Description of models and scenarios used to assess European decarbonisation pathways

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ABSTRACT

This study describes the models employed, the main scenario constraints and the energy and climate policy assumptions for a companion study on "European decarbonisation pathways under alternative technological and policy choices: A multi-model analysis". We describe the main characteristics, the coverage and applications of seven large-scale energy-economy EU models used in the aforementioned study (PRIMES, GEM-E3, TIMES-PanEu, NEMESIS, WorldScan, Green-X and GAINS). The alternative scenarios modelled and the underlying assumptions and constraints are also specified. The main European energy and climate policies assumed to be implemented in the Reference scenario are outlined. We explain the formula used for the decomposition of carbon emissions reduction achieved in the basic decarbonisation scenario relative to the reference. Detailed model results for the power generation mix and RES deployment in the basic decarbonisation scenario in the EU are also presented. We conclude the description of our modelling approach with a brief comparison of the strengths and weaknesses of the models used.

1. Introduction

In their study titled "European decarbonisation pathways under alternative technological and policy choices: A multi-model analysis" [1], Capros et al. explore 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 [2, 3], i.e. the 80% GHG emissions reduction target and the equivalent carbon budget by 2050. For this purpose the authors employ seven large-scale energy-economy models, namely PRIMES, GEM-E3, TIMES-PanEu, NEMESIS, WorldScan, Green-X and GAINS, which have been extensively used for the assessment of EU energy and climate policies, in order to simulate alternative EU decarbonisation pathways under technological limitations and climate policy delays. A multi-model inter-comparison analysis is undertaken with regard to decarbonisation strategies, energy system restructuring, associated energy system costs and further macro-economic implications incurred for the EU. The authors expand the model-based analysis provided in the EU Roadmap study [3] by using a variety of well-established energy-economy models for the EU, by considering alternative technological limitations and by combining climate policy delays with technological failures. 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 results show that the EU decarbonisation target is feasible with...
This paper complements in several ways the aforementioned study [1]. Towards this end the paper provides: i) a detailed discussion of the main characteristics of the seven energy-economy models used, including their methodological approaches, theoretical foundations, exogenous assumptions and sectoral and regional coverage, ii) a thorough analysis of the series of scenarios simulated with the aforementioned large-scale models, iii) an extension at a considerable level of detail of the Reference scenario design and the main energy and climate policy assumptions simulated, iv) a presentation of the methodological approach used to decompose carbon emissions reductions in the decarbonisation scenarios relative to the reference and v) an enhancement of the discussion on modelling approaches employed in Ref. [1] with the comparative analysis of the main strengths and weaknesses of the alternative models used.

In this way the paper aims at adding in a systematic way to methodological approaches and simulation alternatives used to model EU energy and climate policies. The thorough review of the methodological approaches of the seven EU energy-economy models is carried out for the first time at such an extent with the aim to improve the transparency of the models used, to enhance the understanding of the model structures and differentials and thus to facilitate future modelling of the energy-economy system. The Reference scenario serves as the benchmark against which the alternative scenarios are studied and compared. The specification of the Reference scenario includes a very detailed assessment of the various energy and climate policies that are already firmly decided by the EU and the member states. The detailed presentation of the series of decarbonisation scenarios complements the discussion on energy and climate policies in the EU and can provide the basis for the future design of similar scenarios for exploring alternative European decarbonisation pathways under technological limitations and climate policy delays.

The remainder of the paper develops as follows: Section 2 describes the models employed in Ref. [1]. Section 3 presents the detailed specifications for the series of the alternative scenarios simulated. Section 4 summarizes the main EU energy and climate policies implemented in the Reference scenario. The methodology used for emissions reductions’ decomposition is presented in Section 5, while Section 6 discusses the model results for the EU power generation mix and RES penetration in the basic decarbonisation scenario. Last section compares the strengths and weaknesses of the models used in the study and concludes.

2. Description of models

The following subsections summarize the main characteristics and applications of the seven large scale EU energy-economy models employed in Ref. [1].

2.1. The PRIMES model

The PRIMES model [4] has been extensively used for energy and climate policy analysis providing key input for benchmark studies of the European Commission [2,3,5]. Other model applications include studies of Refs. [6–8]. PRIMES is a modelling system that simulates a market equilibrium solution for energy supply and demand for the current 28 EU member states until 2050 by five-year periods. The model determines the equilibrium by finding the prices of each energy form such that the quantity producers find best to supply matches the quantity consumers wish to use. The equilibrium is static (within each time period) but repeated in a time-forward path, under dynamic relationships. The model is organised in modules which interact via the exchange of fuel quantities and prices, leading to the overall equilibrium of the energy system.

The model is organized in sub-models (modules), each one representing the behaviour of a specific (or representative) agent, a demander and/or a supplier of energy. The agent’s behaviour is modelled according to microeconomic foundation: the agent aims to maximise its benefit (profit, utility, etc.) from energy demand and/or supply, under constraints that refer to activity, disposable income, comfort, energy equipment, technological options, environment or fuel availability. The agent is assumed to be a price-taker as energy demander and/or a price-maker as energy supplier, depending on assumptions about the prevailing market competition regime. All economic decisions of the agents are dynamic and concern both operation of existing equipment and investment in new equipment. The agent’s investment behaviour consists of building or purchasing new energy equipment to cover new needs, or retrofitting existing equipment or even for replacing prematurely old equipment for economic reasons. Microeconomic foundation is a distinguishing feature of the PRIMES model and applies to all sectors. Although the decision is assumed to be economic, many of the constraints and possibilities reflect engineering restrictions. The model thus combines economics with engineering, in order to ensure consistency. PRIMES is more aggregated than engineering models and far more disaggregated than econometric (or reduced form) models.

All formulations of agent behaviour consider explicit energy technologies, either existing or expected to become available in the future. The technology selection decisions depend on technical-economic characteristics of these technologies, which change over time either autonomously (exogenous) or because of the technology-selection decisions (learning and scale effects). The agent’s investment behaviour, the purchasing of durable goods and the energy saving expenditures involve capital investment, which enter the economic calculations as annuity payments for capital. Annuity payments depend on a (real) interest rate which is assumed to be specific to each agent (sector). Energy prices are calculated from supply costs, fossil fuel import prices and infrastructure costs depending on assumptions about the prevailing market competition regime and price regulations. The prices influence energy demand and so the model simulates a closed loop between energy demand, supply and prices. The model incorporates alternative policy instruments that influence energy demand, supply and prices, such as: taxes and subsidies, tradable certificates, tradable emission allowances, emission limitation standards, energy efficiency performance standards, obligations (e.g. for renewables, CHP,4 etc.) and technology push mechanisms (e.g. promotion of energy savings). Final energy demand in PRIMES comes from three main sectors: industry, domestic (which includes households, services and agriculture) and transport (both private and public transport are included). Within these broad categories the model identifies a variety of subsectors and explicit specific energy uses.

PRIMES includes 72 different plant types per country for the existing thermal plant types, 150 different plant types per country for the new thermal plants and 30 different plant types per country for intermittent

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2 Renewable Energy Sources.
3 Carbon Capture and Storage.
4 Combined Heat and Power.
plants. The electricity and steam production module solves a least-cost non-linear optimisation problem under several constraints, such as electricity demand, operation and grid, reliability and power reserve constraints, fuel availability and their cost/supply curves, policy restrictions. PRIMES represents endogenously load curves, network interconnections (DC linear electricity network), capacity expansion, dispatching of power plants, cogeneration of power and steam, district heating, industrial boilers and their substitution possibilities. The model represents time-of-use varying load of network-supplied energy carriers to synchronize electricity, gas and steam/heat in all sectors of demand, supply and trading. Load curves are computed by the model in a bottom up manner depending on the load profiles of individual uses of energy. The PRIMES modelling suite includes satellite sector-specific models for transport (PRIMES-TREMOVE), biomass supply, gas supply, refineries and hydrogen supply.

The model computes energy related carbon emissions and considers emission-related and technology-related policies and standards. Abatement of energy-related CO₂ emissions is an endogenous result of the model and depends on the energy mix, technological choice of consumers (uptake of low and zero carbon energy technologies), carbon prices and energy efficiency standards. In cases that assume the imposition of a carbon budget constraint, the model considers the shadow value of the carbon constraint, which is termed carbon value and influences demand and supply decisions of agents. A carbon value differs from carbon taxes as it does not entail direct payments, although it may induce higher indirect costs. CO₂ from process emissions are computed through simple relationships which involve physical production of the relevant industrial commodities (e.g. cement). In order to reduce such emissions, the model includes marginal abatement cost curves and CCS technologies. PRIMES also calculates emissions of non-CO₂ GHGs based on calculations using marginal abatement cost curves and projections quantified by the GAINS model of IIASA.

The PRIMES model is used to produce energy outlooks, scenario construction and impact assessment of energy and climate policies up to 2050. The PRIMES’ main output is a fully detailed energy balance per EU country by 2050. The model can support policy analysis in the following fields:

- security of supply, energy strategy, energy system costs
- environmental issues including climate change mitigation,
- pricing policy, taxation, standards on technologies,
- new technologies and renewable sources,
- energy efficiency in the demand-side,
- policy issues regarding electricity generation, gas distribution and new energy forms.

2.2. The GEM-E3 model

The GEM-E3 model [9] 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 transport and employment policies [8,10]. GEM-E3 is handled, operated and maintained by ICCS-E3MLab and by the European Commission at DG JRC IPTS.

GEM-E3 is a multi-region, recursive dynamic computable general equilibrium 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 environmental policies, in particular GHG emission reduction policies. GEM-E3 covers the entire economy and can evaluate consistently the distributional effects of policies on national accounts, investment, consumption, public finance, foreign trade and employment for the various economic sectors and agents across countries. The 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 behaviour of the economic agents which are considered to optimize individually their objectives while market derived prices guarantee global equilibrium. The geographical regions are linked through endogenous bilateral trade (Armington specification). The labour market is modelled following the efficiency wages approach which allows for non-voluntary unemployment and flexibility in wages.

In the standard version, the model includes all 28 countries 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 16) and institutional agents of the economy. Electricity production is depicted in a detailed manner with bottom-up representation of technological aspects of the power generation technologies. A set of production functions explicitly represent competition among the main power generation technologies (coal, oil, gas, nuclear, wind, biomass, solar, hydro, CCS coal and CCS gas). The competition of technologies to meet total electricity demand is formulated through MCP. Similarly, the other emission reduction options are represented in the model, such as energy efficiency improvement, electric vehicles, CCS technologies and biofuels.

The model is able to compare the macro-economic impacts of various environmental instruments, such as 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 revenue recycling. The model calculates the energy-related and non-energy related emissions of CO₂ and other non-CO₂ GHGs, such as CH₄, N₂O, SF₆, HFC, and PFC. There are three 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 a decline in production and consumption, and (iii) purchasing abatement equipment.

2.3. The NEMESIS model

NEMESIS is regularly used to study BAU as well as alternative scenarios for the EU in order to reveal future economics, environmental [11,12] and societal challenges (projections of sectorial employment, short and medium-term economic path, long-term economic path, etc.). It has also been used for policies assessment in terms of research and innovation (Horizon 2020, FP7, 3% GDP RTD objective, etc.), environment and energy policies (European climate mitigation policies, nuclear phasing-out in France, etc.).

The NEMESIS model [13] is based on detailed sectoral models for each of the EU-27 member-states. Each model starts from an economic framework which is linked to an energy/environment module. The construction and the description of macro-economic pathway established by the NEMESIS model could be viewed as a “hybrid”, i.e. “bottom-up” forces resulting from sectorial dynamics and interactions and “top-down” ones coming from macro-economic strength (labour force, international context, financial aspects, etc.). The sectorial interactions come not only from input/output matrix but also from more innovative exchange matrix: knowledge spillovers matrix based on patent data and fed by R&D investments. The NEMESIS model is “econometric”, implying that equations are not directly derived from the traditional optimality condition even if the agents’ behaviour is implicitly governed by utility or profit maximization.

On the supply side, NEMESIS distinguishes 30 production sectors. Production in sectors is in this way represented with CES production functions with five production factors: capital, low skilled labour, high skilled labour, energy and materials. Interdependencies between

* Constant elasticity of substitution.
sectors and countries are finally modelled with a collection of convert matrices describing the exchanges of intermediary 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 enhance these interdependencies. Furthermore, the energy/environment module computes (i) the primary and final energy demand by ten different energy products through CES functions and (ii) the resulting energy related CO₂ emissions.

On the demand side, representative households’ aggregate consumption depends on current income, population structure, etc. Consistent with the other behavioural equations, the disaggregated consumption module is based on the assumption that there exists a long-run equilibrium but rigidities are present which prevent immediate adjustment to that long-term solution. Altogether, the total households aggregated consumption is indirectly affected by 27 different consumption sub-functions through their impact on relative prices and total income, to which demographic changes are added.

External trade in NEMESIS takes place through two channels: intra-EU and extra-EU trade. The intra- and extra-EU export equations are separated into two components, namely income and prices. The stock of innovations 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 as GDP, prices and competitiveness, employment and revenues, the NEMESIS energy/environment module gives detailed results on energy demand by product and sector, on electricity mix and on CO₂ and GHG emissions. The inclusion of detailed data on population and working force in the model allows the projection of many social indicators as employment by sectors and skills, unemployment by skills, etc. NEMESIS can be used for many purposes in order to provide short and medium-term economic and industrial projections and to analyse Business As Usual (BAU) scenarios and economy long-term structural change, research and innovation policies, energy supply and demand, environment and more generally sustainable development.

### 2.4. The TIMES-PanEu model

The Pan-European TIMES model (short: TIMES PanEU [14,15]) is a multi-regional model containing all countries of the EU-27 plus Switzerland, Norway and Iceland. The model minimises an objective function representing the total discounted system costs over the time horizon from 2000 to 2050. A perfect competition among different technologies and pathways of energy conversion is assumed in the model. TIMES PanEU covers on country level all sectors connected to energy supply and demand, namely the supply of resources, the public and industrial generation of electricity and heat, as well as the end use sectors industry, commercial, households and transport. Both, Greenhouse Gas emissions (CO₂, CH₄, N₂O) and also pollutant emissions (CO, NOₓ, SO₂, NMVOC, PM10, PM2.5) are modelled in TIMES PanEU.

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

In the transport sector, road transport, rail transport, navigation and aviation are modelled separately. Road transport includes five demand categories for passenger transport (car short distance, car long distance, bus, coach, motorbike), and one for freight service (truck). Rail transport includes the three categories rail passenger transport (short and long distance), and rail freight transport. The transport modes navigation and aviation (domestic, international intra-EU/extra-EU) are represented each by a non-specified generic process. In each of the transport modes, the model comprises a variety of alternative fuels (e.g. biofuels, methanol, natural gas, LPG, DME, hydrogen, electricity, etc.) and power trains (e.g. hybrid, plug-in hybrid, battery electric or fuel cell electric vehicles) that can be employed in order to achieve ambitious climate targets.

The residential sector contains eleven demand categories (space heating, air conditioning, water heating, cooking, lighting, refrigeration, washing machines, laundry dryer, dishwasher, other electrics, other energy use) of which the first three are specified according to building types (single family houses in urban and rural areas and multi-family houses, each category being separated into stock and new buildings). The commercial sector is represented by a similar reference energy system and consists of nine demand categories (space heating, air conditioning, water heating, cooking, refrigeration, lighting, public street lighting, other electrics, other energy use). The first three of them are subdivided according to different building types (large/ small). The agriculture sector is described by a general process with a mix of several energy carriers as input and an aggregated demand of end use energy as output.

The industrial sector is divided into energy intensive and non-energy intensive branches. While the intensive ones are modelled via a process orientated approach, the other industries have a similar generic structure consisting of five energy services (process heat, steam, machine drive, electrochemical, others). The energy intensive industries consist for example of the sub-sectors iron and steel or the cement industry. In these sub-sectors, next to the use of different fuels or more efficient technologies, there is the possibility to use different production processes to reduce the CO₂ emissions (like electric arc furnaces instead of blast oxygen furnaces or like recycling processes in the aluminium or glass industry). Among the non-intensive sub-sectors, the food and tobacco industry and the other industries are modelled more in detail. These two sub-sectors have an additional demand for space heat, warm water, cooling, lighting and different mechanical appliances. Times PanEU is used for detailed analyses of the emission reduction potentials of the single industrial sub-sector.

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

Due to its high degree of detail, TIMES PanEU considers country specific particularities, e.g., decommissioning curves, potentials for renewable energy production and national carbon storage potentials. An interregional electricity trade is implemented in the model, so that exports and imports of electricity according to the existing border capacities are endogenous to the model. The model is technology orientated and characterised by a comprehensive database which contains various GHG mitigation technologies for all sectors of the energy system (including the different types of CCS power plants), representing a valid basis for this analysis.

### 2.5. The GAINS model

The GAINS model [16,17] is a bottom-up technology-oriented integrated assessment model. It covers some 1000 types of emission sources in all economic sectors in each member state, and estimates the impact of various policies on these. The core of the model is a database of thousands of mitigation technologies, characterized by their unit costs and emission reduction efficiencies. The GAINS model has been used previously, inter alia, in the design of EU air pollutant and mitigation policies, as well as in other policy planning processes in Europe and Asia. For the present study it is used to project the emissions and
Table 1
Specifications of the alternative scenarios considered in the study.

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<th>Scenario code</th>
<th>Scenario name</th>
<th>Scenario description</th>
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<tr>
<td>AM5S1</td>
<td>EU27 Reference scenario</td>
<td>The EU has established an internal target to reduce overall GHG emissions by 20% from their 1990 levels and to increase RES share in gross final energy demand to 20% by 2020. The Reference scenario reflects these policies up to 2020. Beyond 2020, the Reference scenario assumes a linear annual reduction of the ETS cap (−1.74% per year), no additional policies for efficiency and RES (but it may be that measures implemented until 2020 will continue to deliver efficiency and RES facilitation after 2020 without specifying further targets beyond 2020). Limited electrification of transport and non-ETS emissions remaining above the cap specified for 2020. ETS emission targets are implemented by imposing a CO2 (equivalent) tax that leads to the achievement of those targets. Non-CO2 gases and other radiative forcing agents: Models which consider also non-CO2 GHGs (N2O, CH4, SF6, CF4, and long-lived halocarbons) use the resulting CO2-price from the cumulative CO2 budget constraint to price non-CO2 gases (using 100 year GWP as provided in IPCC AR4). Non EU countries are assumed to implement the low end of Cancun–Copenhagen pledges until 2020 and to not intensify their GHG emissions reduction effort after 2020. The EU decarbonisation target is implemented by imposing the cumulative CO2 (GHG) emissions budget (see Table 3). The budget refers to total CO2 emissions from all sectors, excluding the sector LULUCF. The overall carbon budget is imposed on top of the climate policies and measures that were implemented in the reference case (scenario AM5S1) until 2020. A carbon price, ensuring full flexibility of emissions reductions, is established in both ETS and non-ETS sectors after 2025. Foresight models are free to adopt the intertemporally optimal GHG emissions reduction trajectory. This means that emissions reductions in 2020 might deviate from the 2020 emissions reductions in the reference case. All emissions reduction options (including transport electrification) are available and optimistic technical progress is considered regarding the carbon free technologies, especially for RES and CCS in power generation and batteries for electric vehicles. The models decide on the optimal mix of different decarbonisation options and technologies, including energy efficiency improvement in all sectors. Non-CO2 gases and other radiative forcing agents: Models which consider also non-CO2 GHGs (N2O, CH4, SF6, CF4, and long-lived halocarbons), use the resulting CO2-price from the cumulative CO2 budget constraint to price non-CO2 gases (using 100 year GWP as provided in IPCC AR4). Non EU countries undertake strong emission reduction effort for achieving the 450 ppm stabilization target. Carbon budget for the world, i.e. total cumulative CO2 emissions from all sectors including land use, does not exceed 1400 Gt of CO2 in the period 2000–2050 (for the models that do not include CO2 emissions from land use the carbon budget for the period 2000–2050 is 1300 Gt of CO2). Non-CO2 GHGs are priced with the same carbon price as CO2 emissions.</td>
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<tr>
<td>AM5S2</td>
<td>Decarbonisation scenario with high energy efficiency gains and high RES penetration</td>
<td>All decarbonisation options are available (like in the AM5S2 scenario), but emphasis is given to energy efficiency gains and high RES penetration (wind, solar, hydro, biomass, geothermal, tidal, etc.) in the energy mix. Both RES and energy efficiency contribute close to maximum possibilities, but the actual mix is left to be determined by the models. These two options are facilitated by bottom-up policies (standards, financing, obligations, feed-in tariffs, etc.) and technology push. Electrification of the transport sector through the gradual penetration of plug-in and electric vehicles in car stocks is included as a decarbonisation option (like in the basic EU decarbonisation scenario AM5S2). The deployment of other emissions reduction options, specifically nuclear power and CCS technologies, is assumed to be lower than in the AM5S2 scenario. All other specifications of the scenario (including the EU carbon budget in the period 2010–2050 and the climate action assumptions for the non-EU regions) are identical to the basic decarbonisation scenario (AM5S2 case).</td>
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<tr>
<td>AM5S3</td>
<td>Decarbonisation scenario with high energy efficiency gains and high RES penetration</td>
<td>No CCS deployment is allowed in the energy sectors (including industrial applications and power generation). No nuclear power plants beyond those already under construction or firmly planned. In addition, no lifetime extensions beyond the retirement rate assumed in the models are implemented. The nuclear phase out concept is driven by public scepticism about nuclear technology. In this scenario energy efficiency improvements are considered as the most important option in order to achieve the decarbonisation target for the EU-27 member states and a series of bottom-up policies and obligations are assumed to be implemented so as to give first priority to energy efficiency. RES deployment is kept moderate (higher but comparable to the basic decarbonisation scenario). Electrification of the transport sector through the gradual penetration of plug-in and electric vehicles in car stocks is included as a decarbonisation option (like in the AM5S2 scenario). All other specifications of the scenario (including the EU carbon budget in the period 2010–2050 and the climate action assumptions for the non-EU regions) are identical to the basic decarbonisation scenario (AM5S2 case).</td>
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<tr>
<td>AM5S4</td>
<td>Decarbonisation scenario with high energy efficiency gains, no CCS and nuclear phase out</td>
<td>No CCS deployment is allowed in the energy sectors (including industrial applications and power generation). In all the EU member states and for all combinations with fossil fuels (coal and natural gas) or bioenergy due to public acceptability concerns. Nuclear phase out is defined as no construction of new nuclear power plants beyond those already under construction or firmly planned. In addition, no lifetime extensions beyond the retirement rate assumed in the models are implemented. The nuclear phase out concept is driven by public scepticism about nuclear technology. In this scenario energy efficiency improvements are considered as the most important option in order to achieve the decarbonisation target for the EU-27 member states and a series of bottom-up policies and obligations are assumed to be implemented so as to give first priority to energy efficiency. RES deployment is kept moderate (higher but comparable to the basic decarbonisation scenario). Electrification of the transport sector through the gradual penetration of plug-in and electric vehicles in car stocks is included as a decarbonisation option (like in the AM5S2 scenario). All other specifications of the scenario (including the EU carbon budget in the period 2010–2050 and the climate action assumptions for the non-EU regions) are identical to the basic decarbonisation scenario (AM5S2 case).</td>
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marginal abatement cost curves of non-CO₂ GHGs in the EU member states.

2.6. The Green-X model

The model Green-X has been developed by the Energy Economics Group (EEG) at the Vienna University of Technology under the EU research project “Green-X-Deriving optimal promotion strategies for increasing the share of RES-E in a dynamic European electricity market” [18] (Contract No. ENGI-CT-2002-00607). Initially focused on the electricity sector, this modelling tool, and its database on renewable energy (RES) potentials and costs, has been extended to incorporate renewable energy technologies within all energy sectors.

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<tr>
<td>AM555</td>
<td>Decarbonisation scenario with high RES penetration, no CCS and nuclear phase out</td>
<td>No CCS deployment is allowed in the energy sectors (including industrial applications and power generation), in all the EU member states and for all combinations with fossil fuels (coal and natural gas) or bioenergy due to public acceptability concerns. Nuclear phase out is defined as no construction of new nuclear power plants beyond those already under construction or firmly planned. In addition, no lifetime extensions beyond the retirement rate assumed in the models are implemented. The nuclear phase out concept is driven by public scepticism about nuclear technology. In this scenario, RES deployment is considered as the most important option in order to achieve the overall decarbonisation target and thus RES facilitation policies and higher learning by doing for RES technologies are assumed. All RES technologies (including wind, solar, hydro, biomass, geothermal, etc.) penetrate the energy mix and gain higher shares than in the basic decarbonisation scenario (AM5S2). Energy efficiency gains are assumed to be comparable to the AM5S2 scenario. Electrification of the transport sector is included as a decarbonisation option (like in the AM5S2 scenario). All other specifications of the scenario (including the EU carbon budget in the period 2010–2050 and the climate action assumptions for the non-EU regions) are identical to the basic decarbonisation scenario (AM5S2 case). Electrification of the transport sector is not included as an emissions reduction option for the EU decarbonisation effort. Plug-in hybrids and electric vehicles are not introduced massively in the European car stock even by 2050, as a result of significant delays in the improvement of technical and economic characteristics of batteries, delayed development of the recharging infrastructure and low uptake of electric vehicles by consumers. Thus the only option to decarbonise the transport sector is the extensive use of biofuels, which is however constrained by feedstock potential limitations in the EU. All other emissions reduction options (energy efficiency, CCS development, large scale RES penetration in the energy mix, nuclear power) are available, like in the basic decarbonisation scenario AM5S2. All other specifications of the scenario (including the EU carbon budget in the period 2010–2050 and the climate action assumptions for the non-EU regions) are identical to the basic decarbonisation scenario (AM5S2 case). The delayed climate action scenario assumes the achievement of the EU energy and climate package for 2020 (20% reduction in GHG emissions compared to 1990, 20% RES share in gross final energy mix), but it assumes that in the decade 2020–2030 no further climate action is implemented apart the ETS regulations. As a result, CO₂ emissions in AM5S7 scenario are close to the Reference scenario until 2030. After 2030, the EU decarbonisation effort is intensified in line with the specifications of the basic decarbonisation scenario so as to deliver the overall carbon budget (2010–2050) as specified for the series of decarbonisation scenarios. All emission reduction options are available after 2030 and are optimally deployed, but obviously at a much higher degree than in the AM5S2 as emission reduction will have to take place in a shorter period of time. The models also assume lower learning rates for renewables, CCS technologies and batteries until 2030 as an indication of the difficulties to improve technologies in a shorter period of time. The overall carbon budget in the period 2010–2050 is the same as in the basic decarbonisation scenario (AM5S2). The emissions of the period 2010–2030 are subtracted from the total carbon budget of the period 2010–2050 and the remaining emissions are imposed as a constraint in the period 2030–2050. Non-CO₂ gases and other radiative forcing agents: Models that consider also non-CO₂ GHGs use the resulting CO₂-price from the cumulative CO₂ budget constraint to price non-CO₂ gases (using 100 year GWPs as provided in IPCC AR4). Non EU countries undertake strong emission reduction effort for achieving the 450 ppm stabilization target (and the equivalent global carbon budget as specified in the scenario AM5S2) after 2030. In the period 2010–2030, non EU countries follow the climate policies assumed in the Reference scenario. The overall abatement cost curves of non-CO₂ GHGs are in the EU member states. In this scenario, RES deployment is considered as the most important option in order to achieve the overall decarbonisation target and thus RES facilitation policies and higher learning by doing for RES technologies are assumed. All RES technologies (including wind, solar, hydro, biomass, geothermal, etc.) penetrate the energy mix and gain higher shares than in the basic decarbonisation scenario (AM5S2). Energy efficiency gains are assumed to be comparable to the AM5S2 scenario. Electrification of the transport sector is included as a decarbonisation option (like in the AM5S2 scenario). All other specifications of the scenario (including the EU carbon budget in the period 2010–2050 and the climate action assumptions for the non-EU regions) are identical to the basic decarbonisation scenario (AM5S2 case). Electrification of the transport sector is not included as an emissions reduction option for the EU decarbonisation effort. Plug-in hybrids and electric vehicles are not introduced massively in the European car stock even by 2050, as a result of significant delays in the improvement of technical and economic characteristics of batteries, delayed development of the recharging infrastructure and low uptake of electric vehicles by consumers. Thus the only option to decarbonise the transport sector is the extensive use of biofuels, which is however constrained by feedstock potential limitations in the EU. All other emissions reduction options (energy efficiency, CCS development, large scale RES penetration in the energy mix, nuclear power) are available, like in the basic decarbonisation scenario AM5S2. All other specifications of the scenario (including the EU carbon budget in the period 2010–2050 and the climate action assumptions for the non-EU regions) are identical to the basic decarbonisation scenario (AM5S2 case). The delayed climate action scenario assumes the achievement of the EU energy and climate package for 2020 (20% reduction in GHG emissions compared to 1990, 20% RES share in gross final energy mix), but it assumes that in the decade 2020–2030 no further climate action is implemented apart the ETS regulations. As a result, CO₂ emissions in AM5S7 scenario are close to the Reference scenario until 2030. After 2030, the EU decarbonisation effort is intensified in line with the specifications of the basic decarbonisation scenario so as to deliver the overall carbon budget (2010–2050) as specified for the series of decarbonisation scenarios. All emission reduction options are available after 2030 and are optimally deployed, but obviously at a much higher degree than in the AM5S2 as emission reduction will have to take place in a shorter period of time. The models also assume lower learning rates for renewables, CCS technologies and batteries until 2030 as an indication of the difficulties to improve technologies in a shorter period of time. The overall carbon budget in the period 2010–2050 is the same as in the basic decarbonisation scenario (AM5S2). The emissions of the period 2010–2030 are subtracted from the total carbon budget of the period 2010–2050 and the remaining emissions are imposed as a constraint in the period 2030–2050. Non-CO₂ gases and other radiative forcing agents: Models that consider also non-CO₂ GHGs use the resulting CO₂-price from the cumulative CO₂ budget constraint to price non-CO₂ gases (using 100 year GWPs as provided in IPCC AR4). Non EU countries undertake strong emission reduction effort for achieving the 450 ppm stabilization target (and the equivalent global carbon budget as specified in the scenario AM5S2) after 2030. In the period 2010–2030, non EU countries follow the climate policies assumed in the Reference scenario. The overall abatement cost curves of non-CO₂ GHGs are in the EU member states.</td>
</tr>
</tbody>
</table>
Green-X covers the EU-27, and can be extended to other countries, such as Turkey, Croatia and Norway. It allows the investigation of the future deployment of RES as well as the accompanying cost (including capital expenditures, additional generation cost of RES compared to conventional options, consumer expenditures due to applied supporting policies) and benefits (for instance, avoidance of fossil fuels and corresponding carbon emission savings). Results are calculated at both a country- and technology-level on a yearly basis. The Green-X model develops nationally specific dynamic cost-resource curves for all key RES technologies, including for renewable electricity, biogas, biomass, biowaste, wind on- and offshore, hydropower large- and small-scale, solar thermal electricity, photovoltaic, tidal stream and wave power, geothermal electricity; for renewable heat, biomass, sub-divided into log wood, wood chips, pellets, grid-connected heat, geothermal grid-connected heat, heat pumps and solar thermal heat; and, for renewable transport fuels, first generation biofuels (biodiesel and bioethanol), second generation biofuels (lignocellulosic bioethanol, biomass to liquid), as well as the impact of biofuel imports. Besides the formal description of RES potentials and costs, Green-X provides a detailed representation of dynamic aspects such as technological learning and technology diffusion.

Through its in-depth energy policy representation, the Green-X model allows an assessment of the impact of applying (combinations of) different energy policy instruments (for instance, quota obligations based on tradable green certificates/guarantees of origin, (premium) feed-in tariffs, tax incentives, investment incentives, impact of emission trading on reference energy prices) at both country or European level in a dynamic framework. Sensitivity investigations on key input parameters such as non-economic barriers (influencing the technology diffusion), conventional energy prices, energy demand developments or technological progress (technological learning) typically complement a policy assessment.

Within the Green-X model, the allocation of biomass feedstock to feasible technologies and sectors is fully internalised into the overall calculation procedure. For each feedstock category, technology options (and their corresponding demands) are ranked based on the feasible revenue streams as available to a possible investor under the conditioned, scenario specific energy policy framework that may change on a yearly basis. Recently, a module for extra-European trade of biomass feedstock has been added to Green-X that operates on the same principle as outlined above but at a European rather than at a purely national level. Thus, associated transport costs and GHG emissions reflect the outcomes of a detailed logistic model. Consequently, competition on biomass supply and demand arising within a country from the conditioned support incentives for heat and electricity as well as between countries can be reflected. In other words, the supporting framework at MS level may have a significant impact on the resulting biomass allocation and use as well as associated trade. Moreover, Green-X was recently extended to allow an endogenous modelling of sustainability regulations for the energetic use of biomass. This comprises specifically the application of GHG constraints that exclude technology/feeding combinations not complying with conditioned thresholds. The model allows flexibility in applying such limitations, that is to say, the user can select which technology clusters and feedstock categories are affected by the regulation both at national and EU level, and, additionally, applied parameters may change over time.

2.7. The WorldScan model

WorldScan can simulate the economic impacts of climate and air policy scenarios (Lejour et al., 2006 [19]; Bollen and Brink, 2012 [20]), and is a recursive dynamic sectoral computable general equilibrium model fitting in the neoclassical tradition of growth models. The model is calibrated to GTAP-7 and has 5 regions and 18 sectors. Regional disaggregation within Europe concerns old (EU1) and new member states (EU2), the rest of Annex-1 countries, Asia and the ROW. The costs and the potential of emission control options differ significantly between these regions. The sectors represent heterogeneous activities causing emissions of GHGs and air pollutants. We distinguish ETS (electricity and the energy-intensive sector) participating in the EU emission trading system and the other sectors (NETS). Coal, oil and natural gas are primary energy sectors.6

WorldScan simulates deviations from a "Business-As-Usual" (BAU) path by imposing specific additional policy measures such as taxes or restrictions on emissions. The BAU used in this paper is not designed with WorldScan, but instead the model reproduces the main characteristics of the 'Reference' path as well as the development of emissions of CH\textsubscript{4}, N\textsubscript{2}O, and air pollutants from GAINS. Basic inputs for the baseline calibration are time series for population and GDP by region, energy use by region and energy carrier, world fossil fuel prices by energy carrier, and emissions of air pollutants. The electricity technology specification (based on Boeters and Koornneef, 2011 [21]) also incorporates learning-by-doing. Learning rates are taken from the IEA (2009).

The WorldScan model distinguishes five electricity technologies: (1) fossil electricity, (2) wind (onshore and offshore) and solar energy, (3) biomass, (4) nuclear energy and (5) conventional hydropower. Often the approach is to calibrate the BAU, and hence fix the shares of these technologies in total electricity production. In policy scenarios, wind and biomass change endogenously, while nuclear and hydropower are kept at their BAU levels (as in Ref. [21]).

3. Detailed scenario specifications

The alternative decarbonisation scenarios assessed in study [1] include the basic/optimal decarbonisation scenario for the EU in line with the Energy Roadmap 2050 [2] and a series of decarbonisation scenarios under technological limitations (e.g. nuclear power phasing out, non-availability of CCS technologies, limited transport electrification) and delayed climate policy until 2030. All decarbonisation scenarios simulated refer to the time period after 2012. The models respond to future climate policy (in any model variable) in the first

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6 The sector OIl delivers mainly to Petroleum and coal products, which in turn delivers fuels to various sectors (in particular the transport sectors) and to households.
model year (or period) following 2012 and they reproduce historic economic, energy and climate data until 2010/11. Tables 1 and 2 include the detailed scenario descriptions.

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.1

The models implement the energy efficiency and RES supporting policies in the most appropriate way depending on modelling methodology. The macro-economic models used in the study (GEM-E3, WorldScan and NEMESIS) which in general have a less detailed energy sector compared to the energy system models have adopted a simple modelling method for accommodating the scenario assumptions for RES penetration, CCS development and nuclear phase-out, 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). The models that are not inter-temporal assume emission restrictions by year (usually 2020, 2030 and 2050) which are consistent with the cumulative carbon budget of the period 2010–2050 (the annual emission restrictions are different for the delayed action scenarios which are assumed to deliver the same carbon budget but in a shorter period of time). Table 3 contains the EU GHG emissions trajectory imposed in the models in the basic decarbonisation scenario and the cumulative decarbonisation carbon budget in the period 2010–2050.

Table 3
EU GHG emissions trajectory in the basic decarbonisation scenario.

<table>
<thead>
<tr>
<th>Year</th>
<th>GHGs emissions in Mtn CO2-equiv</th>
<th>Cumulative emissions in Gtn CO2-equiv</th>
</tr>
</thead>
<tbody>
<tr>
<td>1990</td>
<td>5532.3</td>
<td>4114.0</td>
</tr>
<tr>
<td>2020</td>
<td>2030</td>
<td>2050</td>
</tr>
<tr>
<td>2010</td>
<td>329.5</td>
<td>305.7</td>
</tr>
<tr>
<td>2011</td>
<td>304.9</td>
<td>33.6</td>
</tr>
<tr>
<td>2012</td>
<td>33.6</td>
<td>9.8</td>
</tr>
<tr>
<td>2013</td>
<td>6.8</td>
<td></td>
</tr>
</tbody>
</table>

Table 4
Key energy and climate policies reflected in the Reference scenario for the EU.

1. Full implementation of the EU Climate and Energy package for 2020 [24]
3. Gradual implementation of the Eco-design Framework Directive and the associated regulations
4. 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)
5. 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 emissions reduction policy in place beyond 2020 and the main driver for the continued emission reductions in the Reference scenario.
6. GHG Effort Sharing Decision [22]. Member states targets for non-ETS sectors are achieved in the period 2013–2020. After 2020, stability but not strengthening of the policy is assumed.
7. Regulation on CO2 standards for vehicles as pertaining over time in the current legislation (emission limits introduced for new passenger cars and for new heavy-duty vehicles)
8. Strong national RES support policies (in line with the RES directive [25]), including feed-in tariffs, subsidies, green certificates, favourable tax regimes, quota systems and other financial incentives as specified by member state and anticipated to strengthen where necessary to meet the RES targets in 2020.

Table 5
EU-ETS cap in the Reference scenario.

<table>
<thead>
<tr>
<th>Year</th>
<th>ETS cap in Mtn CO2-equiv</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>2257</td>
</tr>
<tr>
<td>2011</td>
<td>2257</td>
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<tr>
<td>2012</td>
<td>2257</td>
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<td>2013</td>
<td>2257</td>
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<td>2014</td>
<td>2257</td>
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<td>2015</td>
<td>2257</td>
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<td>2016</td>
<td>2257</td>
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<td>2017</td>
<td>2257</td>
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<td>2018</td>
<td>2257</td>
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<tr>
<td>2019</td>
<td>2257</td>
</tr>
<tr>
<td>2020</td>
<td>2257</td>
</tr>
</tbody>
</table>

Table 6
Cumulative EU-ETS cap in the Reference scenario.

<table>
<thead>
<tr>
<th>Year</th>
<th>ETS cap</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>1548</td>
</tr>
<tr>
<td>2011</td>
<td>1530</td>
</tr>
<tr>
<td>2012</td>
<td>1513</td>
</tr>
<tr>
<td>2013</td>
<td>1496</td>
</tr>
<tr>
<td>2014</td>
<td>1479</td>
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<tr>
<td>2015</td>
<td>1461</td>
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<tr>
<td>2016</td>
<td>1444</td>
</tr>
<tr>
<td>2017</td>
<td>1427</td>
</tr>
<tr>
<td>2018</td>
<td>1409</td>
</tr>
<tr>
<td>2019</td>
<td>1392</td>
</tr>
<tr>
<td>2020</td>
<td>1375</td>
</tr>
</tbody>
</table>

Beyond 2020, the Reference Scenario assumes a linear annual reduction of the EU ETS cap (~1.74% per annum), no additional policies for energy efficiency and RES penetration (but the measures implemented until 2020 will continue to deliver energy efficiency gains and RES facilitation after 2020 without specifying further targets beyond that date), limited electrification of the transport sector and non-ETS GHG emissions to remain below the cap specified for 2020.

Table 4 summarizes the key energy and climate policies assumed in the Reference scenario for the EU. The policies included in the Reference scenario by 2020 are also assumed to apply in the series of decarbonisation scenarios. The Reference scenario for regions outside the EU follows the global Reference policy scenario (RefPol) as described in the AMPERE study [23]. In this setting, non-EU countries are assumed to implement the low end of their Copenhagen pledges up to 2020. After 2020, regions outside the EU are assumed to maintain the level of CO not strengthening of the policy is assumed.


4. Climate policies assumed in the Reference scenario

This section presents the EU energy and climate policies pursued in the Reference scenario (AM5S1), which reflects to a large extent the main policy assumptions of the Reference scenario of the European Commission as specified in the EU Energy Roadmap 2050 [2]. The scenario assumes the operation of the ETS carbon market until 2050 with linearly decreasing allowances and the inclusion of a series of directives on car regulations, energy efficiency standards and air pollution in the member-state legislations. The Reference scenario also assumes the full implementation of the GHG Effort Sharing Decision that establishes binding annual GHG emission targets for non-ETS sectors for the EU member states in the period 2013–2020 [22].

Beyond 2020, the Reference Scenario assumes a linear annual reduction of the EU ETS cap (~1.74% per annum), no additional policies for energy efficiency and RES penetration (but the measures implemented until 2020 will continue to deliver energy efficiency gains and RES facilitation after 2020 without specifying further targets beyond that date), limited electrification of the transport sector and non-ETS GHG emissions to remain below the cap specified for 2020.

Table 4 summarizes the key energy and climate policies assumed in the Reference scenario for the EU. The policies included in the Reference scenario by 2020 are also assumed to apply in the series of decarbonisation scenarios. The Reference scenario for regions outside the EU follows the global Reference policy scenario (RefPol) as described in the AMPERE study [23]. In this setting, non-EU countries are assumed to implement the low end of their Copenhagen pledges up to 2020. After 2020, regions outside the EU are assumed to maintain the level of CO2 (or GHG) intensity improvement at a rate that is roughly consistent with their pre-2020 action.

Table 5
EU-ETS cap in the Reference scenario.

<table>
<thead>
<tr>
<th>Year</th>
<th>ETS cap in Mtn CO2-equiv</th>
</tr>
</thead>
<tbody>
<tr>
<td>2020</td>
<td>2257</td>
</tr>
<tr>
<td>2021</td>
<td>2070</td>
</tr>
<tr>
<td>2022</td>
<td>1909</td>
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<tr>
<td>2023</td>
<td>1871</td>
</tr>
<tr>
<td>2024</td>
<td>1832</td>
</tr>
<tr>
<td>2025</td>
<td>1794</td>
</tr>
<tr>
<td>2026</td>
<td>1756</td>
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<tr>
<td>2027</td>
<td>1718</td>
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<tr>
<td>2028</td>
<td>1680</td>
</tr>
<tr>
<td>2029</td>
<td>1641</td>
</tr>
<tr>
<td>2030</td>
<td>1565</td>
</tr>
</tbody>
</table>

Table 6
Cumulative EU-ETS cap in the Reference scenario.

<table>
<thead>
<tr>
<th>Year</th>
<th>ETS cap</th>
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<tbody>
<tr>
<td>2012</td>
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Table 4 summarizes the key energy and climate policies assumed in the Reference scenario for the EU. The policies included in the Reference scenario by 2020 are also assumed to apply in the series of decarbonisation scenarios. The Reference scenario for regions outside the EU follows the global Reference policy scenario (RefPol) as described in the AMPERE study [23]. In this setting, non-EU countries are assumed to implement the low end of their Copenhagen pledges up to 2020. After 2020, regions outside the EU are assumed to maintain the level of CO2 (or GHG) intensity improvement at a rate that is roughly consistent with their pre-2020 action.
Table 5 presents the annual EU ETS cap assumed for the Reference scenario. Banking is allowed but no borrowing from the future. ETS includes aviation and includes the effects of CDM carbon credits; thus the ETS cap can be considered as applying on domestic EU emissions and CDM is ignored in the modelling.

5. Methodology for decomposition of emission reductions

This section details the methodology used for the decomposition of emissions reductions in Section 3.2 of the main study [1].

With continuing economic growth, GHG mitigation poses a difficult challenge given that meeting higher demand for energy services (mobility, heating and cooling, lighting, cooking, etc.) is part of increasing welfare and rising standards of living. Upward pressure on energy consumption and the corresponding CO₂ emissions from economic growth depends on GDP, which is projected to nearly double between 2010 and 2050 in the EU. The 80% emissions reduction objective in the EU by 2050 will however require deep cuts in energy related CO₂ emissions, which in turn require energy consumption to decrease substantially as well.

A useful tool to analyse the model differences in terms of CO₂ emission reductions is the Kaya identity [26]. In the current study we use an expanded version of the Kaya identity that enables us to decompose emissions into factors denoting energy intensity of GDP, fossil fuel intensity of energy demand and carbon intensity of the fossil fuel mix. The decomposition is carried out using the following formula:

\[
\text{CO}_2 = \left( \frac{\text{Primary energy}}{\text{GDP}} \right) \times \left( \frac{\text{Fossilfuels}}{\text{Primary energy}} \right) \times \left( \frac{\text{CO}_2}{\text{Fossil fuels}} \right) \times \text{GDP}
\]

(1)

The factors in parentheses can be interpreted as primary energy intensity of economic activity (GDP), the share of fossil fuels in total primary energy (one minus the share of carbon free energy sources) and the carbon intensity of fossil fuels mix, respectively. Each model implements the carbon budget target with a different combination of each of the four factors. In order to compare the decarbonisation scenario with the reference case, the terms of the above equation are transformed into a linear expression involving rates of change (equation (2)).

\[
d\ln(\text{CO}_2) = d\ln \left( \frac{\text{PE}}{\text{GDP}} \right) + d\ln \left( \frac{\text{FF}}{\text{PE}} \right) + d\ln \left( \frac{\text{CO}_2}{\text{FF}} \right) + d\ln(\text{GDP})
\]

(2)

The four components of the above decomposition formula are interpreted as follows:

1. A reduction in the ratio of primary energy to economic activity (GDP) corresponds to energy savings enabled by the promotion of energy efficiency policies and standards, such as better buildings insulation, use of more efficient electric and heating appliances, transportation using more efficient vehicles, lower mobility levels, etc., or behavioural changes of energy consumers.

2. A reduction in the ratio of fossil fuels to primary energy can be translated into a higher penetration of carbon free energy sources (RES and nuclear) into the energy mix. RES can provide carbon free energy both for final demand (biofuels in transport, biomass for heat in stationary applications, solar thermal heating, geothermal heat) and for electricity production (wind on-shore and off-shore, biomass and waste, geothermal, photovoltaics, hydroelectricity, tidal, concentrated solar power), while nuclear power is a carbon free power generation source that is fully dispatchable and can economically accommodate base load demand.

3. A reduction in the ratio of CO₂ emissions over fossil fuel consumption corresponds to substitutions within the fossil fuel mix, for example natural gas substituting for coal or oil, and the emergence of Carbon Capture and Storage technologies in the power generation sector and in industrial processes especially after 2030.

4. A change in GDP directly influences carbon emissions, as a reduction in GDP leads to lower energy demand by final consumers that in turn leads to lower carbon emissions both in final energy demand sectors and in the power generating sector. The macro-economic models GEM-E3, WorldScan and NEMESIS are able to quantify GDP impacts implied by decarbonisation, whereas the energy system models, like PRIMES and TIMES, do not include changes of GDP in the decarbonisation scenarios relative to Reference scenario levels.

The decomposition of CO₂ emission reduction is calculated for the basic decarbonisation scenario (AM5S2) relative to the Reference scenario (AM5S1) for all the models participating in the study for 2030 and 2050 and the decomposition results are presented in Table 4 of the main paper [1].

6. Power generation mix and RES deployment in AM5S2

Model projections for the power generation mix in the basic decarbonisation scenario (AM5S2) are illustrated in this section. These projections supplement and expand the analysis in Sections 3.4 and 3.5 of the main study [1].

Fig. 1 depicts the share of CCS in EU power generation in AM5S2 scenario. The models show that CCS is not a meaningful power generation option before 2030 primarily because of technological immaturity, public acceptability concerns with regard to sequestration of large volumes of CO₂ underground and relatively moderate ETS carbon price.
levels. However, the models confirm that CCS technologies are deployed in the basic decarbonisation scenario (cost-optimal) after 2030 as a result of increasing carbon prices. The share of CCS in the EU power generation requirements is projected to reach 20–22% in 2050.

The models show different role for natural gas in electricity production in the period 2010–2050 in the AM5S2 scenario. PRIMES, NEMESIS and GEM-E3 show that the share of natural gas in EU power generation amounts to 20% in 2030 and 15% in 2050 mainly due to the high penetration of gas combined cycle technology combined with CCS after 2030. On the other hand, the share of natural gas in TIMES-PanEu is lower compared to the other models in the period 2010–2050 (Fig. 2), as TIMES-PanEu shows higher deployment of nuclear power plants and coal in combination with CCS technologies relative to PRIMES and GEM-E3 by 2050.

The TIMES-PanEu model shows high deployment of nuclear power in the basic decarbonisation scenario. The share of nuclear power in total EU power generation is projected to increase from 27% in 2010 to nearly 35% in 2040, while the other models (PRIMES, GEM-E3 and NEMESIS) show a constant reduction in the share of nuclear in the period 2010–2050 (Fig. 3). This difference is mainly due to the different modelling assumptions regarding costs for new nuclear power plants and public acceptability concerns in several EU member states.

Fig. 4 shows the RES energy production in the EU by technology in TW h in PRIMES and Green-X models in the basic decarbonisation scenario in 2030. As a general trend it can be observed that the model results are in the same order of magnitude with regard to RES technology contribution. Significant differences between the models occur for solar electricity and wind offshore, which contribute a lot less in the Green-X-lcgen case (and partly in the Green-X-lcpol case), which shows lower deployment of RES technologies with high learning potential relative to PRIMES. In addition PRIMES favours solar thermal over geothermal heat in the heating sector and sees significantly less biomass and waste potential for district heating than Green-X. The different model projections for RES-E (especially wind and solar) and RES-H (especially biomass), already shown in Fig. 6 of the paper [1], can also be observed here. In general, the electricity sector offers more options than the heat or transport sector, while biomass and wind develop as the most important RES technological options in the EU by 2030.

7. Discussion and conclusions

This paper complements the study [1] which uses seven large-scale, well-established energy-economy models in order to analyze alternative decarbonisation pathways for the EU energy system by 2050 under technological limitations and climate policy delays. The methodological approaches, theoretical foundations and coverage of the participating models are presented in detail while useful insights for the design of alternative decarbonisation scenarios for the EU, simulated with the models, are provided.

The set of models used in study [1] and in the present paper include partial equilibrium 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). The GEM-E3, WorldScan and NEMESIS models are able to quantify the macro-economic implications of the alternative decarbonisation pathways for the EU, in terms of GDP and consumption losses and changes in employment, investments and production per economic sector. GEM-E3 and WorldScan represent endogenously the global economy and thus they can also quantify the adverse effects on the EU economy stemming from the global GHG mitigation action and the impacts of the imposition of strong emission reduction policies on the international competitiveness of the European exports.

The partial equilibrium energy system models (PRIMES and TIMES-PanEu) do not include the closed loop feedback of climate policies on the overall economic activity and thus they fail to capture the full economic costs of decarbonisation. On the other hand, they are equipped with a wide portfolio of energy technologies and emissions reduction options both on the demand and on the supply side of energy, they include a detailed representation of the power supply system with bottom-up modelling of engineering constraints and incorporate a disaggregated simulation of the energy markets. Thus they can provide detailed results on the required energy system transformations and on the associated energy system costs in the case of strong decarbonisation effort. Green-X provides a bottom-up simulation for the
deployment of RES technologies in the EU member states, while GAINS explicitly represents thousands of mitigation technologies and projects non-CO2 GHG emissions.

This study emphasizes on the comparison of results obtained using a variety of models, the strengths and weaknesses of the different methodological approaches employed and the combined use of the energy-economy modelling tools in order to overcome specific model limitations and enhance the analysis of climate policies and alternative EU decarbonisation pathways. The macro-economic models usually calibrate the evolution of the energy system, especially the structure of power generation, to the projections provided by the detailed energy system models in order to ensure consistency of their energy projections. For instance, the PRIMES and TIMES-PanEu models simulate in sufficient detail the additional costs for electricity storage, balancing provision by flexible units, grid enhancement and long term reserve that are required for massive penetration of intermittent renewables (wind and solar) in the power generation mix, while GEM-E3, NEMESIS and WorldScan use rather simplistic approaches to model RES integration requirements. Thus the energy system models are used in order to support the feasibility of energy results obtained from the macro-economic models. The results of PRIMES and TIMES-PanEu can also be complemented and compared with detailed technology-rich analysis for RES deployment in the EU member states (provided by the Green-X model) and bottom-up modeling of non-CO2 GHG emissions (provided by GAINS).

The differences in model structure, solution algorithm, theoretical foundations and sectoral and regional coverage reflect different choices on how to best approach the analysis of EU decarbonisation pathways. The technological details in the energy sector, the substitutability of energy carriers and the representation of GHGs are other key model differences that influence model results. The diversity in methodological approaches and model assumptions (e.g. costs of technologies, RES potentials and fossil fuel endowment) and the explicit strengths of the alternative models employed in the study allows us to use the models in a complementary manner in order to provide valuable insights for the formulation and analysis of robust energy and climate policies for the EU.

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