



Shaping our energy system – combining European modelling expertise

Case studies
of the European energy system
in 2050



Imprint

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Disclaimer

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1. Executive Summary

The Energy System Analysis Agency (ESA²) is a lighthouse innovation project of KIC (Knowledge and Innovation Communities) InnoEnergy under the leadership of the European Institute of Innovation & Technology (EIT) and is additionally funded by the State of Baden-Württemberg. Energy system models are combined to analyse the European energy system in collaboration with different research institutes from five European countries within ESA². Energy models are powerful tools for simulating the development of energy systems and energy markets. They can for example be used as test beds for energy policy measures to simulate the impact of different policies on the energy system addressing not only technical aspects of the system but also impacts on the environment, economy and society. Due to the scope and diversity of questions and the different time horizons as well as framework conditions, it is clear that one single method or one energy model cannot answer all questions. Nevertheless, it is very important to be able to cover a broad field of aspects of the whole system when policy or investment decisions are made.

In this consortium's approach, optimisation models, agent-based models, and life cycle assessment (LCA) based approaches have been linked together on a harmonised data basis. ESA² has defined three case studies focusing on different aspects and criteria for assessing the various challenges in order to achieve the EU's decarbonisation objective by 2050. For each case study, ESA² has selected a set of models to be coupled based on the requirements defined by the respective questions in each case allowing an in-depth analysis of the specific research question.

- The title of the first case study is “What is the cost-optimal way of achieving an 80% reduction in GHG emissions in the EU?”. It assesses the cost-optimal pathway of achieving the emissions reduction target without restricting the use of technologies. The aim is to analyse how the future energy system could look like with just one overall, not sector specific GHG target. This cost-optimal case shows a slight increase of primary energy consumption along with the decarbonisation of the electricity sector. Besides renewables, technologies like carbon capture and storage (CCS) or nuclear power play an important role in this case under the estimated future investment costs.
- The question of the second case study is “What are the effects of legally binding targets on the EU energy system?”. The freedom of action is partially limited by considering legally binding renewable energy and energy saving targets. Electricity imports into the EU, mainly from North African solar energy, are higher in this case than in the previous cost-optimal case. This demonstrates that targets for the proportion of renewables and energy efficiency have a strong impact on the European energy system. The adding of normative targets to the EU energy system leads to less flexibility in reaching the GHG emission reduction target. Additionally, single aspects of the future energy system are analysed by applying environmental life-cycle assessment (LCA). This is because a drawback of most energy system models is the insufficient consideration of non-GHG environmental impacts. As an example of an in-depth analysis of the environmental impacts of the energy system transition, an analysis is made of the increasing use of forest-based energy carriers in Sweden. The impact assessment has shown that process improvements in forestry are necessary in order to reduce environmental impacts. This is particularly the case for terrestrial ecotoxicity and marine eutrophication and should help to achieve a wider objective for energy system sustainability.
- The third case study (“How far can we get with a combined energy efficiency and renewable energy supply strategy?”) focuses on the electricity sector. Still assuming a combined renewable energy and energy efficiency strategy, an explorative approach is chosen to determine the feasibility of decarbonising our electricity supply system and quantifying future grid expansion requirements. Due to an increasing electricity demand, the share of renewables in the electricity generation portfolio has to be increased significantly by 2050 in order to achieve the CO₂ emission reduction target. A local shifting of the surplus renewables feed-in, which can be achieved by grid extension,

facilitates the integration of renewables in the European electricity market better than a temporal shifting by storing the electricity.

As more overall results following conclusions can be drawn: Renewables and energy efficiency will certainly dominate, but there is also a need for investment in a diversified electricity generation mix, e.g. fossil power plants with CCS and nuclear. It is obvious that this heavily depends on the development of the costs and also on the acceptance of the technologies. But the results show that normative targets could block cost-optimal use of technologies and that there are partially conflicting targets. The future electricity load curve will be more volatile due to new electricity based appliances, as well as the increased use of heat pumps and electric vehicles. Demand side management (DSM) can also help considerably with the system integration of renewables. From an economic point of view, it makes sense to partly curtail the electricity from renewables that cannot be used and not to store every kWh produced. The expansion of the grid seems to be mandatory to geographically level out the fluctuations of renewable sources. In the short-term there is no need for relevant additional storage capacities. Due to the higher shares of renewables beyond 2030 storage technologies become more and more important. Besides, heating supply should play a more prominent role in the discussion of GHG emission reducing strategies. Finally, the results show negative impacts of an increasing use of biomass on the environment and on human health.

The presented model-based analysis extends beyond the traditional use of models. The ESA² competences in modelling and supporting energy policy analyses including the three case studies in this report create opportunities to look at the European energy prospects from various points of view. The consortium demonstrates that the combination of the model linkage applied and the expertise from a number of reputable European research institutes provide insights into the design of the future EU energy system under the normative GHG emission reduction target from -80% in 2050 compared to 1990 levels. The great benefit of ESA² is that in the cooperation of the research institutions within this KIC InnoEnergy lighthouse project and additionally in the linkage of models, a one-stop-shop for energy system models can be offered.

2. Introduction

A secure and economically efficient energy system is essential for the development of modern societies. The energy challenge is also identified by the European Commission as “one of the greatest tests which Europe has to face” (EU COM 2011c, p. 4). The main goals of the common European energy policy are a low carbon economy, increased competition in the European energy markets, and improved security of supply. Furthermore, it is intended that a European Strategic Energy Technology Plan will be produced to develop technologies in areas such as renewable energy, energy conservation, low-energy buildings, 4th generation nuclear power, clean coal and carbon capture. Underlying aspect of these goals is to limit the global temperature change to no more than 2 degrees above pre-industrial levels.

The importance of the energy sector leads to perseverance in discussions resulting in numerous changes with regard to the political and legal framework conditions, for example concerning CO₂ emission obligations and the support of renewable energies in European countries. Greenhouse gas (GHG) emission reduction targets and objectives for the installation of renewable energies will particularly transform the current energy systems within the coming years. This will necessitate the integration of fluctuating renewables into the energy system as wind and solar power belong to the most competitive renewable technologies. The main challenge in this context is to provide permanent system stability (e.g. through compensation of fluctuations) and security of supply within a system of widespread energy production and a shrinking share of conventional power plants.

To identify adequate strategies to meet these requirements, energy system models are widely used. These models have been developed and applied in energy system analysis since the 1970s, the period

of the oil crises, to analyse the future development of energy systems under different framework conditions. One of the major drawbacks of today's energy system analysis is that most models are applied on a stand-alone basis. Usually one model is focused on a limited number of aspects. To consider spatial or temporal requirements, different models are required. Not only does this arrangement lead to a limited scope of application of each model, but eventually also to a lack of data harmonisation, consistency and transparency if several models are used independently. Furthermore, the integration of environmental analysis models has additional benefits when addressing issues related to energy and environmental policy.

In order to overcome these drawbacks and to exploit synergies between different models the idea of an independent and internationally operating agency called ESA² (Energy System Analysis Agency) has been created. ESA² originated from a lighthouse innovation project which is part of the KIC InnoEnergy formed under the leadership of the European Institute of Innovation & Technology (EIT) and additionally funded by the State of Baden-Württemberg (Ministry for Science, Research and Art). This initiative has been launched by renowned universities and research institutions from five European countries in order to provide qualified decision support for public and private clients in areas related to energy and environmental policy. The approach is based on three main pillars addressing the drawbacks of today's energy system analysis:

- the application and coupling of established energy systems and environmental analysis models,
- a consistent and comprehensive data base, and
- the leveraging of our partners' European-wide experience and competencies.

The agency's work is underpinned by its goal to assess potential pathways towards a low-carbon economy. At the same time ESA² enables decision-makers from politics and economics to use scientific know-how, methodologies and models to analyse their own specific questions. ESA² can draw upon a diverse portfolio of energy system and environmental analysis models (among others TIMES, FORECAST, eLOAD, ELTRAMOD, PowerACE, PERSEUS, and PIAM). This includes:

- conventional bottom-up models with minimisation of energy costs,
- agent based simulation models, and
- hybrid models which merge energy analyses, for example with pollutants emissions and deposition or with environmental impact assessment methods using life cycle assessment approaches.

Furthermore these models have different geographical scopes ranging from a Europe wide coverage to individual countries. Thus, the consortium is capable of analysing a variety of research questions by consolidating these different approaches and models. A flexible tool kit can be created from which different models can be selected and combined in the most suitable way to fulfil the specific demands of clients. In combination with a harmonised data set, ESA² can offer a more comprehensive and consistent energy and environmental system analysis.

This report is the result of the model coupling, adaptations and analyses that have been carried out by the ESA² consortium. The overarching aim of the case studies analysed is to address the question of how the European energy system can be suitably transformed and how the ambitious climate goals in Europe and in the different member states can be achieved in an economically reasonable way. In other words the design of the future energy system in Europe is analysed against a background of a safe, sustainable and affordable energy supply for everyone, together with a strengthening of the European business location. For this purpose ESA² applies its in-depth modelling expertise to provide scenario calculations complementing the EU Energy *Roadmap* 2050, published by the European Commission in December 2011 (EU COM 2011a, referred to as the *Roadmap* in the following). The overall methodological objective has been to demonstrate how model coupling and data harmonisation can lead to superior results in terms of scope, consistency, and transparency. For this purpose a selection and coupling of several models tailored to answer the research questions addressed has been undertaken.

Obviously there are several different questions to be answered on the design of the future European energy system. This requires a combination of models with harmonised input data and well-defined interfaces. Therefore three case studies have been defined and conducted focusing on different

aspects and criteria for assessing the various challenges in order to achieve the EU's decarbonisation objective by 2050.

- The first case study (“What is the cost optimal way to reach -80% GHG in the EU?”) assesses the cost-optimal pathway to achieve the emissions reduction target with no preference as to the technologies applied.
- The room to manoeuvre is partially limited in the second case study (“What are the effects of legally binding targets on the EU energy system?”) by considering legally binding renewable energy and energy saving targets. Additionally, single aspects of the future energy system are analysed by applying an environmental impact assessment method based on a life-cycle approach. This links to the evaluation of environmental aspects of energy scenarios not covered by bottom-up energy system models.
- The third case study (“How far can we get with a combined energy efficiency and renewable energy supply strategy?”) focuses on the electricity sector. Still assuming a combined renewable energy and energy efficiency strategy, an explorative approach is chosen to determine the feasibility of decarbonising our electricity supply system and quantifying future grid expansion requirements.

For each case study ESA² has selected a specific setting of models to be coupled according to their competencies, allowing an in-depth analysis of the specific research question.

The report is structured as follows. In chapter 3 an overview of the applied methods and models is given. This chapter includes a presentation of the model family under the umbrella of ESA² and of the basic model coupling approach. This is followed by the calculation of a reference data set based on the assumptions of the reference scenario in the *Roadmap*. Finally this chapter provides a brief description of each model used in the three case studies. Chapter 4 comprises the outline, results and discussion of each case study. The report concludes in chapter 5 with the main conclusions with regard to potential pathways towards a safe, sustainable and affordable energy supply in Europe by 2050.

3. Methodology

Key messages:

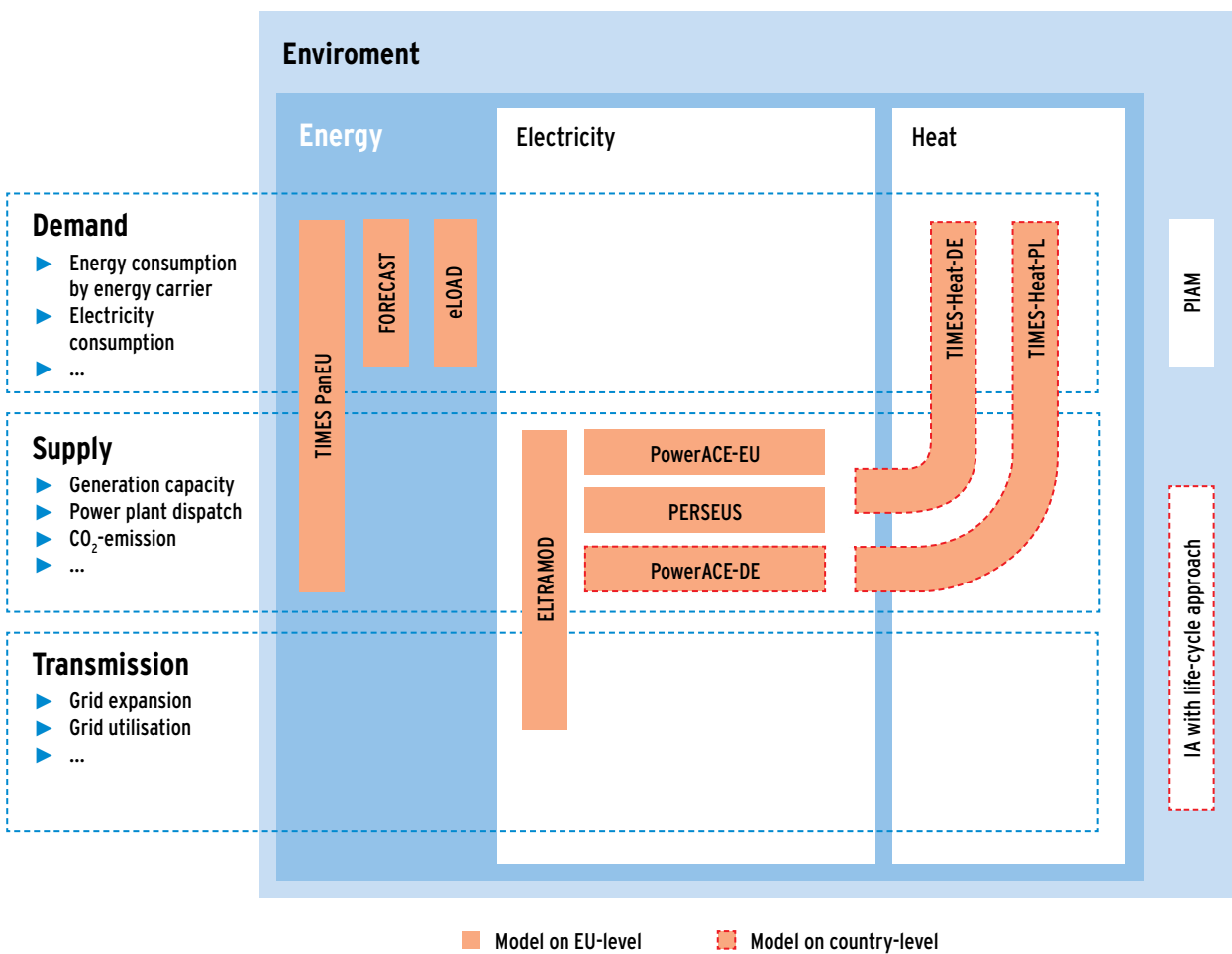
- ESA² combines a high variety of competences in the field of energy modelling in order to answer energy related research questions with an accurate degree of coverage and substantial level of detail.
- ESA² is capable of adequately selecting and coupling its different energy modelling tools, in order to meet the specific requirements of different research questions.
- ESA² has created a common database with an appropriate degree of input data harmonisation, taking into account the special data requirements of each modelling tool.

3.1 Model overview

The ESA² consortium combines a high variety of competences in the field of energy modelling. Within this report, the ESA² consortium has selected a set of complementary models to respond to the research questions posed with an adequate degree of coverage and level of detail. Thereby the consortium has taken significant efforts to join the model competences and to set-up common scenarios and model assumptions. Further a common database was created which includes a harmonised input data set that is used by most of the models. Figure 1 displays the models which are involved in the researches

of this report¹. The models are classified according to their focus within the value chain of energy and according to the energy carriers considered. The miscellaneous models and their corresponding focus allow an in-depth analysis for several research questions. For example, some models focus on the whole European energy system to answer questions at an aggregated level, such as the optimal way to reach the EU renewable targets. Others examine local markets, such as the heat sector in Poland or Germany, in detail. Thus ESA² provides research on different local levels as well as for all steps on the value chain of energy and for all sectors. In addition analysis on environmental impact assessment is also performed by ESA². Due to this wide spread portfolio of ESA², various models can be coupled and/or selected to meet the specific requirements of different research questions. Thereby the strength of each model can be optimised.

Figure 1: Fields of study within ESA² and respective models within this report



To prepare the models and their interaction in the subsequent case studies a reference data set was generated. This allowed a sample of results to be calculated through coupling the models with common reference data. This chapter explains this model coupling procedure as well as the main assumptions of the corresponding reference data (chapter 3.2) and describes each model concerning its research focus, model characteristics and sample results (chapter 3.3).

1 The model portfolio of ESA² is broader than the application in this report. For example, ESA² also uses the global energy system model TIAM (Vito) and the General Equilibrium model NEWAGE (IER). An overview of all models of the ESA² consortium and respective fields of research can be found on the ESA² homepage www.esa2.eu.

3.2 Reference data set

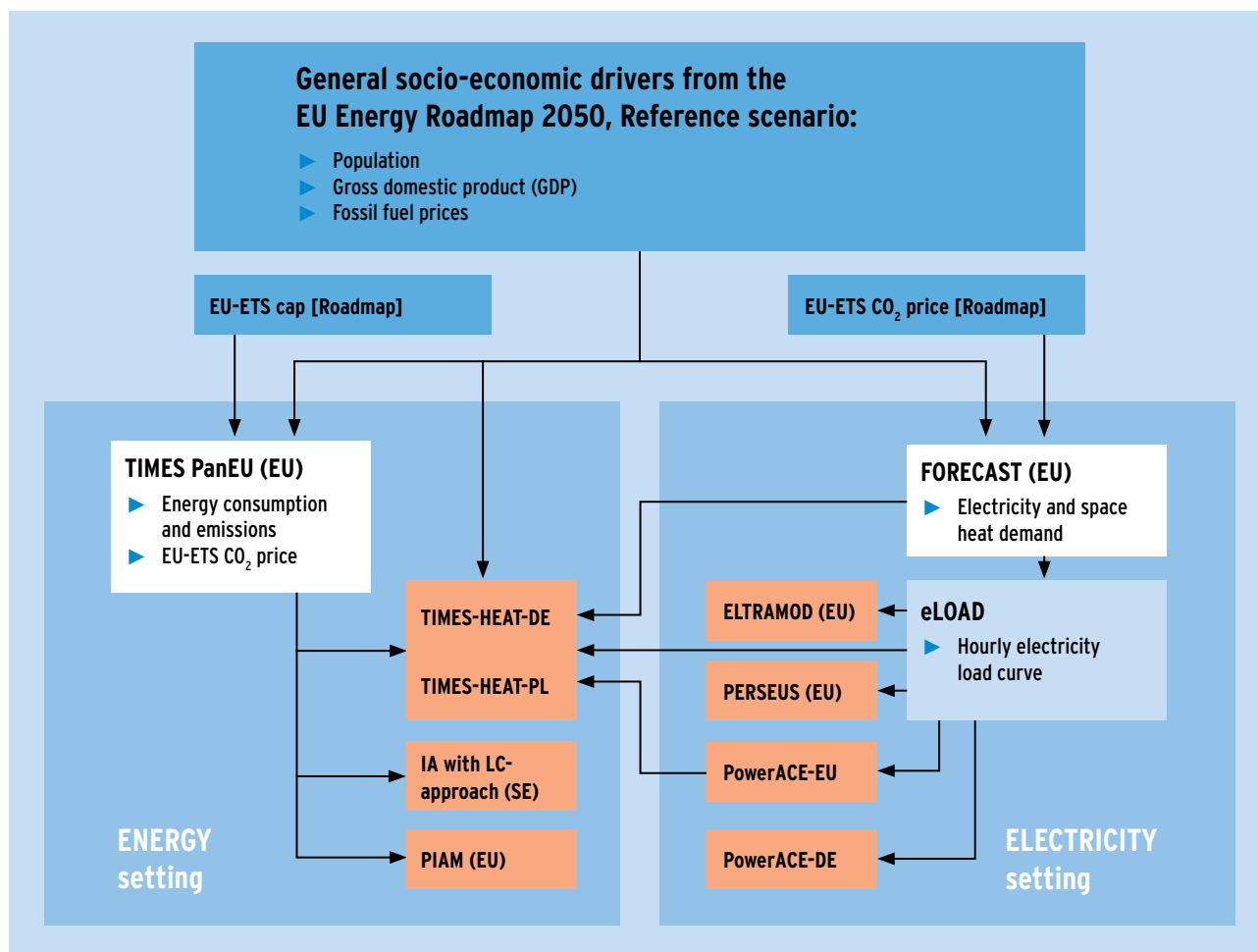
3.2.1 Model coupling

One of the key challenges for the case studies within this report was finding a way of how to couple various energy related models that have different methodical approaches. To combine the strengths of the different models, data has been transferred between them. Certain models use other model's outputs and some results serve as additional inputs for other models. This has been organised within a two settings-approach (see Figure 2): "Energy-setting" and "Electricity-setting". The basic idea behind this is to handle data flows efficiently by grouping models with a similar focus. The broader "Energy-setting" focuses on the general European energy system, whereas the "Electricity-setting" analyses the electricity sector more specifically. Each model setting consists of one broader upstream model, which is independent from other models' results, and further downstream models that use the upstream results as an input.

The upstream model of the Energy-setting is the European energy system model TIMES PanEU. It is used to analyse the development of the whole energy system up until 2050 including all supply and demand sectors, considering the socio-economic drivers from the *Roadmap*. The model output on energy consumption and emissions serves as input to the downstream models: the national heat and electricity market models TIMES-Heat (DE and PL), the European integrated assessment model PIAM and the life-cycle (LC) based assessment models to evaluate the environmental impacts of changed demand for bioenergy. The TIMES-Heat models depict the role of residential heat technologies within the European energy system by offering in-depth analysis of the residential heat systems in Germany and Poland. The LC-based impact assessment (IA) models for bioenergy highlight the importance of broadening the scope to include environmental assessments, given the increasing role that bioenergy can be expected to play in a future energy system. As for the two models just mentioned, the current IA is an in-depth country-specific analysis, in this case for Swedish forest bioenergy, and is an example of how such an assessment may be used for the wider energy system in future work. PIAM shows the link between human-caused drivers (e.g. energy use), environmental pressures (e.g. emissions), and consequent changes of the environmental state (e.g. change in concentration of pollutants) as well as resulting impacts on ecosystems and human health.

The Electricity-setting has a particular focus on the European electricity sector. By using the European demand projection model FORECAST as the upstream model we assess how annual electricity demand will evolve by the year 2050 considering the socio-economic drivers from the *Roadmap*. In a second step the demand projection is transformed into hourly national load curves by applying the load curve adjustment model eLOAD. The load curves are then matched with the capacities and the generation from Renewable Energy Sources (RES) which is taken from the *Roadmap* in the PowerACE-EU and the ELTRAMOD model. While the first model has a clear focus on the power plant dispatch, the second model assesses in detail the required grid infrastructure and storage capacities. The models PERSEUS, PowerACE-DE, TIMES-Heat-DE and TIMES-Heat-PL carry out the capacity investment analysis and the resulting power plant dispatch considering very specific framework conditions on a national level.

Figure 2: Model coupling - assumptions and data flow for the calculations of the reference data set



3.2.2 Assumptions

Each ESA² model has its own dynamic development and corresponding assumptions meaning that each model has specific exogenous model drivers (inputs) and specific endogenous variable results (outputs) (see model descriptions in chapter 3.3). The reference data set imposes specific policy assumptions on top of these settings. These mainly follow the assumptions of the reference scenario of the *Roadmap*. This is a projection aimed at providing an “analysis of possible future developments in a scenario of unchanged policies” (EU COM, 2011a). Unchanged policies refer to those policies implemented by March 2010. There is no GHG emission reduction target beyond 2020 besides the EU Emissions Trading System (EU-ETS) directive. Furthermore, assumptions on the macroeconomic framework regarding GDP development as well as assumptions on ETS targets, fossil fuel prices and ETS prices are included²:

² The complete set of assumptions will be published on the ESA² homepage www.esa2.eu in April 2013.

- The GDP growth rate is assumed to be 1.7% p.a. on average for 2010-2050.
- Fossil fuel prices are assumed to rise constantly. The oil price, for example, is assumed to be 106 \$/barrel in 2030 and 127 \$/barrel in 2050 (at 2008 prices).
- The emissions cap for the EU-ETS sectors is cut from 2379 Mt CO₂ in 2005 to 1717 Mt CO₂ in 2030 (-28%) and 1227 Mt CO₂ in 2050 (-48%).
- Correspondingly, the ETS carbon price rises from 40 €/t CO₂ in 2030 to 52 € in 2040 and flattens out to 50 € in 2050.
- Regarding carbon assumptions, the Energy-setting draws upon carbon quantities in terms of the EU-ETS CO₂ cap whereas the Electricity-setting uses carbon prices in terms of the EU-ETS CO₂ prices.

Furthermore, harmonised assumptions have been made for all case studies and models on the discount rate as well as on investment costs and efficiencies of electricity and/or heat generation facilities. Given the fact that the data from the *Roadmap* is only available at EU level, a break-down at a national level was carried out for specific issues (e.g. share of renewable energies). This was based on historic figures and scenarios from other studies, ensuring that the overall sum of the national figures is nearly identical to the EU data of the *Roadmap*.

3.3 Model description and sample results

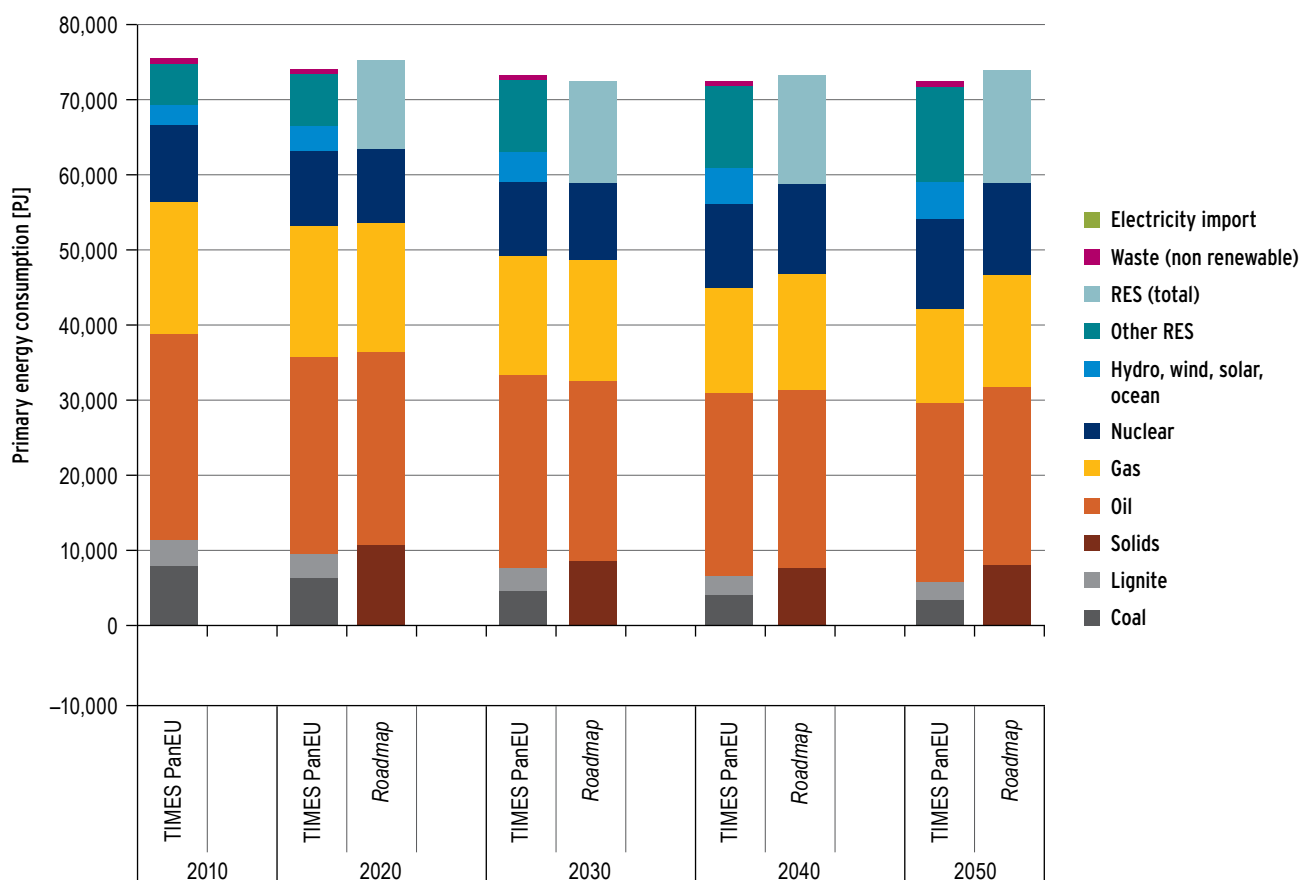
In the following the main focus and methodical approach of the different models are briefly described. The model descriptions are grouped according to the two-setting-approach in the calculations of the reference data set. Additionally, sample results based on the calculations of the reference data set are presented to highlight the specific role and strengths of each model within ESA².

3.3.1 Energy setting

TIMES PanEU

TIMES PanEU is a bottom-up, technology orientated, multi-regional European energy system model comprising all countries of the EU-27 plus Switzerland, Norway and Iceland. It is a linear optimisation model which minimises an objective function representing the total discounted energy system costs over the whole modelling time horizon from 2000 to 2050. Perfect competition among different technologies is assumed. TIMES PanEU covers, at the country level, the whole energy system. This includes in detail the supply of resources and reserves, the public and industrial generation of electricity and heat as well as the industry, commercial, households, transport and agriculture of the end-use sectors. In addition, both GHG and other emissions are modelled. TIMES PanEU considers country-specific particularities, such as decommissioning curves, potentials for renewable energy production and national carbon storage potentials. An interregional trade of electricity, biofuels and energy crops is implemented in the model. TIMES PanEU models interactions between the different sectors which could arise for example as a result of a GHG emission reduction pathway and lead to price effects and adjustments in all sectors. These sector reactions could be, for example, increased energy efficiency in both demand and supply sectors, or increased used of electricity or biomass. Therefore the biomass market is also modelled. TIMES PanEU was used for multiple different projects, most of them with a European focus. A more detailed model description can be found for example in Blesl et al. (2012) or Blesl et al. (2010).

Figure 3: Primary energy consumption in the EU-27 as a result of TIMES PanEU compared to the Roadmap



Within this ESA² case study TIMES PanEU is used to cover the whole energy system including all supply and demand sectors. Thus, in the model coupling structure, other more specific models use the output of TIMES PanEU as an input. Typical results used from this model within this project are primary or final energy demand, electricity demand by sector, the use of renewables, emissions by sector or emission certificate prices. Within the calculations of the reference data set, the results of TIMES PanEU at EU level are compared to the figures of the *Roadmap*. In general, results are quite similar. Total primary energy consumption in the EU-27, for example, stays at a quite constant level of about 73,000 PJ (see Figure 3). The ETS certificate price only shows small changes (in the *Roadmap*: 52 €/t in 2040, 50 €/t in 2050; TIMES PanEU results: 51 €/t in 2040, 54 €/t in 2050). The use of fossil fuels, especially petroleum products decreases, while more renewables and slightly more nuclear energy are used. Solid fossil fuels are, in the long term, mainly used in combination with Carbon Capture and Storage (CCS). Compared to the *Roadmap* the TIMES PanEU results show a slightly lower use of solids. This is due to the lower use of CCS and also a lower use of gas. The use of renewable energy sources is a little bit above the *Roadmap* values.

TIMES-Heat-DE and TIMES-Heat-PL

TIMES-Heat-DE and TIMES-Heat-PL are developed in the TIMES modelling environment for the in-depth analysis of the electricity and residential heat systems in Germany and Poland respectively. As with TIMES PanEU, they also use the TIMES model generator being based on linear programming and belonging to the class of integrated capacity and dispatch planning models. They are also bottom-up demand driven and technology oriented models. The main output of TIMES-Heat-DE and TIMES-Heat-PL is the cost-minimal mix of electricity and residential heat generating technologies and their dispatch for a planning horizon up until 2050.

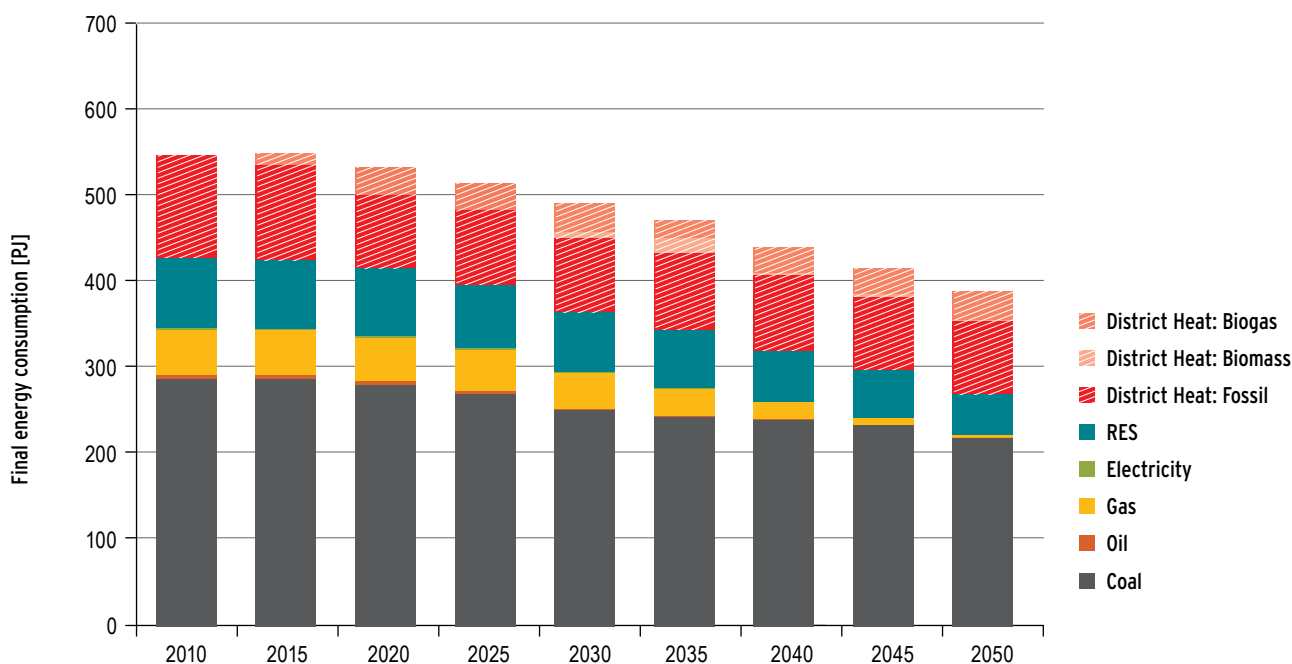
In the German electricity system, thermal power plant technologies as well as power plants based on renewable energy are aggregated into clusters according to their year of commissioning and installed power. In the Polish electricity sector, existing capacity is represented at plant level. Combined heat and power plants (CHP) are aggregated into four main types according to the fuel used and type of installed turbine (Pluta et al. 2012). In both models, the model-exogenous residential heat demand is split into space heat and domestic hot water and across 48 demand classes in which buildings are grouped depending on their size, specific heat demand and available infrastructure, e.g. access to district heat and gas network (McKenna et al. 2011).

The models are supported by a database of existing and new heating technology options. In TIMES-Heat-DE, as well as conversion technologies, thermal insulation measures at different levels of effectiveness can be included in the optimisation. In addition to object based heating systems, TIMES-Heat-PL also considers district heating. For TIMES-Heat-DE, there is a special focus on the investigation of the economic potential of innovative and energy efficient technologies at the interface of the heat and electricity systems. This particularly concerns micro-CHP technologies and heat pumps in residential buildings (Merkel et al. 2012).

Within this study, TIMES-Heat-DE and TIMES-Heat-PL are used to analyse the electricity and residential heat system at the country-specific level of Germany and Poland. With regard to model coupling, key input parameters are derived from upstream models, e.g. the demand for electricity across all sectors from TIMES PanEU or the evolution of the space heat demand from FORECAST in the residential building stock.

Figure 4 shows the final energy consumption for heating in the Polish residential sector.

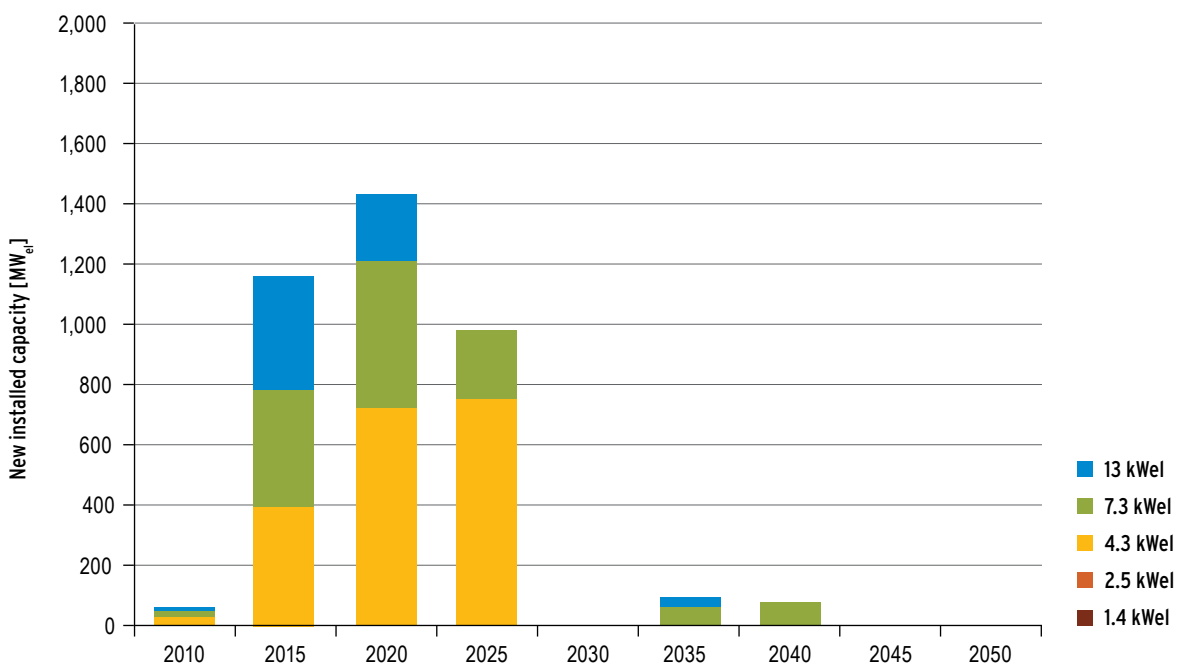
Figure 4: Final energy consumption for heating in the Polish residential sector as a result of TIMES-Heat-PL



A specific feature of the Polish centralised power sector is the large share of electricity produced through cogeneration (ca. 17% in 2010). In comparison to other Member States, Polish district heating (DH) networks cover an exceptionally large share of the thermal needs of the cities, supplying heat to about 12 million of Polish citizens. Heat produced in the district heating systems is distributed in particular to small and large multi-family houses. In future, the amount of heat supplied by centralised DH systems will be affected by contradictory trends. In line with the increase in per capita GDP, the per capita living space of Poles is likely to increase. To mitigate the problem of air pollution, particularly in cities, individual heating systems will be gradually replaced by DH systems. However, any corresponding rise in energy consumption should be staunchly by improved insulation. Consequently, the final energy consumption for district heating stagnates in the scenario (cf. Figure 4). The use of coal is observed in the single and two family houses whereas the heat produced in the district heating systems is distributed to small and large multi-family houses. The relatively high price of gas leads to a switching from this fuel to coal after 2025 (in this study the exploration and use of domestic unconventional gas was not considered).

Within the calculations of the reference data set, model runs also allow for a thorough analysis of technologies as they are implemented in a detailed bottom-up way. Figure 5 depicts the new installed electric capacity of micro-CHP in the German residential sector for different levels of rated power. The considerable expansion of this technology is mainly realised by units in the power range of 4 kW_{el} and greater thus supplying buildings ranging from large single family houses to large multi-family houses. Results also show that a moderate evolution of end-consumer prices and of the renovation rate as assumed for the reference data set significantly favours the deployment of micro-CHP. Then again, micro-CHP deployment stagnates from 2030 due to improved thermal building standards and the considerable increase of end-consumer energy prices in the residential heat sector.

Figure 5: New installed electric capacity of micro-CHP in the German residential heat sector as result of TIMES-Heat-DE



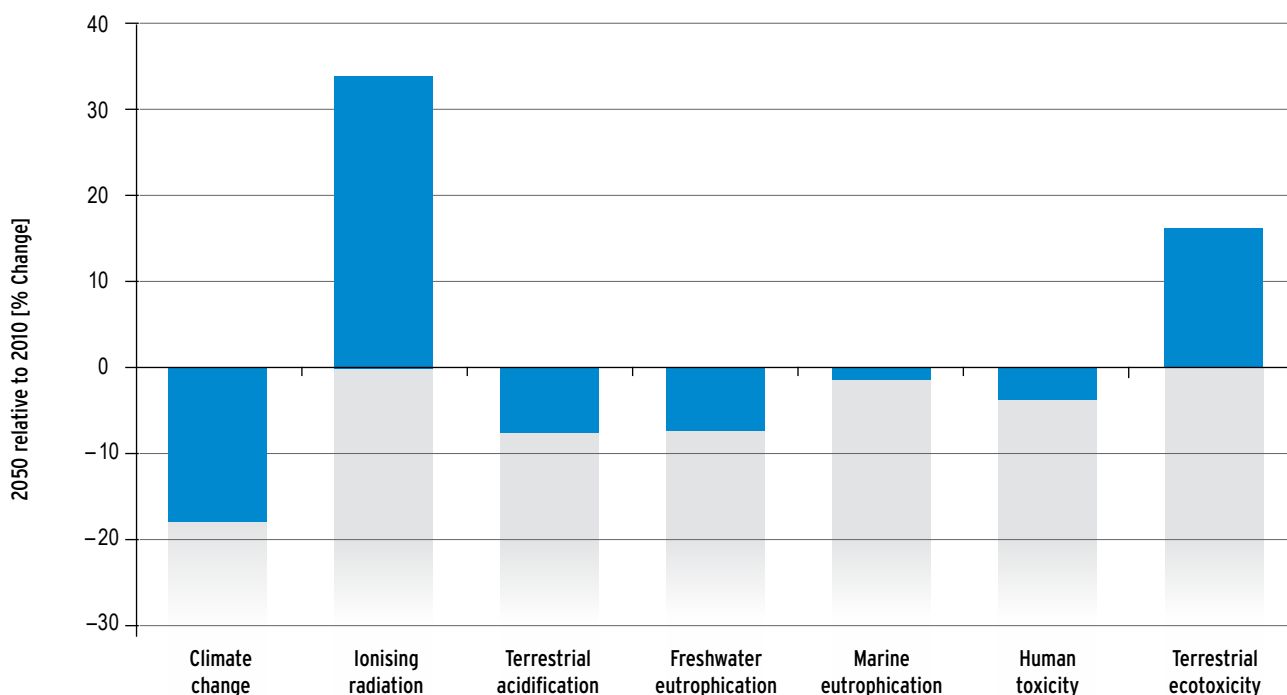
Environmental impact assessment with life-cycle approach (IA with LC-approach)

The increasing importance of bioenergy within any future energy system requires broadening the scope of environmental impact analysis. Whereas bioenergy is seen as carbon-neutral, other environmental impacts, such as ecotoxicity (measuring the impact of toxic emissions to the ecosystem in general), could diminish the expected advantages of biogenic energy carriers. An LC-approach is important for decision makers to avoid sub-optimal solutions due to incomplete knowledge of environmental impacts, e.g. by not being aware of the impacts on the man-made or natural habitat due to increased emissions to the soil or air, or changes in land-use as a result of an intensified forest management. The approach is therefore a natural and important addition to the ESA² toolbox since it extends systems data produced by ESA²'s energy models to quantitative information on the environmental sustainability of modelled future energy systems. The option of using life-cycle assessment (LCA) in strategic environmental assessment (SEA) of municipal energy planning has been demonstrated (Björklund, 2012), and ESA² aims to extend the approach to the assessment of energy scenarios and systems on a larger scale. Ekvall, et al. (2009) describes how life-cycle methodology may be used to assess policy instruments based on future scenarios for waste management.

The IA performed in this study is on the woody material that is extracted from Swedish and German productive forest land during one year and consumed directly for energy purposes (hereafter "forest bioenergy"). This definition includes all sawmill and pulp mill wastes and the environmental impacts is assessed for the years 2010 and 2050. The crucial role of biogenic energy carriers has already been raised, but the most important is that of woody materials. This is due to the high energy density, the significant availability within the EU and the fact that such material does not directly compete with food production for agricultural land. Although the calculations for this report are carried out for Sweden and Germany, for the time being only the results for Sweden are presented in more detail.

Figure 6 shows the change in indicative environmental impacts due to the Swedish forest bioenergy life-cycle for the reference data set between 2010 and 2050. The relatively minor decrease in climate change impact is due to the fact that transport of forest biomass is still largely fossil fuel dependent. Meanwhile the increase in terrestrial ecotoxicity is due both to a relative increase in wood ash treatment in 2050 causing such emissions and the (albeit limited) use of biofuels for transport in the life-cycle. This contrasts with the minor decrease in human toxicity (measuring toxic substances in the human food chain), which is mainly due to the decreased requirement for treatment of mining tailings in 2050. The increase in ionising radiation (measuring exposure to human-caused background radiation due to the entire nuclear fuel cycle) is due to the fact that supply chain electricity contains a higher proportion of nuclear in 2050 than in 2010 in this case, increasing exposure to ionising radiation. The marginal decrease in terrestrial acidification (measuring the impact due to emissions of acidifying substances such as sulphur dioxide) is due in large part to the assumed increased efficiency of harvest vehicles. The decrease in freshwater eutrophication (measuring impact due to the emission of phosphorous and nitrogen nutrients to freshwater) occurs because of a reduction in emissions of such substances from mining tailings. Meanwhile, the decrease in marine eutrophication is due to the decrease in fuel demand in harvesting machines. Taken together the results demonstrate how the inclusion of quantified results for environmental impacts expands the information available to decision makers when considering the future development of the energy system. As shown in the case study considering binding targets for energy efficiency and renewables, another focus of the approach is to establish the specific fuel types that are required to fulfil calculated total demand for forest bioenergy.

Figure 6: Changes in indicative environmental impacts between 2010 and 2050 per kWh of forest primary bioenergy based on IA with LC-approach methodology



PIAM

PIAM – the Platform for Integrated Assessment Modelling has been developed in line with the Driver-Pressure-State-Impact-Response (DPSIR). The concept of DPSIR links:

- (i) human-caused **drivers** e.g. energy use, social and economic development, exerting
- (ii) **pressures** on the environment such as emissions, and
- (iii) consequent changes of the environmental state e.g. changes in the concentration and deposition of pollutants,
- (iv) resulting in **impacts** on ecosystems, human health, and society and
- (v) human **responses** to correct the situation, made either by governments or other players.

Drivers and pressures as well as responses are addressed with the use of TIMES PanEU. Changes in the environmental state are calculated with the use of Polyphemus (Mallet et al. 2007), which is a full modelling system for air quality. Its main element is an Eulerian chemistry-transport-model (Polair3D) used for both gaseous and aerosol species. Among traditional air pollutants, particulate matter (PM) with a diameter less than or equal to 2.5 [µm] (PM2.5) was identified to be the most harmful for human health. The gridded values of PM2.5 concentration obtained, are set against data on population density and concentration-response functions to estimate the impact of human exposure to air pollution on human health (e.g. Loss of Life Expectancy-LLE) (Wyrwa 2010). Human exposure to PM can have various effects which have been widely described in scientific publications in observational epidemiology. LLE is one of the available indicators relating human exposure to PM2.5 concentration with the number of years of life lost for a given population cohort.

Figure 7: Decrease in PM2.5 yearly average concentration at ground level [$\mu\text{g}/\text{m}^3$] (left) and corresponding increase in life expectancy [number of days gained per person] (right) in 2030 compared to 2010

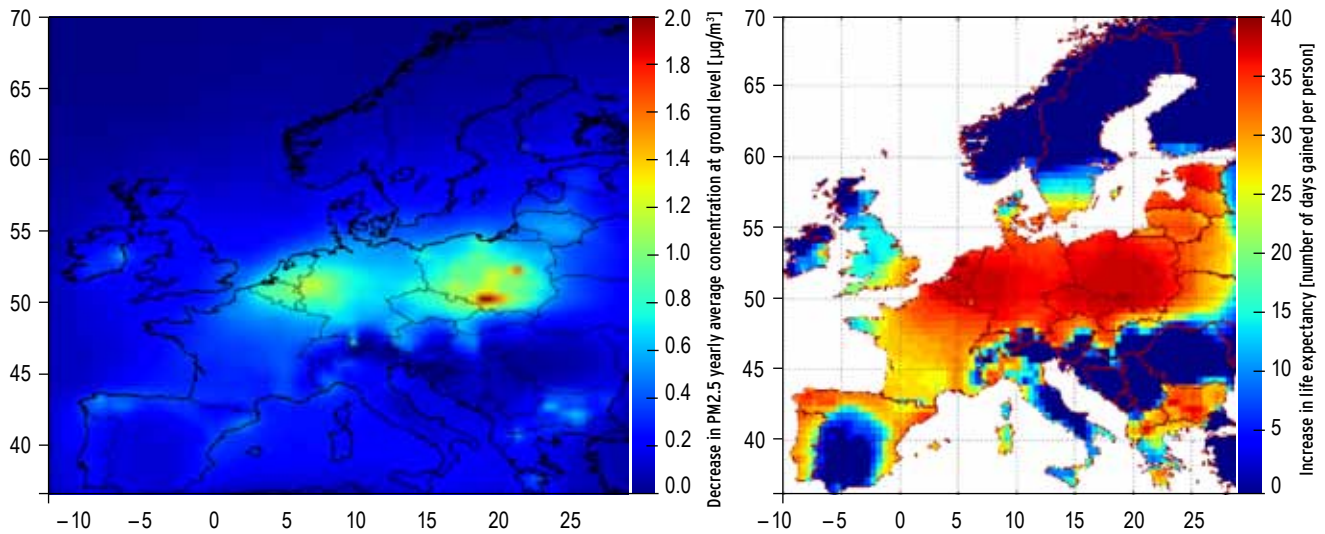


Figure 7 presents the decrease in PM2.5 concentrations and increase in life expectancy in 2030 compared to 2010 associated with the reference “Energy-setting”.

The results show the highest decrease in PM2.5 concentrations over Poland, Germany (mainly the Ruhr area) and Benelux countries (Figure 7 – left). This decrease is mainly due to emission reduction in energy industries (e.g. resulting from implementation of directive on industrial emissions establishing more stringent emission limit values). Consequently the decrease in Loss of Life Expectancy (i.e. increase in life expectancy) in 2030 compared to 2010 can be observed as people, in general, will be exposed to lower PM2.5 concentration.

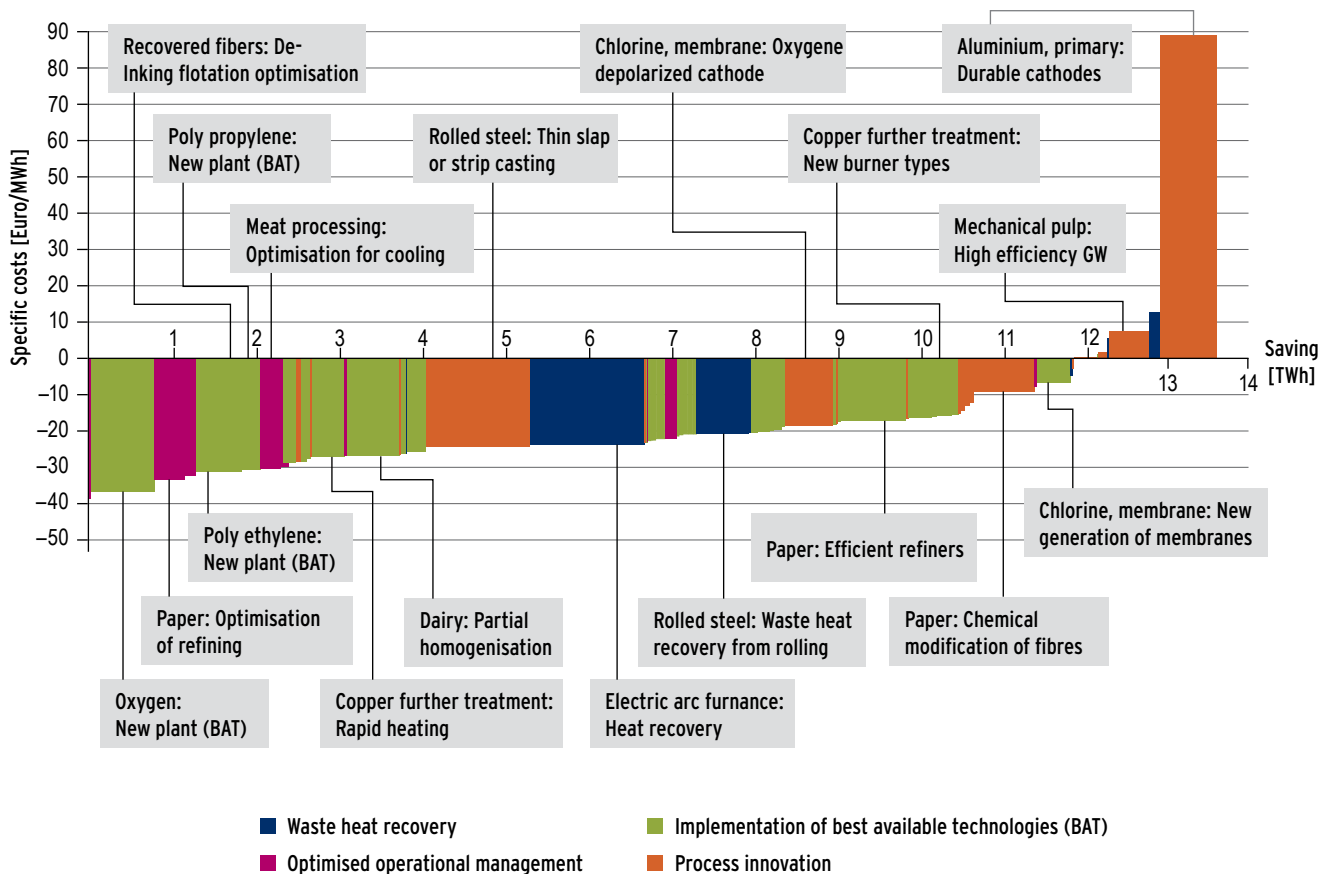
3.3.2 Electricity setting

FORECAST

FORECAST is a long-term simulation model that covers the energy demand of the EU-27+3 (Norway, Switzerland, Turkey) region on an annual basis. However, as the modelling of electricity based technologies is on a very high level of disaggregation, FORECAST is often applied where detailed, electricity specific, analysis is required. The model consists of six modules, whereby one module is used to calculate the socio-economic drivers for each energy demand sector (FORECAST-Macro) and the other five modules represent the sectors (industry, households, tertiary, transport and agriculture). The input parameters for FORECAST-Macro include the population, the gross domestic product and wholesale prices on a country basis. Sample results of the macro module are the tons of physical production delivered by the industrial sector, the gross value added generated in the tertiary sector, or the number of households in the residential sector. As the characteristics and energy demand dynamics of each sector are very heterogeneous the calculation algorithm is designed in a sector-specific way. All five sector modules apply a technology discrete bottom-up approach that allows the future energy demand and greenhouse gas emissions to be determined in relation to the technological development in each sector. On the one hand this approach allows technological trends and policy regulations to be taken into account when quantifying the impact on certain technologies. On the other hand it enables conclusions to be drawn on whether the assessed energy scenarios are close to reality, given the fact that every single scenario is based on a specific technological evolution.

Within this project, FORECAST is applied to the electricity demand in all demand sectors at a country level. As displayed in the modelling coupling structure (cf. Figure 2), the results provided by FORECAST are used as input data for all other models within this setting. For example it is used by eLOAD (see below) to transform the annual electricity demand into hourly load curves, and by the country specific heat models TIMES-Heat-DE and TIMES-Heat-PL, which use the energy carrier prices and the useful heating demand for the residential sector (Elsland et al. 2012). Within the reference data set, FORECAST is applied to accomplish a detailed technology specific analysis for each energy demand sector. As technology diffusion is calculated using a cost based approach, electricity saving options with a high return on investment usually permeate more quickly into the market if there are no significant barriers. Thus, one of the key results provided by FORECAST are cost curves for each sector that illustrate the energy and cost savings potential of each saving option (Fleiter et al. 2012). An example of results for the industrial sector in Germany, emphasising the high level of detail, is displayed in Figure 8. Sample results of the reference data set depict an increase of European electricity consumption up to a level of approximately 3530 TWh (+26%, compared to 2010) by 2050. Compared to the reference scenario of the *Roadmap* the increase of electricity consumption is lower by 21%.

Figure 8: Cost curve of electricity saving options in the industrial sector. Example for Germany in 2035 (electricity and EUA prices included) as a result of FORECAST

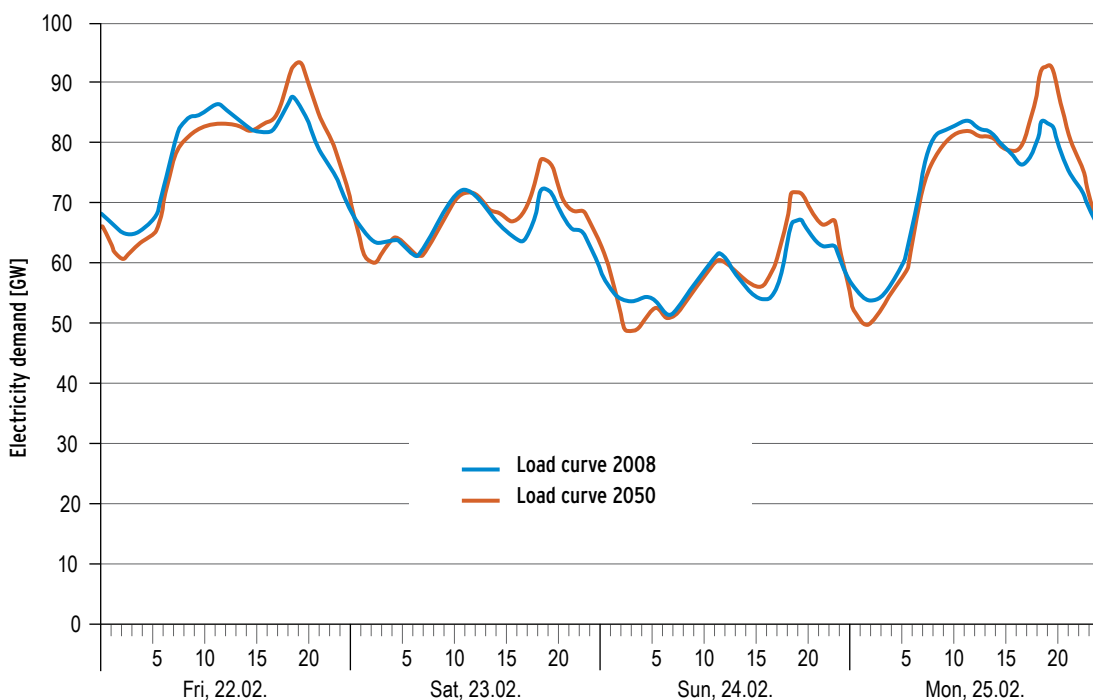


eLOAD

The energy load curve adjustment model eLOAD is a transformation tool that provides national hourly load curves for different energy carriers. The generation of electricity load curves is based on technology discrete, annual electricity demand projections, such as delivered by the FORECAST model. Applying the tool permits the generation of hourly load curves incorporating endogenous structural changes within the load curve. These are due to shifts in the annual end-use related electricity demand. eLOAD is based on a partial decomposition approach that models the deformation of the historic load curve by breaking down the increase or decrease in electricity demand of the most relevant appliances (those which experience the most significant change in annual electricity demand between the base year and the projection year). This is done on an hourly basis using 24 hour load profiles for typical days. Importantly, this approach conserves the characteristic irregularities of the empiric load curve while the basic structure of the load curve is adapted according to the main shifts in annual electricity demand. Figure 9 depicts a four-day extract of the German electricity load curve for the years 2008 and 2050. A clear increase of the evening peak demand triggered by electric vehicles can be observed along with the intensified use of heat pumps and information and communication technologies in households. At the same time the nightly electricity consumption features a clear decrease resulting from the phase out of night storage heating systems and efficiency improvements in residential lighting. This results in the conclusion that the future load curve will experience a deformation of its overall shape, challenging the electricity supply side to cover increasingly volatile and irregular electricity demand. Hence flexible peak load capacities or alternative adaptation strategies, such as demand side management or grid extensions, will be required.

Apart from the load curve adjustment due to changes in overall electricity demand, eLOAD is capable of performing an optimal smoothing of the residual load curve by modelling demand response measures. These ensure an improved integration of renewable energy sources and the efficient

Figure 9: Four-day extract of the German electricity load curve in the year 2008 and 2050 derived from the eLOAD model



utilisation of conventional power plants. This has crucial impacts on determining the extent of the future electricity supply system. In most of the currently existing energy system analysis studies (e.g. in the *Roadmap*) such aspects are not considered. Further information on the model can be found in Boßmann et al. (2012).

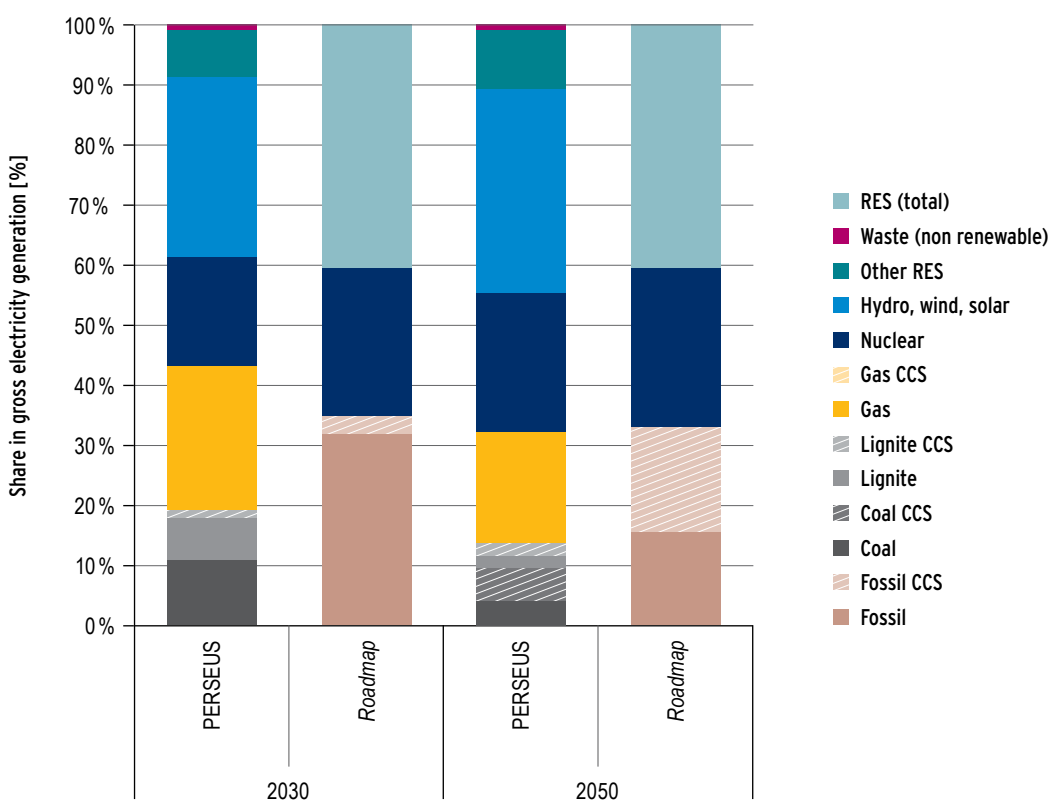
In the present case eLOAD is only used in the simple mode, i.e. it scales the historic load curve according to the projection of the overall electricity demand as provided by FORECAST and TIMES PanEU.

PERSEUS

The multi-periodic energy and material flow model PERSEUS (Program Package for Emission Reduction Strategies in Energy Use and Supply) provides a detailed representation of the existing European electricity supply system with its specific techno-economic characteristics and constraints. The modelling time horizon is from the year 2007 to 2050, where one year is represented by a typical week and weekend day for the seasons, resulting in 44 time intervals for one year. The model comprises a large variety of different fossil and non-fossil fuel resources, including renewable energy sources (RES). The connection of all energy producers within the system to these resources, by separate energy and material flows, permits the consideration of regional fuel supply characteristics like upper or lower flow limits, prices, and transport costs.

The model is based on linear and mixed-integer programming approaches with perfect foresight. The target function consists of a minimisation of all decision-relevant expenditures within the entire system. A detailed description of the model can be found in Möst and Fichtner (2010) or Eßer-Frey (2012).

Figure 10: Share in gross electricity generation in the EU-27 as a result of PERSEUS compared to the *Roadmap*



Within this study, PERSEUS is used to cover the whole electricity supply system. Thus in the model coupling structure PERSEUS uses the electricity demand calculated by FORECAST and eLOAD as an input. Other more specific models use the output of PERSEUS as an input. Typical results used by other models within this project are: (i) installed capacity of conventional and renewable energy power plants, (ii) country specific electricity exports and (iii) imports or emission certificate prices. Comparing the gross electricity generation with the results from the *Roadmap* (cf. Figure 10) for the reference data set, it is apparent that they are quite similar. The main difference in the year 2030 is the use of fossil fuel and nuclear energy, whereas the shares of renewable energy are nearly the same. The results of PERSEUS further show a slightly higher use of renewables in 2050 than the *Roadmap*. However it should be noted that since the underlying electricity demand for the calculations with PERSEUS is calculated by FORECAST, it is lower than the electricity demand of the *Roadmap*.

PowerACE

The agent-based model family PowerACE (Power Agent based Computational Economics) consists of two bottom-up electricity market models that aim to match hourly demand and supply while considering reserve markets and power flows between countries. The model is linked to extensive databases for power plants, electricity demand and installed capacities of renewable energy sources, for which generation profiles based on detailed meteorological data are used. The model can be used to simulate the whole electricity sector of the EU-27+2 region (EU-27+CH+NO) – extendable to some of the countries of the MENA region (Middle East & North Africa) – (PowerACE-EU, see Figure 11) and is able to provide especially detailed insights into the electricity market of Germany. A detailed model description can, for example, be found in Sensfuß et al. (2008) or Genoese et al. (2012).

The model simulates the main actors of the electricity market: generators, traders and consumers. Trading agents submit hourly bids for the power plants of the generators as well as for the demand of the consumers. These bids are then aggregated into demand and supply curves. The interception of these curves determines the market price. The bids for power plants are based on variable costs but are modified by including expected start-up costs or subtracting avoided start-up costs.

The model is able to simulate the long-term capacity extension. Based on the expected capacities and the demand in the future, as well as the results of the spot and forward prices, the profitability of new units is checked. The agents evaluate the technology options available by computing the net present value. In the case of the European model version, the model is also able to calculate the optimal extension of net transfer capacities between the European countries including Norway and Switzerland.

Within this study, PowerACE-EU was used to calculate the power plant dispatch for all European countries based on the capacity extension of the Reference scenario from the *Roadmap*. In 2050, the model suggests that nearly half of the electricity would be provided by renewable energy sources, 27% by nuclear, 17% by coal and 9% by gas power plants. The proportion of nuclear power is similar to that of the *Roadmap* whereas the production from RES is about 5% lower in the *Roadmap* which favours fossil fuels. This is partially related to the fact that the overall electricity demand is lower than in the reference scenario of the *Roadmap*; energy savings give rise to an increase in the relative share of RES in electricity generation. With regard to national electricity generation the contribution of RES is very heterogeneous, ranging from 10% in Poland up to 89% in Austria (see Figure 11).

Figure 11: Share of electricity generation in the countries of EU-27 in the year 2050 based on results from PowerACE-EU

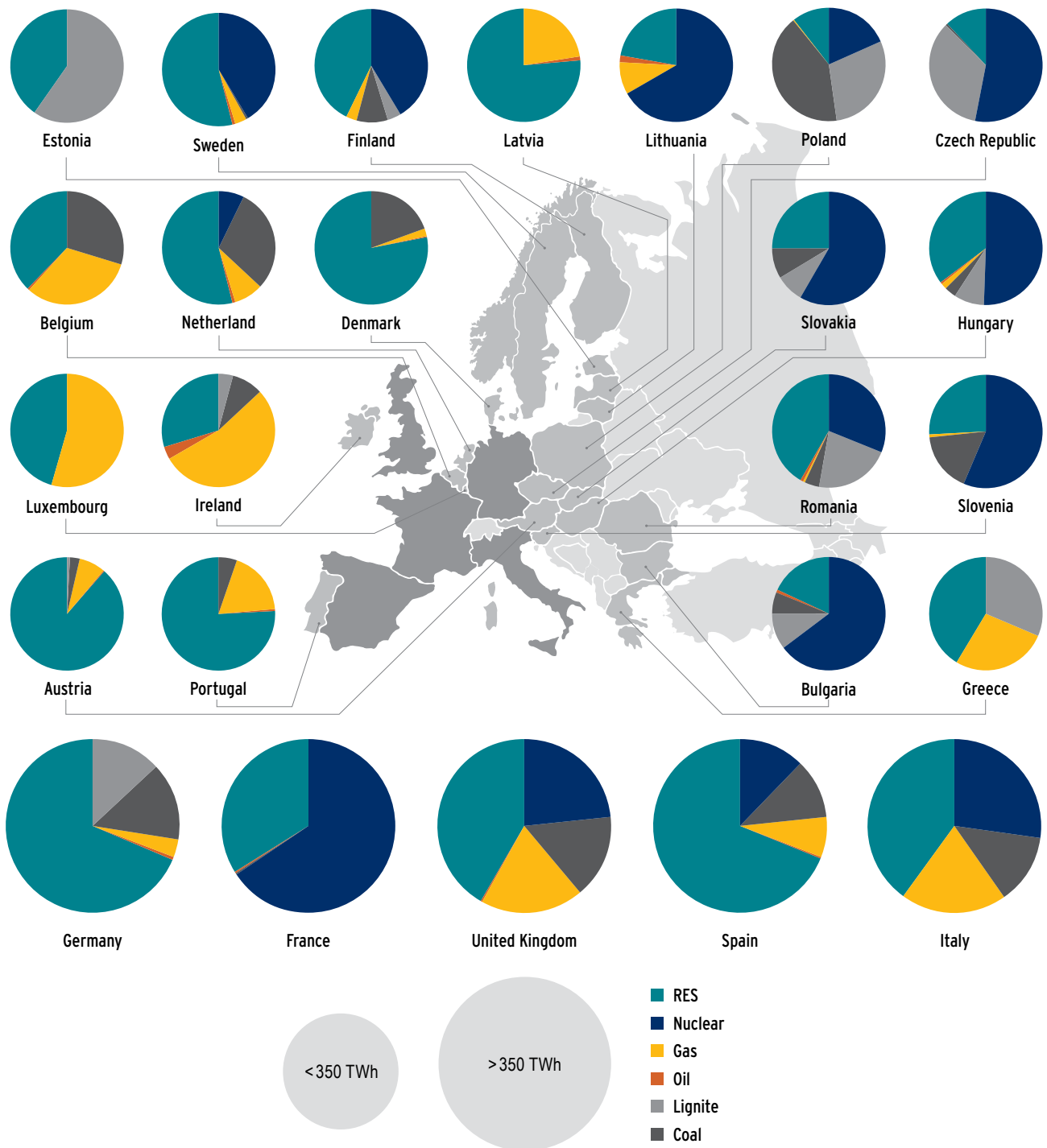
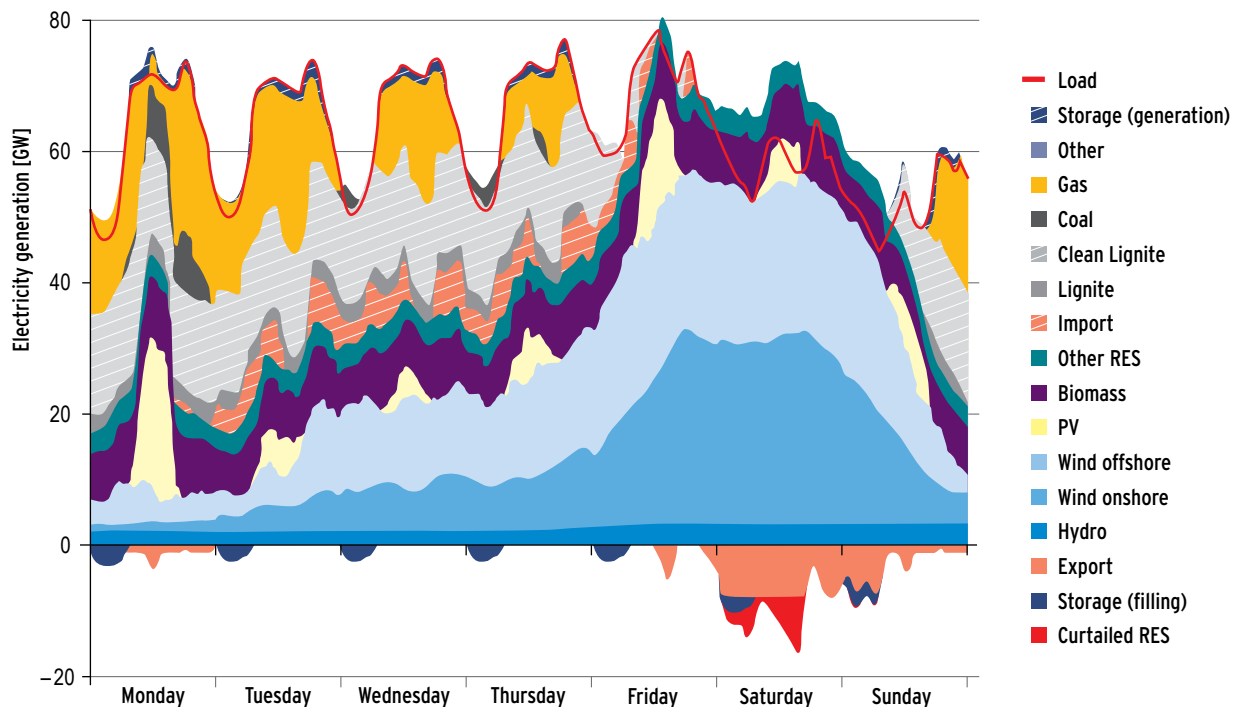


Figure 12: The electricity generation in Germany for a sample week in the year 2050 based on results from PowerACE-DE



PowerACE-DE allows a particular focus on Germany where all nuclear power plants are shut down by 2022. In 2030, 80% of the electricity generation from thermal power plants comes from gas fired power plants which are the main type of power plant built in this period. Afterwards, some lignite power plants using the CCS-technology are built and replace capacities reaching the end of their technical lifetime. In 2050, situations will occur where the feed-in from renewable energies exceeds the demand, i.e. the sum of load, export and storage (filling). In order to balance offer and demand, renewable energies have to be curtailed (see Figure 12). Unlike models that do not provide an hourly temporal resolution of 8760 hours, PowerACE is able to deeply analyse situations such as curtailment that are the result of the interaction of several factors.

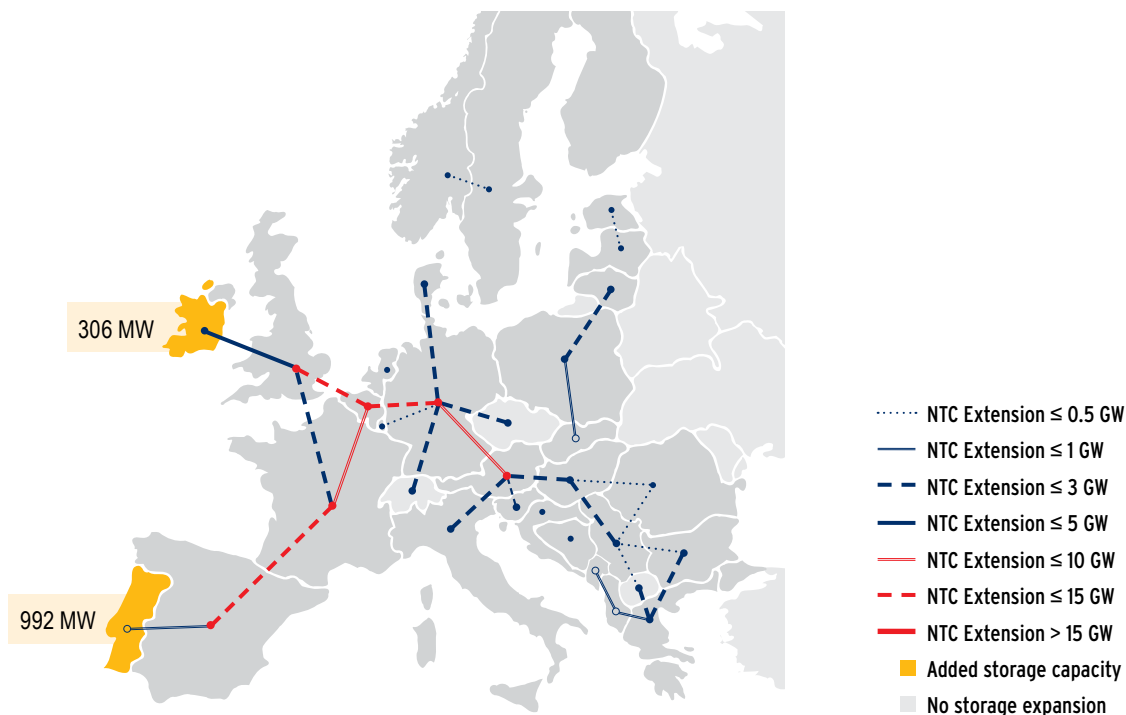
ELTRAMOD

ELTRAMOD is a bottom-up electricity market model incorporating the electricity markets of the EU-27 states, Norway, Switzerland and the Balkan region as well as the Net Transfer Capacities (NTC) between these countries. Each country is treated as one node with country specific hourly time series of electricity demand and renewable feed-in. The country specific wind and photovoltaic feed-in is characterised by the installed capacity and an hourly capacity factor. The capacity factors are calculated with the help of publically available time series of wind speed and solar radiation from 2009 and 2010. ELTRAMOD is a linear optimisation model which calculates the cost-minimal generation dispatch and investments in additional transmission lines and storage facilities. The set of conventional power plants consists of fossil fired, nuclear and hydro plants where different technological characteristics are implemented, such as efficiency, emission factors and availability. Daily prices for CO₂ allowances, as well as daily wholesale fuel prices supplemented by country specific markups are implemented in

ELTRAMOD. The country and technology specific parameters and the temporal resolution of 8760 hours allow an in-depth analysis of various challenges of the future European electricity system. For example, the trade-off between network extension and storage investment as well as import and export flows of electricity in Europe can be analysed. A more detailed model description and exemplary results can be found in Gunkel et al. (2012) or Müller (2012).

It is often claimed that the integration of energy from renewable sources necessitates additional grid and storage investments. But what level of storage and grid investments will become necessary in a future energy system with a higher proportion of renewables? Is there a trade-off between grid and storage investments? These two questions are addressed with ELTRAMOD by ESA². Two options were considered: An energy system with and without feed-in obligation of renewable energy. Figure 13 indicates the need for additional NTC and storage capacities by 2050 considering a feed-in obligation of RES.

Figure 13: Grid and storage expansion in 2050 as a result of ELTRAMOD



Within this scenario the electricity demand calculated by FORECAST and the power plant portfolio of the reference case of the *Roadmap* were used as an input. Among these assumptions only Portugal and Ireland require additional storage capacities from 2030 onwards (see Figure 13). Within Central Europe the surplus of renewable feed-in can be compensated by the highly meshed European electricity grid. From 2030 onwards the connection from the periphery of the European continent, e.g. Great Britain and Spain, to central Europe substantially increases. This development, as well as the high grid extension from Germany to its neighbouring countries, illustrates the need of NTC to compensate the increasing share of intermittent renewable feed-in by 2050. In addition the conventional generation portfolio and the existing storage capacities substantially compensate for the fluctuation from RES feed-in. Consequently the cost optimal integration of renewable energy in the European electricity market primarily requires a highly flexible power plant portfolio and additional transmission capacities.

4. Case studies

4.1 Case study 1: What is the cost optimal way to reach -80% GHG in the EU? (cost-optimal case)

Key messages:

- A diversified technology mix is the cost-optimal way to reach the GHG emission reduction targets
- A strong decarbonisation of electricity generation in combination with an extended use of electricity in the end-use sector contributes to the cost-optimal GHG emission reduction
- While GHG emission reduction is an important objective, potential unintended side effects have to be carefully monitored

4.1.1 Case study outline

In this case study the cost optimal way to reach an EU-27 wide GHG emission reduction target is explored. In comparison to the other case studies this case is the most flexible with regard to technology preference in achieving the target; evaluating policies concerning nuclear, CCS, energy efficiency and RES is the study's main focus. In order to analyse the cost optimal path of decarbonisation, optimising energy system models are coupled and applied. At the EU-27 level, TIMES PanEU is used for the analysis of the whole energy system whereas in TIMES-Heat-DE and TIMES-Heat-PL a special focus is put on two member states with contrasting nuclear energy promotion policies (Poland: introduction; Germany: phase-out). With no other targets (e.g. increased energy efficiency or a high proportion of renewable energy) apart from the EU-27 wide CO₂ emission reduction target, the energy mix might still rely on conventional power plants. Thus, a particular focus is put on studying the impacts of non-GHG emissions (e.g. loss of life expectancy). This analysis is carried out with PIAM.

The results of this case study can be used to analyse how the future cost optimal energy system looks like without targets additional to the GHG emission reduction target. It can be determined whether focus should be on a specific technology or whether the reduction options are blocking or supporting each other. Moreover, the model setup in this case study is able to give a more detailed insight at national levels and in the often neglected heating sector and non-GHG emission development.

In order to analyse the defined problem and policy question the following assumptions are chosen to build the framework of the case study. The main general assumptions for this decarbonisation scenario are the development of the economic activity, fuel price pathways and the emission reduction target. The assumptions concerning the economic activity are identical in all evaluated cases. They are taken from the Reference Scenario of the *Roadmap* and assume a GDP growth rate of 1.7% p.a. on average for

2010-2050. In contrast, the fuel price pathways are the same for all three decarbonisation scenarios but differ both from the reference data set and from the fuel prices used for the decarbonisation scenarios of the *Roadmap*. Up until 2030 the fuel prices equal the prices of the reference case and show an increase over time. Afterwards the relative changes from the decarbonisation prices from the *Roadmap* between 2030 and 2050 are applied, representing an opposite trend (see Table 1).

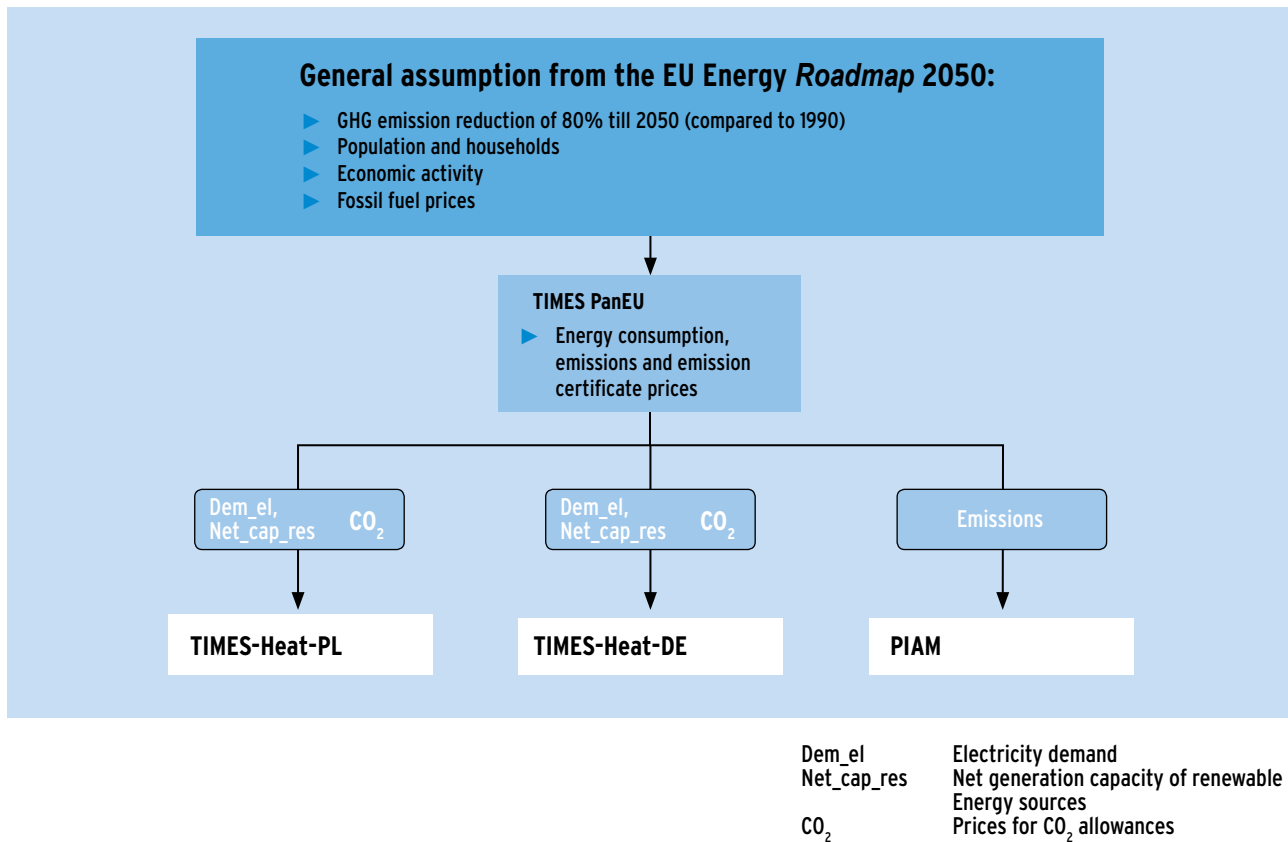
Table 1: Fuel price development in the decarbonisation scenarios

	UNIT	2010	2015	2020	2025	2030	2035	2040	2045	2050
Coal	€2008/GJ	2.6	2.8	3.2	3.7	3.7	3.5	3.4	3.0	3.0
Crude oil	€2008/GJ	9.4	9.0	9.8	11.3	11.8	11.6	11.5	11.0	10.4
Fuel oil	€2008/GJ	10.3	9.9	10.7	12.2	12.7	12.5	12.4	11.9	11.3
Nuclear	€2008/GJ	0.9	0.9	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Gas	€2008/GJ	5.9	5.4	6.9	8.2	8.6	8.6	7.9	7.2	6.9

For all decarbonisation cases, the same overall GHG emission reduction pathway is assumed. This reduction target is related to all sectors and not only to the ETS sectors. The given reduction is 25% by 2020, 40% by 2030, 60% by 2040 and 80% by 2050 (compared to 1990). To analyse the cost-optimal way of reaching an 80% GHG reduction target the key idea is to allow more flexibility in finding the optimal solution. With regard to the technology-specific assumptions, the extended use of nuclear energy including life time extensions is an option for countries that agreed on the use of nuclear energy. The use of CCS is limited only by the availability of storing options, and the support of renewable energy sources is reduced in comparison to the other case studies to avoid the strong support of one technology group in advance.

Given the above mentioned problem description and assumptions, the participating models in this case study are coupled as shown in Figure 14. The upstream model of the cost-optimal case is TIMES PanEU. TIMES PanEU determines the cost optimal energy system using the primary input assumptions such as GHG emission reduction targets and fuel prices. The main model outputs (annual energy consumption, GHG emissions, electricity demand, emissions certificate prices) are input into the TIMES-Heat-DE and TIMES-Heat-PL models to calculate the cost-optimal capacity investment and dispatch in national electricity and residential heat supply in Germany and Poland. Furthermore, the PIAM model uses the pollutant emissions calculated by TIMES PanEU for calculating the impact of air pollution on human health.

Figure 14: Model coupling - assumptions and data flow for the calculations of the cost-optimal case



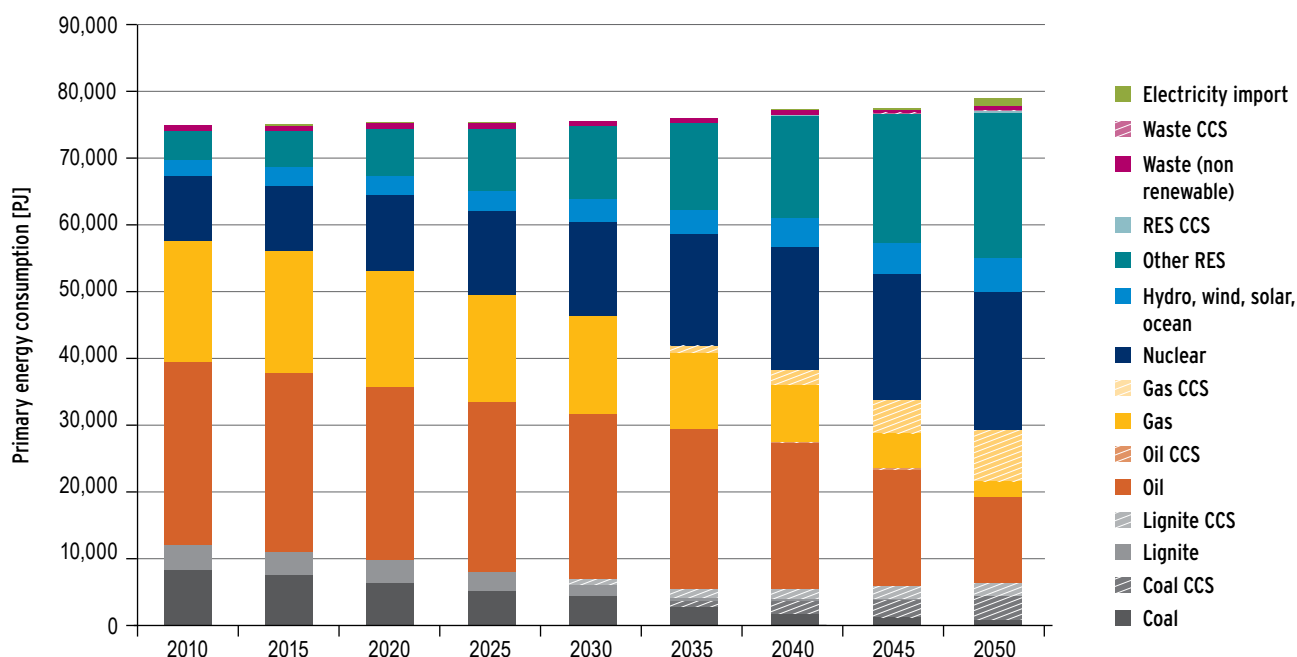
4.1.2 Results and discussion

After defining the outline of the case study, this section summarises the most important model results and conclusions. The results presented follow the model coupling structure; the first results at EU level are followed by national results with a detailed look at the residential heat supply in a cost optimal energy system. Finally this chapter examines the results of non-GHG emissions.

The cost-optimal case shows a slight increase of primary energy consumption up to a level of about 78,750 PJ in 2050. A mix of options is required to deliver the cost-optimal reduction of GHG emissions, rather than just the focus on a single technology group. Due to the use of different options to cut GHG emissions, an increased use of nuclear (+10,730 PJ of primary energy from 2010 to 2050), CCS (+12,981 PJ), renewables like wind or solar (+3,554 PJ), and other renewables (+17,148 PJ) can be observed. At the same time the use of fossil fuels (especially without CCS) is clearly decreasing (cf. Figure 15). None of these emission reduction options is either blocked or strongly supported by any additional target (like a target on renewables or energy efficiency) or other policies.

The additional primary energy consumption of nuclear corresponds to an additional electricity generation in nuclear power plants of 984 TWh (from 2010 to 2050). Key countries of this extended use are UK (+208 TWh) and Finland (+107 TWh). The additional capacities of nuclear power plants are based on the investment costs assumption of 3,796 €/kW for new nuclear power plants within this ESA² case study. This number is comparable to the assumptions of the *Roadmap* of 3,859 €/kW in 2030 and 3,618 €/kW in 2050. A sensitivity analysis has shown that no more additional capacity will be installed at an investment cost level of more than 5,500 €/kW. This level leads to a nuclear phase out, although in general, the use of nuclear energy is more a question of social acceptance than of the costs. Other renewables play a key role in 2050 (22,110 PJ of primary energy). They are composed mainly of biogenic energy carriers (15,357 PJ), ambient heat used in heat pumps (3,988 PJ) and geothermal energy (2,765 PJ).

Figure 15: Primary energy consumption in the EU-27 as a result of TIMES PanEU



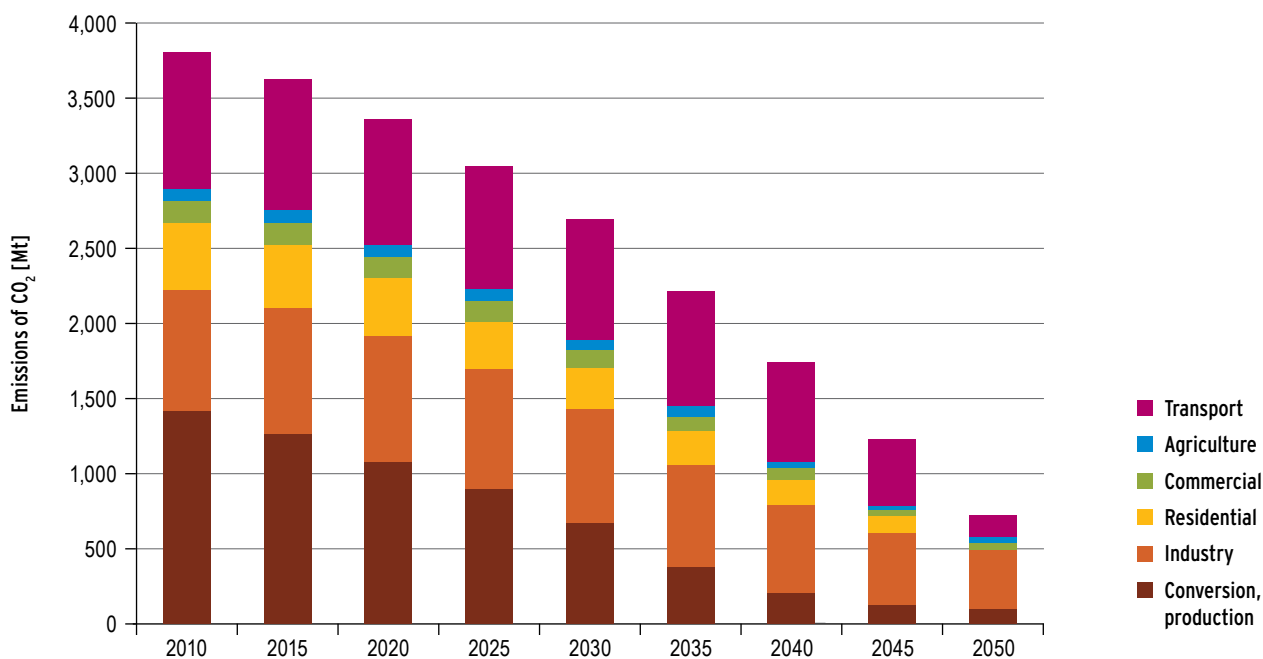
Some of these cost-optimal options to reduce the GHG emissions entail an increase in primary energy consumption. This can be mainly explained by the intensified use of technologies such as nuclear energy, CCS and biomass, which provide the cost-optimal emission reduction, but draw a higher primary energy consumption due to their lower conversion efficiency (e.g. wind and solar are calculated with 100% conversion efficiency, nuclear power with 33%).

In this case the use of the different technologies is driven by their costs and, due to the emission reduction target, by their emission reduction potential. Comparing some of the different available electricity generation technologies, the investment costs, the emissions and other technological constraints, like the availability factors, determine which of them are used under cost-optimal conditions. It has to be pointed out that additional energy policy targets like energy supply security or domestic work places, and GDP development, are not taken into account in this case study. The inclusion of such targets may lead to a different evolution of the technology options.

A strong decarbonisation can be observed, especially in the electricity sector. The specific emissions of public electricity generation are reduced down to a level of 8 kg/MWh in 2050 (compared to about 350 kg/MWh in 2010). Due to the technological flexibility in the cost-optimal case, the extended use of electricity in the end-use sectors is highly attractive in reducing the overall GHG emissions at least cost. An overall and not sector specific GHG emission reduction target is assumed. The analysis done by an energy system model shows the cost-optimal way to reduce these emissions by considering the competition and interactions between the different sectors both on the demand and supply side. As a result of considering all these interactions, the use of electricity increases in the long run when the GHG emission reduction target becomes more stringent, especially in the transport and industrial sector. In total, the electricity demand of the end-use sector increases especially after 2035 from about 3,000 PJ to more than 4,100 PJ in 2050. During this period (2035-2050), the use of electricity increases in the industrial sector by 460 TWh and in the transport sector by 339 TWh. In the industrial sector, electricity is extendedly used in the long run on the one hand to provide thermal energy (like the extended use of heat pumps to provide space heat or low temperature process heat or the extended use of electric furnaces in the iron and steel industry). On the other hand, thermal energy demand is substituted by electric appliances (like mechanical drying instead of thermal drying in the paper/pulp industry). In both cases, the demand for fossil energy carriers is reduced by (low carbon) electricity. In the transport sector electricity is mainly used for e-mobility in short distance cars.

CO₂ emissions are clearly reduced in all sectors (cf. Figure 16). Substantial long-term emission cuts in the transport sector occur only with a stringent reduction target, therewith bringing about a high CO₂ certificate price. The largest overall reduction takes place in the conversion sector, mainly driven by a strong decarbonisation of the public heat and electricity supply. The largest amount of emissions continues to be in the industrial sector, being mainly process related emissions.

Figure 16: CO₂ emissions by sector in the EU-27 as a result of TIMES PanEU



In total, the cost-optimal case leads to lower energy system costs compared to a scenario with the same GHG emission reduction target but additional normative targets on renewables and energy efficiency (RES-EE-EU-targets) (cf. Figure 23 of the next case for the difference in the energy system costs). The cost-optimal annual costs are reduced by more than 200 Bn. € in the year 2050 and the main driver for the lower costs are lower investments. As a percentage of the total GDP, this cost difference in the cost-optimal case equals 0.23% in 2020 (reduced costs / GDP) and 1.03% in 2050 (see also Figure 23 and the discussion of this figure). The higher level of flexibility and the use of technologies based only on their technical and economical parameters lead to the lowest energy system costs.

The model setup in this case study enables a closer look at the German and Polish electricity and residential heat sector. Figure 17 illustrates the fuel mix for electricity generation in Germany and Poland as a result of TIMES-Heat-DE and TIMES-Heat-PL. Here, the different policy constraints lead to different cost-optimal emission reduction approaches. In Germany there is a nuclear phase out, while in Poland there is a higher prevalence of district heating and a greater inclination to use domestic coal in electricity and heat supply rather than relying on gas imports. More precisely, the Polish generation mix increasingly incorporates nuclear power, whereas gas and lignite based CCS becomes the dominant technology in Germany. However, both countries strongly rely on the import of electricity. Technologies based on renewable energy sources, whose capacity and generation are a model input based on TIMES PanEU results, are less important in the national generation mix in both countries.

Figure 17: Electricity generation by fuel type in the German and Polish electricity sector as a result of TIMES-Heat-DE and TIMES-Heat-PL, based on model input from TIMES PanEU

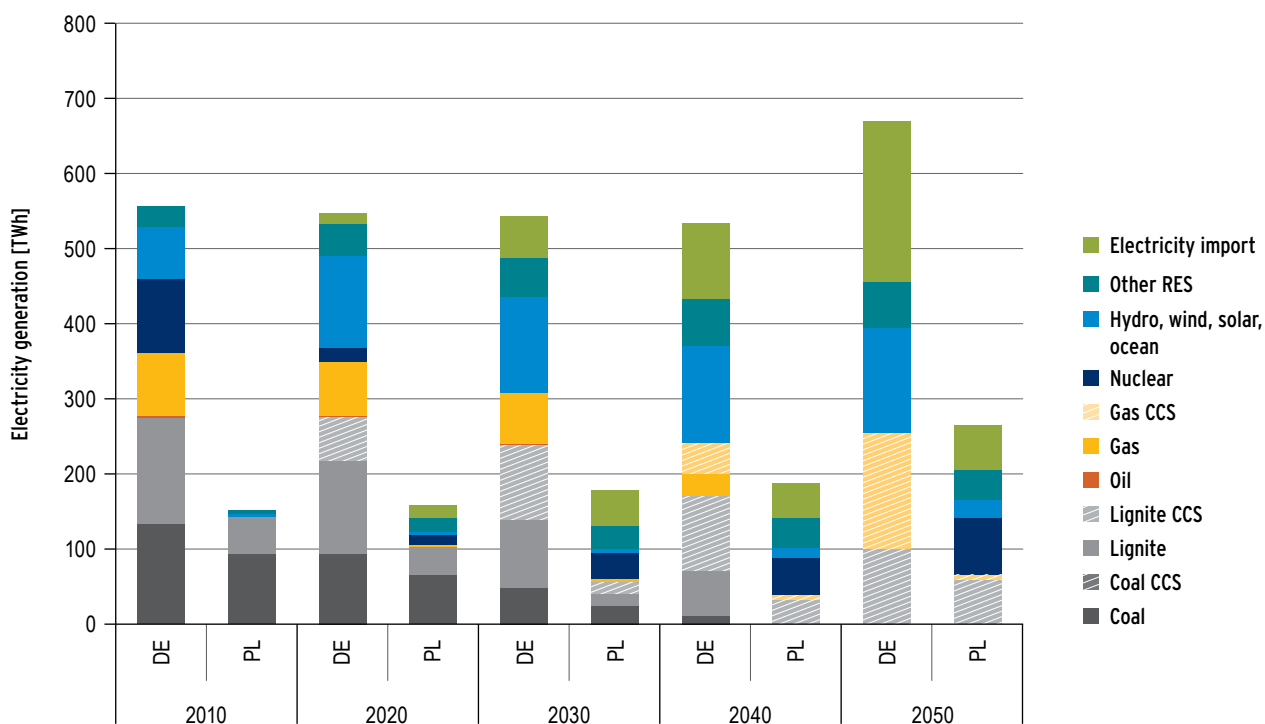
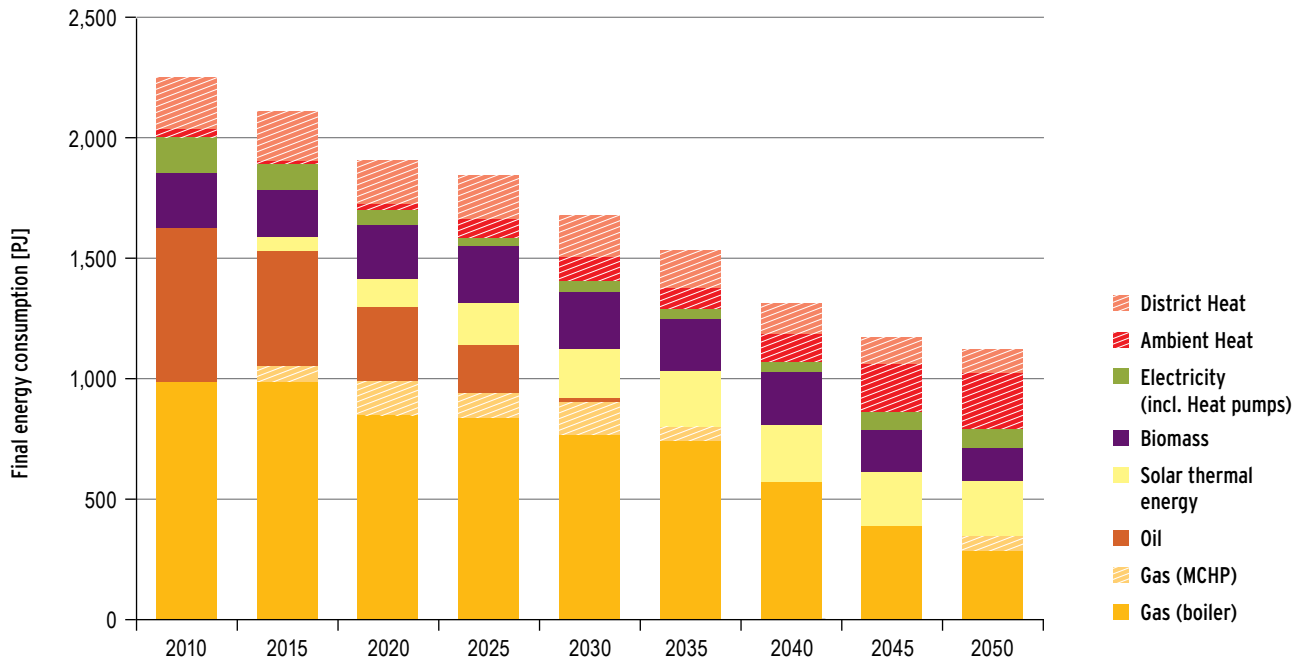


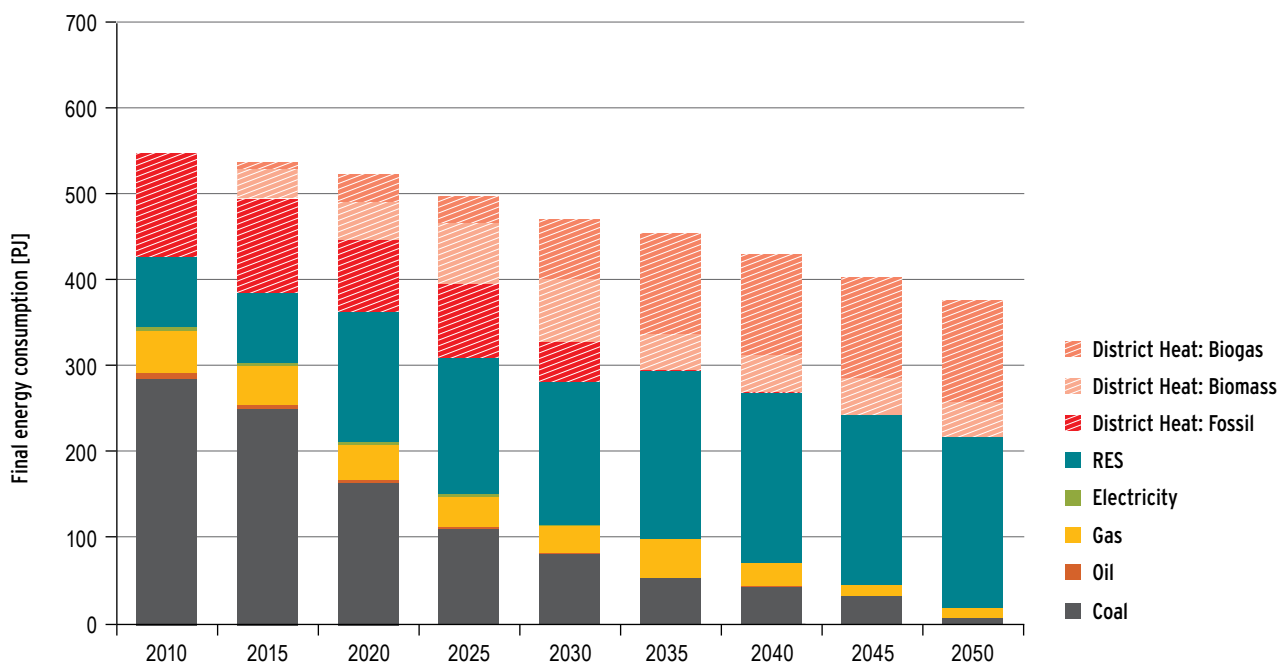
Figure 18 depicts the fuel mix for residential heat supply in Germany that is derived under the premise of minimum system costs. Increasing end-consumer prices for fossil energy carriers lead to a significant increase of the rate of building renovation with regard to energy efficiency. This contributes to cutting the final energy consumption for heat production in the German residential sector by 50% in 2050. When analysing the electricity use for heating purposes, results show a technological shift from direct electric or night storage heating technologies in 2010, towards heat pumps in later years in pursuit of cost-optimality. As heat pump technology boosts the heat output exploiting ambient heat, the amount of total electricity-based heat generation is much higher in 2050 than in 2010 while at the same time the respective electricity consumption in 2050 is actually below the level of 2010 (cf. Figure 18). After becoming a market mature technology in 2020, the use of micro-CHP decreases beyond 2035 due to elevated end-consumer prices for fossil energy carriers and stricter thermal building standards. However, CO₂ emissions in the residential sector are not subject to a CO₂ emission certificate obligation. Therefore the increasing CO₂ certificate price towards the end of the model horizon, being an assumption adopted from TIMES PanEU results (cf. Figure 14), generates a comeback of micro-CHP in the German residential sector in 2050. In this way, micro-CHP contributes to electricity supply to a non-negligible extent.

Figure 18: Final energy consumption for heat generation in the German residential sector as a result of TIMES-Heat-DE, based on model input from TIMES PanEU



The increase in fuel prices for end consumers and particularly the required reduction of CO₂ emissions in the residential sector in Poland, lead to significant changes in the final energy consumption structure compared to the reference data set as presented in Figure 19.

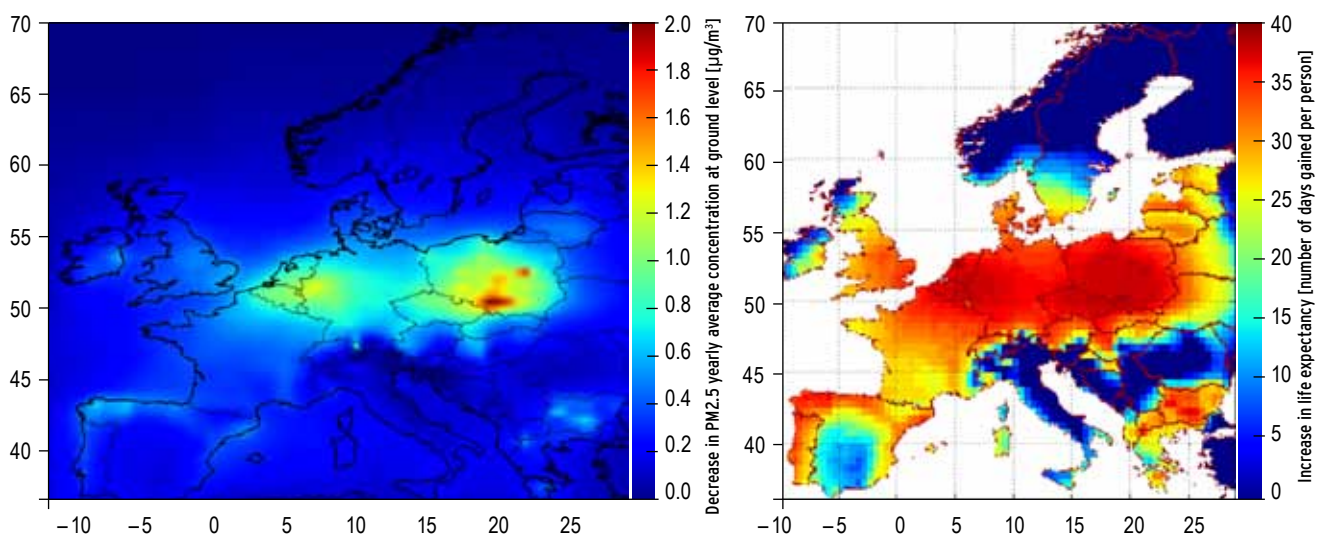
Figure 19: Final energy consumption for heat generation in the Polish residential sector as a result of TIMES-Heat-PL, based on model input from TIMES PanEU



The share of renewables is sharply increasing while the share of coal depicts a reverse trend. Due to the high price of gas compared to other fuels for residential customers, gas consumption in individual heating systems decreases. However, the available potential of low-carbon intensive fuels such as biomass and biogas is fully exploited by 2035. To meet the required CO₂ emission reduction in the domestic sector by this year, the use of gas is necessary. In the following years the slight increase of available biomass potential and reduction of heat demand lead to a further decrease in the use of gas. Biomass boilers dominate individual heating systems in single and two family houses. The share of heat produced in cogeneration from biomass and biogas supplied to small and multifamily houses is also growing.

To analyse the impact of non-GHG emissions in a cost optimal energy system the results of the model calculation of PIAM are used. Figure 20 presents the changes in PM2.5 concentrations and in life expectancy in 2030 compared to 2010.

Figure 20: Decrease in PM2.5 yearly average concentration at ground level [$\mu\text{g}/\text{m}^3$] (left) and corresponding increase in life expectancy [number of days gained per person] (right) in 2030 compared to 2010



The results are quite similar to the reference case. The highest decrease in PM2.5 concentration is observed over Poland, Germany (mainly Ruhr area) and Benelux countries. These are also the areas showing the greatest increase in life expectancy compared to 2010. It is not surprising that the variation in yearly average PM2.5 concentration does not differ much from the reference case as the emission of traditional air pollutants, particularly from energy industries, is well controlled under the current legislation. However, special attention should be paid to regions where low emission intensive fuels such as gas, are substituted with biomass. In such situations the use of biomass without appropriate emission controls may have a positive impact on GHG emissions but a negative effect on the local air quality. The environmental impact of bioenergy is analysed in more detail using a method which makes use of a life-cycle approach in the next case study.

The following main conclusions can be drawn from the calculations:

- 1) with only the emission reduction target in place the results show that a diversified technology mix is the cost-optimal way to reach this target,
- 2) some of these cost-optimal options to reduce the GHG emissions entail an increase in primary energy consumption,
- 3) the diversified technology mix is complimented by a strong decarbonisation of electricity generation in combination with an extended use of electricity in the end-use sector which further contributes to the cost-optimal GHG emission reduction.

The national models (Germany and Poland) show that the 2050 technology mix for electricity production is affected by local conditions. The results for residential heat supply also show differences in the technology mix between these two countries. In Germany results show a decrease of the final energy demand for residential heat generation by about 50% and a technology shift towards heat pumps, micro-CHP, solar thermal, and biomass, while also retaining gas and fuel oil boilers. However, in Poland there is a fuel switch from coal to biogas and biomass in both individual and district heating systems. Thus the diversified European cost optimal energy mix consists of country specific energy mixes. This is also reflected in the change of PM2.5 over Europe. The PM2.5 concentration is decreasing over Europe but the highest decrease is observed over Poland, Germany (mainly Ruhr area) and Benelux countries. The emission of traditional air pollutants particularly from energy industries is well controlled under the current legislation. Special attention should be paid however, to regions where low emission intensive fuels e.g. gas, are substituted by biomass. In such situations the use of biomass without appropriate emission controls may have a positive impact on GHG emissions but negative on the local air quality.

4.2 Case study 2: What are the effects of legally binding targets on the EU energy system? (RES-EE-EU targets case)

Key messages:

- A policy requiring high renewables penetration and lower primary energy demand increases hydro, wind and solar before biomass
- Increasing demand for forest biomass increases competition for raw material with the pulp and paper industry
- Policy mandates for higher energy efficiency and renewables costs more, but improves energy security by reducing imports

4.2.1 Case study outline

This case study aims to calculate a decarbonisation scenario for the entire EU energy system that combines the target for greenhouse gas emissions with legally binding targets for energy efficiency (reduction of primary energy) and renewable energy sources (renewable share at gross final energy consumption of 70% by 2050). These targets are also considered in the *Roadmap*, but within different decarbonisation scenarios and not in combination.

The key objective with this scenario is to show how the additional targets affect the future energy mix. The inclusion of a renewables target and an energy efficiency target in a decarbonisation scenario restricts the use of nuclear and CCS when compared to the cost-optimal case. The use of renewable energy sources however, is affected in different ways by each of the additional targets: The energy efficiency target can restrict the expansion of biomass, whilst other renewable sources like hydro, wind and solar benefit from it. The renewables target clearly promotes all renewable energy sources. By implication, system costs are higher in this scenario than without additional targets.

The case couples two different approaches, each with a different scope. Firstly, TIMES PanEU is used to model the development of the entire EU energy system and an overall energy balance for the EU. The second approach aims to assess the environmental impacts corresponding to the underlying case. However, for the time being a detailed study of country-specific forest-based bioenergy is given for Sweden (impact assessment with life-cycle approach – IA with LC-approach). This latter approach relates to the significance that renewables and specifically biomass energy carriers are given in the overall case. Further details of the different approaches are discussed below.

In investigating the effects of the additional targets, TIMES PanEU quantifies the sectors and technologies playing a key role in reaching these targets for the EU energy system. In particular TIMES PanEU determines which of the possible renewable energy technologies are to be encouraged in future system development and how a reduction of primary energy could be reached. Results of this case study are also compared with the cost-optimal case (also calculated with TIMES PanEU) thereby identifying possible conflicts and synergies between the additional normative targets for energy efficiency and proportion of renewables, and the GHG emission target. It is natural here to focus on the additional cost to achieve such normative targets. However, by considering energy imports and their cost, the key EU energy policy objective of security of supply is also assessed.

The increasing importance of biogenic energy carriers provokes questions regarding the non-carbon environmental impacts, since any use of bioenergy could generate negative impacts on both man-made and natural habitats. The use of IA with LC-approach allows the investigation of environmental impacts due to harvest, transportation, conversion and waste treatment for forest bioenergy. This particularly highlights the environmental impacts that may arise due to increased use of biofuel in the transport sector considering the additional targets in the overall case study. The detailed system description of the forest-based industry deals with the extent to which the increased future demand for forest bioenergy may approach the limits of the forest ecosystem. The results also explore the question of whether bioenergy may compete with the pulp and paper industry for forest resources.

The detailed assessment of environmental impacts focuses on forest-based bioenergy, as the most important renewable energy source, to show the opportunities of coupling IA-approaches with energy system models. The following assessment analyses the Swedish forest in detail. Such an approach addresses the key EU energy policy objective of sustainability in a context wider than the target for reduction of GHG emissions. Forests in Sweden cover almost 50% of the country's total land area and are already exploited to a high degree for timber, pulp and paper as well as bioenergy. These are all sectors in which Sweden leads in Europe. Results of the study are specific for Sweden but may be considered indicative for forest bioenergy as a whole, which is supported by results for Germany.

The case study assumes a normative GHG emission reduction pathway compared to 1990 levels as follows: -25% in 2020, -40% in 2030, -60% in 2040 and -80% in 2050 (as for all decarbonisation scenarios in this report). Meanwhile the target for share of RES at gross final energy consumption is 20% in 2020 and 70% in 2050. The energy efficiency target aims to reduce primary energy (not including non-energy consumption) compared to the baseline projections of PRIMES 2007, by 15% in 2020 (since the official target of 20% does not seem to be within reach) and an assumed 35% reduction in 2050.

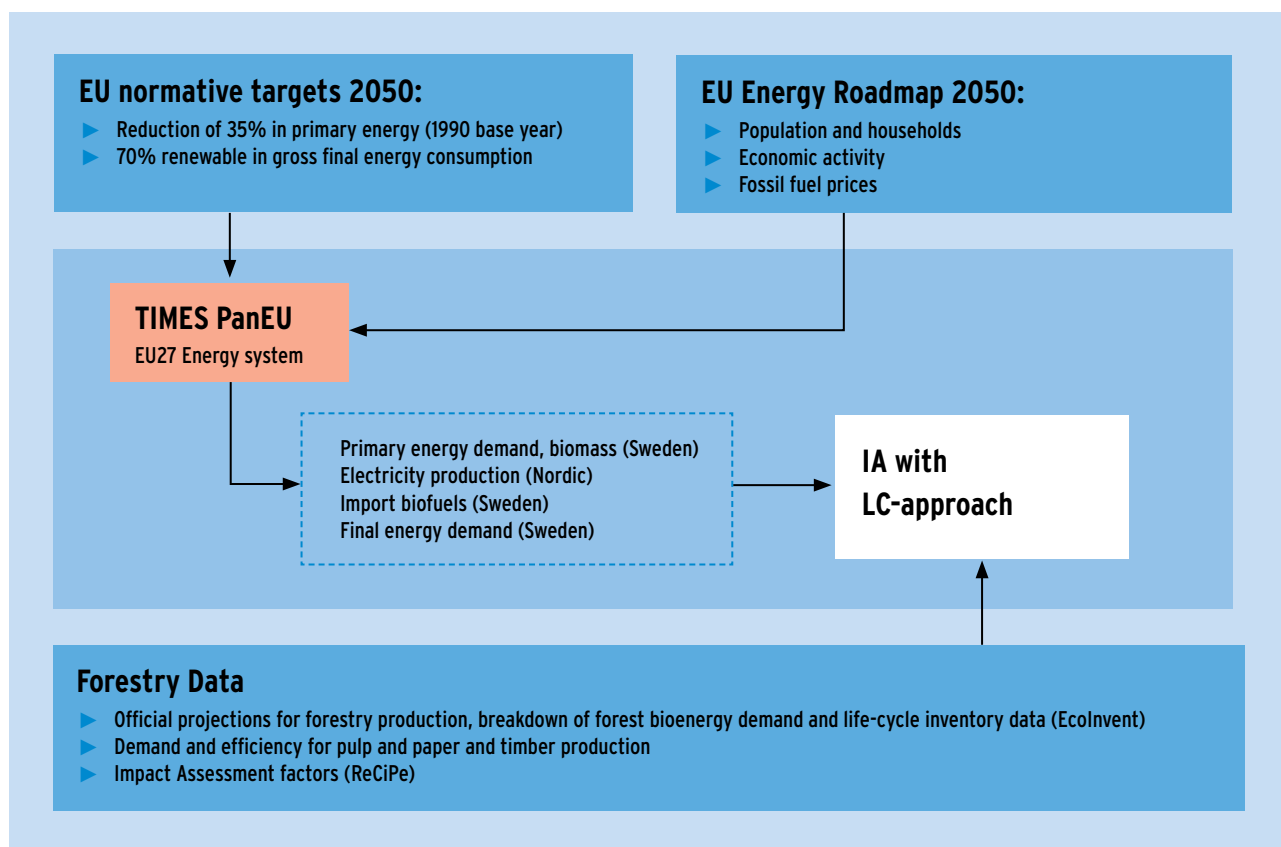
Both the renewables target and the energy efficiency target use the same definition as the EU for these targets. That means that energy efficiency is measured as a reduction of primary energy consumption without non-energy uses and that an increased use of renewables is measured as

a share of gross final energy consumption. The modelling of the normative targets in the TIMES PanEU model corresponds to the way the European Commission measures energy efficiency and use of renewables. Assumptions for population development and economic activity are based on the *Roadmap*. The GHG emission reduction target and the fossil fuel prices in this case are the same as in the cost-optimal case (cf. Table 1).

In addition to these targets, the detailed study of Swedish forest biomass assumes forest production equivalent to the 100-year reference scenario of the Swedish Forest Agency (SFA) (Swedish Forest Agency, 2008). This implies an increase in total possible biomass production of 16% over 2010 levels. Forest bioenergy extraction is limited to the ecological limits applied by the SFA (Swedish Forest Agency, 2008).

Energy mix for direct energy inputs for the Swedish forest biomass life-cycle (i.e. harvest, transport, conversion and waste treatment) is based on output data from TIMES PanEU. Data for capital inputs in the supply chain are taken from the EcoInvent life-cycle inventory database. Agricultural yields (relevant for biofuels used in the supply chain) are assumed to increase by 0.5% per year, as also assumed in the EU Low Carbon Economy *Roadmap* (EU COM, 2011b). Tank to wheel efficiency for road and rail transport is assumed to increase by 40% up until 2050. These and further assumptions are summarised in the Figure 21.

Figure 21: Model coupling - assumptions and data flow for the calculations of case with legally binding targets for the EU energy system (RES-EE-EU-targets case). IA with LC-approach: environmental impact assessment with life-cycle approach.

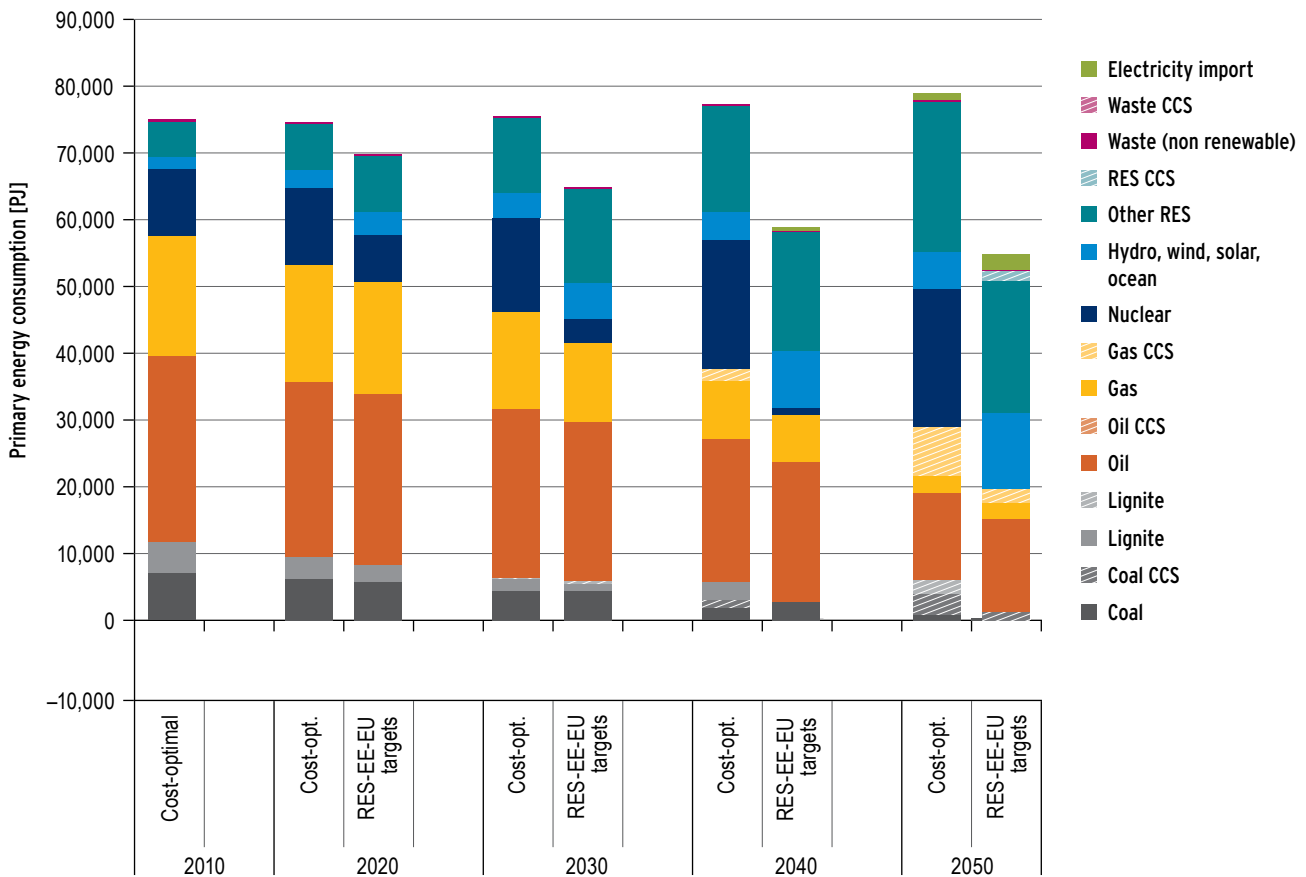


4.2.2 Results and discussion

As shown in Figure 22 the overall development of primary energy consumption is driven by the energy efficiency target in this case study and is lower by 23,665 PJ in 2050 compared to the cost-optimal case. In addition, the share of the different energy carriers and technologies clearly differs from the cost-optimal case. The renewables targets and particularly the energy efficiency targets have a strong impact on the composition of primary energy consumption. The study shows a reduction of 20,644 PJ nuclear energy and 6,153 PJ CCS energy, compared to the cost-optimal case, due to their lower primary energy efficiency. For example, nuclear power is calculated with 33% conversion efficiency, whereas wind and solar are 100% efficient. Both nuclear and CCS play key roles in the cost-optimal case, thus showing that cost-optimal emission reduction pathways are blocked by the energy efficiency target.

In contrast, primary energy from hydro, wind or solar (+5,494 PJ in 2050), and electricity imports to the EU (+1,671 PJ, being mainly electricity from solar energy from North Africa) are higher in this case than in the cost-optimal case. These technologies are more attractive in this scenario due to the renewables target and also due to their reducing impact on the primary energy consumption (i.e. the energy efficiency target). Thus, targets for share of renewables and energy efficiency have a strong impact on the European energy system and lead to a deviation from the cost-optimal emission reduction pathway. Although primary energy consumption is lower in the RES-EE-EU-target-case, total energy system costs are higher (cf. Figure 23). This shows that lower energy consumption does not always go hand in hand with lower total costs.

Figure 22: Primary energy consumption in the RES-EE-EU-targets case compared to the cost-optimal case in the EU-27 as a result of TIMES PanEU

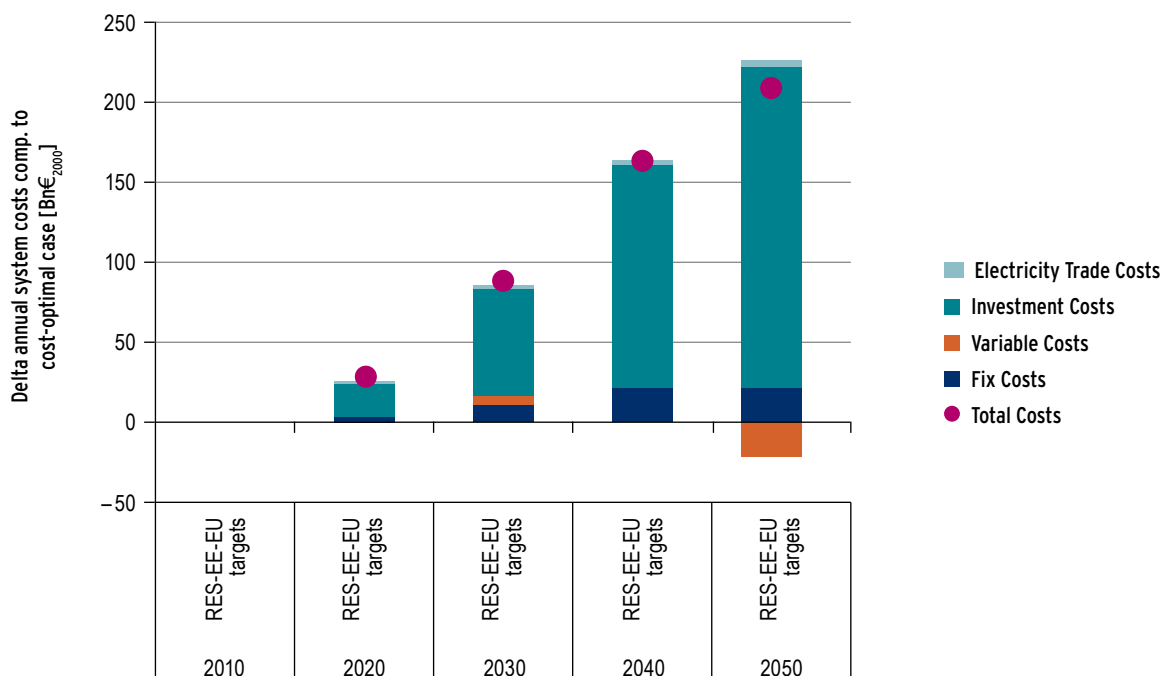


Including normative targets in the EU energy system leads to less flexibility in reaching the GHG emission reduction target and therefore to higher energy system costs. The additional annual costs may total more than 200 Bn. € higher than the cost-optimal case in the year 2050 (cf. Figure 23).

The main driver for the cost difference is the additional investment costs (+199.6 Bn. €) for the renewable energy technologies and technologies with a lower specific energy consumption to fulfil the two additional targets. In general, these technologies have lower specific energy consumption and lead to reduced primary energy consumption or an extended use of renewables. However, they also have higher investment costs and lead to higher total system costs. Besides investment costs, fixed costs (+23.7 Bn. €) and costs for electricity imports to the EU (+4.4 Bn. €) are also higher compared to the cost-optimal case. On the other hand the variable costs, which are strongly influenced by the fuel costs, are lower in the RES-EE-EU-target-case in the long term (-21.3 Bn. € in 2050). The reason for this is that the extended use of renewables does not give rise to fuel costs. There is also reduced total energy consumption.

The average additional annual energy system costs of the RES-EE-EU-targets-case compared to the cost-optimal case of the period 2010 – 2050 are 97.2 Bn. €. The results of the *Roadmap* show a comparable average additional annual cost between their “High Energy Efficiency” scenario and their “Diversified supply technologies” scenario of 65 Bn. €. The additional annual costs shown in Figure 23 increase constantly from 0.23% of GDP in 2020 to 1.03% of GDP in 2050 (using *Roadmap* data for GDP in both cases).

Figure 23: Additional annual undiscounted energy system costs in the RES-EE-EU-targets case compared to the cost-optimal case in the EU-27 as a result of TIMES PanEU

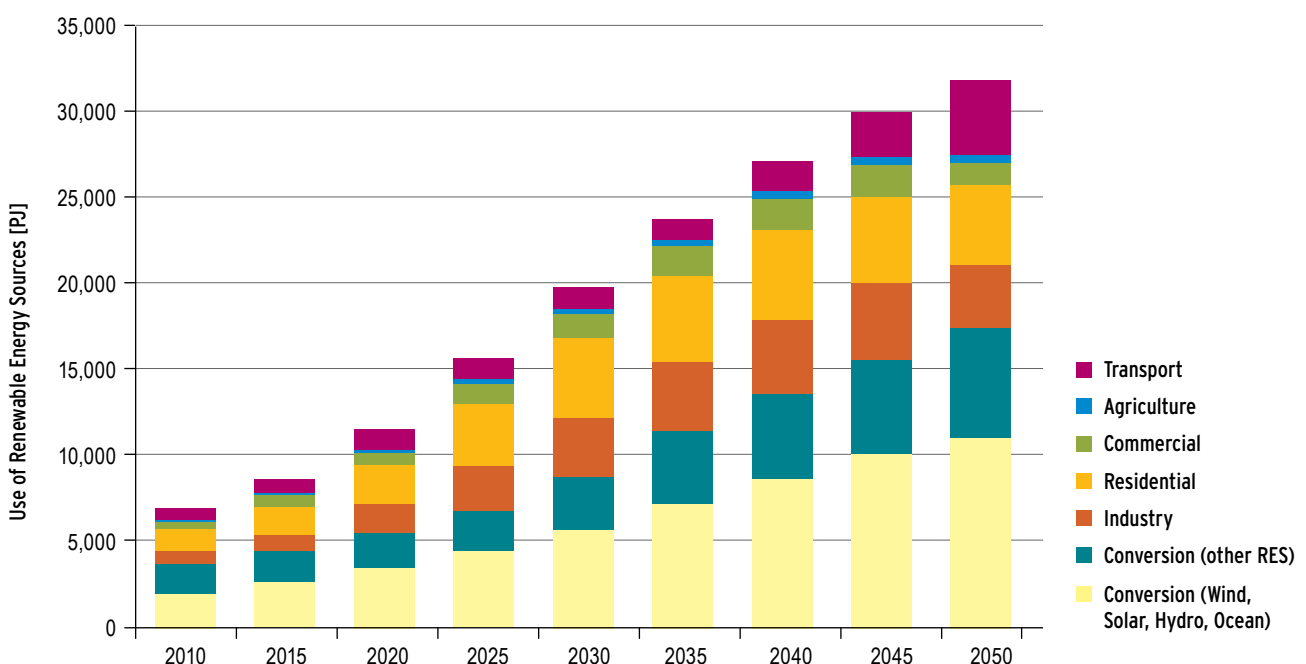


But even if these normative targets block the use of the most cost-effective energy technologies and lead in total to higher system costs, they have benefits in terms of reducing the use of primary energy (-23,665 PJ in 2050), decreasing European energy imports and the related external fuel bill and thereby increasing security of supply. This case indicates that in 2050, the import of fossil fuels into the EU are reduced by almost 7,000 PJ. The main driver of this reduction is the reduced amount of imported gas (-5,000 PJ in 2050). The imports of electricity to the EU are increasing (+1,671 PJ).

Apart from their use in the conversion sector to provide electricity, renewables are used in the end-use sectors. They are used to provide space heating in the residential, commercial and industrial sectors, and in the industrial sector for similarly low temperature process heat (e.g. in the pulp and paper industry).

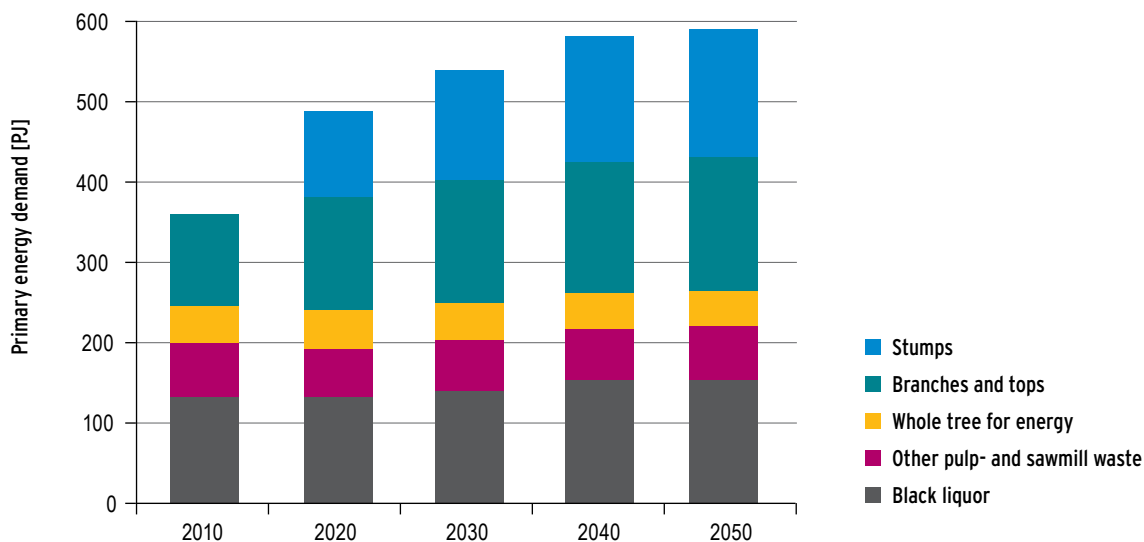
While the overall use of renewables is constantly increasing, there is a shift between the sectors in later periods. With stricter GHG emission reduction targets there is an increased emission reduction in the transport sector and an increased use of renewables. Due to the limited potentials of renewables, they are used more in the transport sector than in the other end-use sectors. This shift is accounted for by a different use of biomass. Instead of using it in the residential sector (reduction of 1,105 PJ between 2030 and 2050), commercial sector (reduction of 533 PJ) and industrial sector (reduction of 438 PJ) for the supply of low temperature heat, it is used in the transport sector (increase of 3,261 PJ) to provide bio-fuels. The emission reduction options in the transport sector are limited, especially with respect to freight transport and aviation. The use of biofuels is sometimes the only option in parts of the transport sector and hence the use of biomass in this sector is increasing. Other sectors can use other mitigation possibilities such as insulation, being an example of a measure to reduce demand in the residential sector. Due to the higher costs of these additional measures, they are only used in the later periods when emission certificate prices are high. In the long run, to reach a GHG emission reduction target of 80%, all sectors have to contribute. Given the different options and costs, clear emission reduction in the transport sector occurs in the later periods when targets are stricter. This strong change is effective after 2040.

Figure 24: Use of renewables in the EU-27 as a result of TIMES PanEU



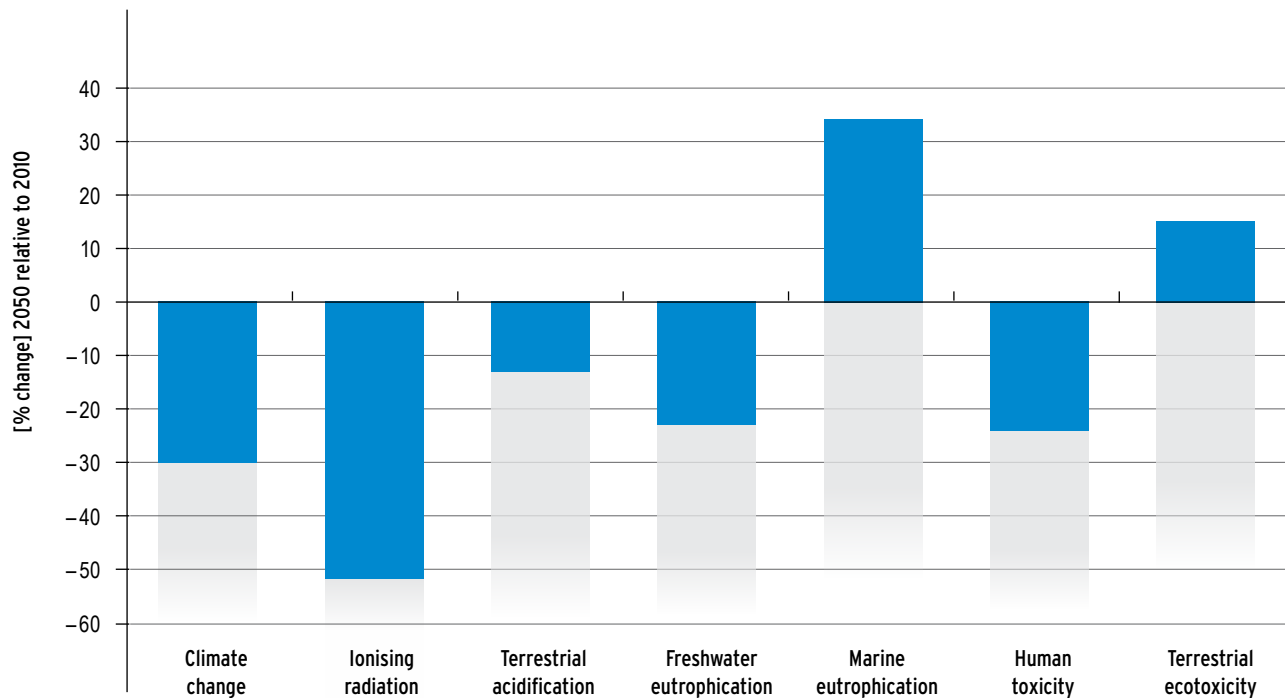
As the demand for biomass in the EU as a whole increases towards 2050 (cf. Figure 22), Figure 25 shows that demand for Swedish forest bioenergy also increases. In 2050, the demand for forest bioenergy is 589 PJ representing 33% of the total Swedish primary energy demand, and over 90% of the established ecological capacity of the forest. The Figure shows that stump removal will be required to meet the increased demand from 2020, causing soil disturbance and consequent negative impacts to the forest ecosystem. However, with changes in forest management methods it may be possible to meet a demand increase such as that shown in the Figure and avoid the need for stump removal on a large scale. The demand increase shown in Figure 25 also causes an increase in the extent of nutrient removal from the forest, such that new ash recycling processes are necessary in 2050 to maintain an ecologically sound nutrient balance. This highlights the need for significant changes in sectors other than the traditional energy sector in order to meet the case study targets as well as wider sustainability objectives.

Figure 25: Primary energy demand for Swedish forest biomass by fuel type for RES-EE-EU-targets case 2050 based on IA with LC-approach methodology



These results suggest that environmental pressure in forest ecosystems across the EU27 as a whole may increase significantly due to the increased demand for bioenergy. Of wider EU significance, such pressures will clearly put energy in competition with other uses for forestry biomass, notably for pulp and paper.

Figure 26: Changes in indicative environmental impacts between 2010 and 2050 per kWh of forest primary bioenergy for this case study based on IA with LC-approach methodology



The life-cycle climate impact for forest bioenergy was 0.025 and 0.018 kg CO₂-e/kWh in 2010 and 2050 respectively. These impacts are low compared to indicative climate impacts for total primary energy in both 2010 and 2050 and Figure 26 shows that the climate impact decreases by 29% over the period. In this impact assessment it is assumed as in other LC-approaches that since carbon dioxide released from biomass combustion is biogenic it does not have a climate impact. However, it must be noted that using forest products for bioenergy (Figure 25) decreases carbon accumulation in forest soil that would otherwise occur without this use.

Figure 26 also shows that other non-climate life-cycle environmental impacts also decrease between 2010 and 2050. The impacts that are measured in each of the categories shown in the figure are explained in Chapter 3, Methodology. Ionising radiation decreases due to decreased nuclear power in the Nordic electricity mix in 2050. Terrestrial acidification decreases due to the reduction in specific emissions due to combustion of forest biomass. The largest single contributor to the reduction in freshwater eutrophication is a reduction in emissions from mining processes associated with fossil fuels and infrastructure materials (metals and concrete) that are used in the life-cycle. Finally, the reduction in human toxicity is due to the reduced presence in the human food chain of toxic substances from both treatment of ash from forest biomass combustion and from reduced run-off from mining processes.

Having said that, Figure 26 also shows increases in marine eutrophication and terrestrial ecotoxicity. These occur due to the fact that liquid biofuels (in this case assumed biodiesel) are more widely used in the 2050 forest biomass life-cycle chain. These impacts increase in spite of the assumed increase in transport efficiencies and agricultural yields. For the case of Swedish forest bioenergy such a result demonstrates the importance of efficient supply chain logistics in mitigating environmental impacts, particularly in the low-GHG emission 2050 energy system under consideration. From the point of

view of the EU energy system as a whole these results highlight that the increase in the use of forest biomass towards 2050 may cause increased negative environmental impacts (besides the positive impact on climate change). Having said that, measures such as widespread increase in fertiliser efficiency through precision application may mitigate such effects. Both results highlight the need for concerted and coordinated measures in the agricultural and forestry sectors to achieve the key EU energy system policy objectives for sustainability.

This case study has shown that the normative system targets considered promote solar, wind and hydro power, though at higher system costs than would otherwise be required to achieve the climate target in a cost-optimal way. However, reduced energy imports point to increased energy security. The environmental impact assessment for Swedish forest bioenergy shows that the increased demand from this sector will place significant strain on the Swedish forest ecosystem and increase resource competition with the pulp and paper industry. The impact assessment has further shown that process improvements in agriculture and forestry are necessary in order to reduce environmental impacts from energy demand in 2050 (particularly for terrestrial ecotoxicity and marine eutrophication) and achieve a wider objective for energy system sustainability. The main findings of the Swedish case are confirmed by investigations into the German forest-based industry. The magnitudes of the changes however, differ between both industries. For example greenhouse gas emissions decline by 15% in the German case, whereas for Sweden a decline of 30% is calculated. The differences result from the different structure of the woody energy carriers. For example, removing of stumps is not relevant in Germany.

4.3 Case study 3: How far can we get with a combined energy efficiency and renewable energy supply strategy? (RES-EE-exploring case)

Key messages:

1. Combining energy efficiency and renewable energy measures provide an efficient way of emission reduction.
2. Electricity will dominate the future energy mix. Hence the decarbonisation of the electricity sector, e.g. with the help of electricity generation from RES, is a major step towards a low carbon European economy.
3. In the midterm grid expansion, rather than storage expansion is necessary to integrate the increasing RES generation.
4. Curtailing surplus renewable feed-in is a long-term cost-effective way of reducing the requirements for grid and storage expansion.

4.3.1 Case study outline

Energy efficiency as well as electricity generation from renewable energy are seen as major measures to reach the emission reduction targets by the European Commission and the Member States. Within the *Roadmap* both instruments were analysed in different scenarios. Hence the results of the merged scenarios have not been derived and a more detailed analysis about the interaction and effectiveness

of a policy combining both measures is not possible. However it is important to combine them in one single scenario in order to investigate how a combined policy affects the European electricity market and to what extent the CO₂ emission can be reduced. Therefore the following case study combines energy efficiency measures and renewable energy targets. The focus of this case study is the European electricity sector which gives rise to a large proportion of the European CO₂ emissions and it features the opportunity for a nearly full decarbonisation through the application of various options such as RES. One main challenge the European electricity system will face in the future is the increasing reliance on RES and its intermittency. This case study therefore analyses the effects of a large share of renewable energy sources on the electricity market. It deals with the following questions:

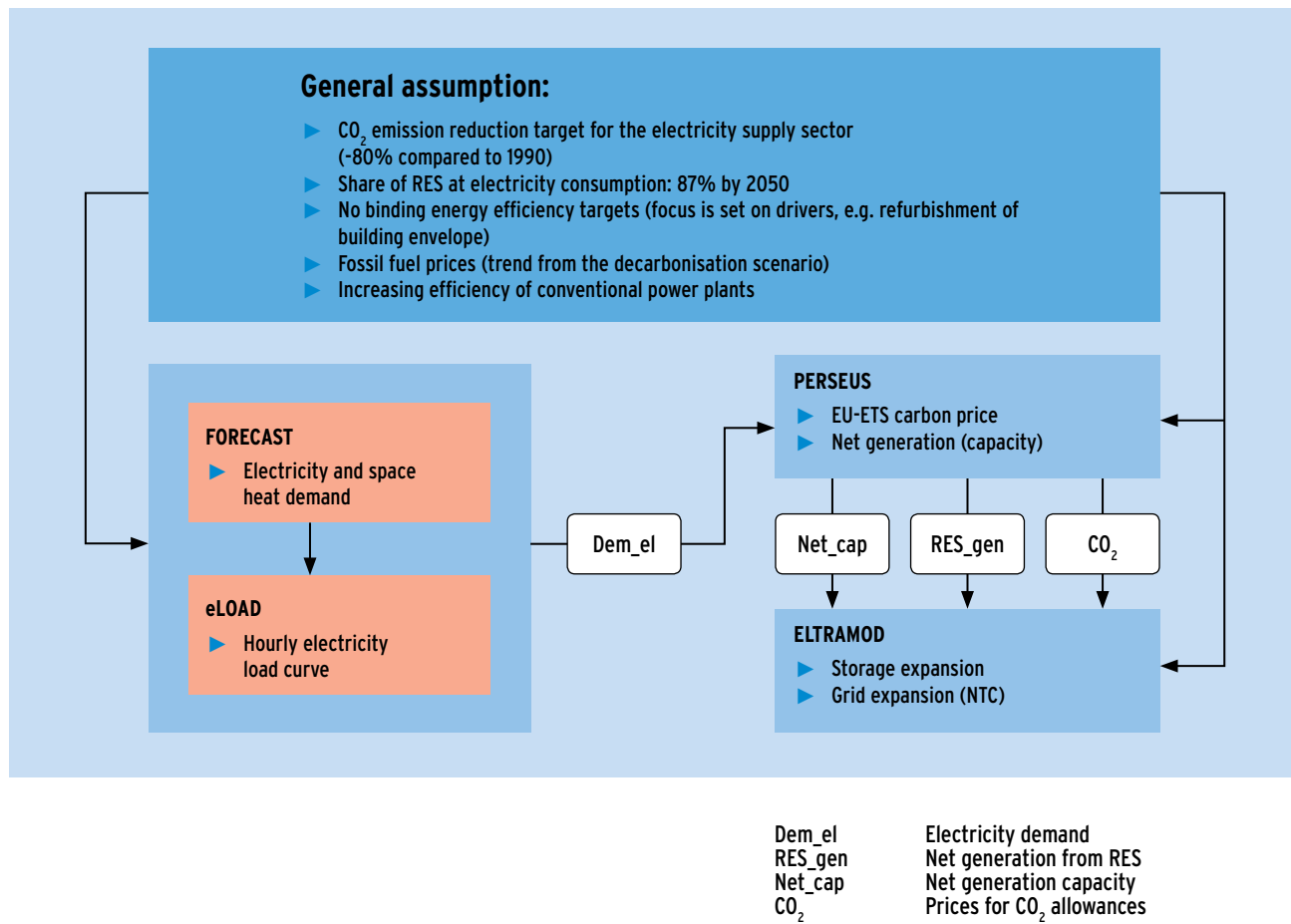
- to what extent can electricity consumption be reduced considering the growing significance of electricity in the energy system,
- how can an optimal grid and storage expansion be carried out, and
- how can curtailment be treated in the future.

Thereby the trade-off between grid and storage expansion is investigated.

The aim of this case study is to analyse the extent to which RES and energy efficiency measures can support each other in reducing GHG emissions. In contrast to the second case study, where the energy system as total was considered, the focus is only on the electricity sector (supply and demand) due to its growing significance and the opportunity to provide a full decarbonisation. Instead of considering binding energy efficiency targets, as in the second case study, an explorative approach has been taken, assuming very ambitious efficiency policies. This incorporates an ambitious efficiency technology diffusion pathway and minimum efficiency requirements for conventional power plants. The RES target is defined as the share of the overall electricity demand and is assumed to be 87% in 2050. This assumption is derived from the high RES scenario of the *Roadmap*. It was also assumed that countries which have already decided upon a nuclear phase-out will not construct nuclear power plants, whereas for other countries the yearly construction capacities are strongly limited. Assumptions about the future development of socio-economic drivers are used to define the framework parameters of the scenario. To ensure comparability, the assumptions about population and GDP development are equal in all case studies and based on the Reference scenario of the *Roadmap*. The GDP growth rate is assumed to be 1.7% p.a. on average for 2010-2050. Fossil fuel prices are assumed to be the same as in the two other decarbonisation case studies (see table 1). Furthermore it was assumed that the CO₂ emissions in the electricity sector can be reduced by 80% in 2050 compared to 1990. Since there is no emission reduction target for the electricity sector, this target is set on the basis of the overall GHG emissions reduction target and acts as a minimum level. The CO₂ emission reduction in this case study is primarily driven by the high proportion of RES and the integration of RES into the grid.

The electricity system was analysed with the help of FORECAST, eLOAD, PERSEUS and ELTRAMOD. All models address the electricity sector but each has another focus. FORECAST and eLOAD model the demand side, while PERSEUS models the supply side and ELTRAMOD focuses on the infrastructure of the electricity system. Combining these models within this case study allows an in-depth analysis of all fields of the electricity sector. The model coupling is shown in Figure 27. In all models the general assumptions regarding socio-economic framework parameters and policy regulation are harmonised. FORECAST models the future demand for residential space heat and the overall electricity demand for all end use sectors by considering emission certificate prices and diffusion pathways of efficient technologies. In a subsequent step eLOAD transforms the yearly results of electricity demand into national hourly load curves. Based on the electricity demand, the CO₂ emission reduction target and the RES target, PERSEUS models the EU-ETS carbon price as well as the net generation capacities of all supply technologies (conventional power plants and RES) and their dispatch. These parameters are used as an input in ELTRAMOD to determine the required grid and storage expansion.

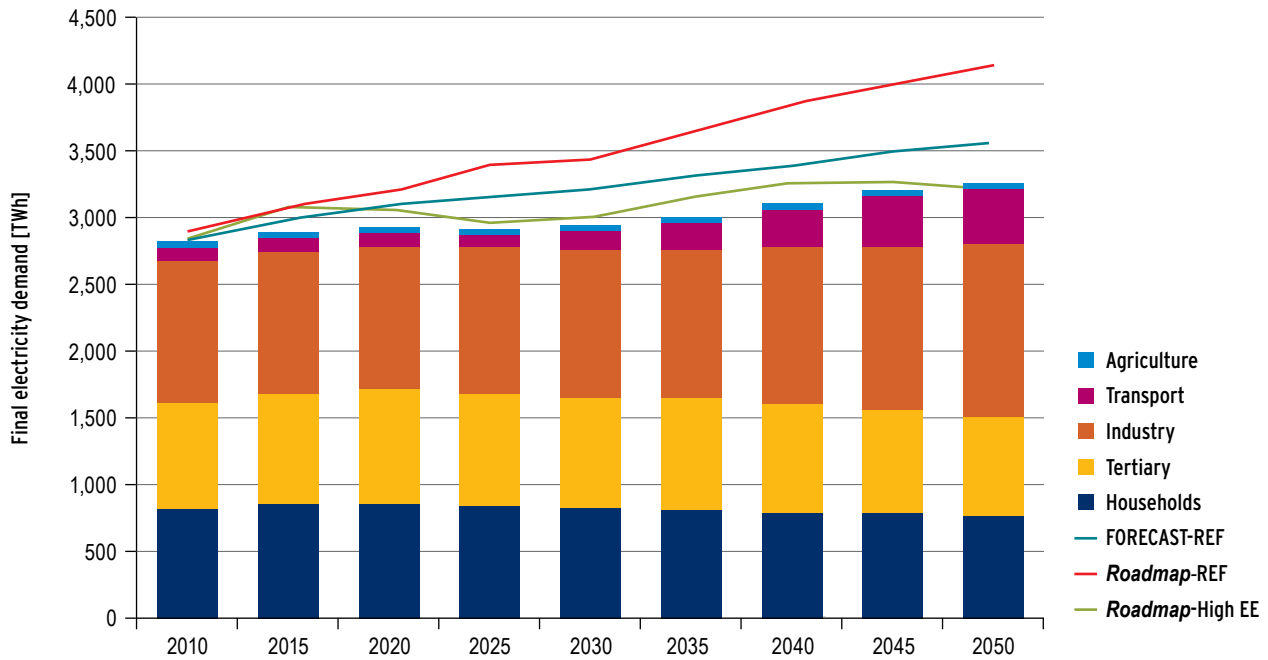
Figure 27: Model coupling - general assumptions, data flow and model focus for the calculations of the RES-EE-exploring case



4.3.2 Results and discussion

Very ambitious emission reduction targets lead, on the one hand, to a significant long-term decrease of final energy demand, but on the other hand to a disproportionately strong increase of electricity demand due to its potential for decarbonisation. Thus, electricity becomes even more dominant in the energy carrier mix, despite energy saving efforts. In this scenario the overall electricity demand increases by 16% by 2050 (compared to 2010), regardless of a strong distribution of efficiency technologies. The saving potentials exploited are mainly compensated through increasing demand from electric vehicles (+422% in the transport sector) and electrification in the industry sector (e.g. electric arc furnaces replacing blast furnaces; +21% in the industry sector) by 2050. In Figure 28 the overall electricity demand of this scenario is compared to the reference data set of the FORECAST model setting (*FORECAST-REF*). In the latter, electricity is 8.2% lower in 2050. In comparison with the reference scenario of the *Roadmap (Roadmap-REF)* electricity demand decreases by 21.3% by 2050. In the residential and tertiary sector only a slight decrease is noted (-8% and -4%, respectively), since most of the savings from white appliances and ICT appliances are compensated by the sharp

Figure 28: Development of EU-27 electricity demand by sector until 2050 as a result of FORECAST compared to the Roadmap

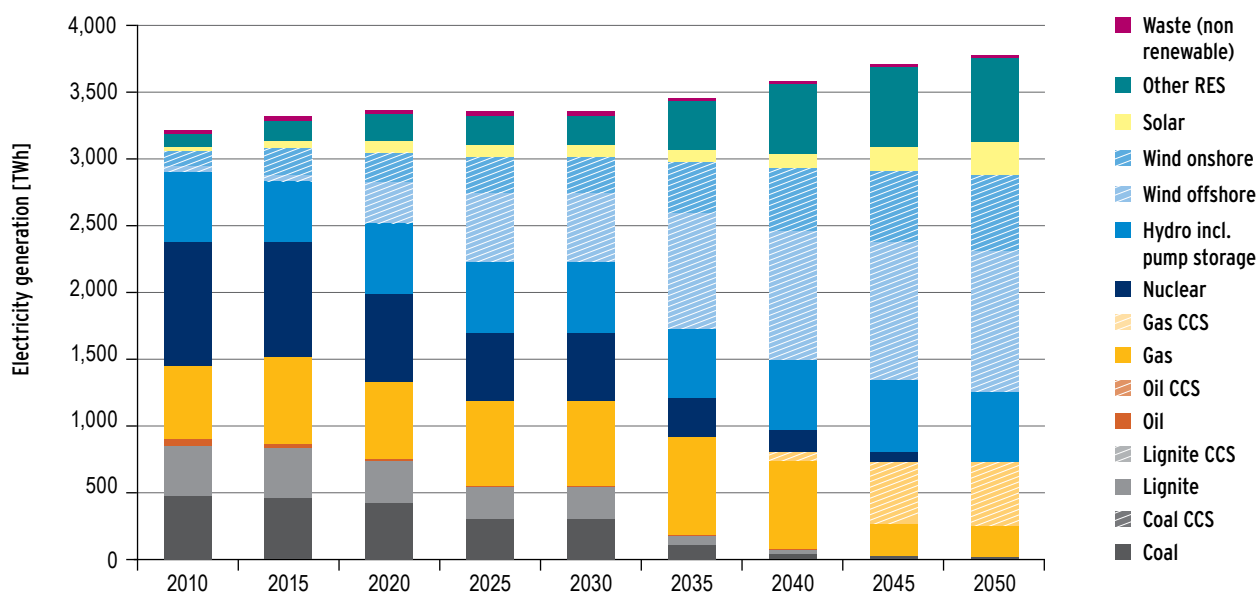


proliferation of heat pumps. Compared to the Energy Efficiency scenario of the *Roadmap*, in this case study the increase of electricity by 2050 is similar even though it takes place in a more continuous way (Figure 28). Overall, policy targets set for the proportion of RES in the supply side mix will be harder to reach, as there is a long-term increase in electricity demand.

A more detailed analysis of the results from the bottom-up electricity demand projection facilitates the identification of a number of end-use appliances that feature a significant change in demand over time. This change in demand has an important impact on the future shape of the electricity load curve. The extensive proliferation of electric vehicles and heat pumps leads to a further increase of the existing load peak in evening hours, which implies an even steeper load gradient towards the nightly base load hours. The phase-out of night storage heating systems in some countries as well as the declining production of primary aluminium triggers a further lowering of the demand in night hours.

On the one hand a growth of maximum load can be observed on an annual basis along with an augmented number of peak load hours (e.g. for Germany, the maximum load would increase from currently about 90 GW up to more than 100 GW). On the other hand minimum load will further decrease, resulting in a steeper slope of the national load duration curves. Given the increased electricity production from PV systems, which is concentrated on midday hours, and other volatile RES generation, the residual load curve that needs to be covered by conventional power plants will be further distorted. Therefore demand side management may become more meaningful in the future as an alternative or supplement strategy to grid extension and investment into flexible power plant capacities. A more concrete statement would require further modelling work.

Figure 29: Electricity generation by fuel for EU-27 based on the results of PERSEUS



According to the assumptions the results of PERSEUS show a high increase in electricity production from RES, which results in an electricity production of 3025 TWh (87% of the electricity demand) in the year 2050. Due to the restrictive CO₂ emission reduction target the electricity production from CO₂ intensive fossil fuels, especially coal and lignite, decreases, whereas flexible gas fired power plants, also with CCS, play a major role (see Figure 29). Base load technologies like nuclear are no longer economic because the operating hours are too small due to the high share of RES.

For further analysis of the optimal integration of the fluctuating RES, the results of PERSEUS are used in ELTRAMOD to calculate the impact on grid and storage expansion, which are seen as major instruments for integrating a high share of RES into the electricity system. To analyse the impact of the feed-in from renewables on the need for additional storage and Net Transfer Capacities (NTC), the following options will be discussed:

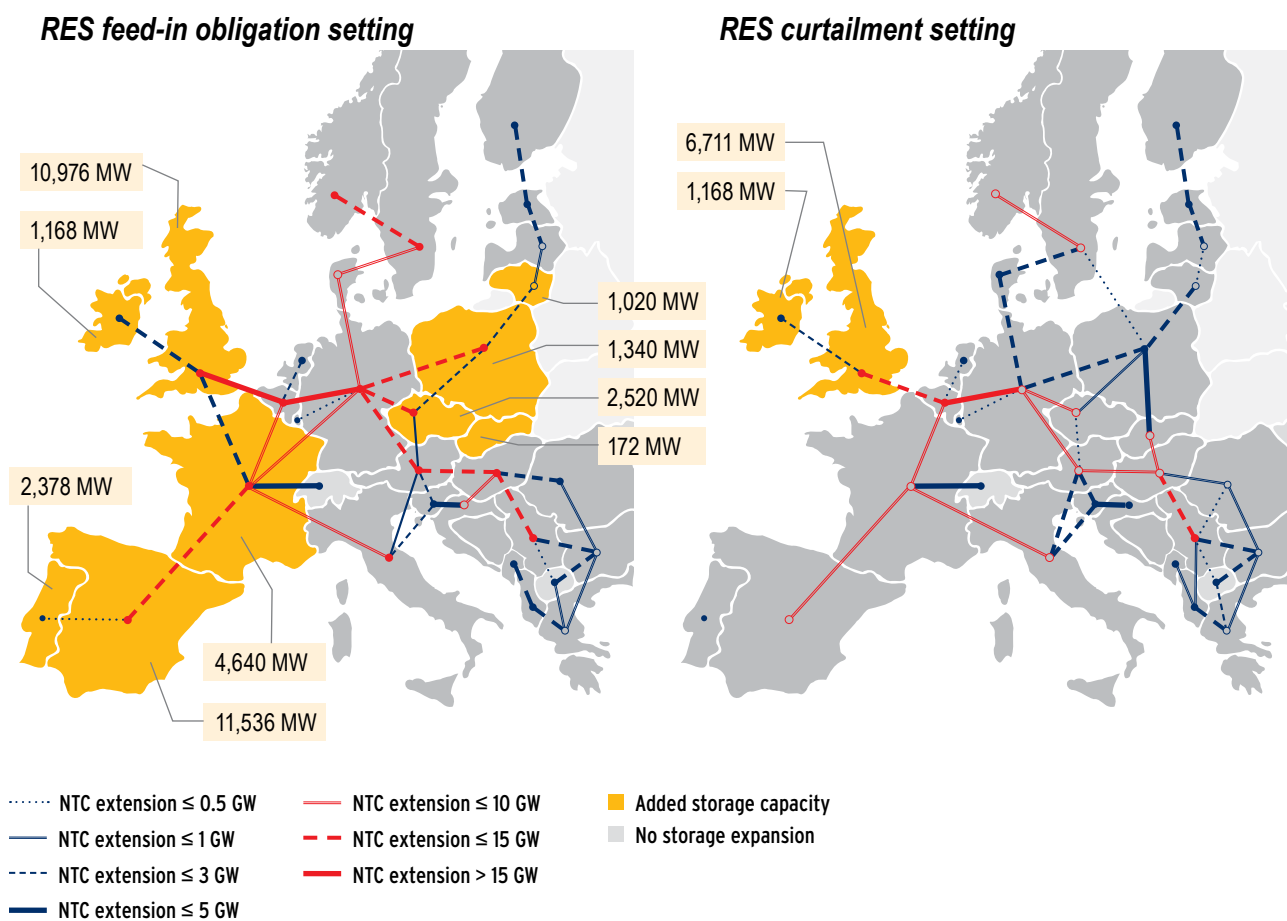
- *RES feed-in obligation* (every produced kWh of RES electricity is utilised), and
- *RES curtailment* (based on an economic assessment, the surplus of RES electricity can be curtailed).

Within the *Roadmap*, only the approach of RES feed-in obligation was considered. However, it is seen as important to also investigate an electricity system where curtailment of RES is considered since both the proportion of RES and the resulting surplus hours will significantly increase by 2050. Figure 30 shows the required NTC and storage expansion by 2050 for both model settings. The *RES feed-in obligation* leads to a much higher need of NTC and storage capacities than *RES curtailment*. In the *RES feed-in obligation setting* ca. 253 GW³ additional Net Transfer Capacity is needed while in the *RES curtailment setting* barely half of this is needed (ca. 143 GW). The investments in new storage capacities particularly depend on the presence of a RES feed-in obligation. Assuming that the surplus of RES electricity can be curtailed, additional storage capacities are only needed in Great Britain and Ireland (in total ca. 8 GW). If every kWh of RES electricity produced must be saved, new storage capacities are also needed in France, the Iberian Peninsula and East Europe by 2050 (in total ca. 36 GW⁴). The necessity of new storage capacities largely depends on the penetration of RES.

3 NTC is no constant value but varies permanently due to changing situations in the electricity system. ENTSO-E (European Network of Transmission System Operators for Electricity) publishes twice a year the export/import value to/from each country, which presents an ex-ante estimation of the seasonal transmission capacity. In 2010 the Net Transfer Capacity in EU-27 can be approximated at 68 GW (ENTSO-E 2010; ENTSO-E 2011).

4 In 2010 about 16 GW of pumped storage plants were installed in the respective countries.

Figure 30: Grid storage expansion, relative curtailment of RES and CO₂ emissions in 2050 for the *RES feed-in obligation setting* and *RES curtailment setting* based on the result from ELTRAMOD



	RES feed-in obligation	RES curtailment
Relative curtailment of RES w/o expansion	10.2%	11.9%
Relative curtailment of RES with expansion	0.9%	3.7%
Added NTC-capacity by 2050	252.5 GW	143.0 GW
Added storage capacity by 2050	35.7 GW	7.9 GW
CO ₂ -emission w/o expansion	177.5 Mio. t	177.3 Mio. t
CO ₂ -emission with expansion	95.5 Mio. t	114.0 Mio. t

Therefore, the requirement for additional storage capacity becomes important beyond 2040 when the penetration of RES is about 80%.

Regardless of the presence of feed-in obligation, investments in additional NTC are needed within Europe in the upcoming years in both settings (see Figure 30). The connection from peripheral areas (e.g. Great Britain or the Iberian Peninsula) to central Europe particularly needs to be increased to maintain security of supply in these countries and to integrate the growing share of RES. Hence, market coupling becomes more and more important in the forthcoming years. Furthermore, the amount of surplus RES electricity, which has to be curtailed, decreases with higher grid and storage capacities in both settings. In the *RES feed-in obligation setting* 0.9%⁵ of the available RES needs to be

5 Even in the setting *RES feed-in obligation* curtailment of RES occurs in order to maintain system balance.

curtailed to achieve system balance even when additional grid and storage capacities are built. In the *RES curtailment setting* however, 3.7% of the available RES needs to be curtailed in 2050. In contrast, the investment costs in additional storage and NTC are nearly 50% higher in the *RES feed-in obligation setting* than in the *RES curtailment setting*. The model calculation shows that the setting *RES curtailment* leads to significantly lower costs although the difference in the amount of RES curtailment between both settings is relatively low. Hence the presence of a RES feed-in obligation strongly affects the investments in additional storage capacities and NTCs in the forthcoming years as well as the costs for the future energy system and the reduction of CO₂ emissions.

With the help of grid and storage expansion, CO₂ emissions can be reduced by compensating for fluctuations of RES through additional storage and grid facilities rather than by conventional power plants. As a result, the generation of fossil thermal power plants and the corresponding emissions, decrease. With a feed-in obligation the CO₂ emissions in 2050 (in case with grid and storage expansion) are about 19 Mio. t_{CO₂} lower than in the *RES curtailment setting*. This is about 17% of the CO₂ emissions in 2050 in the *RES curtailment setting* (see Figure 30). Due to a higher share of curtailed RES electricity and lower investments in storage facilities and grids, the CO₂ emissions are higher with RES curtailment. Nevertheless the EU reduction target is significantly overachieved in both settings since the CO₂ emissions can be reduced by approx. 90%⁶ compared to 1990 in both cases (see Figure 30).

The following main conclusions can be drawn from the calculations: The significance of electricity will increase despite or even because (given the electrification in the heat and transport sector) of efficiency measures. In order to still achieve the CO₂ reduction target the share of RES in the electricity generation portfolio has to be increased significantly by 2050. As a result the volatility of the residual load curve will also grow. This urges a stronger focus on demand side management which might reduce the need for additional storage and grid capacity. However, the case study showed that the increasing share of RES requires investments in additional storage and grid capacities in the future, although from an economic point of view not every produced kWh from renewable sources should be integrated. This is obvious as it does not make sense to upgrade the grid or invest in storage capacities for the last kWh produced from renewables. That is probably the reason why the High RES scenario from the *Roadmap* is the most expensive one. From an economical point of view, it can be stated that in the middle to long-term the abolition of the feed-in priority of renewables might be one important step towards integrating renewables in the electricity system. Furthermore, in the mid-term perspective the grid extension is more important than the extension of storage capacities. Consequently, a local shifting of the surplus RES feed-in, facilitates the integration of renewables in the European electricity market better than a temporal shifting. To sum up it can be stated that combining energy efficiency and renewable energy is more effective than considering each alone. Both support each other and ensure not only that emission reduction is efficient but that supply is secure.

6 In 1990 the CO₂ emission caused by power generation and district heating were approximately 1484 Mio t_{CO₂} (EU COM, 2011a).

5. Conclusions

The ESA² competences in modelling and supporting energy policy analyses create opportunities to look at the European energy prospects from various points of view. This report demonstrates that the combination of the model linkage applied and the expertise from a number of reputable European research institutes provide insights to three major research questions into the design of the future EU energy system under the normative GHG emission reduction target from -80% in 2050 compared to 1990 levels:

- *“What is the cost optimal way to reach -80% GHG in the EU?”*
- *“What are the effects of legally binding targets on the EU energy system?”*
- *“How far can we get with a combined energy efficiency and renewable energy supply strategy?”*

These were selected for demonstration purposes. The main lessons learned from these three case studies are as follows:

Renewables and efficiency – they are more effective together than alone

Cost-effective energy efficiency measures reduce the necessity for investments in supply side assets (power plants, grids, and storage technologies) and help, amongst other things, to fulfil ambitious renewable targets. However, very ambitious energy efficiency efforts lead, on the one hand, to a significant reduction in final energy demand, but, on the other hand, to an increase in electricity demand due to fuel shift and new electric applications entering the market. Examples include heat pumps and electric vehicles, and replacement of industrial processes such as oxygen steel by electric arc furnaces. More or less CO₂-free electricity via renewables (RES) is an attractive solution to cope with the increasing electricity demand. In order to realise a reduction of the primary energy demand, regardless of decarbonisation, and to ensure security of supply, the overall aim should be to get the most out of the electricity (in terms of energy services), and electricity should be provided in the most efficient manner.

Renewables and energy efficiency will dominate, but under the aspect of cost-minimization there is also a need for investment into a diversified electricity generation mix, e.g. fossil power plants with CCS and/or nuclear

To achieve the GHG emission reduction objectives set up by the European Commission, a mix of technologies needs to be installed, with an emphasis on energy efficiency, RES and flexible gas power plants. Given the focus on the cost-optimal way to reach ambitious GHG emission reduction targets in the energy sector, investments in gas and coal power plants with CCS as well as nuclear power plants are viable to reduce the entire cost of energy supply. Of course, this result heavily depends on the chosen framework conditions (e.g. investment costs have a high influence) and on the acceptance of the technologies. However, it is necessary to view this discussion in its entirety including additional aspects such as security of supply, GDP growth, creation of local jobs and further cost evolution of specific technologies (RES but also nuclear and CCS).

An ever increasing need for Demand Side Management (DSM)

The future electricity load curve will experience a significant deformation due to a number of new electricity based appliances coming onto the market, along with the increased use of energy efficiency measures such as heat pumps and electric vehicles. Demand volatility will also increase in the future, as will the peak load and the number of peak load hours. Given the increased electricity production from PV systems, which is concentrated on midday hours, the residual load curve that needs to be covered by conventional power plants will be additionally distorted.

Therefore, demand side management (DSM) becomes more meaningful in the future as an alternative/supplement to grid extension and investment in flexible power plant capacities. Moreover, DSM considerably facilitates the system integration of renewable energy sources.

Curtailement of surplus renewables makes good economic sense

In this study, the requirements for additional storage, networks and flexible production capacities in the context of varying proportions of RES in the electricity generation system have been assessed by applying two different approaches:

1. Feed-in obligation: every produced kWh of RES electricity must be used (as assumed in the scenarios of the official EU Energy Roadmap scenarios),
2. Economic assessment: grid and storage expansion are modelled in order to integrate just the optimal generation of RES electricity. Thus, a temporary limit to electricity generation from RES is applied.

The calculations show that an economic assessment leads to significantly lower costs because investments in storage or grid capacities for a very limited number of kWh are very expensive. Further, with an economic assessment, the majority of produced kWh based on RES can be integrated into the energy system, reducing the curtailed RES surpluses.

Grid expansion is mandatory

For the creation of a European energy market with an increasing proportion of renewable energy sources, the further expansion of the existing grid infrastructure is essential (as an extension of the current market coupling) to minimize the energy supply cost. The expansion of international transmission capacities facilitates the system integration of RES, the accomplishment of the EU emission reduction targets with lower total system costs (than without grid expansion) and the establishment of a genuine internal market for energy on a European level. Therefore, high investments are required in the coming decades. There is a strong need for grid expansion especially in countries with poor connection to the European networks, such as the Iberian Peninsula and Great Britain.

In the short-term, there is no need for additional storage capacities. These are only required in the long-term perspective as the proportion of renewables increases substantially

Assuming an economic evaluation, substantial additional storage capacities are required in Central Europe when proportions of RES become high (above 80% on a European level, so probably well after 2030). Given a very high penetration of RES, storage is increasingly important in the years after 2030, because of the generation of surplus electricity in most countries. Given this temporary shift, storage gains in importance over spatial displacement (grid expansion). In the short-term, however, the focus should clearly be on grid expansion rather than storage extension.

Normative targets for RES expansion and primary energy consumption could block cost-optimal use of technologies, causing partially conflicting targets

Normative targets regarding the expansion of RES, or decrease in primary energy consumption in connection with an ambitious GHG emission reduction target over 80%, block the most cost-effective use of energy technologies and thus lead to higher costs. Under a simple emission reduction target, a cost-effective approach provides a balanced mix of technologies, where no technology is particularly encouraged or blocked. At the same time, however, this triggers a higher overall energy consumption. This is for example the case with the intensified use of technologies such as nuclear energy, CCS and

biomass which draw a higher primary energy consumption due to their lower conversion efficiency (e.g. wind and solar are calculated with 100% conversion efficiency, nuclear power with 33%). With a focus on cost minimisation it may be a conflict between the three objectives of emission reduction, expansion of renewable energy and efficiency increase. An efficiency target which is defined as a reduction of primary energy consumption especially excludes some cost minimal emission reduction options.

Heating supply sector should play a more prominent role in the discussion about GHG emission reduction strategies

In previous discussions about strategies to reduce greenhouse gas emissions, the heating supply sector has usually played a minor role. The analyses in this report, with the help of models focusing on the heat sector however, show that a considerable emission reduction potential is located in this sector. In addition to the use of RES, the increased usage of heat pumps represents an important option for emission reduction not least due to the ever decreasing CO₂ emissions of electricity.

Potentially negative impacts of an increasing use of biomass on the environment and on human health

The increased use of biomass in the GHG emission reduction cases also needs to be discussed given that they could result in other negative impacts on environment and human health. For example, particulate matter emissions could increase due to extensive biomass use. Therefore, the scope of future analyses also needs to include also non-GHG emissions and other environmental impacts when evaluating energy strategies such as realized in this study by applying an LCA-based environmental impact analysis.

ESA² is the one-stop-shop for energy system models

The model-based analysis presented in this report extends beyond the traditional use of models to allow a variety of approaches and points of view to be taken for the forecasts, and an optimal adjustment of the energy system to its continuously changing state. The ESA² case studies show that a set of models can be linked together very effectively. Such models range from conventional bottom-up models with optimisation of energy costs, to agent based simulations, and hybrid models which merge energy analyses with pollutant emissions and deposition or with environmental impact assessment. The work on case studies enables the ESA² team to not only combine the selected models but strengthen the cooperation between partners and further develop the team capacity in an integrated energy system analysis. Furthermore, model coupling, as well as the harmonisation process, improves the input data used for modelling.

The results prove that the methodology applied improves the performance of exercises and credibility of the results. Using various models for the analysis of the same case gives wider insights into the relationship between driving forces and the variability of the results.

Further development of the model coupling is projected to go in the direction of facilitating data transfers, identification of feedback and deeper analyses of the results. ESA²'s intention is to make the exercises transparent by making the important input data and results available on the web page.

The case studies presented and discussed in this study refer to policy questions raised, but they also indicate the prospects for particular energy technologies which is information of utmost importance for potential investors. The models and exercises can be tailored to tackle more detailed relationships, thus responding to problems that are of great interest for policy institutions as well as commercial companies on a national and European level.

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