Power sector decarbonisation: Metastudy

WP 2.2 Quantitative analysis of existing EU-wide studies

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Content

1 Introduction

By means of the EU Renewable Energy Directive of 2008 an ambitious target was set to increase the EU's share of renewable energy sources to 20% in the overall energy demand by 2020. Some European Union's (EU) member states already demonstrate an appreciable use of renewable energy sources, while others still have to make efforts to reach their national targets.

Nevertheless, it is common knowledge within society and politics that the fossil paths of energy supply need to be abandoned in favour of a future energy system based on more renewable energy sources. Reasons for this necessity are the demand for climate protection, the security of energy supply within the context of resource scarcity, decoupling from rising fossil energy prices and the possibilities of renewable energy sources enabling more actors to share energy supply ("democratisation" of energy supply). Environmental protection also plays a crucial role – especially synergies between climate protection and improvements of air quality should be mentioned in this context.

Against this background the EU's energy and climate package, which sets national and EU-wide targets, is of high importance. To meet the 2020 targets as well as longer-term climate protection targets, it is essential for the right decisions to be taken, e.g. regarding the design of policy instruments and support schemes for renewable energy. Energy scenarios are an important and frequently used tool to visualise the changes that need to be made for a more renewable-based energy future. Energy scenarios demonstrate (alternative) paths for the possible mid- or long-term development. Back-casting approaches indicate which political decisions ought to be taken today or within the short-term future in order to be able to meet certain targets. Energy scenarios should not be equated with concrete forecasts, as they do not aim to continue developments from the past into the future. Rather they try to develop a range of possible future paths, based on a set of assumptions.

In particular the crucial attributes (wide range of paths and set of assumptions) of scenarios make it difficult to compare different scenarios with one another. Different assumptions, combined in many cases with a lack of transparency and missing disclosures regarding the underlying data, constrain the comparison of various scenario studies and different scenario paths in particular. Obviously this makes it difficult to come to conclusions regarding the pathways and energy policy measures to be pursued.

The scope of the "Power Sector Decarbonisation: Metastudy" research project is to provide an overview of the relevant energy scenarios in order to help overcome the described difficulties by applying the so-called decomposition methodology. Analysing different scenario studies with this method involves systematically disaggregating their calculated emission reductions into the underlying causal factors (or components). By this decomposition of the CO_2 emissions the methodology provides value added in increasing the transparency of modelling exercises within the various scenario studies.

While paper 2.1 provides an overview on relevant EU-wide scenario studies, this paper focuses on an in-depth analysis of selected studies applying the decomposition methodology[1]. For this analysis four studies were taken into account:

- Greenpeace/EREC (European Renewable Energy Council), 2010. Energy Revolution – Towards a Fully Renewable Energy Supply in the EU-27.
- EURELECTRIC, 2009. Power Choices - Pathways to Carbon-Neutral Electricity in Europe by 2050.
- ECF (European Climate Foundation), 2010. Roadmap 2050 – Practical Guide to a Prosperous, Low-Carbon Europe. Technical Analysis.
- McKinsey, 2010. Transformation of Europe’s power system until 2050.

These four studies were selected because of their general importance in the public discourse as well as because of the relatively detailed data they provide. In order to make a meaningful comparison and decomposition analysis of different scenario pathways from different studies, certain data needs to be available for all scenarios. The four studies selected provide this minimum level of data. However, while a quantitative comparison of electricity demand and supply is possible with the McKinsey study, data quality and quantity of the scenarios of this study were not sufficient to perform a meaningful decomposition analysis.

Following this introduction the paper at hand first provides an introduction of the scenario studies and a general comparison of electricity demand and electricity supply in the scenarios of the four studies (Chapter 2). An individual analysis of the various scenarios of three of the studies with the decomposition approach will follow in Chapter 3. The paper ends with a conclusion (Chapter 4).

[1] For a detailed description of the methodology see the paper for work package 1.2.

2 Introduction of scenario studies and general comparison of their scenarios

Chapter 2 will introduce the scenario studies and compare the studies' scenarios in respect to general electricity system features. Section 2.1 introduces the four selected scenario studies and their respective backgrounds while Section 2.2 compares the studies' scenarios in regard to electricity demand by sectors, electricity supply by sources and electricity sector CO_2 emissions.

2.1 Introduction of scenario studies

Four different studies on the European energy/electricity system released within the past two years have been chosen for the detailed analysis within this work package. Before the quantitative analysis and comparisons of these studies' scenarios in Section 2.2 and Chapter 3, the four studies are briefly introduced in the following.

2.1.1 ECF Roadmap 2050

The "Roadmap 2050 - A practical guide to a prosperous, low-carbon Europe. Technical analysis" study was published in April 2010 as the first of three volumes. It provides a technical and economic assessment of a series of decarbonisation pathways for achieving a pre-defined decarbonisation goal in 2050. The study aims to clarify short-term requirements to achieve this goal. The area under focus is the EU-27 plus Norway and Switzerland.

"The mission of the Roadmap 2050 study is to provide a practical, independent and objective analysis of pathways to achieve a low-carbon economy in Europe, in line with the energy security, environmental and economic goals of the European Union." The study investigates the technical and economic feasibility of achieving an 80% reduction in GHG emissions (compared to 1990) by 2050 under the constraint that today's levels of electricity supply reliability, energy security, and economic growth are maintained or improved.

The study applies a back-casting approach by stipulating an end-state of the energy system in 2050 (80% GHG reduction compared to 1990 levels and the energy system delivering at least as much as today, no dependency on international carbon offsets). It then derives plausible pathways on how to achieve this goal. These pathways comprise different shares of a range of low to zero carbon supply technologies which are already commercially available or in a late stage of development. The pathways have been defined based on these assumptions: 1) at least 95% power sector decarbonisation in 2050 (compared to 1990), 2) provision of electricity supply reliability as outlined above, and 3) to be credible and plausible, not necessarily optimised.

Baseline assumptions are based on external 2030 projections and are extrapolated to 2050. The baseline assumptions originate from the WEO 2009 and from a CGE model with focus on the energy sector, provided by Oxford Economics (2007). Shares of energy and power demand, and supply by region are based on PRIMES (see Capros, et al., 2010). The transmission system is modelled by a power system analysis framework developed by the

Imperial College London and minimises total system costs while maintaining system reliability and respecting operating constraints.

Besides a baseline development the study considers three scenarios which all have different mixes of electricity generating sources to achieve a low-carbon energy system in 2050. The share of RES in 2050 in the three scenarios is 40%, 60% and 80% respectively. Fossil with CCS and nuclear supply make up the corresponding 60%, 40% and 20% share in each of the pathways. The share covered by fossil with CCS and nuclear is simply split evenly. The results regarding the end-state are the same by definition, only the electricity mix differs according to the given shares of generation technologies. Generation technologies include hydro, coal and gas plants with CCS, solar PV and CSP, wind turbines on- and offshore, biomass plants and geothermal plants.

2.1.2 Power Choices

The "Power Choices - Pathways to carbon-neutral electricity in Europe by 2050" study was published in November 2009 by the Union of Electricity Industry (EURELECTRIC). Data within the study on power plant technology and costs were provided by VGB PowerTech. The area under focus is the EU-27.

In March 2009, Chief Executives of power companies representing over 70% of EU electricity production have signed a declaration in which they commit to work towards a carbon-neutral power sector by 2050. The Power Choices study was set up by EURELECTRIC to examine how this vision can become a reality and aims to show how a "cost-effective and secure pathway to a carbon-neutral power supply by 2050" can be realised. One of the purposes of the study is to analyse the policy options that will be required to attain deep cuts in carbon emissions by 2050.

The PRIMES energy model developed and run by E3MLab of the National Technical University of Athens was used to examine this study's scenarios up to 2050. PRIMES has been under development since 1993. It simulates a market equilibrium solution for energy supply and demand within each of the 27 EU member states. Driven by engineering and economic principles, PRIMES determines the market equilibrium by finding the prices of each energy fuel that match the supply and demand of energy. PRIMES is structured around modules that represent different fuel supply (i.e. oil products, fossil gas, coal, electricity and heat production, the so-called 'sub-system'), energy conversion and end-use demand sectors: household, commercial, transport and (nine) industrial sectors. The technological component of the model is explicit and detailed for both the supply and demand sides and also for environmental abatement technologies.

The Power Choices scenario sets a 75% reduction target for greenhouse gases across the entire EU economy until 2050 (compared to 1990 levels). It is assumed that nuclear power remains available and carbon capture and storage (CCS) technology is commercially available from 2025 on. Electricity becomes a major transport fuel, energy efficiency is pushed by specific policies and the price of CO_2 applies uniformly to all economic sectors. Additionally "[n]o binding RES-targets are set after 2020; RES support mechanisms remain fully in place until 2020 and are gradually phased out during 2020-2030" (eurelectric 2010, p. 6).

Beside the Power Choices scenario, the study develops a Baseline scenario for the EU-27 countries for the 1990-2050 period. This follows the Baseline 2009 scenario developed for DG TREN for the projections to 2030 and then extrapolates the trends to 2050.

The robustness of the results of the main scenario, Power Choices, were tested by quantifying several sensitivity analyses: CCS Delay (the commercialisation of CCS is delayed and becomes mature only from 2035 onwards), Nuclear Facilitated (abolishing the nuclear phase-out in Belgium and Germany), Less Onshore Wind (difficulties arise for onshore wind development) and No Efficiency Policies (none of the policies such as penetration of technology advanced appliances or development of electrified road transportation take place).

2.1.3 Energy [R]evolution

The study “energy [r]evolution - Towards a Fully Renewable Energy Supply in the EU-27” was published in July 2010 by Greenpeace International and the European Renewable Energy Council (EREC). The lead developer of the study’s scenarios was the Institute of Technical Thermodynamics of the German Aerospace Centre. Some other institutes provided additional research on specific aspects of the scenarios; for example, the data on energy efficiency potential is based on work by Ecofys Netherlands. As the study’s name already suggests, the area under focus is the EU-27.

Greenpeace and EREC have previously released scenarios of the European energy system, the first one in 2005. Three global as well as various national energy scenarios have also been released in the “energy [r]evolution” series in the past few years. With these scenarios the two organisations aim to show that significant improvements in energy efficiency together with a rapid expansion of renewable energy technologies can lead to a sustainable energy system by mid-century. The scenarios “are designed to indicate the efforts and actions required to achieve their ambitious objectives and to illustrate the options we have at hand to change our energy supply system into one that is sustainable.” (Greenpeace International & European Renewable Energy Council 2010, p. 28)

With their scenario studies Greenpeace and EREC also wish to show that the transition to a sustainable energy system does not need to rely on power plants using carbon capture and storage (CCS) or on nuclear power plants. Due to uncertainty about the future prospects of CCS as well as a generally sceptic view of this mitigation technology by the commissioning organisations, the use of CCS is not assumed in their scenarios. All alternative scenarios assume that nuclear power is phased out over the coming decades and will no longer contribute to electricity generation by the middle of the century.

To model energy supply in the scenarios the technologically detailed bottom-up simulation model MESAP/PlaNet was used. The assumed growth rates of the various renewable energy technologies were important drivers of the model. These growth rates were determined, taking into account the natural potential of each renewable energy source and the expected economic improvements in each technology. The authors use the concept of learning curves to determine future technology costs. This means that based on empirical studies the typical cost reductions of a given technology for each doubling of its installed base is determined and extrapolated into the future. Energy demand in the two alternative scenarios is based on an Ecofys study of energy efficiency potential. For this latest energy

[r]evolution study, the MESAP/PlaNet model has been extended and now also calculates the investment pathways and employment effects.

In this latest energy [r]evolution scenario study for the EU-27 one reference scenario and two alternative scenarios are developed for the period up to 2050. The reference scenario is based on the reference scenario of the IEA's World Energy Outlook (WEO) 2009. It has been extended to 2050 since the WEO 2009 only covers the time horizon until 2030. In the reference scenario energy-related CO_2 emissions are only 16% lower in 2050 than in 1990. The share of renewables in electricity generation reaches 41% by the middle of the century.

One of the two alternative scenarios is called the "energy [r]evolution scenario". Here it is assumed that efficiency measures are successfully enacted in all sectors of the economy, thereby exploiting to a large extent the significant energy efficiency potential identified. For instance, demand for heat is reduced by 23% in 2050 compared to the reference scenario through a significant increase in energy-related renovation of the existing stock of residential buildings, as well as the introduction of low and "passive house" energy standards for new buildings. Energy-related CO_2 emissions are 76% below 1990 emissions in 2050, while the share of renewables in electricity generation reaches 88% by this time.

The second alternative scenario is called "advanced energy [r]evolution scenario" and is even more ambitious. While technological advances in efficiency are assumed to be identical to the "energy [r]evolution scenario", a speedier market uptake of many energy-efficient technologies (like efficient combustion vehicles, electric vehicles and CHP technology for industry) is assumed. In the electricity sector the maximum lifetime of coal-fired power plants is limited to 20 years and an assumed faster implementation of grid expansions and grid improvements allow for a higher share of fluctuating renewable electricity from wind and solar energy. A faster expansion of solar and geothermal heating systems is also assumed. Furthermore some behavioural change is assumed in the transport sector as the amount of annual vehicle kilometres travelled is reduced in this scenario compared to the other two scenarios. By mid-century, energy-related CO_2 emissions in the EU-27 are 95% lower than in 1990 and renewables have a 97% share in electricity generation.

2.1.4 McKinsey&Company – Transformation of Europe's power system until 2050

This scenario study was released in fall 2010. It was prepared by McKinsey&Company and supported by "various academic institutes", which are not, however, listed in the report. The study does not analyse the entire energy sector but only the power sector of Europe and it develops various potential pathways for the sector for the years 2020 to 2050.[2] The area under focus is the EU-27 plus Norway and Switzerland. In separate sections the report specifically focuses on scenario implications for the power sector of Germany.

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[2] Unlike other scenario studies, this study does not assume differences in the sector's development until 2020 as the evolution of the European power sector until 2020 "is largely predefined by the commitment of the European Union to reach a set of sustainability targets". The study assumes that these targets, known as the 20-20-20 targets, are met.

Apparently a key motivation for McKinsey to prepare this report was the conviction that both "Europe's and Germany's current transformation paths are leading to unnecessarily high costs." The report aims to show a cost-optimal pathway for the European power sector to fulfil its long-term climate protections targets, specifically a 95% reduction in greenhouse gas emissions. It is however not entirely clear why McKinsey chose to prepare and release a scenario study of the European power sector just a few months after release of the study "Roadmap 2050 - A practical guide to a prosperous, low-carbon Europe" (see section 2.1.1), which McKinsey helped to prepare on behalf of the European Climate Foundation and which includes power sector pathways that are different from this study's pathways in regard to electricity supply.

The target function of the modelling process is to meet an exogenously given European power demand at the lowest total system cost. This target is to be met by linking three separate models in an iterative process to derive future power supply. The three models are as follows: A renewables model determines the renewable capacity additions between 2020 and 2050 as well as the associated costs. A power model, based on the commercial power market modelling tool "Plexos" does the same for the conventional generation capacity, while also determining the least-cost full load profiles of all capacity (conventional and renewable) by feeding back to the renewables model. A third model is the grid and backup planning model, which determines backup/reserve capacity needs as well as power plant curtailments. Its output is the required grid infrastructure and the associated costs. Assumptions on electricity demand and future technology costs are exogenous and are based on the ECF Roadmap 2050 study (see section 2.1.1). All three models have a relatively high geographical resolution, separating Europe into 56 regions.

The study develops and analyses three scenarios for the European power sector. One scenario is called the "lean" scenario and can be regarded as a reference scenario. Here no targets are defined for greenhouse gas emissions reductions or for electricity generation from renewable sources. The build-up of power plants is based purely on economic optimization. Another scenario is called the "clean" scenario. Here the power sector is to achieve greenhouse gas emission reductions of 95% by 2050 compared with 1990 levels. However, no separate renewables goals are set so renewable technologies compete with conventional generation technologies in terms of cost. This is different in the "green" scenario, where renewables achieve a predefined target of 80% in electricity generation by 2050. Unlike in the other two scenarios of the study, in the green scenario the Desertec project is realized, envisioning European electricity imports in the coming decades originating from renewable energy sources (especially sun and wind) in the Middle East and North Africa. The greenhouse gas reduction target is the same as in the "clean" scenario.

2.2 General comparison of scenarios

The following scenario comparison includes all the scenarios of the four studies which provide sufficient data on how energy demand and energy supply will change until the year 2050. The scenarios with sufficient data include:

- All three scenarios of the Energy [R]evolution study (Greenpeace/EREC 2010)
    - Reference

  - Energy [R]evolution
  - Advanced Energy [R]evolution
- All four scenarios of the ECF Roadmap 2050 study (ECF 2010)
  - Baseline
  - 40% RES
  - 60% RES
  - 80% RES
- The main scenario of the Power Choices (EURELECTRIC 2009) study
  - Power Choices
- The two alternative scenarios of the study “Transformation of Europe’s power system” (McKinsey 2010).

The baseline scenario and the various sensitivity scenarios of the Power Choices study as well as the baseline (“lean”) scenario of the study by McKinsey do not provide sufficiently detailed data to be included in the following comparisons.

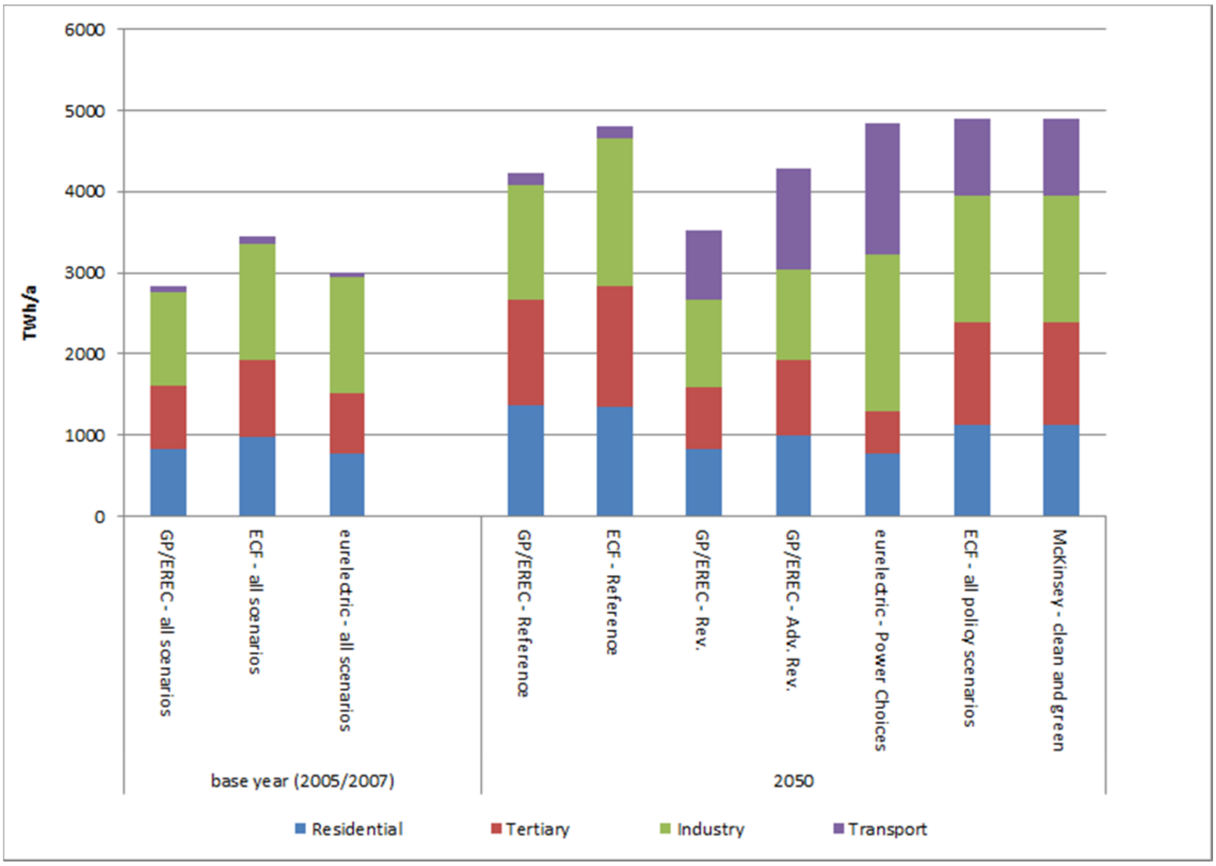
In order to keep the comparisons concise the comparison will focus on the year 2050, for which detailed data is available for all scenarios.

2.2.1 Electricity demand by sectors

The following figure shows electricity demand per sector in the studies’ base years (2007 for the scenarios in Energy [R]evolution, in ECF Roadmap 2050 and in “Transformation of Europe’s power system” and 2005 for the scenarios in Power Choices) and in the year 2050.[3]

[3] It should be kept in mind that the Roadmap 2050 study (ECF 2010) and the “Transformation of Europe’s power system” study (McKinsey 2010) include not only the EU-27 but also Switzerland and Norway, while the other two studies look at only the EU-27. This explains the higher electricity demand in the base year in the ECF study and should also be kept in mind when comparing the scenarios’ electricity demand in 2050.

Figure 1 Electricity demand in the base year and in 2050 per sector in the different scenarios



Source: Compiled from data provided by the given studies

The respective relative changes in electricity demand in the four sectors between the base year and the year 2050 are shown in Table 1. This table as well as the above figure show that while there is a general consensus among the scenarios that electricity demand will grow, there is much uncertainty in regard to the development of electricity demand in the individual sectors. Interestingly, except for the transport sector there is for every sector at least one scenario in which electricity demand is reduced by 2050. On the other hand, there are for each sector other scenarios which describe an increase in electricity demand by 19 to 35%. In the transport sector a significant increase in electricity demand is expected in all policy scenarios as a result of electrification of individual transportation. Compared to the respective base years an 11-fold (Energy Revolution) to 24-fold (Power Choices) increase is described. As a result the transport sector turns from a sector with insignificant electricity demand to the sector with either the highest (Adv. Energy Revolution) or the second highest (Energy Revolution and Power Choices) electricity demand in most policy scenarios within four to five decades.

Table 1 Relative changes in electricity consumption per sector in 2050 (compared to the base year) in the different scenarios

	GP/EREC Reference	ECF Baseline	GP/EREC Rev.	GP/EREC Adv. Rev.	ECF All policy scen.	eurelectric Power Choices	McKinsey Transformation Study
Residential	65%	38%	-1%	19%	15%	1%	15%
Tertiary	65%	57%	-1%	19%	34%	-30%	34%
Industry	23%	26%	-6%	-4%	9%	35%	9%
Transport	85%	67%	1067%	1602%	956%	2380%	956%
Total	49%	39%	24%	50%	42%	61%	42%

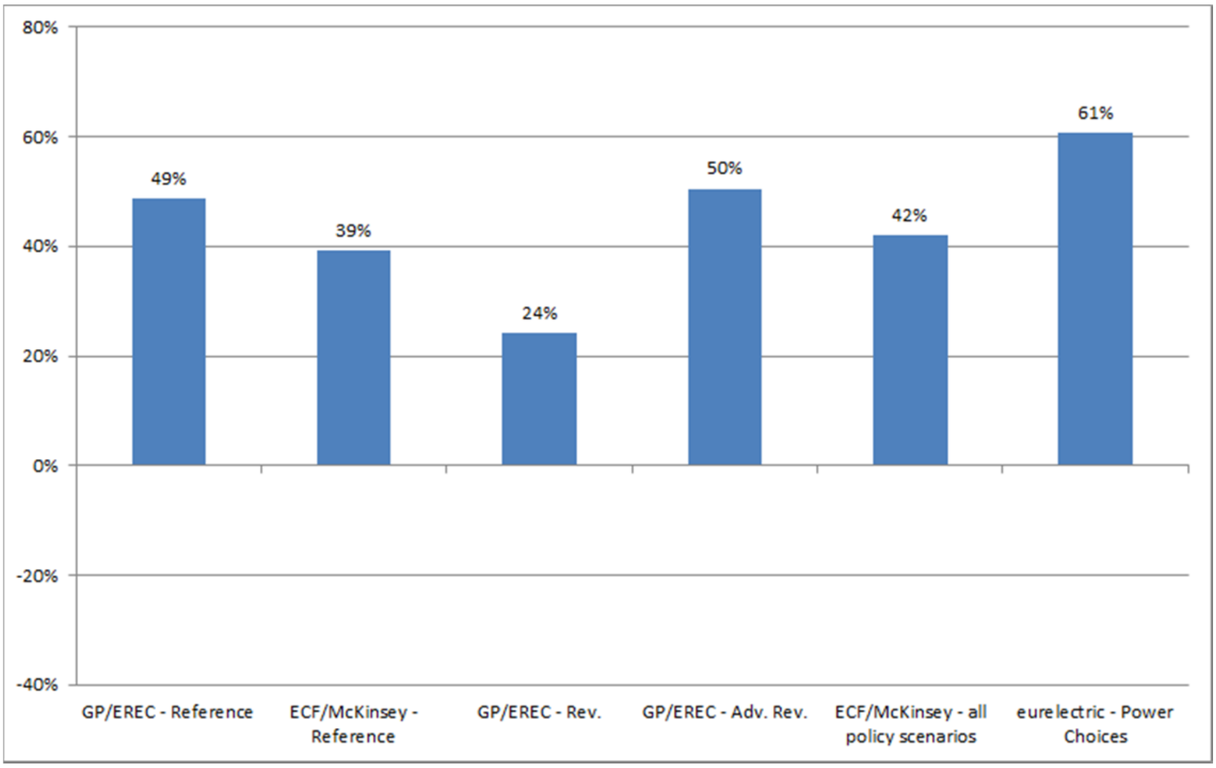
Source: Compiled from data provided by the given studies

In all scenario studies total electricity demand increases compared to the respective base years by 24 to 61% (see Table 1 and Figure 2 below). Interestingly, the three studies for which reference scenarios are provided in sufficient detail indicate that a strategy to decarbonise the energy system could lead to similar overall electricity demand in 2050 compared to a business-as-usual pathway. The reasons for this are two opposing developments, which in combination could largely cancel each other out in respect to overall electricity demand:

- Faster, more pronounced improvements in the efficiency of electricity-using technologies (e.g. more efficient household appliances)
- A shift away from fuels like petrol, fuel oil and natural gas towards electricity (especially electric vehicles and heat pumps)

The Energy Revolution scenario of the Greenpeace/EREC (2010) study is able to limit the increase in electricity demand between 2007 and 2050 to 24% by assuming aggressive efficiency improvements while limiting the fuel shift towards electricity. The Power Choices scenario foresees the highest increase. Here electricity demand rises by 61% between 2005 and 2050. While more ambitious energy efficiency progress is assumed compared to a business-as-usual pathway (the latter of which is based on the baseline scenario of the IEA's World Energy Outlook 2009), efficiency improvements are not as pronounced as in the policy scenarios of the other two studies. Furthermore, as in all other scenarios, the stronger use of new electricity applications in the form of electric vehicles and heat pumps is a main reason for the growing electricity demand until the middle of the century.

Figure 2 Relative change in electricity consumption in 2050 (compared to the base year) in the different scenarios



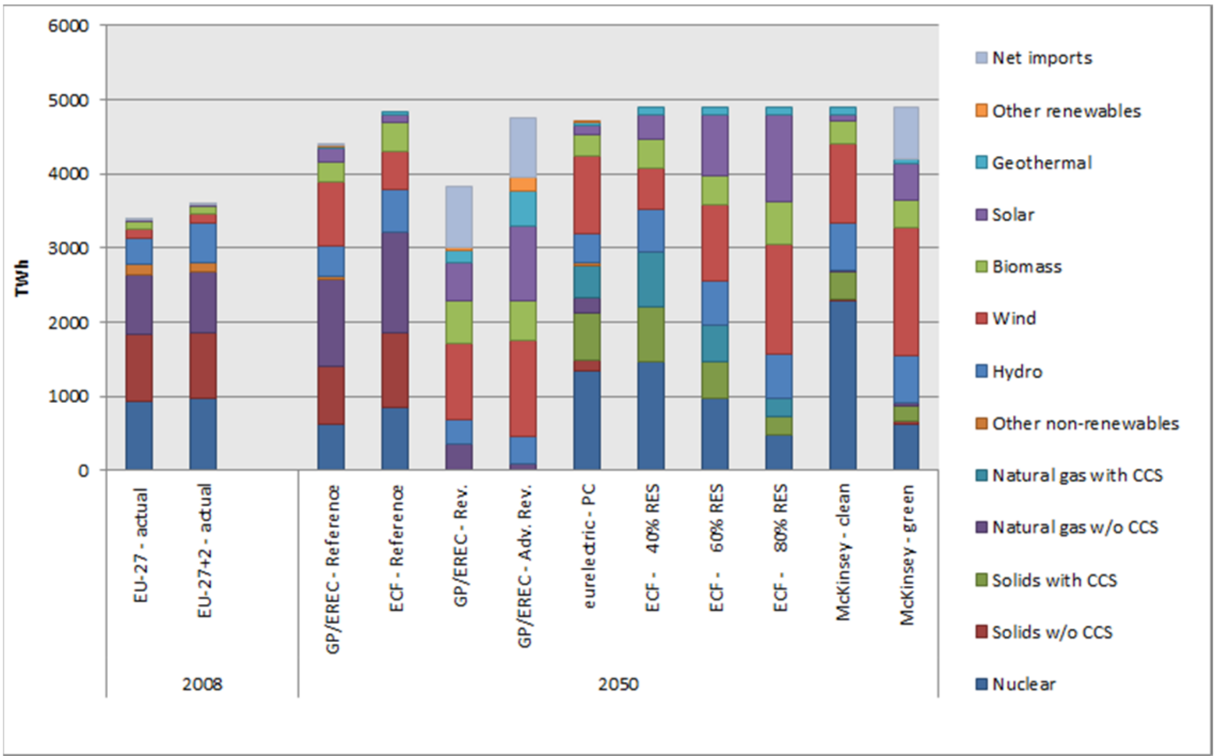
Source: Compiled from data provided by the given studies

2.2.2 Electricity supply by sources

Figure 3 shows electricity generation by sources (plus net imports where applicable) in 2050 in both reference and all policy scenarios compared to actual electricity generation in 2008.[4] In line with the overall goal of all the studies' policy scenarios, electricity generation in Europe in 2050 is based entirely or almost entirely on zero- or low-CO_2-emitting sources. However, the actual mixture of these zero- or low-CO_2-emitting sources is very different from scenario to scenario. As nuclear power is phased out and CCS is not seen as a viable or desirable technology in both Greenpeace policy scenarios, the electricity supply is based almost entirely (more than 90%) on renewable sources in 2050, including electricity imports from renewable sources. The rest is supplied by natural gas power plants.

4 Electricity generation in 2008 is given for both, EU-27 as well as EU-27 plus Norway and Switzerland, as this "EU-27 plus 2" region is analysed in the Roadmap 2050 (ECF 2010) scenarios.

Figure 3 Electricity generation by source (including net imports) in 2008 (actual) and in 2050 according to the different scenarios

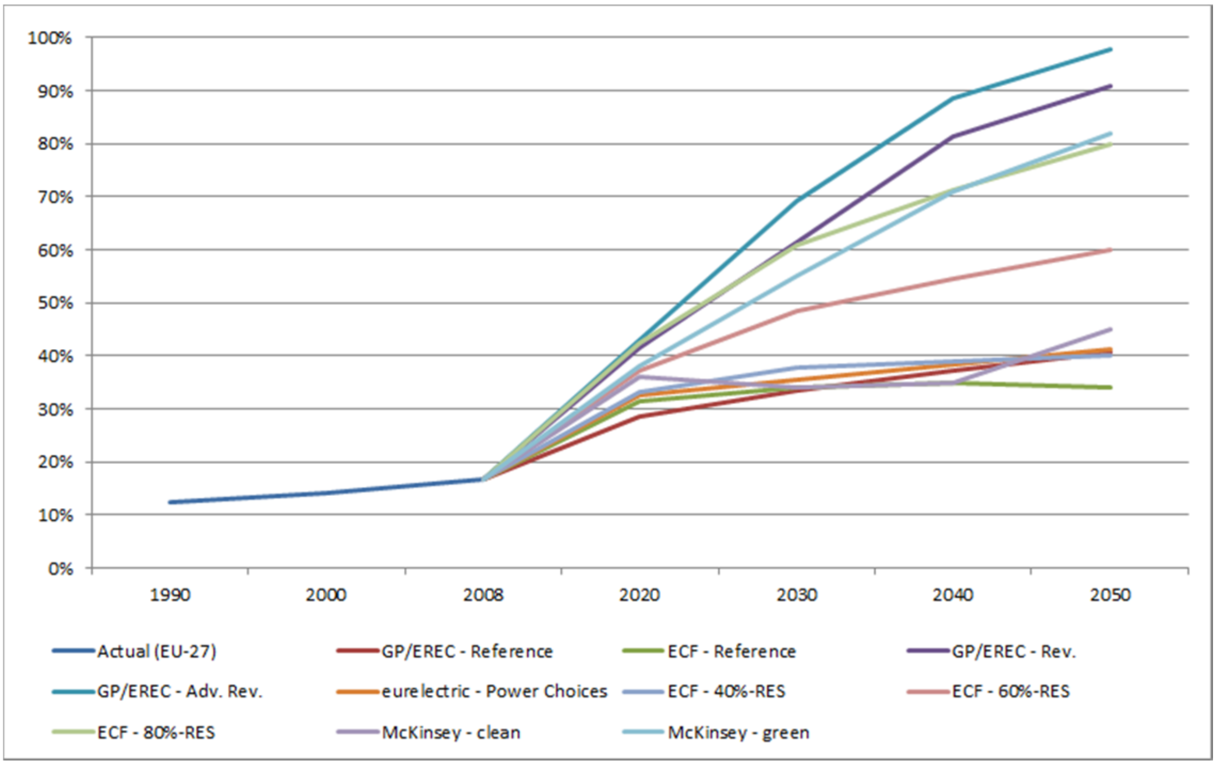


Source: Compiled from data provided by the given studies and for actual 2008 data by Eurostat (2010), Bundesamt für Energie (2010) and Statistics Norway (2010)

In contrast, the Power Choices scenario as well as the 40% RES scenario from the ECF Roadmap 2050 study and especially the “clean” scenario (McKinsey 2010) rely to a significant extent on nuclear power. In the two scenarios mentioned first the absolute electricity generation from nuclear power is increases by about 40 to 50% compared to 2008, leading to a nuclear share in electricity generation of about 30% in both scenarios in 2050. In the “clean” scenario the absolute amount of nuclear power even increases by more than 130%, leading to a share of 47% in 2050. CCS coal and natural gas power plants are also used to a significant extend in the Power Choices scenario and the 40% RES scenario from the ECF Roadmap 2050 study, providing 23% (Power Choices) to 30% (40% RES) of electricity supply in 2050. The 60% RES and 80% RES scenarios can be seen as “middle-of-the-road” scenarios compared to the almost all-renewables Energy Revolution scenarios on the one hand and the nuclear and fossil-CCS heavy “clean”, Power Choices and 40% RES scenarios.

However, in all but one policy scenario (the exception being the “clean” scenario) renewable energy sources combined contribute more to electricity supply in 2050 than either fossil fuels or nuclear power. The share of renewables in power supply increases from 17% in 2008 to between 40% (40% RES) and 98% (Adv. Energy Revolution) in 2050 in the policy scenarios, as Figure 4 shows. In both reference scenarios the share also increases, but only to 34% in the reference scenario of the ECF study and to 41% in the reference scenario of the Greenpeace/EREC study.

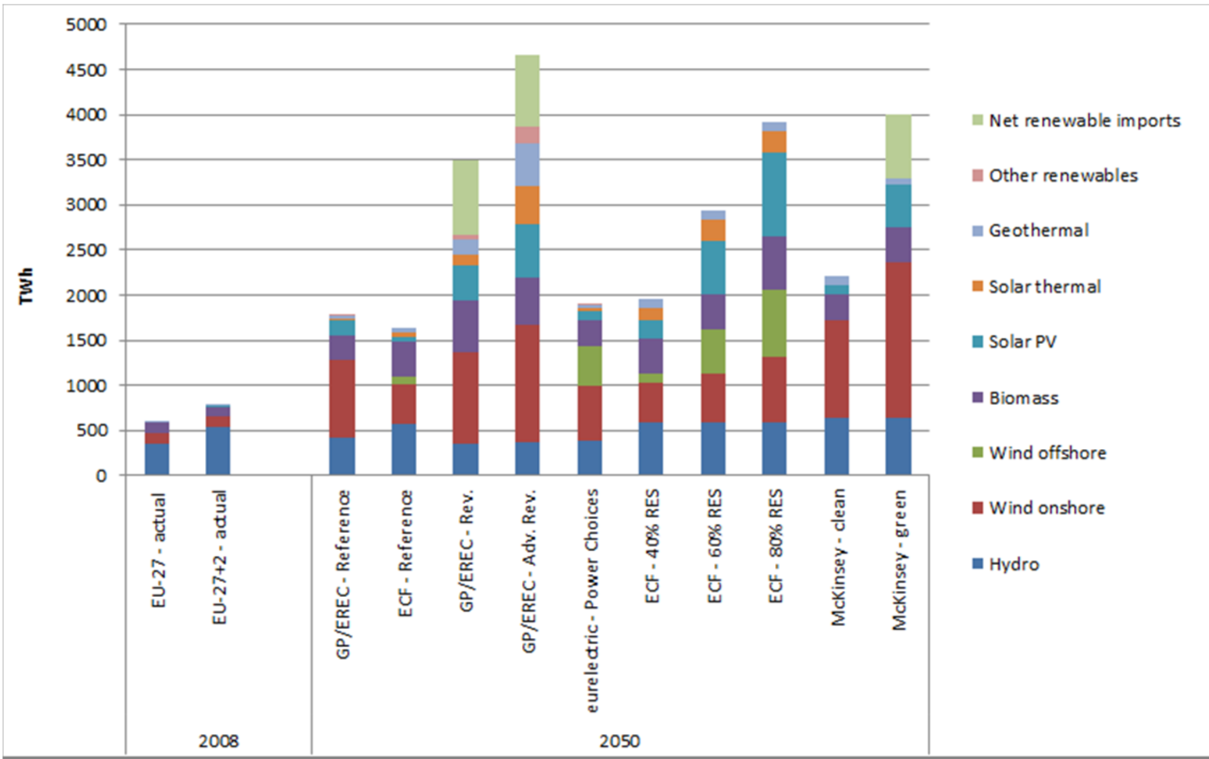
Figure 4 Development of the share of renewable energy sources in electricity generation (including net imports) in the different scenarios



Source: Compiled from data provided by the given studies and by Eurostat (2010)

The following figure takes a closer look at renewable electricity generation in Europe in the year 2050. In most policy scenarios wind power (onshore and offshore combined) becomes the most important renewable energy source in domestic electricity generation, usually followed by solar energy (PV and solar thermal combined). This however is not true for those scenarios in which renewable energy reaches only a limited share in electricity generation: In the Power Choices scenario and the “clean” scenario solar energy plays only a small role even in 2050 while in the 40% RES scenario the contribution of wind power (especially offshore) is very limited compared to the other scenarios. Only the two Greenpeace/EREC (2010) policy scenarios foresee an important role for geothermal electricity generation. These two scenarios as well as the “green” scenario are also the only scenarios which rely on net imports to a significant extent.

Figure 5 Electricity generation from renewable sources in Europe (including net renewable imports) in 2008 (actual) and in 2050 according to the different scenarios

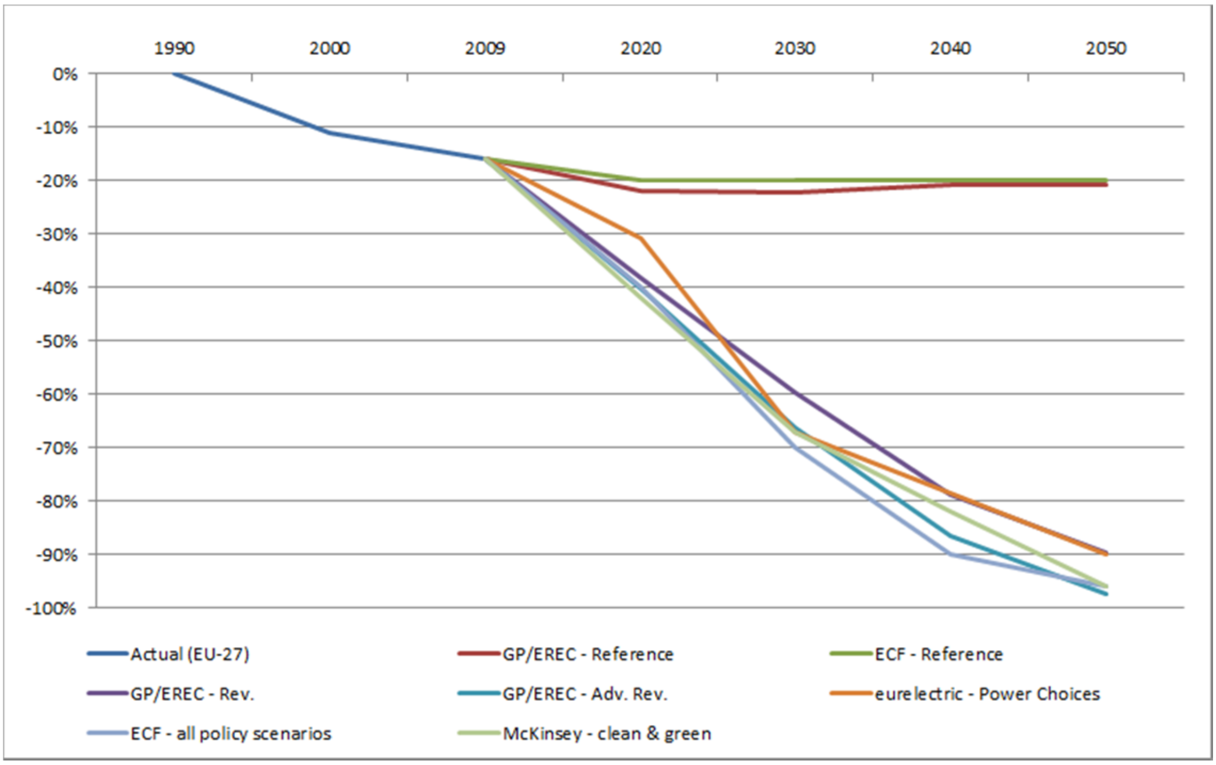


Source: Compiled from data provided by the given studies and for actual 2008 data by Eurostat (2010), Bundesamt für Energie (2010) and Statistics Norway (2010)

2.2.3 Electricity sector CO_2 emissions

All policy scenarios achieve electricity sector CO_2 emission reductions of at least 90% until 2050 compared to the respective emissions in 1990. Both, the Power Choices scenario as well as the Energy Revolution scenario reduce emissions by exactly 90%. The three policy scenarios of the ECF Roadmap 2050 as well as the two policy scenarios of the "Transformation of Europe's power system" study all achieve reductions of 96% while in the Advanced Energy Revolution scenario emissions are reduced by 97%. The reduction pathways in all policy scenarios are relatively similar and do not deviate much from a linear reduction over time. The Power Choices scenario however exhibits slower emission reductions until 2020 but relatively deep reductions between 2020 and 2030. The main reason for this is the high relevance of CCS power plant technology in this scenario which is however not assumed to be commercially available until 2025. The ECF Roadmap 2050 policy scenarios, especially the 40% RES and 60% RES scenarios also use CCS to a significant extent. Here CCS is assumed to be "progressively available from 2020 onwards". In these high-CCS scenarios of the ECF Roadmap 2050 emissions in 2020 might actually be a little higher than indicated in Figure 6, as only a rough reduction pathway is provided in the study for all scenarios.[5]

Figure 6 Electricity-sector CO_2 emission pathways (relative to 1990) in the different scenarios



Source: Compiled from information provided by the given studies

The two reference scenarios analysed both describe a very similar development of electricity sector CO_2-emissions: Emissions would continue to decline during this decade to reach a level about 20% lower than emissions in 1990. However, afterwards emissions in both scenarios stagnate or even increase slightly so that by 2050 emissions would still be only 20% lower than in 1990. The emission-reducing effects of higher contributions of

5 The study only provides the following information on greenhouse gas emissions from the electricity sector in all policy scenarios: “GHG emissions from the power sector will be 35% to 45% lower in 2020 compared to 1990 levels, compared to 20% lower in the baseline. Assuming that coal plants built in 2011-2020 will be retrofitted with CCS in 2020-2030, and that all new fossil plants will be equipped with CCS from 2020 onwards, this improves to -70% in 2030, -90% in 2040, and -96% in 2050 (with little difference between pathways).” (ECF 2010, p. 66)

renewable energy sources and lower shares of coal in electricity generation are largely compensated in these reference scenarios by growing electricity production.[6]

6 See the decomposition analysis for the reference scenario of the Energy Revolution study for a more detailed analysis of the individual effects determining changes in CO_2 emissions in this reference scenario.

3 Individual analysis of studies with decomposition approach

This chapter provides the individual analyses of the analysed studies with the decomposition approach documented in WP 1.2. The data collected in tier 2 of the common roster of data and information has been utilised for the decomposition analyses, while the data from tier 1 has been used to provide the scenario comparisons on a descriptive base (see WP 2.1 and Chapter 2 of this report). In order to shed light into the tier approach, it is shortly introduced below in Section 3.1, before the actual decomposition of the various scenarios will be presented in Section 3.2.

3.1 Tier approach to data, general gap filling methods, data requirements for decomposition analysis

3.1.1 Tier data

The data collected in the common roster of data and information (WP 1.1) consists of a large set of data that enables the comparison of decarbonisation scenarios in various ways. Depending on the complexity of the comparison that is envisaged, a different set of data needs to be utilised. To account for this purpose, the data is categorized into two tiers (tier 1 and tier 2). A tier contains the data which is relevant for specific purposes. There may be overlaps between the tiers.

The higher the tier number, the more specific the data, and thus the more in-depth are the analyses that can be carried through on the base of that tier's data. In the given project, we adopt the tier approach, which is summarized with examples in Table 2.

Table 2 Tier approach in the project: Power Sector Decarbonisation: Metastudy

Tier	Types of data	Notes
Tier 1	Descriptive and quantitative data used for broad description and comparison of scenarios across studies	Used for summaries provided in WP 2.1 and general information provided in WP 2.2., 2.3, and 3
Tier 2	Quantitative data used for in-depth analysis of scenarios, used for decomposition analysis	Used for decomposition analyses accomplished as part of WP 2.2, 2.3, 3

Source: Author's own

Tier 1 of the roster covers all data and information that is necessary for a qualitative and in partially quantitative comparison of crucial characteristics of the given scenarios across studies. Table 3 lists the data residing in tier 1 of the common roster of data and information.

Table 3 Tier 1 of the common roster of data and information

Tier 1 data
Electricity demand
Electricity generation per generation technology
Share of renewables in electricity generation
Power sector CO2 emissions
GDP
Population
Fuel prices
Type of model(s) used
Geographic coverage

Source: Author's own

Tier 2 of the roster covers the data and information which are of a more complementary nature, but which are important for quantitative in-depth analyses of the scenarios. Thus, tier 2 contains a set of more specific data. The probability of finding the data residing in tier 2 is lower than the probability that data from tier 1 can readily be extracted from the studies. Thus, gap filling data from tier 2 will become necessary in case that data mandatory for the decomposition analysis is missing or cannot be readily extracted from tables or figures. The data attributed to tier 2 of the common roster of data and information is listed in Table 4 along with an indication of whether this data is mandatory (++) or ideally included (+).

Table 4 Tier 2 data with indication of necessity

Total electricity consumption (TWh)	unit	
Traditional appliances (or if not availabe sectoral electricity consumption)		++
Residential	TWh	+
Tertiary	TWh	+
Industry	TWh	+
Transport	TWh	+
New appliances		+
Transport	TWh	+
Heat market	TWh	+
Power input from storage		+
Pumped storage	TWh	+
Compressed air storage	TWh	+
Hydrogen production	TWh	+
Battery storage	TWh	+
Other types of storage	TWh	+
Other consumption	TWh	+
Net electricity exchange		
Imports	TWh	+
Exports	TWh	+

++ = mandatory

+ = ideally included

Net power production CO2 free sources	unit	
Renewables	TWh	++
Hydro	TWh	+
Wind	TWh	+
Wind onshore	TWh	+
Wind offshore	TWh	+
Solar	TWh	+
Solar PV	TWh	+
CSP	TWh	+
Biomass	TWh	+
Geothermal	TWh	+
Other	TWh	+
Nuclear	TWh	++
Storage		+
Hydrogen (storage output)	TWh	+
Synthetic natural gas (storage output)	TWh	+
Other storage output	TWh	+
CCS	TWh	++
Net power production from CO2- emitting sources		
Total net power generation (fossil fuel based)	TWh	++
Total fossil fuel input	PJ	++
Total CO2 emissions	Mt	++

Source: Author's own

3.1.2 General approach to gap filling

The data collected in tier 2 enables a decomposition analysis as documented in its full extent in WP 1.2. However, data may not be available in all studies at such a detailed level. A decomposition analysis can still be carried out on a less detailed level though. Efforts have been undertaken to extract all of the given data from the studies considered, but the availability of data differs from study to study. Where reasonable, gap filling has been accomplished based on the gap-filling methods documented in Table 5.

The stock of data on which the decomposition analysis is carried out differs in its extent from study to study, due to data availability (including a varying level of additional information provided by authors) and varying feasibility of gap filling. However, main characteristics can still be compared across studies. The comparability of the results from the tier 1 part of the common roster of data and information do not suffer from this fact.

Table 5 General gap filling approaches valid for tier 1 and tier 2 of the common roster

Gap filling approach
Only few years of data given and more are needed
Interpolate data on base of hints provided in study, such as figures or notes. If no hints are available, perform linear interpolation between scenario years.
No data given
Decide whether data is necessary for analysis. If yes, a) find external sources for data, preferably from sources referenced in study or b) gap-fill data based on reasonable assumptions. Document assumptions.
No base year values given
Gap-fill data based on data sources indicated in given study. If no indication is made, use a credible source of data and document the source.

Source: Author's own

3.2 Decomposition Analysis

3.2.1 Methodological notes

On gap filling

A decomposition analysis provides an in-depth assessment of the contributions that causal factors such as sources of electricity consumption and electricity generation technologies have on the CO_2 emission reductions reported or projected. The decomposition analysis requires the studies considered to supply data as outlined in Table 4. If a study does not include the data required then it will be necessary to gap fill the missing data. However, this will add uncertainty to the analysis by making assumptions about the characteristics of the missing data. In order to keep uncertainty at a minimal level, only data only data that is considered to be essential for the decomposition analysis has been gap filled.

On CCS technology

Electricity generation from CCS plays a hybrid role in decomposition analysis. This is due to the fact that a share of electricity generated from CCS can be viewed as being CO2-free, while the other share of electricity generation from CCS technology produces emissions. The emission capture rate provides insights into the shares (usually in the range of 90% of the emissions being captured). CCS production thus needs to enter the decomposition analysis at two locations: twice on the production side of electricity (once at the CO2 neutral part and once at the fossil part) and fuel used for CCS production and causing emissions (determined by *1-capture rate*) needs to be attributed to the fossil fuel input, I^{fos} . As documentation standards of studies vary, this attribution may not be easily addressed and several procedures are viable, which are documented in Appendix I of WP 1.2.

On representation of results

The decompostion analysis involves the attribution of emission changes to causal factors such as the consumption or production of electricity, which were previously defined in WP 2.1. These causal factors may either contribute to an increase or a reduction in emissions depending upon the scenario examined. The outcome of the analysis will be presented in a series of tables and figures. The interpretation of the values found in these will be explained here in more detail.

Table 6 Causal factors and their contributions to emission changes (Mt), and their contribution to net emission reductions (%)

causal factor	Mt	%
c1	75	-75%
c2	-50	50%
c3	-75	75%
c4	-50	50%

Source: Author's own

The results of the decomposition analysis will be presented in the format similar to the table above for all of the decarbonisation scenarios considered in this metastudy. The emission change attributed to each causal factor (i.e. electricity consumption, electricity production, fuel input intensity[7] and emission factor of fuel mix[8]) will be presented as either an absolute (Mt) or a relative (%) emission change.

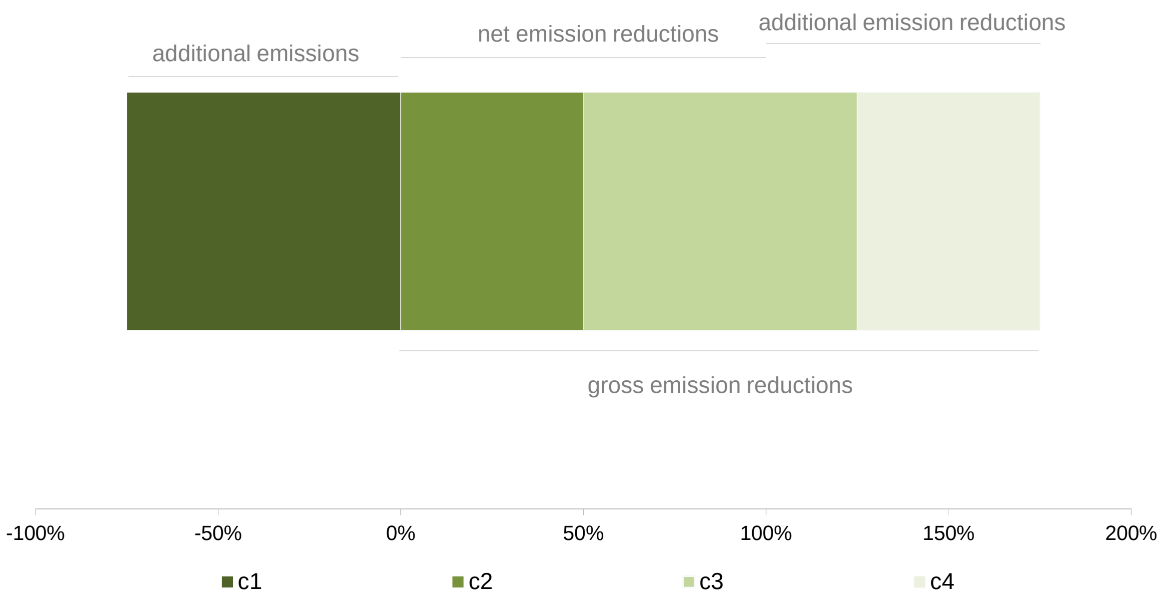
A negative value for an absolute emission change by causal factor expressed in Mt simply represents a reduction in emissions. However, a negative value for a relative emission change by causal factor, which is expressed as a percentage of the total emission reduction in a scenario compared to the base year, represents an increase in emissions. Figure 7

7 Fuel input intensity = fossil fuel input per unit of electricity generated.

8 The emission factor of the fuel mix (hereafter emission factor) refers to CO_2 emissions per unit of fossil fuel input

illustrates that these additional emissions are offset by the additional emission reduction contributions of the other causal factors, which could – in principle – be larger than 100%.

Figure 7 Schematics of net emission reductions, gross emission reductions, additional emission reductions and additional emissions



Note: *gross emission reductions*: emission reductions including an over accomplishment in order to offset additional emissions. *additional emissions*: negative emission reductions: e.g. through additional consumption of electricity from new appliances. *net emission reductions*: the total achieved emission reductions excluding additional emissions and additional emission reductions. *Additional emission reductions*: emission reductions needed to compensate additional emissions

3.2.2 ECF Roadmap 2050

3.2.2.1 Data availability

The tier 1 data availability has been reasonably good and is used in WP 2.1 and in Chapter 2 of this report to compare against the other studies considered. Since the decomposition approach documented in WP 1.2 requires very specific data it can, however, not be expected that a study makes this data readily available. Queries to authors and gap filling according to the methods summarised in Table 5 therefore needed to be completed.

The ECF Roadmap 2050 study depicts a special case in terms of data: It follows a back casting approach, which means that the end state (2050) of the power sector is stipulated by the modelers'. The pathway from now to then is approximated by back-casting. The end states of all scenarios (40% RES, 60% RES, 80% RES), except the baseline, are the same regarding consumption side of electricity. All of these alternative scenarios are characterized by electricity demand of 4900 TWh in 2050 distributed across the power demand sectors industry, transport, residential, and tertiary. The demanded TWh of electricity are then met by the generation mix described in each scenario where the % in the scenarios name describes the share that is met by renewable energy sources (which could be either hydro, wind (on- and offshore), solar power (PV and CSP), biomass, and geothermal plants). The remaining share is then met by either nuclear or CCS technology and in 2050 is split evenly– except in the baseline scenario.

The study reports the data mainly for 2050, some data for 2005. The study references as a source for baseline projections International Energy Agency (2009), which provides a base year of 2007. Thus, the data reported as being gap filled for the base year always refers to 2007 if not stated differently. It must be noted however, that the study also states that shares of energy demand and power demand as well as supply by region are based on PRIMES (European Climate Foundation (2010), p. 31). It is thus assumed that this holds true for the projections, while the base year data is assumed to stem from International Energy Agency (2009).

3.2.2.2 Gap filling

The authors of the study have kindly provided hints on various sources spread across the multitude of appendices. The report provides exact numbers for the end state of the power system in 2050. Thus the caveats of back-casting the tier 2 data in order to obtain a time series exceeds the benefits due to several assumptions that would need to be made for enabling such a back-casting.

Therefore gap filling has only been done for the 2050 data, for the base year data and for the 1990 data and is reported in this order along with an explanation of the data availability within the study if this adds to the understanding of the process.

2050 data

Power demand data for 2050 has been reported for the sectors industry, tertiary, transport and residential and the study has derived this from extrapolating data from (see European Climate Foundation (2010), p. 48). 3400 TWh of the 2050 power demand of 4900 TWh include energy efficiency increases and these have been attributed to traditional appliances according to their consumption shares given in exhibit 3 (European Climate Foundation (2010), p. 33). Power demand from electric vehicles (800 TWh) and building heat and industry heat (500 and 700 TWh) have been attributed to *new appliances in road transport*, and to the *heat market* section of the common roster of data and information respectively.

Fossil fuel input: The study provided shares of electricity production of the above named technologies for the end year 2050. Based on this data and the provided efficiencies of newly built coal and gas CCS plants now and in 2050 (European Climate Foundation (2010), p. 35), To account for the vintage structure of the power plant fleet, the averages of these values were used to gap fill the fossil fuel input in 2050.

Power sector CO_2 emissions for all scenarios except the baseline scenario have been calculated based on information provided on page 66 of the given study which states that power sector emissions in 2050 will have been reduced by appr. 96% compared to 1990 values. To obtain a specific number for each scenario, fuel specific emission factors have been used to calculate the actual emissions that would be produced by using the fuel inputs of the given year.
Baseline power sector CO_2 emissions have been supplied as being 20% less the 1990 power sector CO_2 emissions.

1990 and base year data

Electricity demand by the sectors industry, tertiary, residential and transport are reported for the base year, which we assume to be 2005 (exhibit on page 33 of European Climate Foundation (2010)). This data has completely been attributed to traditional appliances.

Electricity production in the base year has been gap filled by the source the study referred to, the WEO 2009 reference scenario. Values for Norway and Switzerland were not included in this reference scenario. These values have been retrieved for Norway from Statistics Norway (2011a) and for Switzerland from Bundesamt für Energie (2007b).

Fossil fuel input for EU-27 has been gap filled by data from the reference scenario. Data for Switzerland was retrieved from Bundesamt für Energie (2007b) and the data from Norway from OECD (2011).

Total CO_2 emissions of the power sector (for 1990) have been retrieved from the reference scenario. Values for Switzerland have been gap filled from WRI (2011a) and Norway's power related CO_2 emissions have been gap filled by Statistics Norway (2011a).

Total CO_2 emission of the power sector (for 2007, the base year in WEO 2009) have been determined from International Energy Agency (2009) reference scenario for EU-27 and gap filled for Norway and Switzerland from WRI (2011b). The values for Norway and Switzerland include heat.

3.2.2.3 Decomposition analysis

In the following we summarise the decomposition analyses conducted for the 40% RES and 60% RES scenarios in the ECF Roadmap 2050 study.

3.2.2.3.1 40% RES scenario

The 40% RES scenario characterizes an EU-27 plus Norway and Switzerland that generates 40% of electricity from renewable sources. The remaining 60% are split evenly across nuclear and CCS electricity generation technology. The relative emission contributions of each of the causal factors in the decomposition analysis (i.e. electricity consumption, electricity production, fossil fuel input intensity and the emission factor) are presented in Table 7 for the 40% RES scenario.

Table 7 ECF Roadmap 2050 / 40% RES scenario: Relative emission reduction contributions of causal factors in 2050 compared to the base year..

Causal factor	2050
Consumption side	
C: traditional appliances	2.1%
C: residential	0.6%
C: tertiary	0.6%
C: industry	0.9%
C. transport	0.1%
C: New appliances	-63.4%
C: road transport	-33.8%
C: heat	-29.6%
Production Side	
P: Renewables	57%
P: Hydro	-4%
P:Wind	22%
P: Solar	19%
P: Biomass	14%
P: Geothermal	5%
P: Nuclear	8%
P: CCS	76%
Intensities	
fuel input intensity	15%
emission factor	6%
relative emission reduction compared to base year	**93%**

Source: Results from the decomposition analysis.

The decomposition analysis provides useful insights into the contribution of the different causal factors under consideration to emission reductions in the 40% RES scenario.[9] According to the decomposition analysis, efficiency improvements in the electricity consumption of traditional appliances will not offset the increased electricity consumption that will result from the introduction of new appliances such as electric vehicles. It is envisaged within the 40% RES scenario that the electricity consumption from new appliances will increase significantly, which will result in additional emissions in the power sector of 865 Mt CO_2 in 2050 compared to the base year[10] (Figure 8).

Depending upon the energy mix, the production of electricity represents an opportunity to reduce CO_2 emissions. The 40% RES scenario assumes a considerable increase in the share of electricity produced by renewable technology, which results in an absolute

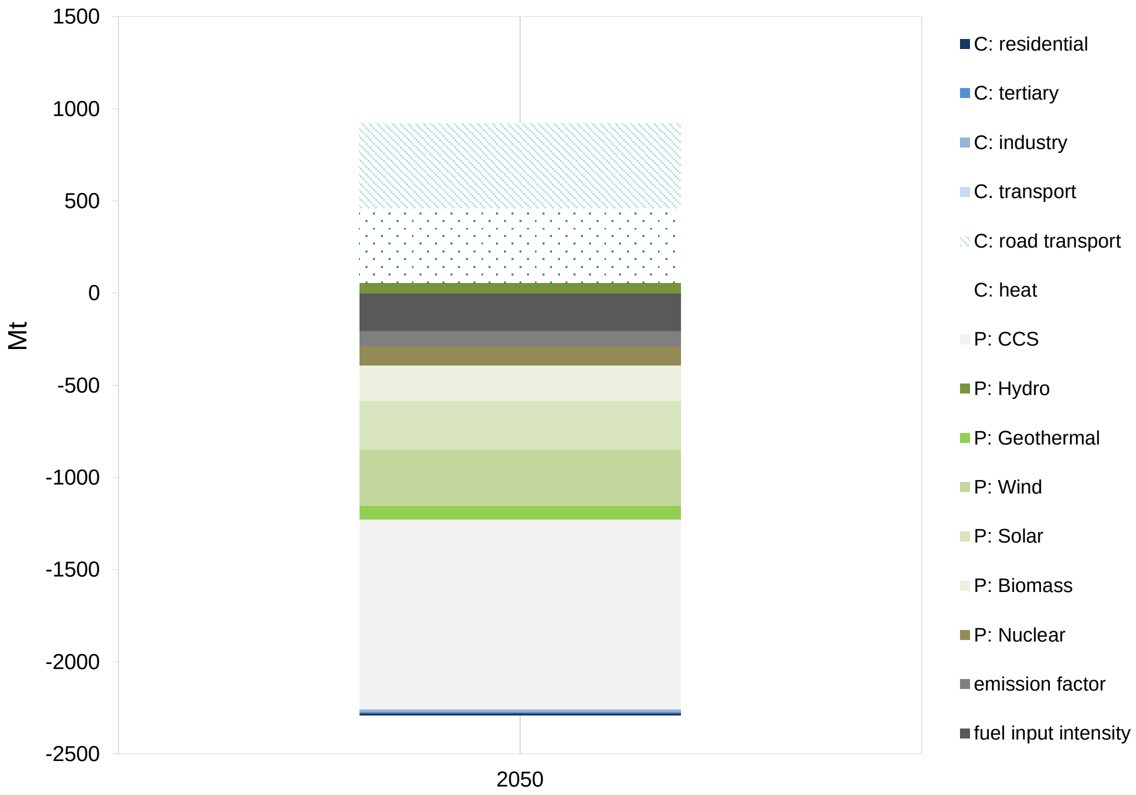
9 Given that it was necessary to gap fill data, it is important to acknowledge that the values used in the decomposition analysis may not reveal the real effect based on the original data used in the study.

10 New appliances add to emissions, as they are newly introduced into the market and did not yet exist in the base year.

emission reduction of 775 $MtCO_2$ in the power sector by 2050 (Figure 8). This contributes 57% of the CO_2 emission reductions compared to the base year by 2050 (Table 7), which nearly offsets the 63% increase in emissions due to the increased electricity consumption from new appliances. Interestingly hydro power does not contribute to emission reductions in 2050 compared to the base year. This is due to the fact that the share of hydro power on overall electricity generation in 2050 is smaller than in the base year. Electricity production from hydro power absolutely grows from 475 TWh in the base year to 588 TWh in 2050, however the share of hydro power on renewable electricity production actually decreases (from 14% to 12%), while the production shares of all other electricity generation technologies from renewable sources increase. It is evident from the decomposition analysis that the deployment of CCS plays an important role, delivering emission reductions in this scenario that are equivalent to 76% of the CO_2 emission reductions in 2050 compared to the base year (Table 7). In the 40% RES scenario nuclear power is not phased out in Europe and by 2050 it is foreseen that 30% of electricity production is still generated by nuclear power. The growing importance of nuclear power in this scenario contributes to an absolute emission reduction of 106 $MtCO_2$ by 2050 compared to the base year (Figure 8).

Fuel input intensity contributes to emission reductions in the magnitude of 205 Mt CO_2, by 2050 compared to the base year due to an improvement in the efficiency of the fossil fuel power plants. In addition, emissions are also reduced in 2050 by an improved emission factor (*E/I*) in 2050: 0.079 (compared to 0.083 in the base year). This suggests that fuel switching to cleaner fuels occurs in thus scenario, but only to a small extent contributing 6% to emission reductions in 2050 compared to the base year (Table 7).

Figure 8 ECF Roadmap 2050 / 40% RES scenario: Absolute emission changes triggered by causal factors in 2050 compared to the base year.[11]



Source: Calculation with decomposition analysis

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[11] Figure 8 depicts the absolute emission changes compared to the base year that each of the causal factors exhibits in the 40% RES scenario. C: indicates consumption areas, while P: indicates production technologies. Pattern-filled segments reflect consumption areas of new appliances.

3.2.2.3.2 60% RES scenario

The 60% RES scenario characterises the electricity generation of EU-27, Norway and Switzerland to be accomplished based on 60% renewable energy sources. The remaining 40% are produced in even shares from nuclear and CCS technology. The relative emission contributions of each of the causal factors in the decomposition analysis (i.e. electricity consumption, electricity production, fuel input intensity and the emission factor) are presented in Table 8 for the 60% RES scenario.

Table 8 ECF Roadmap 2050 / 60% RES scenario: Relative emission contributions of causal factors in 2050 compared to the base year

Causal factor	2050
Consumption side	
C: traditional appliances	2.1%
C: residential	0.6%
C: tertiary	0.6%
C: industry	0.9%
C. transport	0.1%
C: New appliances	-61.6%
C: road transport	-32.9%
C: heat	-28.8%
Production Side	
P: Renewables	109.7%
P: Hydro	-4.1%
P:Wind	49.1%
P: Solar	46.1%
P: Biomass	13.7%
P: Geothermal	5.0%
P: Nuclear	-19.7%
P: CCS	49.1%
Intensities	
fuel input intensity	14.6%
emission factor	5.8%
relative emission reduction compared to base year	95%

Source: Results from the decomposition analysis

The emission reduction contributions in the 60% RES scenario are similar to those in the 40% RES scenario. These scenarios differ in the share of renewable energies used to generate electricity; however the scenarios have similar assumptions regarding the consumption of electricity in 2050 and the rate of energy efficiency improvement. The 60% RES scenario also envisages that improvements in the energy efficiency of traditional appliances will not offset the increased consumption of electricity due to the use of new appliances. Given the expected increase in electricity consumption, the use of new appliances will result in additional emissions of 862 $MtCO_2$ by 2050[12] (Figure 9).

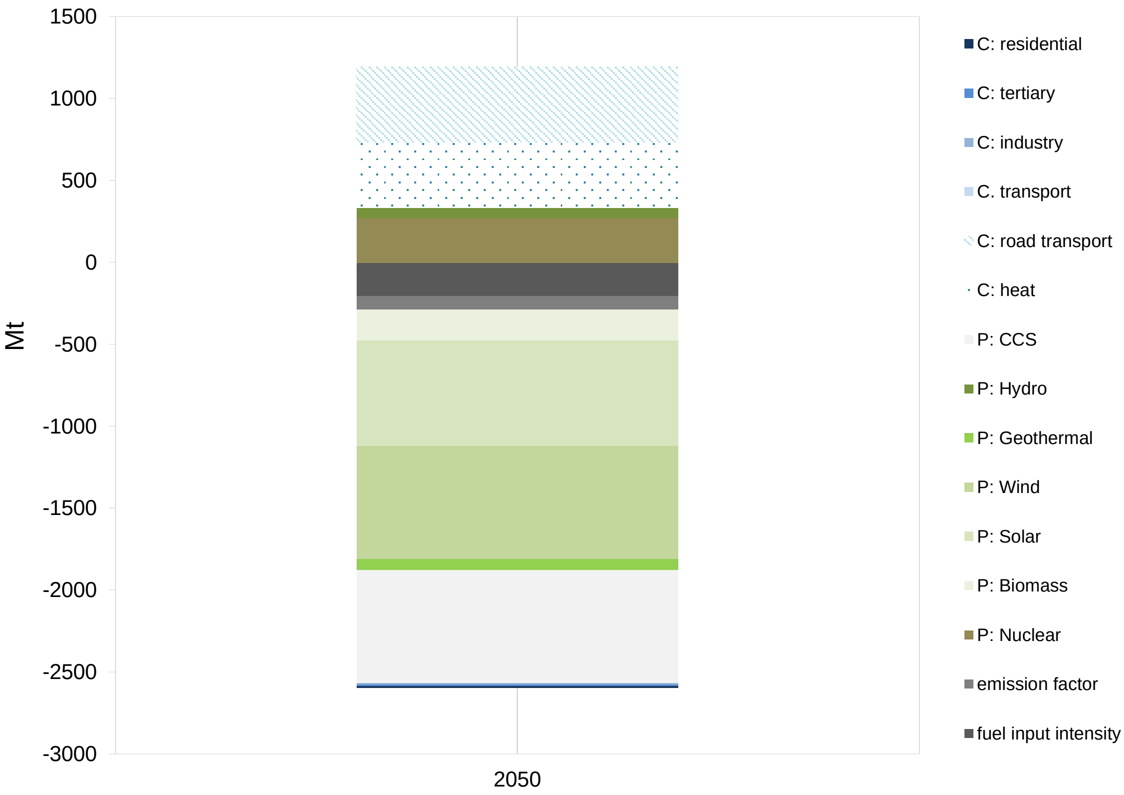
12 New appliances add to emissions, as they are newly introduced into the market and did not yet exist in the base year.

The 60% RES scenario assumes a larger increase in the share of electricity produced by renewable technology than in the previous scenario, which results in an absolute emission reduction of 1,534 tCO_2 in the power sector by 2050. Renewable energies achieve emission reductions of over 100% (109%) and thus offset the addition emissions from other causal factors (Table 8). Hydro power does not contribute to emission reductions and actually increases emissions by 4.1% compared to the base year. This is due to the fact that the share of hydro power on the overall electricity generation in 2050 is smaller than in the base year as other technologies are up-scaled and deployed.

Contrary to the 40% RES scenario the emission reductions attributed to CCS (49% compared to the base year) no longer exceed the emission reduction effect of renewable energies. This is due to the smaller share of CCS production of overall electricity production in this scenario (20%) which accounts for 980 TWh in 2050. In the 60% RES scenario less nuclear power is used in 2050 than in the base year, which results in additional CO_2 emissions of approximately 275 Mt. However these and other additional emissions are offset by the emission reductions from other causal factors (Table 8).

Fuel input intensity contributes to emission reductions in the magnitude of 204 Mt CO_2, due to an improvement by 2050 in the efficiency of the fossil fuel power plants. In addition, emissions are also reduced by 81 Mt in 2050 by an improved emission factor (*E/I*) in 2050. This suggests that fuel switching to cleaner fuels occurs in the 60% RES scenario.

Figure 9 ECF Roadmap 2050 / 60 % RES scenario: Absolute emission changes triggered by causal factors in 2050 compared to the base year.



Source: Calculation with decomposition analysis

3.2.2.3.3 80% RES scenario

The 80% RES scenario characterizes an EU-27 plus Norway and Switzerland that generates 80% of electricity from renewable sources, while the remaining 20% are generated equally by either CCS or nuclear generation technology.

Table 9 ECF Roadmap 2050 / 80% RES scenario: Relative emission contributions of causal factors in 2050 compared to the base year

Causal factor	2050
Consumption side	
C: traditional appliances	2%
C: residential	1%
C: tertiary	1%
C: industry	1%
C. transport	0%
C: New appliances	-58%
C: road transport	-31%
C: heat	-27%
C. Other	3%
Exports	0%
Production Side	
P: Renewables	156%
P: Hydro	-4%
P:Wind	70%
P: Solar	62%
P: Biomass	23%
P: Geothermal	5%
P: Nuclear	-45%
Imports	0%
P: CCS	23%
Intensities	
fuel input intensity	14%
emission factor	5%
total emission reduction absolute	98%

Source: Results from the decomposition analysis

The 80% RES scenario assumes that electricity consumption will increase by 2050 due to the use of new appliances, and therefore additional emissions of 836 $MtCO_2$ will be generated in the power sector by 2050[13] (Figure 10). In agreement with the previous ECF Roadmap 2050 scenarios, it is envisaged within the 80% RES scenario that energy efficiency improvements in the traditional appliances will not offset the increased electricity consumption associated with the use of new appliances. The 80% RES scenario assumes a larger increase in the share of electricity produced by renewable technology than in the previous 60% RES scenario, which results in an absolute emission reduction of 2,228 Mt CO_2 in the power sector by 2050. Renewable energies achieve emission reductions of over 100% (156%) and thus offset some of the additional emissions caused by other causal factors (Table 9). As in the previous ECF Roadmap 2050 scenarios, hydro power does not

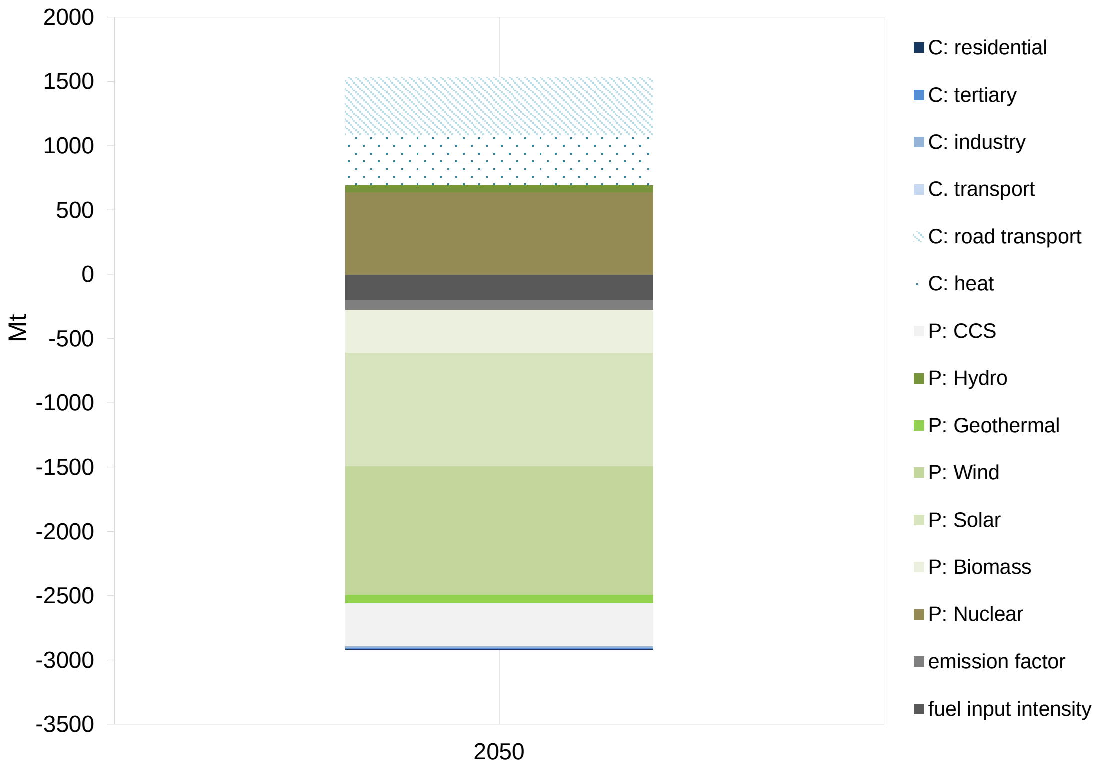
[13] New appliances add to emissions, as they are newly introduced into the market and did not yet exist in the base year.

contribute to emission reductions as the share of hydro power in the energy mix declines by 2050.

The emission reductions attributed to CCS by 2050 are 23% compared to the base year, which is equivalent to an emission reduction of 333 Mt. As in the previous RES 60% scenario, less nuclear power is used in 2050 compared to the base year, and therefore nuclear power actually adds to CO_2 emissions (appr. 637 Mt), however, these and other additional emissions are offset by emission reductions from other causal factors such as the deployment of CCS and fuel switching.

Fuel input intensity contributes to emission reductions in the magnitude of 198 Mt CO_2, due to an improvement by 2050 in the efficiency of the fossil fuel power plants. In addition, emissions are reduced by 78 Mt in 2050 by an improved emission factor (*E/I*) in 2050. This suggests that fuel switching to cleaner fuels occurs in the 80% RES scenario. However, the influence of these two causal factors on emission reductions are lower than in the previous ECF Roadmap scenarios as the electricity generated from fossil fuel plants has reduced considerably by 2050 in this scenario.

Figure 10 ECF Roadmap 2050 / 80 % RES scenario: Absolute emission changes triggered by causal factors in 2050 compared to the base year.



Source: Calculation with decomposition analysis

3.2.3 Power Choices

3.2.3.1 Data availability

Overall, availability of detailed quantitative data in the Power Choices study is relatively limited. While the more general tier 1 data can be found in the report, the more specific tier 2 data is incomplete. Some information, like a differentiation between traditional and new appliances is not included in the report while other important information, like electricity generation by sources, can only be found in figures, making it difficult to derive precise data.

Some data that *can* be found is not very detailed. There is for example no differentiation between solar PV and solar thermal or between hard coal and lignite power plants. For CCS power generation no data is given on the fuel sources. Also, no data on electricity storage is provided.

While a baseline scenario is mentioned in the study, its energy or electricity supply is not provided so it has not been taken into account in the study at hand. Furthermore, apart from the main policy scenario called "Power Choices" there are several more sensitivity scenarios (delayed availability of CCS, more reliance on nuclear power, less use of onshore wind power, less success in realizing available efficiency potential). These are briefly described and are to test the robustness of the Power Choices results. However, data for these sensitivity results are not provided in sufficient detail to be useful for this decomposition analysis.

The study reports data mainly for 2030 and 2050 and provides some historic data for the base year (2005).

3.2.3.2 Gap filling

Some data found in the study is provided in the form of figures (which need to be read off) while other data is given by relative or absolute values in the text itself. Some data required for even a more aggregate decomposition approach could not be found within the study. It is therefore necessary to fill some gaps by making certain assumptions and by relying on external data.[14]

Key socioeconomic assumptions

- Development of population and GDP is provided relative to the base year 2005. In order to derive absolute values, this data has been combined with information from Eurostat (2011) on population and GDP in the base year.

Electricity consumption

- The energy branch listed as a separate sector in the study has been included in the industry sector for our analysis.
- There is no differentiation between the consumption of traditional and "new" appliances within the study. This has not been attempted to solve but instead it was chosen to apply a more aggregate decomposition analysis in this case, simply taking into account total electricity demand (including traditional and new demand) in the four sectors.
- Export and import of electricity from outside EuropeThe net import of electricity is assumed to be the difference between electricity consumption (including losses) and net electricity generation, as no explicit information on the development of net imports is given in the report.

3.2.3.3 Decomposition analysis

In the following we summarise the decomposition analyses conducted for the Power Choices scenario. Unfortunately not enough data is available for decomposing the baseline scenario and the sensitivity scenarios of the study. Decomposition will be shown for 2020 (interpolated between base year and 2030), 2030 and 2050. The Power Choices scenario is the main policy scenario of the EURELECTRIC (2009) study of the same name.

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[14] The data that could not be retrieved has kindly been provided by the author of the study to facilitate the decomposition analysis.

Electricity sector CO_2 emissions in this scenario are reduced by 95% until 2050 compared to 1990 emissions. On the supply side all zero- or low-CO_2 options (renewables, nuclear power, fossil CCS) are expanded until the middle of the century.

Table 10 Power Choices / Power Choices scenario: Relative emission contributions of causal factors in 2020, 2030 and 2050 compared to the base year

Causal factor	2020	2030	2040	2050
Consumption side				
C: Sectoral consumption	-31%	-47%	-77%	-43%
C: residential	-13%	-11%	-5%	1%
C: tertiary	-4%	2%	6%	7%
C: industry	-9%	-13%	-13%	-8%
C. transport	-6%	-26%	-65%	-44%
C. Other	-3%	-4%	-7%	-3%
Exports	-3%	-2%	-1%	-1%
Production Side				
P: Renewables	108%	73%	51%	37%
P: Hydro	1%	-3%	-6%	-3%
P:Wind	79%	57%	44%	31%
P: Solar	7%	6%	5%	4%
P: Biomass	19%	10%	6%	4%
P: Geothermal	1%	1%	1%	1%
P: Other	1%	1%	1%	1%
P: Nuclear	-35%	-18%	-10%	-5%
Imports	-2%	-1%	-1%	-1%
P: CCS	5%	33%	70%	48%
Intensities				
fuel input intensity	43%	40%	46%	37%
emission factor	18%	27%	29%	32%
relative emission reduction compared to base year	28%	49%	79%	95%

Source: Results from the decomposition analysis[15]

As the electricity demand comparison in Chapter 2 has shown, electricity demand in the Power Choices scenario grows the fastest between the base year and 2050 (by 61%) among all scenarios analysed. The decomposition analysis subsequently quantifies this increase in electricity demand by sector in terms of CO_2 emissions. The growth in the electrification of cars and industrial processes are mainly responsible for an additional 44%

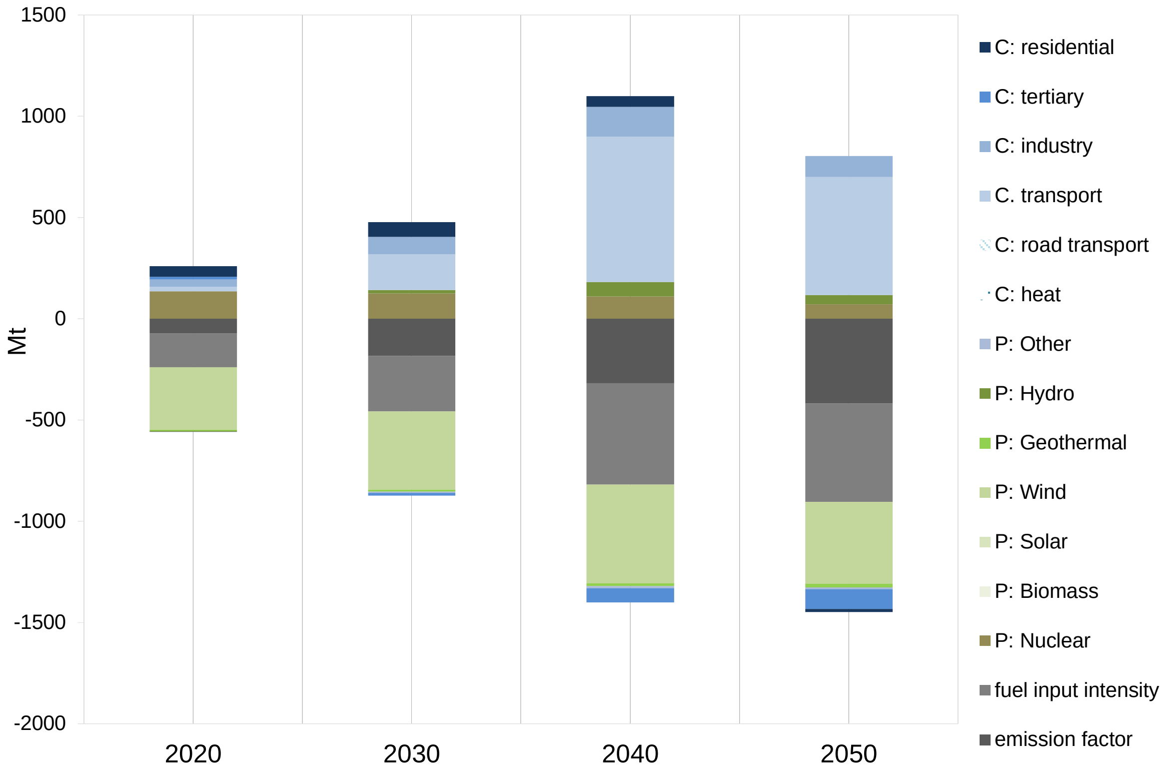
15 Especially towards the end of the scenario period (i.e. by 2040 and 2050) the electricity generation from (only) fossil fuels in power plants cannot fully explain the CO2 emissions as provided within the study. Our calculations indicate that the emissions provided within the study may include a fraction (about 20 %) of the emissions caused by burning biomass in power plants. As this leads to more plausible results, our calculations for the decomposition analysis therefore assume that 20 % of the CO2 emitted by burning biomass are included in the power sector CO2 emissions provided within the study. Though not explicitly mentioned, the authors may have done this to take into account that biomass is not really carbon-neutral when looking at the entire biomass lifecylce. However, as it is common to attribute zero CO2 emissions to biomass in the energy sector and as the other scenario studies follow this approach, we have adjusted the CO2 emissions provided by the Power Choices study accordingly

and 8% increase in the emissions of the transport and industrial sector respectively by 2050 compared to the base year (Table 9). However, according to the authors "energy efficiency is pushed by specific policies and standards on the demand-side during the entire projection period, which will result in slower demand growth" (EURELECTRIC 2009, p. 6).

As in all other policy scenarios, the considerably increased utilisation of renewable energy sources is a major contribution to decreasing CO_2 emissions. Again it is wind power, which is most important among the renewable energy sources contributing to a 31% reduction in emissions in 2050 compared to the base year (Table 9). CCS technology is another major contributor to reducing CO_2 emissions by 48% by 2050 compared to the base year, especially from 2030 onwards, when it is increasingly deployed.

CO_2 emissions per unit of fossil fuel input decrease considerably as a result of the average conversion efficiency of fossil power plants improving over time.

Figure 11 Power Choices / Power Choices scenario: Absolute emission changes triggered by causal factors in 2020 and 2030 compared to the base year



Source: Calculation with decomposition analysis

3.2.4 Energy [R]evolution

3.2.4.1 Data availability

Data availability is comparably good within the Energy Revolution study, mostly due to data tables in the Annex for each scenario and also due to a high number of figures throughout the report. All data classified as tier 1 is provided within the study itself.[16]

In the data tables the most important data is consistently provided for the base year, which is 2007, as well as for the future years 2015, 2020, 2030, 2040 and 2050. However, some of the detailed tier 2 data needed for the decomposition approach is not found in the study itself. Fortunately the study authors at DLR were very helpful in providing us with some of the additional tier 2 data needed. Most importantly we received the following information from the DLR for all three scenarios:

- Development of electricity demand from “new appliances” (electric vehicles and heat pumps)
- Fossil fuel input for electricity generation

DLR also confirmed to us that the gap between electricity production on the one hand and electricity consumption plus transmission losses on the other hand should indeed be regarded as electricity imports from outside the EU-27 and that these net imports, which increase until 2050 are imports from electricity generated by renewable sources, mostly from solar and wind in the MENA (Middle East/North Africa) region.

As the energy model used does not differentiate between onshore and offshore wind power, we were unable to retrieve separate data, so onshore and offshore wind power is looked at in the decomposition analysis in aggregate terms.

No quantitative data is provided in the study on the future need and use of electricity storage plants. Upon request DLR told us that the energy model used does not take into account the need for electricity storage and that this shortcoming was handled by providing for excess capacity of various types of power plants.

3.2.4.2 Gap filling

Some of the tier 2 data needed for a detailed decomposition analysis could not be retrieved even with the support of the authors. To some extent this data was gap-filled where plausible assumptions appeared to be appropriate.

This was the case with electricity demand per sector: While the study does provide this data, it only gives aggregate figures for the household and tertiary sectors. Upon request we were told by DLR that the model used does not differentiate between theses sectors and so figures for each individual sector could not be provided. It was therefore decided to assume that the relative share in electricity consumption between both sectors will remain

16 However, a more detailed description of the modeling approach would be welcome.

the same throughout the entire period. We used actual data for 2005 (EEA 2009) to determine the relative share of both sectors.

Furthermore, only *gross* electricity generation is provided by the study. To derive *net* electricity generation, the power plants' own consumption (provided as a cumulative figure) was subtracted from gross electricity generation, assuming that each type of power plant exhibits the same own consumption per unit of gross electricity generated.

3.2.4.3 Decomposition analysis

In the following we summarise the decomposition analyses conducted for all three scenarios provided by (Greenpeace/EREC, 2010). Decomposition could be performed for all three scenarios, as sufficient and consistent data is available for all of them, including the reference scenario. Decomposition will be shown for 2020, 2030, 2040 and 2050, as data for all these years are available. However, the interpretation will focus on 2050.

3.2.4.3.1 Reference scenario

In the Energy Revolution study a reference scenario is developed in order to compare the study's two policy scenarios with a possible development of the European energy system if no further climate policy measures are enacted. This reference scenario is based on the baseline scenario of the World Energy Outlook 2009 (IEA 2009) and has been extrapolated by the authors of the Energy Revolution study until 2050.

In the reference scenario electricity-sector CO_2 emissions are 22% lower in 2020 than in 1990. From 2020 on the emission level remains largely unchanged until the middle of the century. Compared to the study's base year (2007) emissions in 2020 and onward are 17 to 19% lower. Despite these very limited emission reductions, Table 10 shows that various effects can be determined which have a significant effect on electricity-sector CO_2 emissions. However, the effects leading to higher CO_2 emissions and those leading to lower emissions cancel each other out to a large extent.

Table 11 Energy Revolution / Reference scenario: Relative emission contributions of causal factors in 2020, 2030, 2040 and 2050 compared to the base year[17]

Causal factor	2020	2030	2040	2050
Consumption side				
C: traditional appliances	-47%	-133%	-316%	-801%
C: residential	-17%	-51%	-123%	-315%
C: tertiary	-16%	-48%	-116%	-298%
C: industry	-10%	-26%	-62%	-156%
C. transport	-5%	-8%	-14%	-32%
C: New appliances	0%	0%	-1%	-6%
C: road transport	0%	0%	0%	-4%
C: heat	0%	0%	-1%	-2%
Production Side				
P: Renewables	123%	193%	364%	787%
P: Hydro	13%	11%	12%	16%
P:Wind	80%	127%	238%	516%
P: Solar	14%	28%	60%	137%
P: Biomass	16%	24%	45%	96%
P: Geothermal	1%	2%	4%	9%
P: Nuclear	-64%	-105%	-204%	-448%
P: CCS	0%	0%	0%	0%
Intensities				
fuel input intensity	62%	94%	174%	407%
emission factor	26%	46%	76%	150%
relative emission reduction compared to base year	**19%**	**19%**	**17%**	**17%**

Source: Results from the decomposition analysis

Additional electricity demand, mostly as a result of growing economic activity (and accompanying higher affluence levels) would on its own lead to a significant increase in CO_2 emissions (2002 Mt by 2050 compared to the base year). The same is true for nuclear power. As the absolute as well as relative contribution of nuclear power to electricity supply decreases over the years, the change in use of this source of power shows up as increasing CO_2 emissions of 1120 Mt compared to the base year by 2050 (Figure 12). However, at the same time the use of renewable energy sources is growing even in the reference case, leading to significant emission reductions of 1966 Mt compared to the base year by 2050. Of all renewable energy sources, wind power expansion has by far the most pronounced effect on lowering CO_2 emissions, followed by solar energy and biomass expansion.

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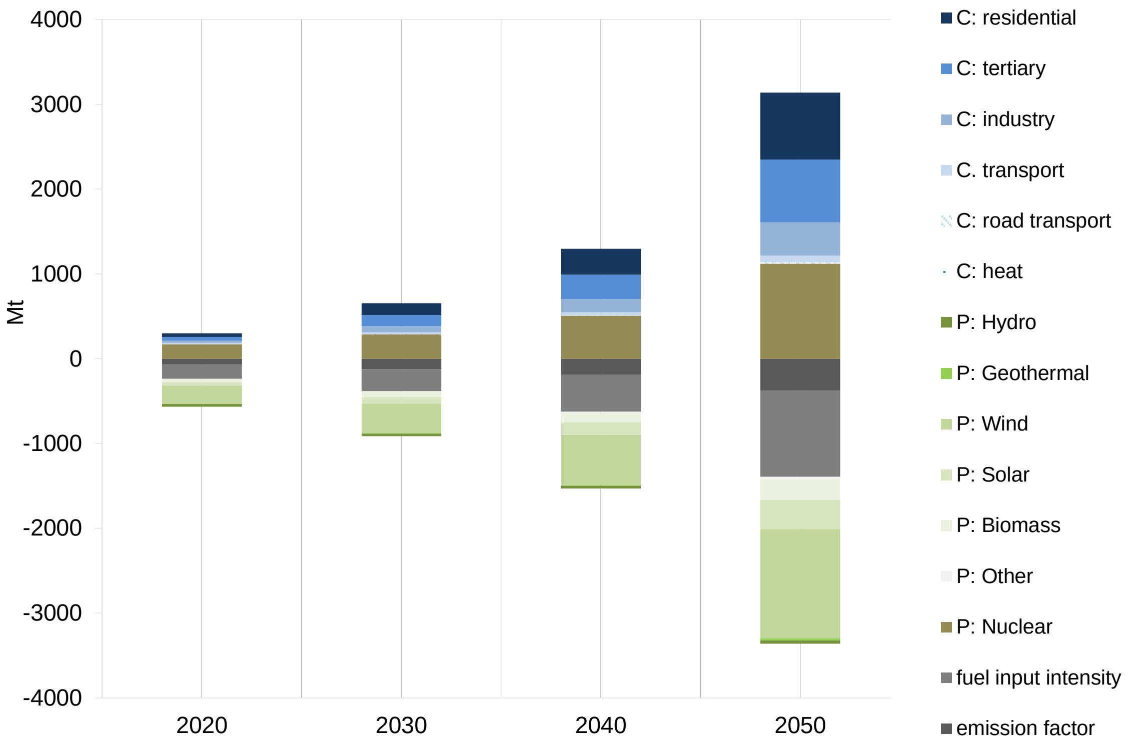
17 Note that the relative contributions of individual effects appear to be very large in Table 10. This is the case because the overall (or net) emission reductions compared to the base year are relatively small, at just over 200 Mt throughout the course of the reference scenario. As the contributions of the individual effects are given relative to this small change, this leads to high numbers for the positive or negative relative changes in CO_2 emissions.

As a result of increasing conversion efficiencies of fossil fuel power plant technology as well as because of a shift towards a higher share of natural gas in fossil power generation[18], fuel input intensity is another factor reducing CO_2 emissions by 1019 Mt compared to the base year by 2050 in this reference scenario. The shift towards a higher share of natural gas in fossil fuel power production (at the expense of hard coal and lignite) also leads to an improvement in the emission factor and thus contributing to emission reductions by 375 Mt by 2050 compared to the base year (Figure 12).

Figure 12 Energy Revolution / Reference scenario: Absolute emission changes triggered by causal factors in 2020, 2030, 2040 and 2050 compared to the base year



Source: Calculation with decomposition analysis

[18] Natural gas power plants (especially the Combined Cycle Gas Turbine or CCGT technology) achieve higher conversion efficiencies as hard coal or lignite power plants.

3.2.4.3.2 *Energy Revolution scenario*

The Energy Revolution scenario is one of the study's two policy scenarios. In this scenario the technologically available energy efficiency potential is assumed to be unlocked to a large extent throughout the course of the scenario. As a result future increases in electricity demand are limited in this scenario (see Section 2.2). At the same time renewable energy technology is expanded significantly over the course of the coming decades. Nuclear power is phased out until the middle of the century and CCS technology is not used.

Table 12 Energy Revolution / Energy Revolution scenario: Relative emission contributions of causal factors in 2020, 2030, 2040 and 2050 compared to the base year

Causal factor	2020	2030	2040	2050
Consumption side				
C: traditional appliances	-4%	0%	2%	3%
C: residential	-2%	0%	0%	1%
C: tertiary	-2%	0%	0%	1%
C: industry	2%	3%	3%	3%
C. transport	-2%	-2%	-2%	-2%
C: New appliances	-4%	-7%	-13%	-23%
C: road transport	-3%	-5%	-12%	-21%
C: heat	-2%	-1%	-2%	-2%
C: storage	-3%	-3%	-3%	-3%
C. Other	1.6%	0.9%	0.3%	-0.2%
Production Side				
P: Renewables	115%	101%	94%	85%
P: Hydro	5%	3%	1%	0%
P:Wind	59%	51%	44%	38%
P: Solar	21%	20%	21%	21%
P: SolarPV	17%	17%	16%	16%
P: CSP	3%	4%	4%	5%
P: Biomass	27%	22%	20%	19%
P: Geothermal	3%	4%	7%	7%
P: Other	0%	1%	2%	2%
P: Nuclear	-70%	-59%	-50%	-45%
Imports	4%	12%	23%	34%
Intensities				
fuel input intensity	34%	22%	19%	21%
emission factor	28%	31%	28%	27%
relative emission reduction compared to base year	36%	58%	78%	89%

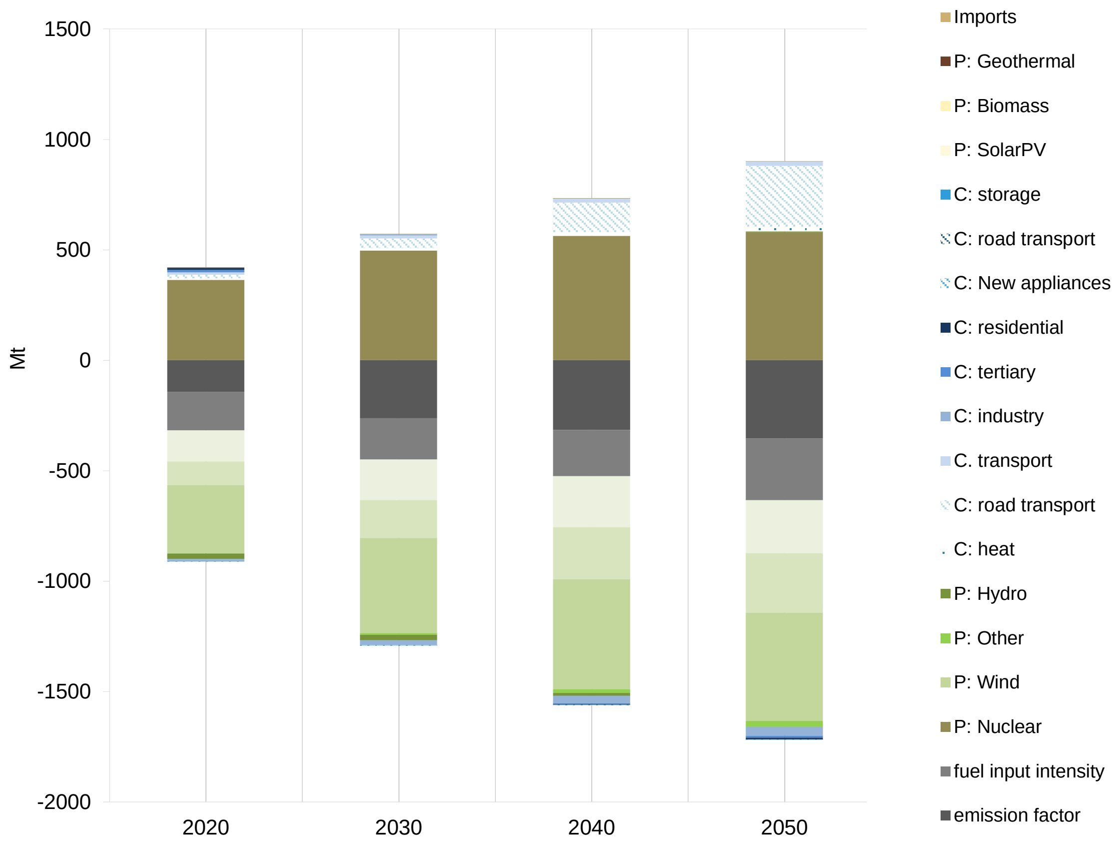
Source: Results from the decomposition analysis

Compared to the base year overall electricity sector CO_2 emission are reduced by about 1,040 Mt by 2050, a 92% reduction over 2007. As the following Table 11 shows, the major improvements assumed in energy efficiency lead to electricity demand from traditional appliances actually having a *lowering* effect on CO_2 emissions (albeit a small one of 36 Mt by 2050 compared to the base year), despite economic growth and an increase in "traditional" energy services. However, in order to achieve reductions in non-electricity energy demand, a shift from other fuels to electricity is assumed to a significant extent, especially in the transport sector and in the heating of buildings. As a result the growth in the use of these “new” electric appliances leads (considered separately) to an additional increase in electricity-sector CO_2 emissions of 296 Mt by 2050 compared to the base year. Electrification of road transportation is by far the more important new appliance in this scenario than the shift towards heating pumps.

Of course the significant expansion of renewable energy technology contributes to a decrease in CO_2 emissions by 2050 of 85% compared to the base year. As in the study’s reference scenario, wind power shows the biggest effect, followed by solar energy and biomass. Wind power and biomass, which today are (in most cases) more competitive than solar and geothermal energy show considerably higher shares in CO_2 emission reductions in earlier years than towards the middle of the century. Figure 13 shows how quickly renewable energy sources contribute to CO_2 emission reductions. Viewed separately, the various renewable energy sources combined would reduce emissions compared to the base year by about 1068 Mt in 2030, reaching by then already 96% of the emission reductions that they realize until 2050 (790 Mt). As nuclear power is completely phased out until 2050, this technology leads to an additional increase in CO_2 emissions of 45% compared to the base year (Table 12).

Both, fuel input intensity and the emission factor contribute to CO_2 emission reductions of -279 Mt and 354 Mt respectively as the average conversion efficiency of the remaining fossil fuel power plants increases over time and the share of natural gas in fossil fuel electricity generation quickly increases, eventually reaching 100%.

Figure 13 Energy Revolution / Energy Revolution scenario: Absolute emission changes triggered by causal factors in 2020, 2030, 2040 and 2050 compared to the base year



Source: Calculation with decomposition analysis

3.2.4.3.3 Advanced Energy Revolution scenario

The Advanced Energy Revolution scenario is a more ambitious policy scenario, reducing CO_2 emissions even further than the basic Energy Revolution scenario. Electricity sector CO_2 emissions in the Advanced scenario are 1.110 Mt or 98% lower in 2050 than in 2007 (99% lower than in 1990). These further reductions in the electricity sector compared to the basic Energy Revolution scenario are achieved by an even stronger expansion of renewable energy technologies. Especially production from solar power (both PV and solar thermal), geothermal power and also wind power is increased. Total energy sector emissions are reduced as fossil fuels in final energy demand are more aggressively substituted by electricity.

Table 13 Energy Revolution / Advanced Energy Revolution scenario: Relative emission reduction contributions of causal factors in 2020, 2030, 2040 and 2050 compared to the base year

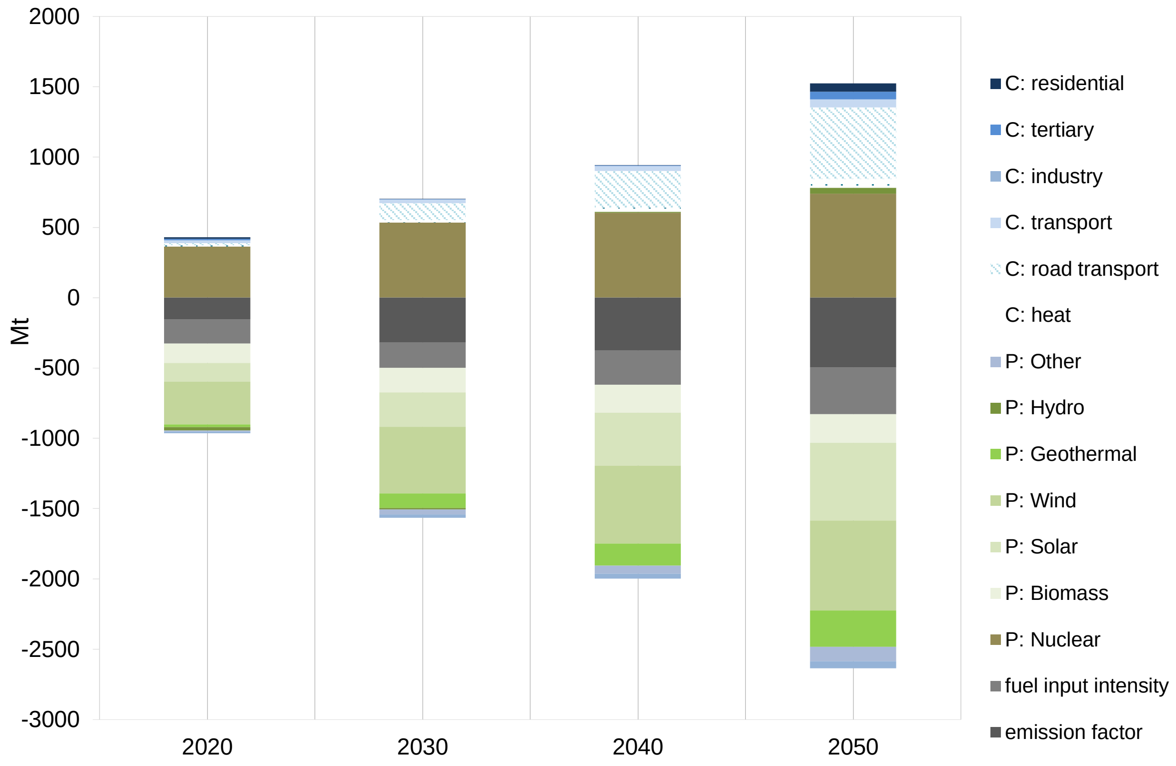
Causal factor	2020	2030	2040	2050
Consumption side				
C: traditional appliances	-5%	-1%	-1%	-8%
C: residential	-2%	0%	0%	-4%
C: tertiary	-2%	0%	0%	-4%
C: industry	2%	2%	3%	4%
C. transport	-4%	-3%	-3%	-4%
C: New appliances	-4%	-14%	-23%	-40%
C: road transport	-3%	-13%	-21%	-36%
C: heat	-1%	-2%	-2%	-5%
C: storage	-3%	-3%	-5%	-10%
C. Other	1.5%	0.8%	0.3%	-0.2%
Production Side				
P: Renewables	114%	110%	107%	121%
P: Hydro	4%	1%	-1%	-3%
P:Wind	55%	50%	44%	45%
P: Solar	24%	26%	30%	39%
P: Biomass	25%	18%	16%	14%
P: Geothermal	4%	11%	12%	18%
P: Other	1%	4%	5%	7%
P: Nuclear	-66%	-57%	-48%	-52%
P: Hydrogen	0%	0%	0%	1%
Imports	4%	10%	20%	31%
Intensities				
fuel input intensity	31%	19%	19%	24%
emission factor	28%	34%	30%	35%
relative emission reduction compared to base year	38%	65%	86%	97%

Source: Results from the decomposition analysis

The increasing level of electrification envisaged in the scenario results in new appliances doubling their contribution to CO_2 emissions by 2050 in absolute terms, from 211 Mt in the basic Energy Revolution scenario to 573 Mt in the Advanced Energy Revolution scenario (see Figure 14). Unlike in the basic Energy Revolution scenario, traditional appliances also lead to additional CO_2 emissions, albeit to a much smaller extent (120 Mt) than the new appliances do. This additional electricity demand of traditional appliances (i.e. all appliances except for electric vehicles and heat pumps) occurs in the household and tertiary sectors as well as in the transport sector even though efficiency assumptions are unchanged compared to the basic Energy Revolution scenario. The following two reasons are likely the reason for this development:

- In the tertiary and household sectors additional energy services (not just heating) might switch more aggressively to electricity, for example cooking.
- In the transport sector the Advanced Energy Revolution scenario foresees a further modal shift in favour of the railway. This increases electricity demand in the transport sector irrespective of the growth of electric vehicles.

Figure 14 Energy Revolution / Advanced Energy Revolution scenario: Absolute emission changes triggered by causal factors in 2020, 2030, 2040 and 2050 compared to the base year



Source: Calculation with decomposition analysis

However, these factors on the demand side leading (viewed separately) to higher CO_2 emissions are by far overcompensated by the emission reductions achieved on the supply side. Renewable energy sources are clearly the most important element for these reductions. As the contribution of these sources to total electricity generation is further increased compared to the basic Energy Revolution scenario, the CO_2 emission reductions for renewable energy sources are higher in the Advanced scenario in 2050 in both absolute (1,716 Mt compared to the base year) as well as relative terms (121% compared to the base year). As nuclear power is phased out also in the Advanced scenario, this (viewed separately) leads to an increase in additional emissions by 2050 compared to the base year of 739 Mt, just like in the basic Energy Revolution scenario.

Fuel input intensity and emission factor both contribute to CO_2 emission reductions by 2050 of 333 Mt and 495 Mt respectively, (Figure 14). This is due to the average conversion efficiency of the remaining fossil fuel power plants increasing over time and the share of natural gas in fossil fuel electricity generation quickly increasing, eventually reaching 100%.

4 Comparison of analysis results and conclusions

The comparison of the *electricity demand by sectors* (see Chapter 2) illustrates that there is a lot of uncertainty regarding the future development of electricity demand – in each sector some studies anticipate an increase while others anticipate a reduction. The transport sector is an exception as all scenarios expect a significant increase in electricity demand within the next decades caused by electrification of a growing share of individual transport. As a consequence total electricity demand increases in all scenario studies. Another driving force for this development is the stronger use of new electrical applications like heat pumps.

The studies vary regarding the assumptions on *sources for zero- or low-CO_2-emitting electricity generation*. Within the Greenpeace study nuclear is phased out and CCS is not seen as viable. Consequently electricity will be generated mainly (over 90%) by renewable sources including imports. In contrast, the Power Choices scenario, the 40%-RES-path from the ECF Roadmap study and especially the "clean" scenario from the study "Transformation of Europe's power system" anticipate a significant extent of nuclear power generation.

In all but one policy scenario *renewable sources* contribute more to electricity supply in 2050 than either fossil fuels or nuclear power. In most policy scenarios wind power becomes the most important renewable energy source in domestic electricity generation, followed by solar energy. In the Power Choices study and the "clean" scenario of the study "Transformation of Europe's power system" solar energy plays a minor role compared to all other policy scenarios. In the 40%-RES scenario the contribution of wind power (especially offshore) is very limited compared to others. The Greenpeace scenarios are the only ones, which expect an important role for geothermal electricity generation.

The electricity-sector CO_2-emission reductions within the different scenarios amount to:

- 90% within the Energy Revolution scenario
- 95% the Power Choices
- 96% within the ECF Roadmap 2050 and the Transformation scenarios
- 97% within the Advanced Energy Revolution Scenario

An important question is, how far these findings from the general comparison are reflected in the results of the *decomposition analysis*.

A methodological challenge is how to separately account for energy efficiency improvements. Currently energy efficiency is "hidden" in electricity demand of traditional appliances. The development of this indicator (electricity demand of traditional appliances) is not only dependent on efficiency but also on demand for actual energy services so the actual improvements in efficiency do not become immediately apparent when looking at the development of electricity demand of traditional appliances. However, disentangling efficiency and demand for energy services is difficult with the little information in the scenario studies on the development of the various forms of energy services.[19]

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[19] While GDP development could be used as a proxy, this would be far from perfect.

The analysis so far in this project has shown how important it is to have sufficiently detailed data to compare various scenario pathways with one another and learn from the differences between theses pathways. Many scenario studies do not provide sufficient data for an in depth analysis or they do not reveal important assumptions. A future standardised (minimum) data format for every energy scenario would be a significant benefit for energy scenario analysis. The table in Appendix I gives a comparing overview on scenario paths.

Comparing the ECF Roadmap 2050 and the Greenpeace paths it becomes evident that the highest absolute and relative reduction by domestic renewable sources is achieved in the 80%-RES scenario. Taking imports into account a similar contribution from RES in overall emission reduction is achieved in the Advanced Energy Revolution Scenario of the Greenpeace study. Only the Greenpeace scenarios take imports of renewable energy into account - here they play quite an important role. The phase-out of nuclear power generation leads to additional emissions in the Greenpeace scenarios, which need to be offset by other causal factors. The decomposition results concerning renewable energies clearly reflect the major importance that all policy scenarios attribute to wind power, with solar power as the second most important renewable energy source in most scenarios. In those scenarios which assume significant use of CCS, the CO_2 reductions achieved by this technology are quite significant, though not quite as high as the contribution of renewables in the high-renewables scenarios. CCS is most significant in the 40%-RES and the 60%-RES scenarios of the ECF Roadmap study.

The similarities and differences identified between the scenarios represent the added value of the decomposition analysis challenging the robustness of the authors' assumptions and quantifying the emissions change associated with all of the causal factors to provide a transparent dataset to support long term planning on how to decarbonise the power sector in Europe by 2050.

5 Appendix I: Decomposition results across scenarios in 2050

Figure 15: Decomposition results across scenarios in 2050

Causal factor	40% RES	60%RES	80% RES	REV	ADV REV	PC
C: traditional appliances	-28.83	-28.72	-27.87	-35.58	120.22	572.45
C: residential	-8.19	-8.16	-7.92	-8.50	59.22	-15.62
C: tertiary	-7.86	-7.83	-7.59	-8.28	54.92	-98.02
C: industry	-12.03	-11.99	-11.63	-39.61	-50.53	104.02
C. transport	-0.75	-0.75	-0.73	20.81	56.61	582.07
C. New appliances	864.90	861.71	836.05	295.88	573.08	0.00
C: road transport	461.28	459.58	445.90	274.62	509.25	0.00
C: heat	403.62	402.13	390.16	21.26	63.83	0.00
C. Storage	0.00	0.00	0.00	38.27	139.74	0.00
C. Other	0.00	0.00	-38.07	2.27	2.90	44.29
Exports	0.00	0.00	0.00	0.00	0.00	10.87
P: Renewables	-774.53	-1534.26	-2228.43	-1108.61	-1716.46	-488.17
P: Hydro	57.86	57.64	55.94	5.08	41.07	45.97
P: Wind	-306.87	-687.04	-999.52	-489.30	-640.72	-405.72
P: Solar	-263.54	-643.87	-883.65	-270.64	-551.47	-50.16
P: Biomass	-191.95	-191.25	-333.52	-240.39	-204.75	-52.63
P: Geothermal	-70.01	-69.76	-67.68	-86.66	-258.55	-16.22
P: Other	0.00	0.00	0.00	-26.69	-102.03	-9.40
P: Nuclear	-106.08	275.61	637.37	578.85	738.70	71.30
P: Hydrogen	0.00	0.00	0.00	0.00	-10.39	0.00
Imports	0.00	0.00	0.00	-436.88	-435.94	7.68
P: CCS	-1033.31	-686.33	-332.95	0.00	0.00	-643.30
fuel input intensity	-205.42	-204.69	-198.68	-278.90	-333.47	-485.05
emission factor	-81.59	-81.36	-78.65	-354.30	-495.38	-418.71
total emission reduction compared to base year	**1364.8**	**1398.0**	**1431.2**	**1299.0**	**1417.0**	**1328.6**

Source: results from decomposition calculation

6 Appendix II: PRIMES scenarios up to 2030

6.1 Introduction

General information

The "*EU energy trends to 2030 – UPDATE 2009*" (Capros et al. 2010) report was prepared by the Institute of Communication and Computer Systems of the National Technical University of Athens and was commissioned by the Directorate-General for Energy in collaboration with Climate Action DG and Mobility and Transport DG. The report is an update of the 2003 published report "European energy and transport – Trends to 2030", and its updates in 2005 and 2007 and was published on 4 August 2010.

Thematic background

Since the last update of the report in 2007, there have been dramatic economic changes due to the global economic crisis. Demand of the energy intensive industry declined dramatically. Further, legislation has been adopted that will significantly affect energy demand and production in the future. With the update of the Baseline Scenario, these changes are now accounted for in the 2009 Baseline Scenario.

Methodology

The Scenarios were derived with the PRIMES energy model, developed and run by E3MLab of the National Technical University of Athens, and are supported by more specialised models for projections for value added by branch of activity, GEM-E3, and for projections for world energy prices, PROMETHEUS PRIMES determines a market equilibrium solution for energy supply and demand within each of the 27 EU member states. Driven by engineering and economic principles, PRIMES is dynamic over time and determines the market equilibrium by finding the prices of each energy fuel that make supply and demand of energy match. PRIMES is used for projections to the future and can thus be used for scenario building and policy impact analysis.

Scenarios / pathways

The current study includes two scenarios, the 2009 Reference Scenario and the 2009 Baseline Scenario. The 2009 Baseline scenario describes the development of the EU energy system under current trends and policies. It takes into account the highly volatile energy import price of recent years. National and EU policies implemented until April 2009 like the ETS and several energy efficiency measures are included but it excludes the renewable energy target and the non-ETS targets. The 2009 Reference Scenario is based on the same macroeconomic, price, technology and policy assumptions as the baseline scenario. In addition to the assumptions of the 2009 Baseline Scenario it includes policies adopted between April 2009 and December 2009. It further assumes that national targets under the Renewables Directive 2009/28/EC and the GHG effort-sharing decision 2009/406/EC are achieved in 2020.

Infrastructural changes within the European power system

The structure of power generation changes significantly in the Reference scenario. Renewable energy sources are being used increasingly because of the RES target and lead to a crowding-out effect regarding other technologies. In this respect, fossil fuel generation declines. Particularly gas generation and also solids experience a much steeper decline as projected before. Hydropower remains constant over time. Other renewables, however, like wind onshore, wind offshore and solar photovoltaics face a major growth. Power generation from geothermal and tidal sources remain minor technologies but expand over time. According to the increase in renewable energy sources in both scenarios, a higher amount of gas-fired power plants to cope with the higher amount of intermittent energy sources is required.

6.2 Decomposition Analysis

6.2.1 Data availability & gap filling

All data for the decomposition analysis was readily available via the documentation tables of the PRIMES scenarios from the EU energy trends to 2030 study (Capros et al. 2010) except fuel specific inputs to CCS electricity generation. A CCS indicator (see p. 125) however allowed for the calculation of the share of electricity produced by CCS technology in the given years. This information was then used to derive the fuel input necessary. Since no indication of CCS efficiencies were given, an assumption of an overall efficiency of 30% has been made. Furthermore it is assumed that the capture rate equals 90%.

The data provided by the PRIMES documentation did not allow for the specific distinction between traditional and new appliances on the consumption side..

6.2.1.1 PRIMES Baseline 2009

The 2009 Baseline scenario describes the development of the EU energy system under current trends and policies. It takes into account the highly volatile energy import price of recent years. National and EU policies implemented until April 2009 like the ETS and several energy efficiency measures are included but it excludes the renewable energy target and the non-ETS targets. reflects the results of the decomposition analysis, based on the assumptions described above.

Table 14 EU energy trends to 2030 – Update *2009* / PRIMES Baseline 2009 scenario: Relative emission reduction contributions of causal factors compared to the base year

Causal factor	2010	2015	2020	2025	2030
Consumption side	**-12%**	**-169%**	**-350%**	**-177%**	**-101%**
C: Sectoral consumption	-19%	-165%	-313%	-152%	-84%
C: residential	-10%	-65%	-119%	-56%	-30%
C: tertiary	-6%	-63%	-115%	-53%	-28%
C: industry	-2%	-32%	-72%	-39%	-23%
C. transport	-2%	-4%	-7%	-3%	-2%
Other	7%	1%	-23%	-20%	-14%
Exports	0.00	-0.04	-13%	-5%	-2%
Production Side	**61%**	**164%**	**295%**	**183%**	**145%**
P: Renewables	134%	315%	480%	214%	118%
P: Hydro	11%	0%	-17%	-9%	-6%
P: Wind	74%	204%	344%	157%	88%
P: Solar	13%	33%	51%	23%	13%
P: Biomass	35%	77%	102%	42%	21%
P: Geothermal	0%	0%	1%	1%	2%
P: Nuclear	-65%	-150%	-242%	-83%	-30%
Imports	-8%	0%	0%	0%	0%
P: CCS	0%	0%	57%	52%	56%
Intensities	**52%**	**104%**	**155%**	**94%**	**56%**
fuel input intensity	50%	144%	328%	81%	-11%
emission factor	2%	-40%	-173%	13%	68%
relative emission reduction compared to base year	**7%**	**5%**	**7%**	**16%**	**35%**

Source: Results from the decomposition analysis

According to the decomposition analysis the increased amount of electricity consumption across all sectors contributes to increasing emissions compared to the base year for all periods considered.

The PRIMES 2009 Baseline scenario assumes an increasing share of renewable energy sources in electricity generation, which results in an absolute emission reduction of 671 $MtCO_2$ in the power sector by 2050. Renewable energies contribute to emission reductions of over 100% (118%) and thus offset negative emission reduction contributions of other causal factors.

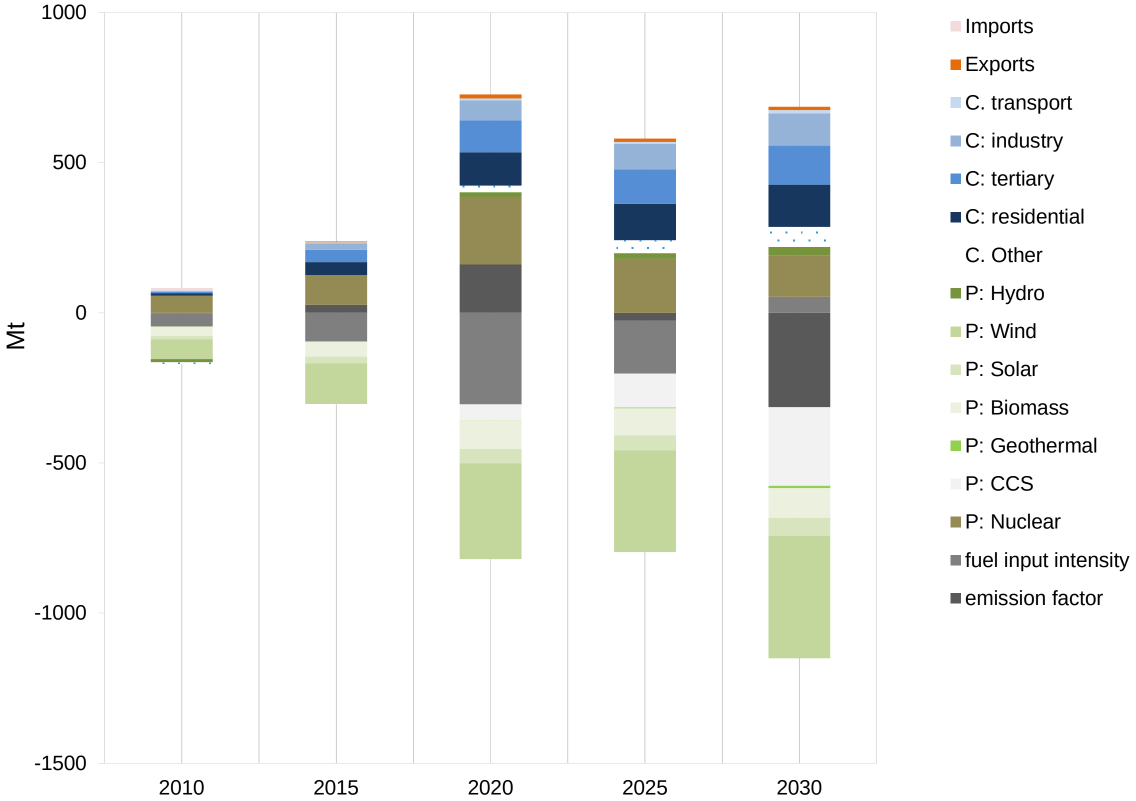
The emission reductions attributed to CCS (56% by 2030) do not exceed the emission reduction effect of renewable energies. More nuclear power is used in 2030 (1087 TWh in 2030 compared to 998 in 2005) than in the base year, the additional emissions caused by the share of nuclear power utilized decrease to appr. 139 Mt in 2030. The additional emissions caused by nuclear power technology are explained by its decreasing share on overall electricity generation from 2010 to 2025, from where on the share increases and thus reduces the additional emissions.

The emission factor decreases starting from 2025 on and positively contributes to emission reductions up to 313 Mt in 2030.

Fossil fuel input intensity contributes emission reductions up to 2025, but then in 2030 adds positively to emissions.

Figure 16 visualises the absolute emission changes triggered by the various causal factors.

Figure 16 EU energy trends to 2030 – Update *2009* / PRIMES Baseline 2009 scenario: Absolute emission changes triggered by causal factors in compared to the base year



Source: Calculation with decomposition analysis

6.2.1.2 PRIMES Reference 2009

The 2009 Reference Scenario is based on the same macroeconomic, price, technology and policy assumptions as the baseline scenario. In addition to the assumptions of the 2009 Baseline Scenario it includes policies adopted between April 2009 and December 2009. It further assumes that national targets under the Renewables Directive 2009/28/EC and the GHG effort-sharing decision 2009/406/EC are achieved by 2020. Table 15 summarises the results obtained by the decomposition analysis.

Table 15 EU energy trends to 2030 – Update *2009* / PRIMES Reference 2009 scenario: Relative emission reduction contributions of causal factors compared to the base year

Causal factor	2010	2015	2020	2025	2030
Consumption side	**-11%**	**-82%**	**-68%**	**-128%**	**-135%**
C: Sectoral consumption	-19%	-81%	-62%	-114%	-120%
C: residential	-10%	-33%	-27%	-50%	-53%
C: tertiary	-6%	-29%	-19%	-33%	-38%
C: industry	0%	-16%	-14%	-28%	-26%
C: transport	-3%	-2%	-2%	-3%	-4%
Other	8%	2%	-3%	-10%	-11%
Exports	0%	-2%	-3%	-4%	-4%
Production Side	**65%**	**128%**	**127%**	**165%**	**173%**
P: Renewables	147%	207%	177%	234%	223%
P: Hydro	13%	2%	-1%	-5%	-6%
P: Wind	84%	140%	116%	157%	152%
P: Solar	15%	18%	18%	26%	27%
P: Biomass	33%	46%	43%	52%	46%
P: Geothermal	1%	1%	2%	3%	4%
P: Nuclear	-73%	-79%	-63%	-84%	-64%
Imports	-10%	0%	0%	0%	0%
P: CCS	0%	0%	13%	16%	14%
Intensities	**46%**	**54%**	**41%**	**63%**	**62%**
fuel input intensity	33%	49%	39%	57%	52%
emission factor	13%	5%	2%	6%	10%
relative emission reduction compared to base year	6%	9%	20%	18%	23%

Source: Results from the decomposition analysis

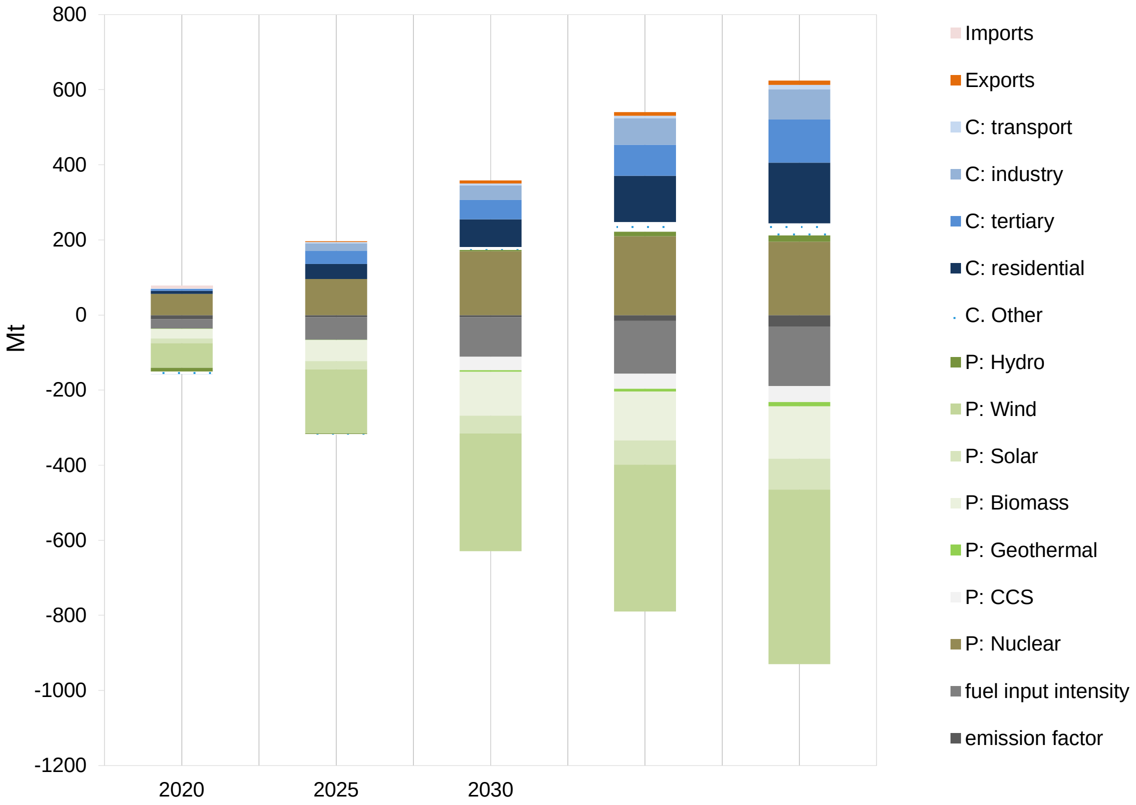
According to the decomposition analysis the increased amount of electricity consumption across all sectors contributes to increasing emissions compared to the base year for all periods considered.

The PRIMES 2009 Reference scenario assumes an increasing share of renewable energy sources in electricity generation, which results in an absolute emission reduction of 680 $MtCO_2$ in the power sector by 2050. Renewable energies achieve emission reductions of over 100% (223%) and thus offset the greatest share of negative emission reduction contributions of other causal factors (Table 15).

The emission reductions attributed to CCS (14% by 2030) do not exceed the emission reduction effect of renewable energies. Electricity production from nuclear power remains relatively constant throughout the time periods (982 TWh in 2030 compared to 998 in 2005) than in the base year, the additional emissions caused by exploitation of nuclear power however increase from 57 Mt in 2010 to appr. 194 Mt in 2030. This is due to the effect that while nuclear power is still exploited, its share in total electricity generation decreases (from 30% in the base year to 24.1 % in 2030).

The emission factor positively contributes to emission reductions. Fossil fuel input intensity contributes increasingly to emission reductions. Figure 17 visualises the absolute emission changes triggered by the various causal factors for the PRIMES Reference 2009 scenario.

Figure 17 EU energy trends to 2030 – Update *2009* / PRIMES Reference 2009 scenario: Absolute emission changes triggered by causal factors in compared to the base year



Source: Calculation with decomposition analysis

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