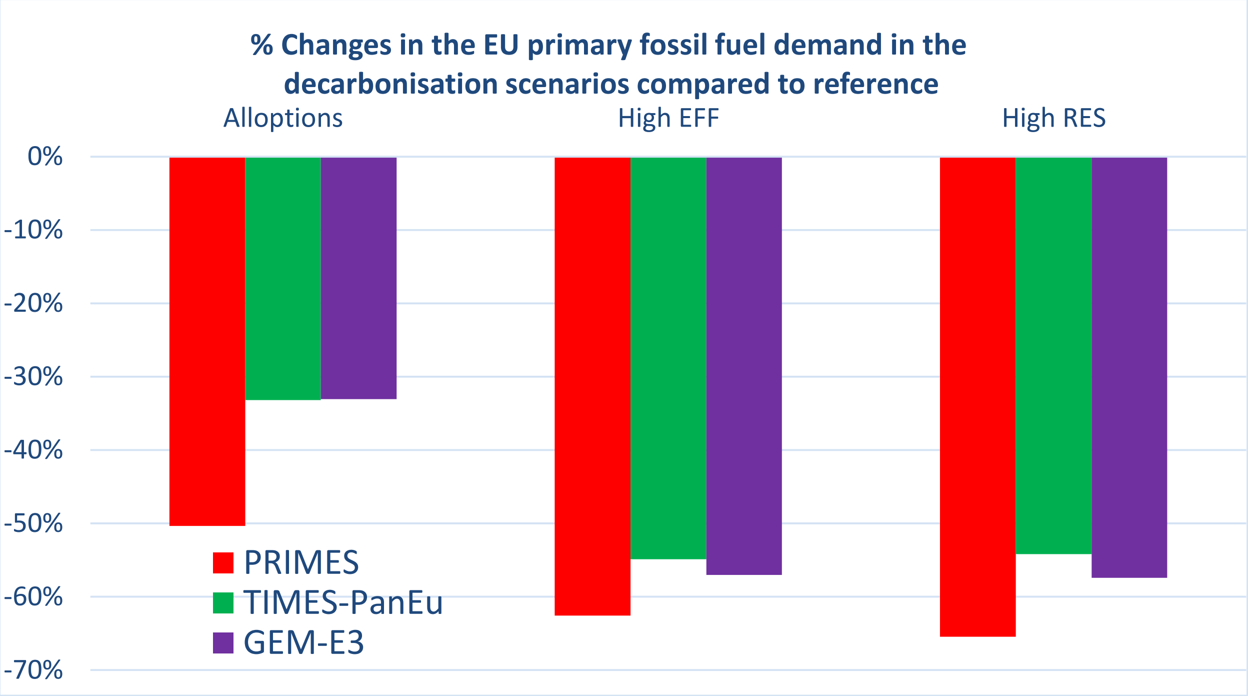
4.3 The role of nuclear and CCS

Nuclear competes against CCS in the market segment for base-load generation due to their cost structure (high capital costs and relatively low variable costs). Scenarios assuming no availability of one of the two options (such as the Energy Roadmap scenarios) have relatively small impacts on generation costs. Impacts are significantly higher when assuming that both options have no/low potential in the future. Lack of CCS implies a further decline of demand for fossil fuels in addition to the declining trend projected in the basic decarbonisation scenario (Figure 10). In the decarbonisation scenarios that combine low CCS deployment with high energy efficiency or high RES, fossil fuel demand is projected to decline by 55-65% compared to Reference in 2050. This translates into 8-9 EJ/year lower fuel imports relative to the basic decarbonisation scenario in

2050 (that is equal to EU-27 gas imports in 2000) implying benefits for the EU in terms of security of energy supply and balance of trade.

Despite the lack of nuclear and CCS, all models have confirmed that the EU stringent emission reduction targets imply that full decarbonisation of power generation is an essential constituent of the decarbonisation strategy. In the absence of nuclear and CCS, power sector will have to deploy renewables on a massive scale.

Figure 10: Impact of low CCS on fossil fuel demand



4.4 The role of transport electrification

Scenario AM5S2 assumes successful implementation of car regulation policies, improvement in technical and economic characteristics of batteries and uptake of electric vehicles by consumers facilitated by timely development of recharging infrastructure. Results show that transport electrification is a crucial element of the optimal decarbonisation strategy. The AM5S6 decarbonisation scenario assumes low transport electrification which implies stressing other decarbonisation options, also in non-transport sectors[18], to perform higher and more costly emission reductions in order to compensate for the lack of emission reduction due to limited electrification in transport. Other decarbonisation options also imply non-linearly increasing marginal costs as they will be required to be used above optimal levels. Therefore, the total (and

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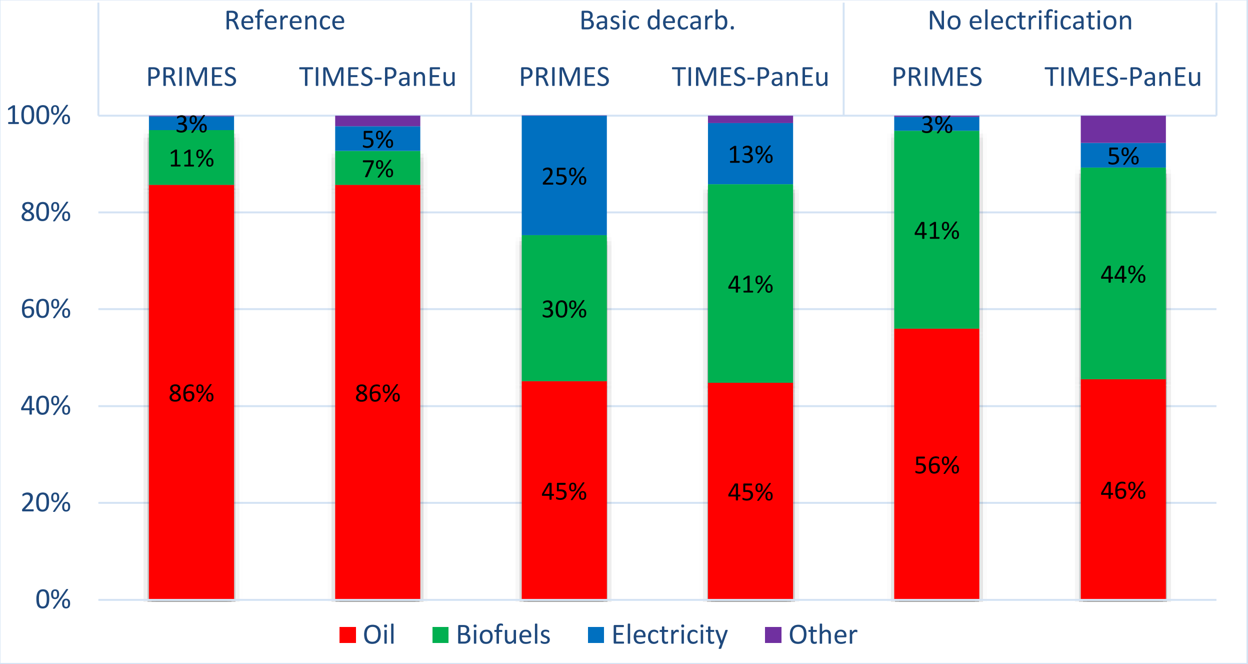
[18] In stationary final energy demand sectors (industries, households, services) and in power generation.

marginal) abatement costs are expected to be higher in AM5S6 relative to the basic decarbonisation scenario.

The share of electricity in transport energy demand in AM5S6 stands at lower levels relative to the AM5S2 scenario, especially in PRIMES where from 25% in 2050 in AM5S2 it drops to less than 3% in AM5S6. The share of electricity is also very low in TIMES-PanEu by 2050 in the AM5S6 scenario. Both PRIMES and TIMES-PanEu show that biofuels have to increase their contribution in transport sector energy needs in AM5S6 to partly offset the emission impact of limited mobility electrification (Figure 11). The additional amounts of biofuels are however rather small because of limitations on EU biomass supply.

Figure 11: Structure of transport energy demand in 2050 in AM5S1, AM5S2 and AM5S6 scenarios



Carbon prices in AM5S6 are considerably higher compared to AM5S2 (Table 8) reflecting the difficulty to pursue strong decarbonisation without transport electrification. GEM-E3 projects a very steep increase of carbon prices after 2030 that reflects substitution rigidities and the difficulty to compensate for emission reductions achieved due to transport electrification.

Table 8: Carbon prices in scenarios AM5S2 and AM5S6

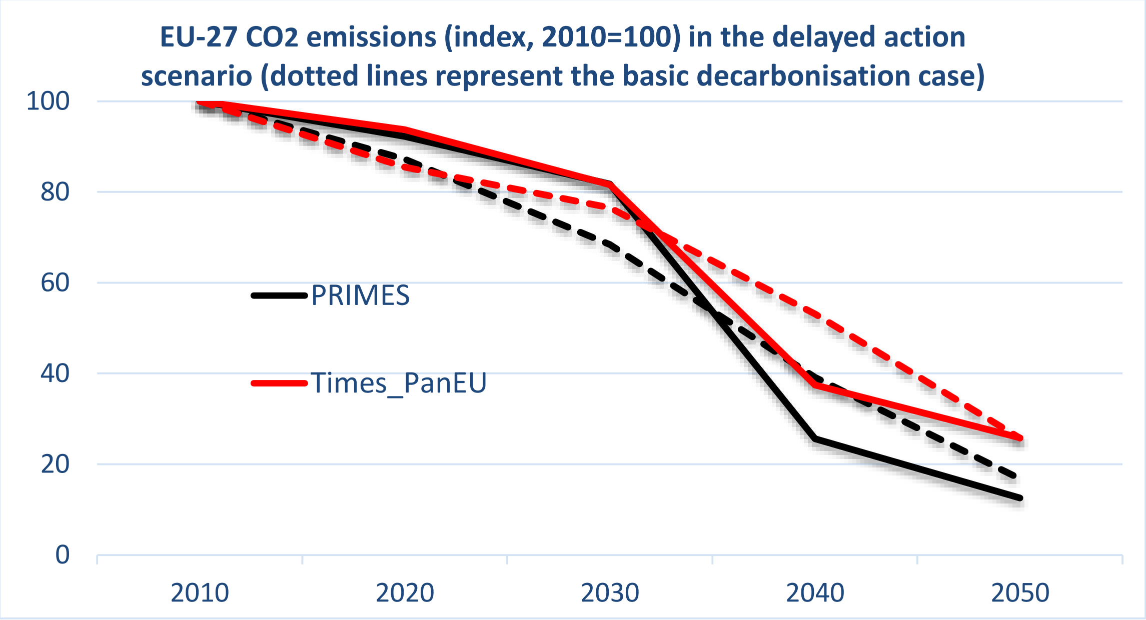
	2030		**2050**	
	AM5S2	**AM5S6**	**AM5S2**	**AM5S6**
PRIMES	49.2	65.0	259.9	299.9
TIMES-PanEu	20.8	22.2	565.4	770.2
GEM-E3	91.4	185.4	243.0	1601.3

The energy system models project that electricity prices increase modestly in the absence of mobility electrification. This happens for two reasons: i) power generation needs to decarbonise further to offset part of the additional emissions in transport and thus requires using expensive segments of RES potential and ii) power load curve is less smooth than in AM5S2 scenario as it is assumed that vehicle recharging is successfully managed by intelligent systems ensuring that recharging takes place mostly in off-peak time segments.

4.5 Delayed climate action

PRIMES and TIMES-PanEu have simulated two additional scenarios, AM5S7 and AM5S8, assuming delayed climate action until 2030 and accelerated emission reduction effort in the period 2030-2050 so as to meet the required cumulative carbon budget in the period 2010-2050. AM5S7 is a variant of AM5S2 and AM5S8 is a variant of AM5S3. Both models require bigger emission reductions in the period 2030-2050 in order to comply with the cumulative carbon budget showing that the most economical way to satisfy the carbon budget constraint is a steeper emission reduction pathway in the decade 2030-2040 (Figure 12) that has adverse effects on decarbonisation costs and questions the feasibility and affordability of these scenarios. PRIMES shows a steeper decarbonisation pathway after 2030 compared to TIMES-PanEu, as the latter reduces non-CO_2 emissions more relative to PRIMES.

Figure 12: CO_2 emissions trajectory in the delayed action scenario

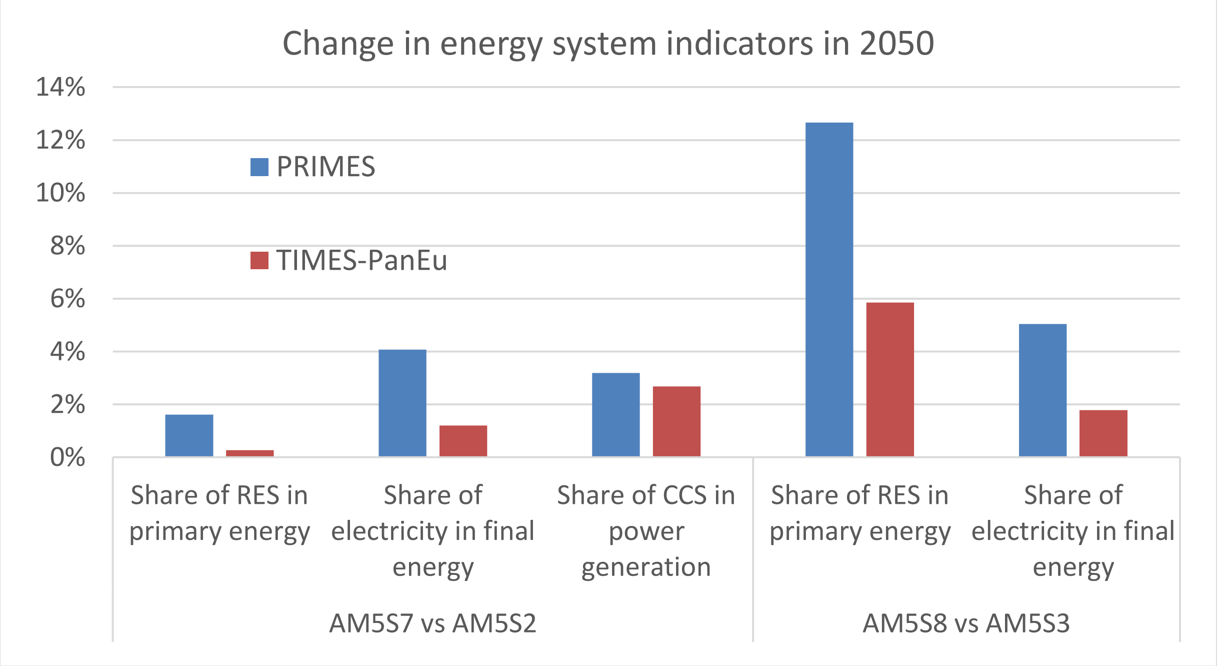


According to PRIMES, strong emission reductions after 2030 have to be met by reducing final energy demand above performance under the non-delayed decarbonisation trajectory. This stresses mainly the buildings sector in which renovation rates have to increase. Costs are influenced by that stress exerting further depressing effects on demand. TIMES-PanEu does not show important demand effects and the required strong emission reductions after 2030 are mostly obtained in the energy supply side, especially in the AM5S8 scenario.

Both PRIMES and TIMES-PanEu show that in order to further reduce CO_2 emissions in the period 2030-2050 beyond the reduction achieved in the non-delaying scenarios, RES have to be deployed at an unprecedented scale (RES share in EU primary energy demand is projected to reach 67% in both models by 2050 in AM5S8 scenario), while electricity has to further penetrate in final energy demand and substitute fossil fuels both for transport and for stationary final uses of energy (Figure 13). After 2030 RES have to increase strongly above levels of non-delaying scenarios, especially in AM5S8 due to the lack of nuclear and CCS options. The strong growth of RES in a rather short period of time implies that expensive segments of RES potential have to be used leading to higher energy system costs.

Delayed climate action until 2030 also implies delays in the construction of infrastructure for CO_2 transportation and storage and in the achievement of commercial maturity of capturing technologies. As a consequence, the prerequisites for successful CCS deployment after 2030 are not fulfilled in the delayed action scenarios and thus costs of CCS technologies increase. Despite the additional costs, the system has to deploy CCS in AM5S7 after 2030 (above the levels of AM5S2) so as to compensate the lack of emission reductions in the previous time period. In both AM5S7 and AM5S8 scenarios, nuclear power is found preferable to develop above AM5S2 and AM5S3 respectively after 2030, due to stronger decarbonisation effort and additional CCS costs resulting from delayed learning and infrastructure development.

Figure 13: Impacts of delayed climate action on the EU energy system



According to PRIMES the stress implied by the additional emission reduction effort after 2030 induces higher carbon prices and hence higher power generation costs and drives electricity prices upward after 2030 compared to the non-delaying scenarios (Table 9). Other possible reasons for electricity price increases include delays in infrastructure development, lock-ins in energy sector[19] and delays in learning progress for RES and CCS technologies which are detrimental for electricity costs and prices after 2030 in the delayed action scenarios.

Table 9: Changes in electricity prices in delayed climate action scenarios in PRIMES

	2030	**2050**
AM5S7 vs. AM5S2	-4.6%	4.5%
AM5S8 vs. AM5S3	2.1%	48.9%

Carbon prices follow the reference trajectory until 2030, but are projected to increase substantially in the period 2030-2050 reaching 962 €'05/tCO_2 in PRIMES and nearly 700 €'05/tCO_2 in TIMES-PanEu in 2050, as delayed climate action until 2030 implies a considerably higher effort in the period 2030 to 2050. If delayed climate policy is accompanied by limited potential of nuclear and CCS deployment (AM5S8 scenario), carbon prices are projected to skyrocket by 2050 reaching extremely high values that question the feasibility of this scenario.

4.6 Cost implications

Lacking some of the emission reduction technologies implies an increase in marginal abatement costs, as some of the remaining options need to be used at levels with higher marginal costs and closer to their maximum potential. Thus scenarios which assume technological limitations (nuclear phase-out, low availability of CCS, delays in electrification of transport) and/or delays in climate policy until 2030 lead to higher energy system costs compared to AM5S2, which performs equally in terms of cumulative carbon budget but uses all decarbonisation options at their economically optimum level.

The absence of nuclear and CCS technologies in AM5S3, AM5S4 and AM5S5 scenarios leads to additional cumulative energy system costs that range between 0.2 and 1 percentage points of GDP compared to AM5S2 in the period 2010 to 2050 (Table 10). A large part of the increased costs are oriented to additional reserve capacity, flexible generation, storage and grid investment that are required for high intermittent RES penetration in power generation mix. The learning potential of RES technologies partly offsets, but cannot cancel out, the additional power system costs.

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[19] Especially with regard to carbon-intensive energy technologies with long lifetime such as coal power plants.

The energy system models show that very high RES deployment (including almost 100% share of RES in power generation in the AM5S5 scenario in 2050) is feasible. In this case decarbonisation becomes more difficult as manifested by significantly rising costs. PRIMES shows that high RES development combined with limitations in nuclear and CCS renders decarbonisation very difficult in economic terms. The models differ in terms of cost evaluations when combining high efficiency with high RES. PRIMES projects lower costs in the energy efficiency promoting scenario in contrast with TIMES-PanEu which estimates lower cost impacts in the high RES scenario. This is due to the detailed simulation of the power system in PRIMES, concerning bottom-up treatment of ramping, balance and reserve requirements and smart grids which are required for integrating large amounts of intermittent RES. PRIMES also shows that the combination of high energy efficiency and high RES (AM5S3 scenario) relieves a part of the additional costs induced by high RES deployment, because the reduced energy demand implies less scope for development of highly costly segments of the RES potential. Both PRIMES and TIMES-PanEu show that AM5S6 also implies higher energy system costs compared to AM5S2, reflecting the higher and hence more expensive emissions abatement effort in non-transport sectors beyond the levels of AM5S2 in order to compensate for the limited mobility electrification.

PRIMES shows that delayed climate policy until 2030 leads to an increase in energy system costs relative to the basic decarbonisation scenario; additional energy system costs amount to 0.6-2.1 percentage points of annual GDP in the period 2010-2050. This is due to the more stringent hence more expensive decarbonisation effort in the period after 2030 and to the cost impacts arising from delays in learning for clean energy technologies (RES, CCS, batteries etc.) and in the timely development of the required infrastructure.

Table 10: Impact of technological and policy failures on energy system costs

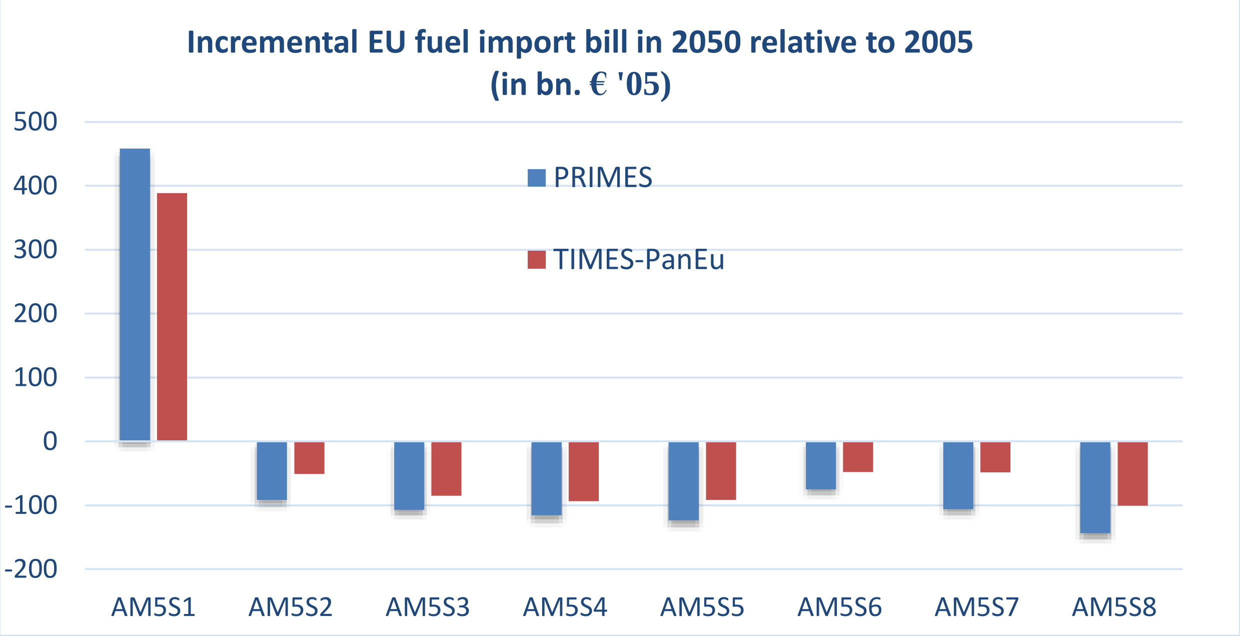
Difference in cumulative energy system costs (as percentage of GDP) relative to the basic decarbonisation scenario in the period 2010 to 2050		
	PRIMES	**TIMES-PanEu**
AM5S3	0.27	0.53
AM5S4	0.57	0.37
AM5S5	0.96	0.18
AM5S6	0.49	0.18
AM5S7	0.60	0.10
AM5S8	2.09	0.27

All decarbonisation scenarios project strong decrease of demand for fossil fuels and thus strong reduction of EU import fuel bill during the period 2005-2050 (Figure 14). The reduction of EU import bill is large relative to the reference scenario already by 2030. This is due to both the reduction of EU fossil fuel demand and the decrease of international fuel prices resulting from global climate action. The cumulative decrease in the EU fuel import bill in AM5S2 compared to the reference amounts to 8.42 trillion € '05 in the 2010-2050 period (1.26% of cumulative EU GDP) according to PRIMES results. If prices remained at the reference levels (in case that the EU unilaterally adopts decarbonisation policies), the bill savings would amount to 4.7 trillion € '08 (0.70% of cumulative GDP). So, the decrease in international fuel prices in the basic decarbonisation scenario is responsible for 44% of the cumulative decrease in the EU import bill in the period 2010 to 2050; the remaining 56% is due to the reduction in fossil fuel demand in the EU.

The decarbonisation scenarios that emphasize energy efficiency and RES lead to a further reduction of 16-40 bn. € '05 in the EU fuel import bill in 2050 compared to AM5S2. On the other hand, the limited transport electrification scenario (AM5S6) leads to a 10% higher fossil fuel import bill compared to AM5S2 in 2050, because of the higher oil imports directed to the transport sector.

TIMES-PanEu confirms the significant savings in the fossil fuel import bill in the decarbonisation scenarios, but at a lesser extent compared to PRIMES. This is related to the distribution of the decarbonisation effort between energy demand and supply. PRIMES projects that demand-side restructuring is responsible for a large part of emission reduction achieved in the decarbonisation scenarios, while TIMES-PanEu shows that decarbonisation is mostly achieved on the energy supply side.

Figure 14: Changes in the EU fuel import bill in the period 2005 to 2050



In the basic decarbonisation scenario (AM5S2), the macroeconomic models project higher cumulative decarbonisation costs than PRIMES and TIMES-PanEu in the period 2015-2050 (section 3.6). The technological constraints and limitations assumed in the scenarios AM5S3-AM5S5 imply additional decarbonisation costs relative to AM5S2 case. The macroeconomic models show that GDP losses in scenarios assuming low nuclear and CCS (compared to the basic decarbonisation case) are modest and remain lower than 0.5% of GDP cumulatively (Table 11). The limited impact of scenarios AM5S3-S5 on decarbonisation costs is partly due to the fact that energy efficiency and RES are more labour intensive than other abatement options having a high activity multiplier which partly offsets the negative effects of higher costs on demand and activity. CGE models are constrained by capital and labour resources and thus part of the beneficial GDP effects of energy efficiency and RES investments is lost due to crowding out effects. The latter are found less intense in the neo-Keynesian model NEMESIS, where capital and labour market constraints are less stringent than in CGE models (thus GDP losses in NEMESIS are much smaller than in the CGE models).

GEM-E3 shows that the lack of electrification in transport and the high carbon taxes, which are required in order to incite additional emissions reduction in non-transport energy sectors compensating for the lack of transport electrification, increase the decarbonisation costs. In this scenario (AM5S6), GDP losses are projected to amount to 0.73% relative to AM5S2 in cumulative terms in the period 2015-2050, while overall EU economic activity stands 3% lower compared to the basic decarbonisation case in 2050.

Table 11: Impact of technology limitations on EU GDP

Cumulative % changes in EU GDP (period 2015-2050) compared to the GDP of AM5S2 scenario			
	GEM-E3	**WorldScan (until 2030)**	**NEMESIS (until 2030)**
AM5S3	-0.27	-0.30	-0.05
AM5S4	-0.43	-0.26	-0.10
AM5S5	-0.13	-0.29	-0.06
AM5S6	-0.73		

5 Conclusions

This paper compares the results obtained from seven large scale energy-economy models on the simulation of the necessary transformations of the EU energy system in order to comply with the GHG emissions reduction target of 80% in 2050 as compared to 1990. This target is consistent with the global target of keeping the temperature increase below 2°C from pre-industrial levels. The multi-model comparison shows some similarities between model results despite the models’ methodological differences, coverage and assumptions that can act as robust conclusions and policy recommendations for energy and climate policy analysts in the EU.

A robust result confirmed by all models is that the EU decarbonisation objective is technically and economically feasible based on currently known technological options, despite the profound structural changes that the EU energy system will have to undergo. The models meet the decarbonisation target at relatively modest costs (lower than 1% of GDP in the period 2010-2050 in cumulative terms).

The multi model analysis confirms the importance of key priorities of the Roadmap 2050 with regards to decarbonisation of power generation, energy efficiency improvements, high RES penetration, transport electrification and development of nuclear and CCS technologies. All models confirm that decarbonising the power generation sector, mainly through higher deployment of RES and CCS technologies and allowing electricity to substitute fossil fuels in inflexible final energy uses like transport is a cost-effective decarbonisation strategy.

The models are used to quantify in depth the impact of possible deviations from the optimal decarbonisation strategy, which may arise as a result of either limited availability of certain decarbonisation options, such as nuclear, CCS and electric vehicles, or delays in implementing the required policies in the decade before 2030. All models identify the existence of large energy efficiency improvement and high RES potential which are not fully exploited in the basic decarbonisation scenario, because they are considered more expensive relative to other emission reduction options (CCS, nuclear and transport electrification). In the case that the deployment of the latter is constrained, all models confirm that energy efficiency and RES have to develop further using high cost segments of their potentials implying increases in carbon prices and energy system costs. A large part of the additional costs will be incurred for further grid investment and for power system balancing, storage and reserve services which are increasingly required in case of high penetration of intermittent RES in the power sector. The learning potential of RES can partly offset the additional power generation costs.

The pursuit of strong decarbonisation policies has positive implications on fossil fuel import bill and the security of energy supply for the EU. The drop in EU fossil fuel imports and the lower international fuel prices assumed in the context of global GHG mitigation effort lead to significant reductions in the EU fossil fuel import bill roughly half due to the fossil fuel savings enabled by decarbonisation and half due to lower world fossil fuel prices.

The model results suggest that the optimal decarbonisation pathway implies at least 40% GHG emission reductions by 2030 below 1990 levels and ETS emissions reducing after 2020 significantly faster than the current stipulation of 1.74% per year. In this context both RES penetration and energy efficiency improvement must accelerate considerably beyond the 2020 EU commitments. The models confirm that meeting 2030 Roadmap milestones implies very small additional energy system and GDP costs (lower than 0.3% of GDP) until 2030 relative to the Reference scenario.

The energy models show that delaying climate action until 2030 would have serious adverse effects on costs if meeting the carbon budget is supposed to take place in the period 2030-2050. If the EU does not pursue strong climate policies and targets for 2030, the energy system models show that a very steep emissions reduction pathway in the decade 2030-2040 has to be followed in order to comply with the cumulative carbon budget of the period 2010-2050. This produces negative effects on energy system costs that increase by 0.6 percentage points of GDP in the period 2010-2050 compared to the optimal non-delaying decarbonisation scenario as a result of higher abatement effort hence higher carbon prices after 2030, lock-ins in the energy sector and delays in RES and CCS technological progress.

Combining delayed climate action until 2030 with technological failures (for CCS and nuclear) implies tremendous adverse effects on energy system costs (that increase by 2 percentage points of GDP according to PRIMES) which render this scenario hardly realistic. This means that in order to be consistent with a cost-effective long-term decarbonisation strategy, in the next decade the EU needs to remove regulatory risks concerning climate policy, to overcome non-market barriers for energy efficiency and renewable energy, to ensure market coordination for timely development of infrastructure (grids, smart metering systems, CCS, recharging infrastructure, energy demand management) and to implement policies aiming at facilitating structural changes both in demand and in supply of energy.

The model-based analysis confirms the importance of pursuing strong climate policies and developing the required infrastructure in the decade before 2030 in addition to the policy commitments for the year 2020. Delaying such policies and failing to deliver the necessary structural changes until 2030 would imply significantly higher costs and seriously undermines the EU system capabilities to reduce emissions in the remaining time period 2030-2050. In this context, a failure in the next decade would entail significant additional costs for energy consumers until 2050.

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Appendix A

Explanation of GEM-E3 and NEMESIS differences

This Appendix supplements Section 3.6 and describes the methodological differences between GEM-E3 and NEMESIS macroeconomic models that affect the model projections for decarbonisation costs.

The NEMESIS model shows a 0.1% cumulative increase in total EU investments by 2030, while GEM-E3 projects a 0.4% reduction cumulatively in the 2015-2050 period. This is largely due to the differences in assumptions about "crowding out" of investments. NEMESIS is a macro-econometric neo-Keynesian model and assumes that it is possible to have a large increase in investments in the energy system (induced from increased decarbonisation effort) without diverting investment from other economic sectors. On the other hand, the GEM-E3 model being a general equilibrium model assumes optimality of investment decisions and is therefore subject to stronger crowding-out effects. This is reinforced by the GEM-E3 assumption to maintain the current account and government savings positions as a percentage of GDP constant across scenarios in order to explicitly rule out the possibility of financing the EU decarbonisation effort from increased borrowing. The decarbonisation restructuring is more capital and material intensive and less fuel intensive compared to the reference scenario. The implied additional demand induces higher investment as it tends to increase domestic activity. This further implies putting 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 as the EU production costs increase due to higher carbon prices. 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 model) then the EU would benefit from higher capital inflows coming from other regions which would of course ease mitigation 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 decarbonisation conditions relative to the reference. In reality, even if such relaxation through the current account balance can be observed during a certain time period, it is unlikely to last over a long period of time. Feedback reactions and adjustments would take place sooner or later. The GEM-E3 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 the 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 implies higher savings, lower private consumption and lower investment under capital mobility conditions ("crowding-out" investment effects).

In the decarbonisation scenarios the EU substitutes the use of imported fossil fuels (coal, oil and natural gas) with domestically produced capital intensive goods and services, which are used to improve energy efficiency and implement the RES and other emission reduction technologies. As a result, overall investments in the EU economy tend to increase in the decarbonisation scenario compared to the reference. On the other hand, the GDP reduction and the deterioration in the EU balance of trade exert a depressive effect on production and investments in several economic sectors. The net effect of the above is highly uncertain and depends crucially on the model assumptions regarding the "crowding out". This is the main reason for the differences observed in the results of the NEMESIS and GEM-E3 models. GEM-E3 is a computable general equilibrium model and imposes capital resource constraints and thus investments needed to decarbonise the energy system imply lower capital availability for agents not involved in the decarbonisation process. This is a crowding out effect that is not taken into account in NEMESIS, which assumes higher capital inflows in the EU from the rest of the World in the decarbonisation scenario relative to the reference case.

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