Power Sector Decarbonisation: Metastudy

Final Report for the SEFEP funded project 11-01

Berlin, Wuppertal 29.2.2012

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Content

1 Summary

This final report of the research project „Power Sector Decarbonisation: Metastudy“ contains the various reports prepared by Öko-Institut and Wuppertal Institute during the course of the SEFEP funded project. A key objective of the project was to make a contribution to the debates within the European Union (EU) and Member States on the EU's Energy Roadmap 2050 publication, which was released in December 2011. This objective was achieved by systematically analysing and comparing recently published scenarios on the European electricity sector commissioned by a range of different stakeholders (environmental NGOs, industry and government agencies).

The following four steps were conducted during the course of the project:

1. Development of a comprehensive analytical framework for a systematic comparison of decarbonisation studies for the power sector with regard to technical structures, economic aspects and implementation issues. A refined CO_2 decomposition approach is at the centre of this analytical framework.
2. Appliance of the analytical framework to existing European energy studies. This phase of analysis focused on “pre-Roadmap 2050” studies released within the past three years and also included for comparison some studies on specific EU Member States.
3. Extension of the analysis to include the scenarios described in the EU's Energy Roadmap 2050 study. The focus of the work in this phase was to contribute with scientific analysis to the debates emanating from the release of the Energy Roadmap 2050, thus advancing the policy debate.
4. Focusing on the lessons learnt from this project in terms of methodologies, data and information. As a result of this phase, on the one hand recommendations were made on the issues, which according to the various scenario studies are of significant importance for the long-term decarbonisation of the power sector. On the other hand it was evaluated where more analytical work by scenario modellers could help to advance strategic planning and policy planning as well as policy implementation.

Overall eight reports were prepared which are briefly described in the following and which can be found in chronological order within this final report[1]:

Comparison methodology (WP 1.2)

This report describes in detail the CO_2 decomposition methodology, which is at the heart of the scenario analysis following in later reports.

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[1] Behind the title of each report the number of the project's Work Package, which each report is based on, is indicated.

Overview over existing EU-wide studies (WP 2.1)

This report summarises six energy scenario studies published since 2009, which all include scenarios describing the European electricity system. The background of these studies as well as their methodology and the key characteristics of their scenarios are explained in the report. However, detailed quantitative analysis of scenario assumptions and results is not yet performed.

Quantitative analysis of existing EU-wide studies (WP 2.2)

This report contains detailed quantitative analysis of the development of the electricity system described in ten different energy scenarios from four scenario studies as well as the key assumptions for these developments. The four studies were chosen among a larger group of scenario studies (see previous report) based on minimum data requirements. For a majority of the scenarios discussed data availability was sufficient to perform a decomposition analysis.

Existing decarbonisation studies on specific EU Member States (WP 2.3)

As a complement to the analysis of the European scenario studies this report analyses and compares three energy scenario studies from three EU Member States (Germany, UK, Sweden). Detailed quantitative analysis (including decomposition analysis) is performed for one of these studies, for which sufficient data was available.

Information for Policy Makers 1. Decarbonisation Scenarios leading to the EU Energy Roadmap 2050 (WP 2.4)

This report summarizes the findings of the previous reports, mainly of those reports based on Work Packages 1.2, 2.1 and 2.2. It is intended to serve as an overview for policymakers on the results, similarities and differences of relevant “pre-Energy Roadmap 2050” scenarios dealing with the European power sector. This report also points out some policy conclusions that can be drawn from the analysis of the energy scenario studies considered.

Quantitative Analysis of scenarios from the EU’s Energy Roadmap 2050 (WP 3.1)

This report analyses in detail the development of the electricity system (as well as the key assumptions for the development) described in the seven different scenarios of the EU’s Energy Roadmap 2050. Decomposition analysis was performed for all scenarios to systematically compare the role of various mitigation options in the power sector in the seven scenarios.

Information for Policy Makers 2. Analysis of the EU’s Energy Roadmap 2050 scenarios (WP 3.2)

This report summarizes the findings of the previous report. It is intended to serve as an overview for policymakers on the results, similarities and differences of the Energy Roadmap 2050 scenarios and the policy conclusions that can be drawn from this.

Promising future meta-research on decarbonisation studies (WP 4)

This final report summarizes the key findings relevant for policymakers that have been derived from the analysis of the various energy scenario studies analysed within this project. It also makes suggestions on how the methodology, transparency and documentation of future scenario studies could be improved to be even more helpful for guiding energy policy decisions and to facilitate future meta research on energy scenario studies.

2 Project Progress

2.1 Deliverables

The operational work on the Metastudy project started in March 2011. The original time schedule of the project with respect to its deliverables is summarized by .

Table 1 Original schedule of deliverables

Deliverable	Title	Due date
1.1	Common roster of data and information	
1.2	Comparison methodologies	March 2011
2.1	Overview of existing studies	March 2011
2.2	Quantitative analysis of existing EU-wide studies	March 2011
2.3	Existing decarbonisation studies on specific EU Member States	May 2011
3	Analysis of additional studies: Emerging EU-wide studies	June 2011
4	Promising future meta-research	November 2011
	ad hoc discussion papers on EU Roadmap process	March to June 2011

In view of various delays with respect to data availability and publications of scheduled studies (e.g. the Energy Roadmap was published in December 2011 instead of November 2011), the schedule of the deliverables has been discussed jointly with the funder and adjusted accordingly. The modified schedule with respect to the deliverables is presented in **Error! Reference source not found.**.

Table 2 Modified schedule of deliverables and delivery dates

Deliverable	Title	Delivery
1.1	Common roster of data and information	Appendix of Policy Paper 1&2 Final version: March 12, 2012
1.2	Comparison methodology	May 30 2011 Revised version: October 31, 2011
2.1	Overview of existing studies	June 1, 2011
2.2	Quantitative analysis of existing EU-wide studies	July 18, 2011 Revised version: October 31, 2011
2.3	Existing decarbonisation studies on specific EU Member States	July 29, 2011 Revised version: October 31, 2011
2.4	Policy Paper: Information for Policy Makers 1. Decarbonisation Scenarios leading to the EU Energy Roadmap 2050.	November 16, 2011 Revised version: January 18, 2012
3.1	Analysis of additional studies: Emerging EU-wide studies	February 14, 2012
3.2	Policy Paper: Information for Policy Makers 2. Analysis of the EU's Energy Roadmap 2050 scenarios.	February 14, 2012
4	Promising future meta-research	February 29, 2012

Instead of the ad hoc working papers two policy papers have been added to the list of deliverables. Deliverable 2.4 has been introduced to an expert public at a workshop in Brussels on ECF premises.

2.2 Meetings

The project partners organized their work along several meetings and regular phone calls. Table 3 provides an overview of meetings and events in course of the projects lifetime.

Table 3 Meetings throughout the project's lifetime

Date	Notes	Participants
14 March 2011	Partner kick-off meeting	Wuppertal Institut, Öko-Institut
16 June 2011	Partner meeting to discuss next steps	Wuppertal Institut, Öko-Institut
5 September 2011	Strategic meeting at Sefep	Wuppertal Institut, Öko-Institut, SEFEP
12 December 2011	Partner meeting to discuss next steps	Wuppertal Institut, Öko-Institut
23 January 2012	Workshop in Brussels to present preliminary results	Wuppertal Institut, Öko-Institut, SEFEP, experts
27 March 2012	Strategic meeting at Sefep	Wuppertal Institut, Öko-Institut, SEFEP

2.3 Dissemination

Results of the project have been disseminated through the expert workshop that took place on January 23, 2012 alongside the publication of the first policy paper. This policy paper, comprehensive background material on methodology, further results and gap-filling procedures are available for download at the SEFEP[2] and the partners' websites[3].

Further dissemination activities include the preparation of a peer-reviewed paper based on the results obtained throughout the project.

3 Appendices

Project reports

- WP 1.1
- WP 1.2
- WP 2.1
- WP 2.2
- WP 2.3
- WP 3.1
- WP 3.2
- WP 4

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[2] WP 2.4: http://www.sefep.eu/activities/publications-1/decarbonisation-scenarios-leading-to-the-eu-energy-roadmap-2050

[3] WP 2.4: http://www.wupperinst.org/uploads/tx_wiprojekt/Metastudy_Info_PolMakers1.pdf,
http://www.oeko.de/oekodoc/1353/2012-005-en.pdf,
WP 1.2: http://www.wupperinst.org/uploads/tx_wiprojekt/Metastudy_comparison_methodology.pdf,
http://www.oeko.de/oekodoc/1351/2012-003-en.pdf,
WP 2.2: http://www.wupperinst.org/uploads/tx_wiprojekt/Metastudy_EU_studies.pdf,
http://www.oeko.de/oekodoc/1352/2012-004-en.pdf,

Power sector decarbonisation: Metastudy

WP 1.2 Comparison Methodology

Berlin, 14.05.2012

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Content

1 Scope

Energy scenarios are an important and frequently used tool for decision makers to visualise the necessary changes towards a low carbon economy in the future. They demonstrate (alternative) paths for the possible mid- or long-term development. Backcasting approaches indicate what political decisions need to be taken today or within the short-term future to make the outlined paths feasible. Energy scenarios should not be equated with concrete projections, as they do not aim to continue developments from the past into the future. They rather try to develop a range of possible future paths, based on a set of assumptions.

In particular the range of paths and various sets of scenarios in the different studies make it difficult to compare them. Different assumptions, combined with a lack of transparency and the missing disclosure regarding the underlying data, hamper the comparison of the scenario studies and single scenario paths in particular. Given these limitations it is currently difficult for policy makers to decide upon a particular scenario to use as the basis for setting environmental policy in order to decarbonise the economy.

The scope of the research project *Power Sector Decarbonisation: Metastudy* is to provide a scenario overview which helps to overcome the difficulties outlined above. Having such an overview will be necessary when the European institutions and Member States start their debates on a Roadmap 2050 during the year 2011. Decisions shall be based on robust evidence from modelling exercises and other analytical work – therefore, it is necessary to analyse the existing and emerging analytical work on decarbonisation strategies for the power sector with a metastudy approach. The purpose of this metastudy is to identify:

- similarities and robust elements of decarbonisation strategies for the power sector;
- key differences and their determinants;
- key issues on implementation.

The scope of this work package (WP 1.2) is to provide an analytical framework for a systematic comparison of decarbonisation studies focusing on the power sector. The methodology involves the systematic disaggregation of emission reductions into the underlying causal factors (or components) that cause emission reductions in the power sector. By decomposing CO_2 emissions into causal factors the present methodology provides value added in increasing the transparency of modelling exercises completed in various studies. The studies considered in the course of this project include for example (Greenpeace International & European Renewable Energy Council 2010; WWF 2009; European Climate Foundation 2010; eurelectric 2010). All of these studies consider several scenarios regarding the future development of CO_2 emissions of the power sector in view of decarbonisation goals and provide a more or less detailed overview of future power generation. However, the assumptions underlying these studies and the scenarios they consider differ, and the specific analysis of the underlying structure of the emission reductions was not among their main goals.

In (WWF 2009) decomposition analysis is applied to attribute emission reductions to a range of underlying causal factors (or components) for a number of sectors. In this paper the decomposition methodology applied in the (WWF 2009) study is adapted for the power sector and expanded to include various causal factors, including for example efficiency improvements of traditional appliances. The methodological framework presented in Section 2 provides the means to disaggregate power sector CO_2 emission reductions into the contributions arising from demand side effects, energy efficiency improvements, renewable energy shares, nuclear shares, CCS shares, storage, and imports and exports. The methodological framework outlined in the following section is described in a clear and transparent manner to enable the approach to be replicated in the future to compare different scenarios for the decarbonisation of the power sector.

2 Methodology

2.1 Methods of decomposition analysis

A decomposition analysis can be used to explain a variable of interest in terms of a whole set of factors/activities that actually determine the value of this variable. Each decomposition analysis starts with defining a governing function relating the variable of interest (i.e. CO_2 emissions) to a number of causal factors (Ang 2004).

There are several ways of approaching a decomposition analysis. The most notable difference is the distinction between methods that produce a full decomposition and do not yield a residual term and those that yield a residual term.

Let us assume that the variable of interest to be decomposed is CO_2 emissions. The Laspeyres method of decomposition measures the isolated contribution of the change of one causal factor to the total change of CO_2 emissions, assuming all the other causal factors remain the same. Each factor playing a role in defining emissions is therefore modified individually while all the others are held at base year values. See for example (Ang 2000) . This can be interpreted as a prospective view (Albrecht et al. 2002) .

In contrast, when applying the Paasche method of decomposition, the contribution of the change of one activity is measured compared to the total change of emissions assuming the end year values of all other causal factors while keeping the element to be considered at base year values. This can be interpreted as a retrospective view (Sun 1998).

Both of these decomposition methods account for the *isolated effects* of each activity considered. As such they produce a residual – an amount that cannot be attributed to those individual effects. This residual is the difference between the total change as observed (e.g. emissions change between *t=0* and *t=1*) and the value to which the integrals of the activities add up to after the approximation[1].

This *residual term* accounts for the mixed effects, i.e. of changes that are triggered by joint changes of causal factors. Thus it reflects the lack of knowledge about the actual underlying functions (Muller 2006). The decomposition is thus not full and the modeller needs to decide on how to proceed with the residual term. Possibilities include neglecting it (if the value is sufficiently small), explicitly considering it, and distributing it among the different isolated effects (Seibel 2003).

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[1] Ideally, these would be integrals; in practice, however, they are sums because observations are only available for discrete time steps.

There are several methods providing a full decomposition without residual terms, for example the LMDI approach as described in (Ang 2005) and the Shapley decomposition described in (Albrecht et al. 2002). These methods account for the residual endogenously.

However, having a residual can be considered as accounting transparently for individual and mixed effects (Muller 2006). It is thus the choice of the modeller to decide which method is appropriate for the given context.

2.2 The implemented decomposition approach

The decomposition approach implemented in this study is based on the Laspeyres method where each causal factor of interest is modified to its future value while all other factors remain at base values. Data for base year and future values are retrieved from the corresponding scenario data documented by the considered studies.

We determine what would happen if the separated factor changed under the assumption that the rest of the power sector remained at base year values, i.e. no change would happen. This is repeated once for each of the factors in question.

The individual contributions (isolated contributions) to emission reduction are then aggregated and the *residual term* which corresponds to the mixed effects triggered jointly by more than one of the causal factors is distributed to each causal factor based on a specified method, explained in Section 2.3.8.

The decomposition methodology includes the means to calculate the traditional Laspeyres index decomposition with attributing the mixed effects proportionally to the calculated contributions of the causal factors. In this sense the methodology provides a refined Laspeyres approach yielding a full decomposition.

In the present study, we are interested in disaggregating CO_2 emission reductions of the power sector into the contributions from the effects summarised in Table 1.

Table 1: Contributions of different effects to be analysed with the decomposition approach for this metastudy

Type of effect	Effects	Sectors considered (if applicable)
Demand side	Energy efficiency changes via traditional appliances	Transport, residential, industry, tertiary
	Demand side effect via new appliances	Road transport, heat market
	Demand side effects via storage input	
	Export share [1]	
Production side	Renewable energy share	Hydropower, wind onshore, wind offshore, solar PV, solar CSP, biogas, biomass, geothermal, other
	CCS share	
	Nuclear share	
	Import share [2]	
	Fossil production share	
Structure / Intensity	Fuel input intensity	
	Overall emission factor of fuel mix	

Note: [1] Exports are accounted for on the demand side under the following assumption: exports relate to electricity consumed by consumers abroad.

[2] Imports are accounted for on the production side: the imports reflect electricity produced abroad.

2.3 Equations

2.3.1 CO_2 emissions (base equation)

The governing function of CO_2 emissions in the power sector is assumed to be composed of the consumption of electricity from various areas C, the share of production from CO_2 emitting electricity generation technologies $(1-\pi^{free})$, fuel input intensity (I^{fos}/P^{fos}), and the overall emission factor of the fuel mix, E/I^{fos}. Equation 1 reflects this equation for time step *t*.

Equation 1

$$E_t = C_t(1-\pi_t^{free})\frac{I_t^{fos}}{P_t^{fos}}\frac{E_t}{I_t^{fos}}$$

with[2]

E_t CO_2 emissions at time *t* (Mt),

C_t total electricity consumption at time *t* (TWh),

π_t^{free} share of electricity generation from non CO_2 emitting generation technologies at time *t*,

I_t^{fos} input of fossil fuel at time *t* (PJ),

P_t^{fos} production of electricity from CO_2 emitting generation technologies (TWh)

The share of CO_2-free electricity production is determined through Equation 2:

Equation 2

$$\pi_t^{free} = \sum_{i=1}^{n}\frac{P_t^i}{P_t}$$

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[2] The share of production from zero carbon electricity generation technologies is calculated by dividing the production of zero carbon electricity generation (Equation 2) by the total production of electricity.

where:

$i = 1,...,n$	non-CO_2 emitting generation technologies,
P_t^i	electricity generation from the non-CO_2 emitting generation technology i in time step *t* (TWh),
P_t	total electricity generation in time step *t* (TWh).

2.3.2 Consumption

Consumption, measured in TWh, is assumed to originate from various sources reflecting contributions to emission reductions via electricity demand side effects. $C_0 \sum_{j=1}^{m} \mu_0^{old,j} (1-\varphi_t^{old,j})$ represents the electricity consumption of traditional appliances (i.e. ventilation systems) at time *t*, $C_0 \gamma_t^{new}$ represents the electricity consumption of new appliances (i.e. electric vehicles) at time *t*, while $C_0 \gamma_t^{store}$ represents the electricity consumption of storage inputs (i.e. electricity storage) at time *t*. Thus, the overall consumption at a given period, *t*, in a scenario can be expressed by the following equation:

Equation 3

$$C_t = C_0 \sum_{j=1}^{m} \mu_0^{old,j} (1-\varphi_t^{old,j}) + C_0 \gamma_t^{new} + C_0 \gamma_t^{store}$$

with

C_t	electricity consumption at time *t* (TWh),
C_0	total consumption of electricity at base year (TWh),
φ_t^{old}	efficiency gain of traditional appliances at time *t* compared to the base year,
μ_0^{old}	share of the electricity consumption of old appliances at base year,
γ_t^{new}	electricity consumption share of new appliances at time *t*, compared to the total base year electricity consumption,
γ_t^{store}	electricity consumption from storage input at time *t*, compared to the total base year electricity consumption.

The efficiency of traditional appliances in time step *t* is determined via:[3]

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[3] The electricity consumption of traditional appliances in time step *t* is calculated by multiplying the total electricity consumption in the base year with the change in electricity consumption of all the traditional appliances in the industrial, tertiary, residential, and transport sectors between time step *t* and the base year. This value is subsequently converted into a share of electricity consumption for the traditional appliances.

$$\varphi_t^{old,j} = \frac{C_0^{old,j} - C_t^{old,j}}{C_0^{old,j}}$$

and the share of the electricity consumption of old appliances at the base year via:

$$\mu_0^{old,j} = \frac{C_0^{old,j}}{C_0},$$

where

old	traditional appliances,
$C_t^{old,j}$	consumption of electricity from traditional appliance *j* at time *t*,
j = 1, , m	consumption areas of traditional appliances (residential, tertiary, transport, industry).

The electricity consumption share of new appliances (compared to the total base year electricity consumption) in time step *t* is expressed as:[4]

$$\gamma_t^{new} = \sum_{k=1}^{x} \gamma_t^{new,k}$$

with

$$\gamma_t^{new,k} = \frac{C_t^{new,k}}{C_0},$$

where

new	new appliances
$C_t^{new,k}$	consumption of electricity from new appliance *k* at time *t*
k=1, , x	consumption areas new appliances (road transport, heat)

with the electricity consumption share of storage (compared to the total base year electricity consumption) in time step *t* expressed as:[5]

$$\gamma_t^{store} = \sum_{l=1}^{y} \gamma_t^{store,l}$$

with

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[4] The electricity consumption share of new appliances in time step *t* is expressed as the change in electricity consumption of all the new appliances for road transport and heat between time step *t* and the base year.

[5] The electricity consumption share of storage appliances in time step *t* is expressed as the change in electricity consumption of all the storage appliances between time step *t* and the base year.

$$\gamma_t^{store,l} = \frac{C_t^{store,l}}{C_0},$$

where

store	storage input
$C_t^{store,l}$	consumption of electricity from storage input *l* at time *t*
l=1, , y	consumption areas storage input.

2.3.3 CO₂ emissions at a given point in time

Substituting π_t^{free} in Equation 1 by Equation 2 yields the CO_2 emissions of the power sector based on the causal factors at time *t*, E_t:

Equation 4

$$E_t = \left(C_0 \sum_{j=1}^{m} \mu_0^{old,j} (1-\varphi_t^{old,j}) + C_0 \gamma_t^{new} + C_0 \gamma_t^{store} \right) \left(1 - \sum_{i=1}^{n} \frac{P_t^i}{P_t} \right) \frac{I_t^{fos}}{P_t^{fos}} \frac{E_t}{I_t^{fos}}$$

Generally speaking, emissions at a given point in time are determined via consumption, production, energy productivity, and overall emission factor of the fuel mix.

Emission changes from one time step to another (e.g. from *t=0* to *t*) can thus be expressed as the difference between emissions at time *t* and emissions at time *t=0*:

$$\Delta E = E_t - E_0 = \Delta E_C + \Delta E_P + \Delta E_I + \Delta E_E + \varepsilon,$$

with

ε residual.

The emissions change can be decomposed into changes of consumption activities ΔE_C, production activities ΔE_P, fuel input intensity ΔE_I and overall emission factor of the fuel mix ΔE_E. These again are caused by different factors as shown by the equations documented in 2.3.4, 2.3.5, 2.3.6, and 2.3.7.

2.3.4 Contribution to emission reductions from electricity consumption changes

The isolated contribution of each of the different sub-categories of electricity consumption *h* (e.g. electricity consumption from traditional appliances, electricity consumption from new appliances and electricity consumption from storage input) to emission reductions can be determined as shown in Equation 5

Index *sec* refers to the sectors considered within the different sub-categories of consumption *h*.

Equation 5

$$\Delta E_c^{h,\sec} = (C_t^{h,\sec} - C_0^{h,\sec})(1 - \pi_0^{free}) \frac{I_0^{fos}}{P_0^{fos}} \frac{E_0}{I_0^{fos}}$$

Equation 5 is derived from the following (generally formulated)[6]:

$$\Delta E_c = C_t\,(1 - \pi_0^{free}) \frac{I_0^{fos}}{P_0^{fos}} \frac{E_0}{I_0^{fos}} - C_0\,(1 - \pi_0^{free}) \frac{I_0^{fos}}{P_0^{fos}} \frac{E_0}{I_0^{fos}}$$

2.3.5 Contribution to emission reductions from electricity production shares of zero carbon electricity generation technologies

The production share from CO_2 emitting electricity generation technologies is given by $(1 - \pi_t^{free})$. To determine the contribution of zero carbon electricity production technologies to emission reduction Equation 6 can be used. Index *i* refers to zero carbon electricity production technologies in the equation.

Equation 6

$$\Delta E_p^{free} = \sum_{i=1}^{n} C_0 \left(-\frac{P_t^i}{P_t} + \frac{P_0^i}{P_0} \right) \frac{I_0^{fos}}{P_0^{fos}} \frac{E_0}{I_0^{fos}} \,,$$

Equation 6 is derived from the following (e.g. for electricity generation from hydro power):[7] power): $\Delta E_p^{hy} = C_0 \left(1 - \frac{P_t^{hy}}{P_t} - \frac{P_0^{nonhydro}}{P_0} \right) \frac{I_0^{fos}}{P_0^{fos}} \frac{E_0}{I_0^{fos}} - C_0 \left(1 - \frac{P_0^{free}}{P_0} \right) \frac{I_0^{fos}}{P_0^{fos}} \frac{E_0}{I_0^{fos}}$,

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[6] In order to determine the emissions change from changes to consumption activities between the base year and time step *t*, it is necessary to input the consumption activity at time step *t* into Equation 1 and then subtract this from an Equation 1 where the consumption activity is set at the base year. The remaining causal factor activities are always set at the base year as required by the Laspeyres method.

[7] The emissions change due to changes in production activities between the base year and time step *t* is calculated by determining the change in the share of zero carbon electricity production. The activity level at time step *t* for every production technology (i.e. hydro power) is individually put into Equation 1 while the

with

$$P_0^{free} = P_0^{hydro} + P_0^{nonhydro}$$

2.3.6 Contribution to emission reductions from fuel input intensity variation

Energy-related statistical conventions for evaluating the electricity generation of nuclear power plants, wind-, water, solar- and geothermal plants and regarding the import of electricity can lead to a distortion of the energy-input variable. An extension of electricity generation from wind-, water-, or solar power and from imports would thus lead to a massive decrease of the energy input for electricity generation. This would lead to an underestimation of the contribution of renewable energies to emission reductions and to an overestimation of the contribution of energy efficiency. The opposite effect would be observed with respect to nuclear and geothermal electricity generation. To account for these statistical conventions fuel input intensity, I^{fos}/P^{fos} , is measured solely on the base of changes in the fossil part of the power plant fleet. This prevents the occurrence of the distortions described above. To determine the contribution of fuel input intensity changes to emissions reduction we apply Equation 7:

Equation 7

$$\Delta E_P^{fos} = C_0(1-\pi_0{}^{free}) \left(\frac{I_t^{fos}}{P_t^{fos}} - \frac{I_0^{fos}}{P_0^{fos}} \right) \frac{E_0}{I_0^{fos}}$$

Equation 7 is derived from the following:[8]

$$\Delta E_P^{fos} = C_0(1-\pi_0{}^{free}) \frac{I_t^{fos}}{P_t^{fos}} \frac{E_0}{I_0^{fos}} - C_0(1-\pi_0{}^{free}) \frac{I_0^{fos}}{P_0^{fos}} \frac{E_0}{I_0^{fos}}$$

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activity of the remaining production technologies is set at the base year. This result is then subtracted from an Equation 1 where the production activities for all technologies are set at time step *t*. In doing so it is possible to attribute the change in emissions associated with a change in the activity of a specific production technology between the base year and time step *t*.

[8] In order to determine the emissions change from changes to energy intensity (i.e. fossil fuel input divided by fossil fuel based production) between the base year and time step *t*, it is necessary to input the energy intensity at time step *t* into Equation 1 and then subtract this from an Equation 1 where the energy intensity is set at the base year. The remaining causal factor activities are always set at the base year as required by the Laspeyres method.

2.3.7 Contribution to emission reductions from overall emission factor of fuel mix variation

To determine the contribution of changes in the overall emission factor of the fuel mix to to emissions reduction we apply Equation 8.

Equation 8

$$\Delta E_E = C_0(1-\pi_0{}^{free})\frac{I_0^{fos}}{P_0^{fos}}\left(\frac{E_t}{I_t^{fos}} - \frac{E_0}{I_0^{fos}}\right)$$

Equation 8 is derived from the following:[9]

$$\Delta E_E = C_0(1-\pi_0{}^{free})\frac{I_0^{fos}}{P_0^{fos}}\frac{E_t}{I_t^{fos}} - C_0(1-\gamma_0^{free})\frac{I_0^{fos}}{P_0^{fos}}\frac{E_0}{I_0^{fos}}$$

2.3.8 Accounting for mixed effects

Mixed effects are accounted for by distributing the residual term proportionally to the individual causal factors according to their contribution to emission reductions. Thus, the isolated contribution of a factor including the mixed effects is determined via the following equation:

$$\Delta E_{t_{incl}}^{factor} = (E_t^{fos} - E_o^{fos})\frac{\Delta E_t^{factor}}{\sum\limits_{factor}\Delta E_t^{factor}},$$

with

factor causal factor.

---

[9] In order to determine the emissions change from changes to emission intensity (i.e. CO_2 emissions divided by fossil fuel input) between the base year and time step *t*, it is necessary to input the emission intensity at time step t into Equation 1 and then to subtract this from an Equation 1 where the emission intensity is set at the base year. The remaining causal factor activities are always set at the base year as required by the Laspeyres method.

3 Summary

The present document provides the suggestion for an analytical framework to decompose emission reductions in the power sector based on data retrieved from studies which provide scenarios of power sector decarbonisation. With the given approach and under sufficient data availability it will be possible to reveal the contributions of demand side effects such as changing consumption patterns in traditional and new appliances and increased electricity demand of new appliances and storage inputs. At the same time a changing power generation structure also contributes to emission reductions and can be explicitly considered. Electricity generation from CCS can be considered if data availability if sufficiently documented and the analysis proceeds as laid out in the Appendix.

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5 Appendix I: Completely considering electricity production from CCS

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 shortly documented here:

1. Primary energy input is documented in a CCS plant specific manner:

   Attribution of that share of electricity production from CCS technology that can be viewed as CO_2 emission free to P^{CCS}. Attribution of the remaining production to the fossil fuel part of production P^{fos}. Attribution of the amount of primary energy input used in CCS plants and where emissions are not captured (*1-capture rate*) to the fossil fuel input variable, I^{fos}.

2. Primary energy input is not documented CCS specific, but plant specific efficiencies are documented:

   Attribution of the electricity production of CCS to P^{CCS} that is emission free (determined by capture rate). Attribution of the remaining production to the fossil fuel part of production, P^{fos}. Utilisation of information on total primary energy input of a specific plant type, information on generation by conventional and CCS plants of this type to calculate the primary energy input for the CCS plants. Attribution of 1-*capture rate* to fossil fuel input

3. If 1. and 2. are not viable, due to data insufficient documentation problems, there are several alternative ways of approaching the decomposition analysis:
   a. make meaningful assumptions and then proceed as documented in 2.
   b. attribute all fuel input to I^{fos}, keep interpretability of P^{CCS} but lose the interpretability of E/I^{fos} and I^{fos}/P
   c. do not decompose the scenario
   d. do not decompose the CCS part of the scenario

Power sector decarbonisation: Metastudy

WP 2.1
Overview over existing EU-wide studies

Berlin, Wuppertal, 1 May 2011

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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 percent 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 installation 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. This is all the more urgent in 2011 as the European institutions and member states begin their debates on a Roadmap 2050. Decisions shall be based on robust evidence from modelling exercises and other analytical work – therefore, it will prove useful to analyse the existing and emerging analytical work on decarbonisation strategies for the power sector using a metastudy approach. The purpose of this metastudy is therefore:

- To identify similarities and robust elements of decarbonisation strategies for the power sector;
- To identify key differences and their determinants; and
- To identify key issues with regard to implementation.

This paper presents a qualitative overview of current scenario studies as a first step before a quantitative in-depth analysis is conducted by applying the decomposition approach (Work Package 2.2). It focuses on providing a standardised way for comparing different study information. The following areas of interest, covered separately by each study, have been identified to provide such an overview:

- General background information about the study
- Thematic background
- Methodology
- Scenarios / pathways presented
- Infrastructural changes within the European power system
- Discussion and recommendation of relevant policies
- Brief quantitative overview

An overview based on these areas of interest enables comparison of sections of studies with each other without the need to locate the area within the studies themselves. As these summaries are rather short in nature, the interested reader can then consult the study to obtain more details.

2 IEA – World Energy Outlook 2010

2.1 General information

The World Energy Outlook (WEO) is the annual energy market analysis and projection provided by the International Energy Agency (IEA). The IEA's flagship publication is produced by the Office of the Chief Economist under the direction of Dr. Fatih Birol, with contributions from other IEA divisions, and consultation with member governments, international organisations and energy companies. The 2010 edition of the World Energy Outlook (IEA 2010) was released in November 2010. Some key energy system figures are provided separately for the EU 27.

2.2 Thematic background

The WEO 2010 is the latest study in the well-known and annually updated World Energy Outlook series of the IEA. The annual energy market analysis provided by the WEO publications aim at supporting policy makers and energy market actors around the world in making their energy policy and energy investment decisions. The publications provide an up-to-date assessment of global energy market developments and assess how the market may develop in the coming years and decades. Every year the WEO takes an in-depth look at a specific current energy topic. The WEO 2010 has a special focus on energy poverty and the energy perspectives of the Caspian region.

2.3 Methodology

Since 1993, the IEA has been using the World Energy Model (WEM) for its medium- to long-term energy projections. The WEM is a large-scale mathematical simulation model designed to simulate energy market development. The main exogenous assumptions concern economic growth, demographics, international fossil fuel prices and technological developments. The model covers 24 regions and generates detailed sector-by-sector and region-by-region projection for various scenarios. The WEM consists of six main modules: final energy demand (with sub-models covering residential, services, agriculture, industry, transport and non-energy use), power generation and heat, refinery/petrochemical and other transformations, fossil-fuel supply, CO_2 emissions and investment. The parameters of the equations of the demand-side modules are estimated econometrically, mostly using – in the version used for the WEO 2010 – data for the period 1971-2008.

2.4 Scenarios / pathways

The 2010 edition of the WEO presents three scenarios: the New Policies Scenario (NPS), the Current Policies Scenario (CPS) and the 450 Scenario (450). The projection period ends in 2035.

The central scenario in the 2010's Outlook is the New Policies Scenario. It takes account of the broad policy commitments and plans that have been announced by countries around the world. It takes into account policy commitments and plans for reductions of greenhouse gas emissions as well as plans to phase-out fossil energy subsidies, even when specific measures and milestones to implement these commitments have not yet been implemented, identified or announced. The Current Policies Scenario was previously called the Reference

Scenario, in which no change in policies as of mid-2010 is assumed. The 450 Scenario sets out an energy pathway consistent with the 2°C target by making the energy system compatible with the goal of limiting the concentration of greenhouse gases in the atmosphere to around 450 ppm of CO_2 equivalent.

2.5 Infrastructural changes within the European power system

While no information can be found in the WEO 2010 about *specific* infrastructural changes within the European power system, the study does point out that managing electricity production from variable sources as well as accommodating the growing use of plug-in hybrid and electric vehicles pose challenges to the electricity system. Technology change and enhancements in electricity system operation are becoming essential to ensure affordable, responsive and reliable service, according to the authors. Smart Grids are mentioned as one option to enable wider deployment of variable technologies, such as wind and solar PV, by observing and responding to changing conditions throughout the entire electricity system and thereby maintaining a reliable service. Improvements and expansion of transmission and distribution infrastructure are essential and „regulatory hurdles“ to investments in this infrastructure will have to be overcome in some countries, according to the IEA.

2.6 Discussion and recommendation of relevant policies

The main conclusions of the 2010 edition of the World Energy Outlook concerning energy policy measures are the following:

- Recently announced policy commitments and plans can have a real impact on energy demand and related CO_2 emissions.
- The 2°C target set in Copenhagen can only be achieved with vigorous implementation of commitments in the period to 2020 and much stronger actions thereafter.
- Policies to encourage energy savings and switching to low carbon energy sources are required to help restrain demand growth for all fossil fuels.
- Renewable energy sources (RES) are entering the mainstream, but long-term support is needed to boost their competitiveness.
- Phasing-out fossil-fuel subsidies is the most effective measure to cut energy demand.

2.7 Quantitative overview

The following table provides an overview of some of the key figures of the study’s three scenarios.

Table 1: Overview of WEO scenarios*

	base year	**2020**			**2030**			**2035**		
	2008	**CPS**	**NPS**	**450**	**CPS**	**NPS**	**450**	**CPS**	**NPS**	**450**
Electricity demand										
• Absolute (in TWh/a)	3339	3614	3572	3540	3934	3832	3706	4094	3938	3771
• Change vs. base year	-	+8%	+7%	+6%	+18%	+15%	+11%	+23%	+18%	+13%
Share in electricity generation										
• Fossil (non-CCS)	55%	49%	44%	40%	47%	38%	23%	46%	34%	16%
• Fossil CCS										
• Nuclear	28%	23%	26%	28%	20%	24%	32%	18%	25%	33%
• Renewables	17%	28%	30%	32%	33%	38%	46%	36%	41%	51%
Power sector CO_2 emissions										
• Absolute (in Mt CO_2)	1377	1245	1049	966	1187	899	393	1190	765	246
• Change vs. base year	-	-10%	-24%	-30%	-14%	-35%	-71%	-14%	-44%	-82%
• Change vs. 1990	-8%	-16%	-30%	-35%	-20%	-40%	-74%	-20%	-49%	-84%
General										
• GDP (in billion €$_{2008}$)	12.5	14.8	14.8	14.8	17.7	17.7	17.7	19.2	19.2	19.2
• Population (in millions)	498	510	510	510	510	510	510	511	511	511
Fuel prices (in €$_{2008}$/GJ)										
• Oil	7.1	13.0	11.7	10.6	15.3	13.0	10.6	15.9	13.3	10.6
• Hard coal	2.6	2.9	2.8	2.3	3.0	2.9	1.8	3.1	2.9	1.7
• Natural gas	5.0	8.3	7.9	7.2	9.5	8.8	7.4	9.8	9.1	7.5

Source: Compiled by the authors based on data provided in the study.

*GDP and population data for 2008 according to Eurostat; for the following years the growth rates provided in the study were applied to calculate GDP and population development; NPS: New Policies Scenario, CPS: Current Policies Scenario, 450: 450 Scenario

3 Power Choices - Pathways to carbon-neutral electricity in Europe by 2050

3.1 General information

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.

3.2 Thematic background

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.

3.3 Methodology

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.

3.4 Scenarios / pathways

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. 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".

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).

In the CCS Delay scenario the cumulative CO_2 emissions are 2.3% higher than in the main scenario. With the assumption that the nuclear phase-out will not be pursued in Germany and Belgium, the CO_2 emissions are 0.9% less than in the main scenario.

The Less Onshore Wind scenario assumes that incremental onshore wind development beyond 2020 is limited to one third of the development under the Power Choices scenario. The CO_2 emissions are almost the same because the onshore reduction is partly offset by the development of additional offshore wind.

The cumulative CO_2 emissions in the No Efficiency Policies scenario are 7.2% lower but the cumulative costs are 4.2% higher than in the main scenario. Due to the absence of the bottom-up policies and the electrification of road transportation, the carbon prices (need to) increase over the entire period.

3.5 Infrastructural changes within the European power system

The study considers 201 existing and 40 new transmission lines. The total capacity of the transmission lines is projected to increase from 179 GW (2005) to 245 GW (2020) to 253 GW (2030). In the period from 2030 to 2050 the transmission capacity remains stable.

It is assumed that investments in advanced power grids, smart metering as well as control and communication systems will take place in a timely manner.

In support of the electrification of road transport, it is assumed that grid extension (to enable charging of vehicles) will start by 2015. "This will be followed by the widespread development of fast charging devices and the development of bi-directional and smart capabilities in the long term". For heavy duty vehicles this process will take place later and progress at a slower pace up to 2050. The pumped storage (hydropower) is projected to more than double in the period between 2010 and 2050.

3.6 Discussion and recommendation of relevant policies

Political action is required to increase the degree of electrification of final energy usage and decarbonised power generation. According to the study, the following actions are required:

- Enable the use of all low-carbon technologies and ensure investments in transmission and distribution lines;
- Support well-functioning carbon and electricity markets so as to deliver carbon reductions at least cost;
- Ensure that all sectors internalise the cost of greenhouse gas emissions;
- Actively promote an international agreement on climate change;
- Ensure that public authorities take a leading role in energy efficiency,

- Adopt standards and incentives to help consumers choose energy-efficient technologies;
- Encourage public acceptance of modern energy infrastructure;
- Recognise that the cost of technology deployment differs substantially across the EU Member States and distribution effects will vary;
- Facilitate the electrification of road transport and efficient electro-technologies for heating and cooling and
- Radically refocus the European and national budgets towards supporting a new intelligent energy economy.

3.7 Quantitative overview

The following table provides an overview of some of the key figures of the study’s two scenarios.

Table 2 Overview of Power Choices scenarios*

	base year	**2020**		**2030**		**2050**	
	2005	**BAU**	**PC**	**BAU**	**PC**	**BAU**	**PC**
Electricity demand (Gross)							
• Absolute (in TWh/a)	3250	3750	3600	4170	4050	4670	5170
• Change vs. base year	-	+15%	+11%	+28%	+25%	+44%	+59%
Share in electricity generation							
• Fossil (non-CCS)	n.s.	49%	39%	34%	25%	33%	16%
• Fossil CCS	0%	0%	0%	6%	11%	4%	12%
• Nuclear	32%	25%	25%	26%	26%	28%	28 %
• Renewables	15%	27%	32%	33%	38%	34%	40%
Power sector CO_2 emissions							
• Absolute (in Mt CO_2)	1423	1275	1050	900	500	750	150
• Change vs. base year	-	-10%	-26%	-37%	-65%	-47%	-90%
• Change vs. 1990	-6%	-16%	-31%	-41%	-67%	-51%	-90%
General							
• GDP (in trillion $€_{2008}$)	10.8	13.9	13.9	16.5	16.5	16.5	16.5
• Population (in million)	491	516	516	522	522	516	516
Fuel prices (€2008/GJ)							
• Oil	6.6	9.9	9.9	11.8	11.8	14.1	14.1
• Hard coal	2.5	4.7	4.7	5.2	5.2	5.3	5.3
• Natural gas	4.2	6.5	6.5	8.1	8.1	10.4	10.4

Source: Compiled by the authors based on data provided in the study.

*Some of the data in the table was read off from figures in the study so slight deviations from actual data may exist; BAU=Baseline2009, PC=Power Choices; GDP and Population for 2005 according to Eurostat

4 energy [r]evolution - Towards a fully renewable energy supply in the EU-27

4.1 General information

The study "energy [r]evolution - Towards a Fully Renewable Energy Supply in the EU-27" (Greenpeace/EREC 2010) 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 suggests, the area under focus is the EU 27.

4.2 Thematic background

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." (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.

4.3 Methodology

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.

4.4 Scenarios / pathways

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.

4.5 Infrastructural changes within the European power system

Regarding infrastructural changes within the power system there is no scenario-specific information but some general information can be found in the Greenpeace/EREC study. Efficient large-scale super grids are said to be needed to link together a number of countries and connect areas with a large supply of renewable electricity to areas with large demand. Connections between southern Europe and northern Africa are given as an example. At the same time local distribution network systems are said to become more important as large amounts of decentralised energy technologies in the alternative scenarios are connected to one another and to nearby consumers.

The authors of the study also stress that the electricity system needs to become more flexible so that it is able to deal with the fluctuations of variable renewable power, e.g. by adjusting demand via demand side management (DSM) or by deploying storage systems. Smart grid technology is also mentioned as an important instrument for this purpose.

4.6 Discussion and recommendation of relevant policies

In a separate chapter of the study (chapter 5) energy policy changes are discussed which the authors believe need to be implemented in order to be able to realise the sustainable pathways described in the two alternative scenarios. Five general recommendations are given, within the scope of which more specific steps are discussed. These five recommendations are:

- Developing a vision for a sustainable energy economy for 2050;
- Adopting and implementing ambitious and legally binding targets for emissions reductions, energy savings and renewable energy;
- Removing barriers to a renewable and efficient energy system;
- Implementing effective policies to promote a clean energy economy;
- Ensuring that the transition is financed.

4.7 Quantitative overview

The following table provides an overview of some of the key figures of the study's three scenarios.

Table 3: Overview of the energy [r]evolution scenarios*

	base year	2020			2030			2050		
	2007	**BAU**	**[E]R**	**ADV**	**BAU**	**[E]R**	**ADV**	**BAU**	**[E]R**	**ADV**
Electricity demand										
• Absolute (in TWh/a)	2840	3138	2942	2963	3497	2973	3206	4220	3527	4274
• Change vs. base year	-	+10%	+4%	+4%	+23%	+5%	+13%	+49%	+24%	+50%
Share in electricity generation										
• Fossil (non-CCS)	56%	50%	45%	44%	48%	36%	29%	45%	12%	2%
• Fossil CCS	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
• Nuclear	28%	22%	12%	12%	19%	5%	3%	14%	0%	0%
• Renewables	16%	29%	42%	43%	34%	59%	68%	41%	88%	97%
Power sector CO_2 emissions										
• Absolute (in Mt CO_2)	1455	1186	937	907	1181	613	511	1205	155	39
• Change vs. base year	-	-18%	-36%	-38%	-19%	-58%	-65%	-17%	-89%	-97%
• Change vs. 1990	-4%	-22%	-38%	-40%	-22%	-60%	-66%	-21%	-90%	-97%
General										
• GDP (in trillion €$_{2008}$)	12.8	15.3	15.3	15.3	18.3	18.3	18.3	24.3	24.3	24.3
• Population (in million)	493	505	505	505	506	506	506	494	494	494
Fuel prices (in €$_{2008}$/GJ)										
• Oil	11.0	19.0	19.0	19.0	21.9	21.9	21.9	21.9	21.9	21.9
• Hard coal	2.3	4.5	4.5	4.5	4.8	4.8	4.8	5.8	5.8	5.8
• Natural gas	5.6	14.8	14.8	14.8	17.2	17.2	17.2	23.2	23.2	23.3

Source: Compiled by the authors based on data provided in the study.
*BAU=Reference Scenario, [E]R=Energy Revolution Scenario, ADV=Advanced Energy Revolution Scenario

5 RE-Thinking 2050 – A 100 % renewable energy vision for the European Union

5.1 General information

The "RE-Thinking 2050 – A 100% Renewable Energy Vision for the European Union (EU)" (EREC 2010) report was published in April 2010 by the European Renewable Energy Council (EREC). EREC is the umbrella organisation of the major European renewable energy industry, trade and research associations active in the fields of photovoltaics, small hydropower, solar thermal, bioenergy, ocean & marine, geothermal, wind energy and solar thermal electricity. The area under focus is the EU 27.

5.2 Thematic background

It is stated in the report that RE-thinking 2050 outlines a pathway towards a 100% renewable energy supply system by 2050 and clearly shows that it is not a matter of technology but rather a matter of making the right choices today to shape tomorrow. According to the International Energy Agency (IEA), the report provides a comprehensive estimate of the economic, environmental and social benefits associated with such a transformation. It also focuses on the policy recommendations considered necessary to tackle the non-technical barriers as well as all three important sectors: electricity, heating & cooling and transport. The report outlines a way towards 2030 and presents a vision for 2050. As mentioned in the report, determining a long-term vision over 40 years is a difficult task and the resulting outlook should by no means be seen as an exact prediction of what the future has in store for us. Projections of economic growth rates, fossil fuel prices and of the overall energy demand are based on assumptions and by no means represent concrete prognoses.

In the report, an abundant range of technologies are referred to that can provide renewable energy services in the form of electricity, heating and cooling as well as transport solutions. In this way, bioenergy, wind, hydropower, all solar technologies, geothermal and ocean energy are taken into account, along with their economic potentials. In addition, the capital investments of each technology for 2020, 2030 and 2050 are analysed and the costs are expressed in Euro/unit installed.

5.3 Methodology

The report does not provide any information on whether an energy model was used to calculate the scenarios and if so what kind of model is used. Future energy demand is derived from existing studies, while a range is given based on different future developments of energy prices. The future economic potential of various renewable energy sources are projections by EREC's member associations in accordance with the underlying assumptions of the respective scenarios.

5.4 Scenarios / pathways

Different scenarios were developed for the future energy systems in EU-27 to analyse the contribution of the different RES and technologies in 2020, 2030 and 2050. Possible future developments of not only the electricity system but of the entire energy system (including the heat and fuel market) are discussed. Given that 2050 is four decades away, the aim of the report is not to accurately forecast the shares of the various RES technologies, but rather to show that achieving a fully sustainable energy system based on renewable energy in the EU by 2050 is feasible.

The final electricity assumptions for 2020 are based on the European Commission's "New Energy Policy" (NEP) scenario contained within the Second Strategic Energy Review. The NEP scenario assumes full implementation of new policies to make substantial progress on energy efficiency. For 2050, both a standard scenario based on the continuation of the NEP scenario (referred to as “Basic” in the table below) as well as an aggressive efficiency (AEff) scenario is analysed. The AEff scenario assumes that overall electricity demand can be reduced by 30% against the consumption for 2050, which corresponds to electricity savings of about 38% compared to today.

According to the basic scenario for 2020, RES technologies in electricity production will contribute about 40% of the total electricity consumption. The RES contribution to power demand increases further in 2030 when it will account for 67%. By 2050, RES will provide 100% of the EU`s power demand in the basic scenario and will even provide a significant surplus in the highly efficient AEff scenario. CO_2 emissions are not provided separately for the power sector, but the use of renewable energy in the whole energy system will be the main factor in reducing emissions by 30% in 2020, 50% in 2030 and more than 90% in 2050 compared to 1990.

5.5 Infrastructural changes within the European power system

The study points out that the EU power sector has been made up of centralised and nationally organised electricity grids in the past. However, in order to meet its 2020 climate and energy targets, the report emphasised that the EU has to accelerate realisation of an EU Super Grid as well as a Smart Grid to facilitate a sophisticated and efficiently interconnected electricity system of both centralised and decentralised renewable energy installations.

5.6 Discussion and recommendation of relevant policies

In the report, chapter 8 consists of policy recommendations to start building tomorrow’s energy system. It is stated that only a clear-cut and consistent mix of these listed measures will give Europe a truly sustainable energy future. For that purpose, the major recommendations are as follows:

- Supporting the transition towards a 100% renewable energy economy in all EU policy areas;
- Binding energy efficiency targets to reduce energy demand;
- Effective and full implementation of the new RES Directive (2009) in EU-27;
- Binding RES targets for 2030;
- Full liberalisation of the energy market;
- Phasing out all subsidies for fossil and nuclear energy and introducing an EU-wide carbon tax.

5.7 Quantitative overview

The following table provides an overview of some of the key figures of the study's two main scenarios.

Table 4: Overview of RE-Thinking 2050 scenarios

	base year	2020		2030		2050	
	2007	**Basic**	**AEff**	**Basic**	**AEff**	**Basic**	**AEff**
Electricity demand							
- Absolute (in TWh/a)	3362	3443	n.s.	3616	n.s.	4987	3491
- Change vs. base year	-	+2%	n.s.	+8%	n.s.	+48%	+4%
Share in electricity consumption							
- Fossil (non-CCS)	84%	60%	n.s.	33%	n.a.	0%	0%
- Fossil CCS							
- Nuclear							
- Renewables	16%	40%	n.s.	67%	n.s.	100%	143%
Power sector CO_2 emissions							
- Absolute (in Mt CO_2)	n.s.	n.s	n.s	n.s.	n.s	n.s	n.s
- Change vs. base year	n.s.	n.s	n.s	n.s.	n.s	n.s	n.s
- Change vs. 1990	n.s.	n.s	n.s	n.s.	n.s	n.s	n.s
General							
- GDP (in trillion €$_{2008}$)	n.s.	n.s	n.s	n.s.	n.s	n.s	n.s
- Population (in million)	n.s.	n.s	n.s	n.s.	n.s	n.s	n.s
Fuel prices (in €$_{2008}$/GJ)							
- Oil	n.s.	12.6	12.6	15.1	15.1	25.2	25.2
- Hard coal	n.s.	n.s	n.s	n.s.	n.s	n.s	n.s
- Natural gas	n.s.	n.s	n.s	n.s.	n.s	n.s	n.s

Source: Compiled by the authors based on data provided in the study.

6 Europe’s share of the climate challenge - Domestic actions and international obligations to protect the planet

6.1 General information

The “Europe’s Share of the Climate Challenge - Domestic Actions and International Obligations to Protect the Planet” study (SEI 2009) was published in November 2009 by the Stockholm Environment Institute (SEI) in partnership with Friends of the Earth Europe (FoEE). The area under focus is the EU 27.

6.2 Thematic background

This report aims to examine how Europe can show leadership in climate protection; firstly, by undertaking domestic actions to rapidly reduce GHG emissions and secondly by fulfilling its international obligations to help other countries address the twin crises of climate change and development. As regards climate change, analysis is offered of how Europe can embark on a transition to a low GHG future by achieving large emission reductions on a rapid timescale. As regards development, while assessing Europe’s international obligations to assist the world’s developing nations in the transition to a low GHG future, Greenhouse Development Rights framework (Baer et al. 2008) is used as a basis.

At the request of FoEE, this analysis aims to explore whether the specified levels of emissions reductions can be met without resorting to certain potentially significant mitigation options. In particular no new nuclear power facilities, no CCS for fossil-based electricity generation and no biofuels, whether produced within EU or imported, are assumed.

6.3 Methodology

LEAP, the Long range Energy Alternatives Planning System, is a widely-used software tool for energy policy analysis and climate change mitigation assessment developed at the Stockholm Environment Institute. LEAP is an integrated modelling tool that can be used to track energy consumption, production and resource extraction in all sectors of an economy. It can be used to account for both energy sector and non-energy sector GHG emission sources and sinks. In addition to tracking GHGs, LEAP can also be used to analyse emissions of local and regional air pollutants, making it well-suited to studies of the climate co-benefits of local air pollution reduction. In this study, LEAP is used as the main organising framework for analysing energy consumption and production, GHG emissions and cost/benefits for the baseline and mitigation scenarios. Rather than simulating decisions of energy consumers and producers, modeller explicitly accounts for outcomes of decisions. So, instead of calculating the market share based on prices and other variables, “accounting frameworks” simply examine the implications of a scenario that achieves a certain market share. LEAP explores the resource, environment and social cost implications of alternative future “what if” energy scenarios (i.e. what will be the costs, emissions reductions and fuel savings if we invest in more energy efficiency & renewables vs. investing in new power plants?). At the same time, LEAP does not automatically identify least-cost systems. In terms of data, LEAP is flexible with low initial data requirements and includes Technology and Environmental Databases (TED), with technical characteristics, costs and emission factors of around 1000 energy technologies.

6.4 Scenarios / pathways

In this study on EU-27, a baseline and a mitigation scenario are developed for the period up to 2050. The baseline scenario examines how Europe's energy system might evolve if current policies continue largely unchanged. In the baseline, GHG emissions grow only slightly up to 2050 as significant economic growth is balanced by improvements in energy efficiency and a gradual transition away from coal as the most carbon-intensive fuel. The baseline is built upon detailed historical energy statistics for each EU-27 country published by International Energy Agency (IEA), which have been extrapolated into the future based on a variety of information sources such as historical trends, a variety of national level studies and the European Commission's own baseline energy projections to 2030 (EC 2008). At the same time, information from these sources has been further expanded and adjusted so as to reflect the impact of recent global economic crisis and to include projections for GHG emissions from international air travel and non-energy sector GHG sources and sinks (industrial processes, land use change, solid waste, and agriculture). Hence, the baseline scenario cannot be directly compared with either the IEA's study or EC energy studies. In the baseline scenario, there is foreseen of dominancy of fossil fired generation and hence no remarkable changes in GHG emissions.

The mitigation scenario is a normative scenario, which examines the technical feasibility of achieving deep cuts in Europe's GHG emissions in the first half of the century. Specifically, for all 27 EU countries it shows how GHG emissions reductions of 40% in 2020 and close to 90% in 2050 can be achieved relative to 1990 levels. This requires radical improvements in energy efficiency, the accelerated phase-out of fossil fuels and a dramatic shift to renewable energy. Hence, all coal is phased out by 2035 and all nuclear power by 2050. It is worth noting that this mitigation scenario should not be viewed as a recommended pathway but rather as a scenario showing the technical feasibility of such a pathway.

6.5 Infrastructural changes within the European power system

No specific emphasis is given to infrastructural changes within the European power system.

6.6 Discussion and recommendation of relevant policies

These issues are handled in Chapter 7 and can be summarised as follows:

- Major political mobilisation of an emergency pathway to meet the climate challenge and realise the mitigation scenario;
- Adoption of an overarching "climate protection framework";
- Annual targets and an EU-wide compliance mechanism to measure progress towards medium- and long-term emission reduction;
- Urgent EU-wide package of policy measures and targets;
- an ambitious binding target for renewable energy;
- ambitious targets for energy savings across all sectors;
- the binding phase-out of nuclear, coal and oil fired power generation as soon as possible;
- an overall GHG or carbon tax to create a stable environment for investment in renewable energy development and infrastructure; and,

- EU-wide feed-in tariffs for renewable electricity and research and development for the production of electricity from wind energy.

6.7 Quantitative overview

The following table provides an overview of some of the key figures for the two scenarios examined in this report.

Table 5: Overview of Europe's Share of Climate Challenge scenarios

	Base year	**2020**		**2050**	
	2010	**Baseline**	**Mitigation**	**Baseline**	**Mitigation**
Electricity demand					
• Absolute (in TWh/a)	2870	3240	3220	3750	2840
• Change vs. base year	-	+13%	+12%	+31%	-1%
Share in electricity generation					
• Fossil (non-CCS)	56%	58%	40%	62%	11%
• Fossil CCS	0%	0%	0%	0%	0%
• Nuclear	27%	23%	19%	20%	0%
• Renewables	17%	19%	41%	18%	89%
Power sector CO_2 emissions					
• Absolute (in Mt CO_2)	1022	1064	649	1221	97
• Change vs. base year	-	+4%	-36%	+19%	-91%
• Change vs. 1990	-11%	-7%	-43%	+6%	-92%
General					
• GDP (in trillion $€_{2008}$)	13.2	15.3	15.0	24.0	20.7
• Population (in millions)	495	498	498	480	480
Fuel prices (in $€_{2008}$/GJ)					
• Oil	n.s.	n.s.	n.s.	n.s.	n.s.
• Hard coal	n.s.	n.s.	n.s.	n.s.	n.s.
• Natural gas	n.s.	n.s.	n.s.	n.s.	n.s.

Source: Compiled by the authors based on data provided in the study.

7 Roadmap 2050 - A practical guide to a prosperous, low-carbon Europe. Technical analysis.

7.1 General information

The “Roadmap 2050 - A practical guide to a prosperous, low-carbon Technical analysis” study (European Climate Foundation 2010a) 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 Roadmap 2050 was published and funded by the European Climate Foundation; McKinsey & Company, KEMA, The Energy Futures Lab at Imperial College London and Oxford Economics were involved in the preparation of this particular volume. The area under focus is the EU 27 plus Norway and Switzerland.

7.2 Thematic background

“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. Further it aims to derive the implications for the European energy system with regard to the next 5 to 10 years.

7.3 Methodology

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 (IEA 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. The PRIMES energy system model is described in chapter 3.3.

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 (European Climate Foundation 2010a). It operates on an hourly resolution.

7.4 Scenarios / pathways

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.

7.5 Infrastructural changes within the European power system

The decarbonisation pathways are determined in the modelling and are seen as feasible from a technological and economic viewpoint. The study highlights milestones for a potential realisation of these pathways. These milestones include:

- The installation of 5000 km^2 of solar panels over 40 years, installation and replacement of almost 100,000 wind turbines;
- Depending upon the scenario, a considerable increase in CCS and nuclear energy capacity;
- The expansion of the transmission capacity, which would increase today's capacity by a factor of three within 40 years;
- The provision of a backup capacity of 190 to 270 GW, which is equivalent to 10 to 15% of total generation capacity in 2050;
- Deployment of electric and fuel cells (magnitude of 200 million) and heat pumps (100 million) across Europe.

The study highlights that these milestones correspond to a fundamental transformation of all energy-related sectors, but does not provide solutions to the implementation challenges.

7.6 Discussion and recommendation of relevant policies

Priority areas of action for the next 5-10 years are stated as energy efficiency, low carbon technology, grids and integrated market operation, fuel shift in transport and buildings, markets (investments in low carbon technologies). Policy recommendations are further elaborated on in a separate volume (European Climate Foundation 2010b).

7.7 Quantitative overview

The following table provides an overview of some of the key figures of the study's three scenarios.

Table 6: Overview of Roadmap 2050 scenarios

	base year	2030			2050		
	2010	**Scen1**	**Scen2**	**Scen3**	**Scen1**	**Scen2**	**Scen3**
Electricity demand							
• Absolute (in TWh/a)	3250	4200	4200	4200	4900	4900	4900
• Change vs. base year	-	29%	29%	29%	51%	51%	51%
Share in electricity generation							
• Fossil	n.s.	n.s.	n.s.	n.s.	0%	0%	0%
• CCS	n.s.	n.s.	n.s.	n.s.	30%	20%	10%
• Nuclear	n.s.	n.s.	n.s.	n.s.	30%	20%	10%
• Renewables	n.s.	n.s.	n.s.	n.s.	40%	60%	80&
Power sector CO_2 emissions							
• Absolute (in Mt CO_2)	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
• Change vs. base year	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
• Change vs. 1990	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
General							
• GDP (in trillion $€_{2008}$)	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
• Population (in million)	n.s.	500	500	500	500	500	500
Fuel prices (in $€_{2008}$/GJ)							
• Oil ($)	n.s.	18.02	18.02	18.02	18.02	18.02	18.02
• Hard coal ($)	n.s.	3.72	3.72	3.72	3.72	3.72	3.72
• Natural gas ($)	n.s.	14.03	14.03	14.03	14.03	14.03	14.03

Source: Compiled by the authors based on data provided in the study.

8 Conclusions and overview of all scenarios discussed

This paper provides an overview of the most important recently released energy scenario studies on the European energy/electricity system. The various backgrounds and methodologies of the studies and their main assumptions and results have been outlined briefly. While the main topics of the scenario studies and their respective methodologies differ, a general consensus among the studies and the various energy experts behind has been found: A significant reduction in energy-related CO_2 emissions on European level of at least 90% compared to 1990 levels is possible over the coming four decades and the power sector will be a focus of mitigation efforts.

Furthermore, all scenario studies whose scenarios run until 2050 indicate that the continent's electricity demand could be largely (at least by 80%) or even entirely be met by a mixture of renewable energy sources by the middle of the century. This is despite the fact that none of the scenario studies assume any revolutionary breakthroughs in renewable energy conversion technologies.

While the overview of scenario studies in this paper has been largely qualitative, some key scenario results have also been quantitatively reproduced. The following table provides a comparison of the main figures of the energy system in 2020 and (where possible) for 2030 and 2050 for all the scenarios discussed above. However, an in-depth analysis of the similarities and differences of the various scenarios requires a more comprehensive and more detailed analysis of the scenarios. The data compiled in this paper is thus only a first step towards the detailed quantitative comparison (including decomposition analysis) to be provided in work package 2.2. This work package will identify the robust similarities and the main differences between the various scenarios of a low-carbon electricity system. By doing so, valuable insights into analytical and methodological challenges for energy system modelling as well as robust energy policy strategies are to be derived.

Table 7: General overview of scenarios analysed

Study, Scenario	Geogr. Coverage	Methodology / Type of model used	Base year	Change in electricity demand vs. base year (%)			Share of renewables in electricity generation (%)			Change in power sector CO_2 emissions vs. 1990 (%)		
				2020	**2030**	**2050**	**2020**	**2030**	**2050**	**2020**	**2030**	**2050**
IEA World Energy Outlook 2010	EU27	Market simulation World Energy Model (WEM)	2008									
• CPS				+8	+18	-	28	33	-	-16	-20	-
• NPS				+7	+15	-	30	38	-	-30	-40	-
• 450				+6	+11	-	32	46	-	-35	-74	-
Power Choices	EU27	Backcasting approach / PRIMES market simulation model	2005									
• BAU				+15	+28	+44	27	33	34	-16	-41	-51
• PC				+11	+25	+59	32	38	40	-31	-67	-90
Energy (R)evolution	EU27	Bottom-up simulation model MESAP/PlaNet	2007									
• BAU				+10	+23	+49	29	34	41	-22	-22	-21
• (E)R				+4	+5	+24	42	59	88	-38	-60	-90
• ADV				+4	+13	+50	43	68	97	-40	-66	-97
RE-Thinking 2050	EU27	Simplified comparison of demand and supply, no complex system modelling	2007									
• Basic				+2	+8	+48	40	67	100	-	-	-
• AEff				-	-	+4	-	-	143	-	-	-
Europe`s share of the climate challenge	EU27	Backcasting approach / Flexible integrated modelling tool (LEAP)	2010									
• Baseline				+13	-	+31	19	-	18	-7	-	+6
• Mitigation				+12	-	-1	41	-	89	-43	-	-92
Roadmap 2050	EU27 + N + CH	Backcasting approach / PRIMES market simulation model	2010									
• Scenario 1				-	-29%	-51%	-	-	40%	-	-	-
• Scenario 2				-	-29%	-51%	-	-	60%	-	-	-
• Scenario 3				-	-29%	-51%	-	-	80%	-	-	-

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Power sector decarbonisation: Metastudy

WP 2.2 Quantitative analysis of existing EU-wide studies

Berlin, Wuppertal, 18.01.2012

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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).

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[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

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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

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.

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.

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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.

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]

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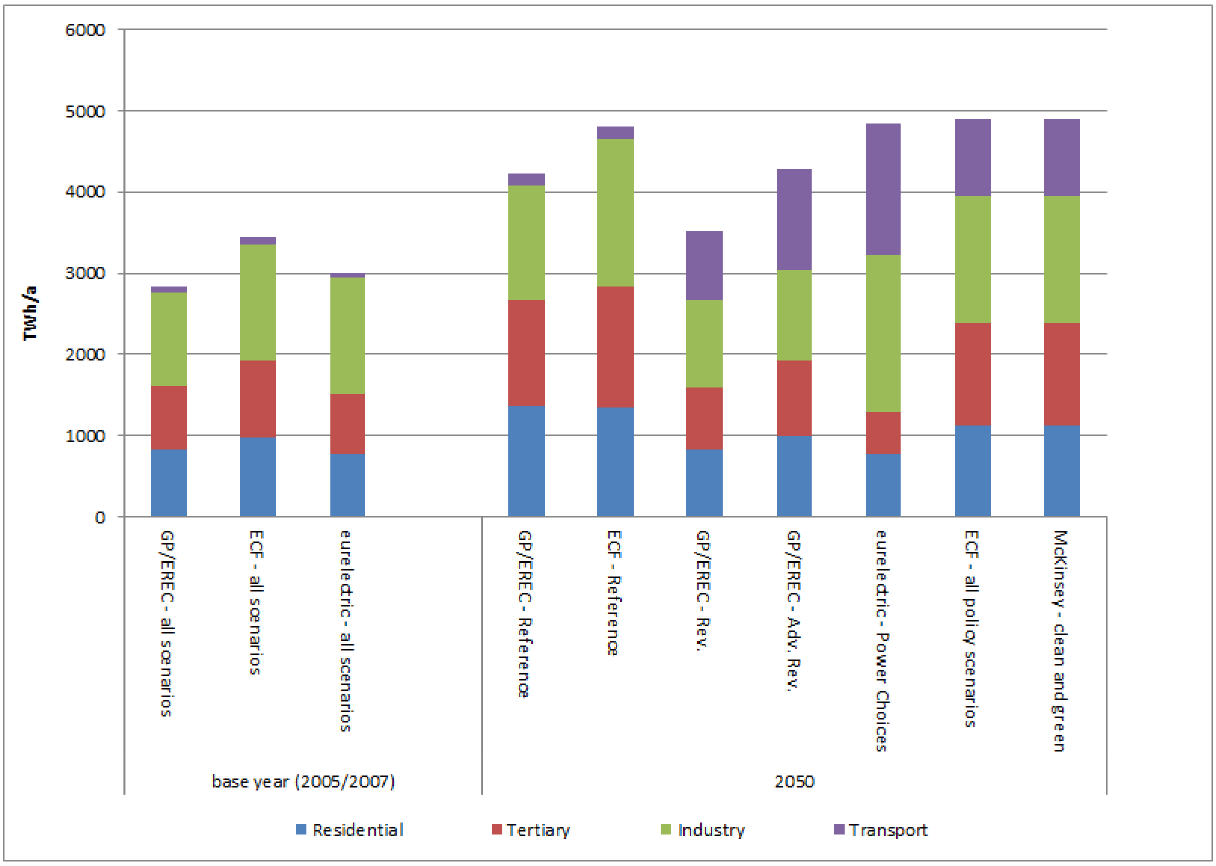
[3] It should be kept in mind that the Roadmap 2050 study (ECF 2010) and the "Transformation of Europe's power system" study (McKinsey 2010) include not only the EU-27 but also Switzerland and Norway, while the other two studies look at only the EU-27. This explains the higher electricity demand in the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

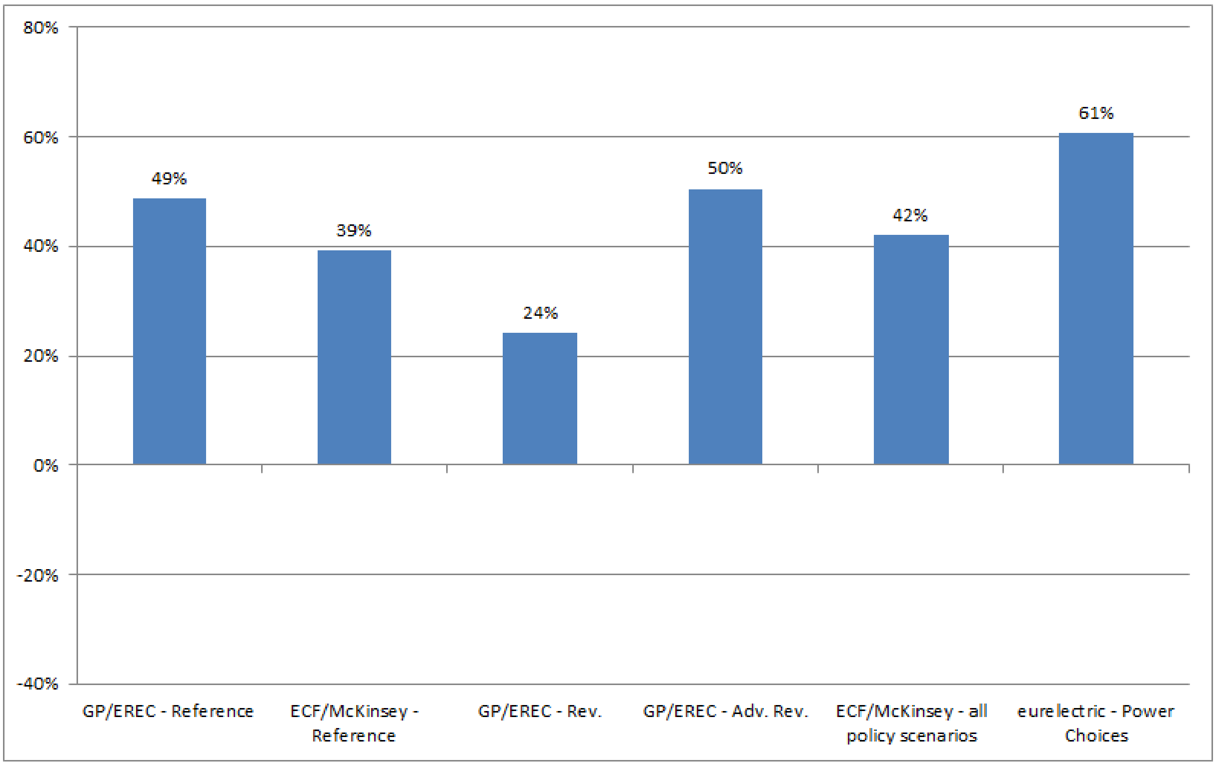
Source: Compiled from data provided by the given studies

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.

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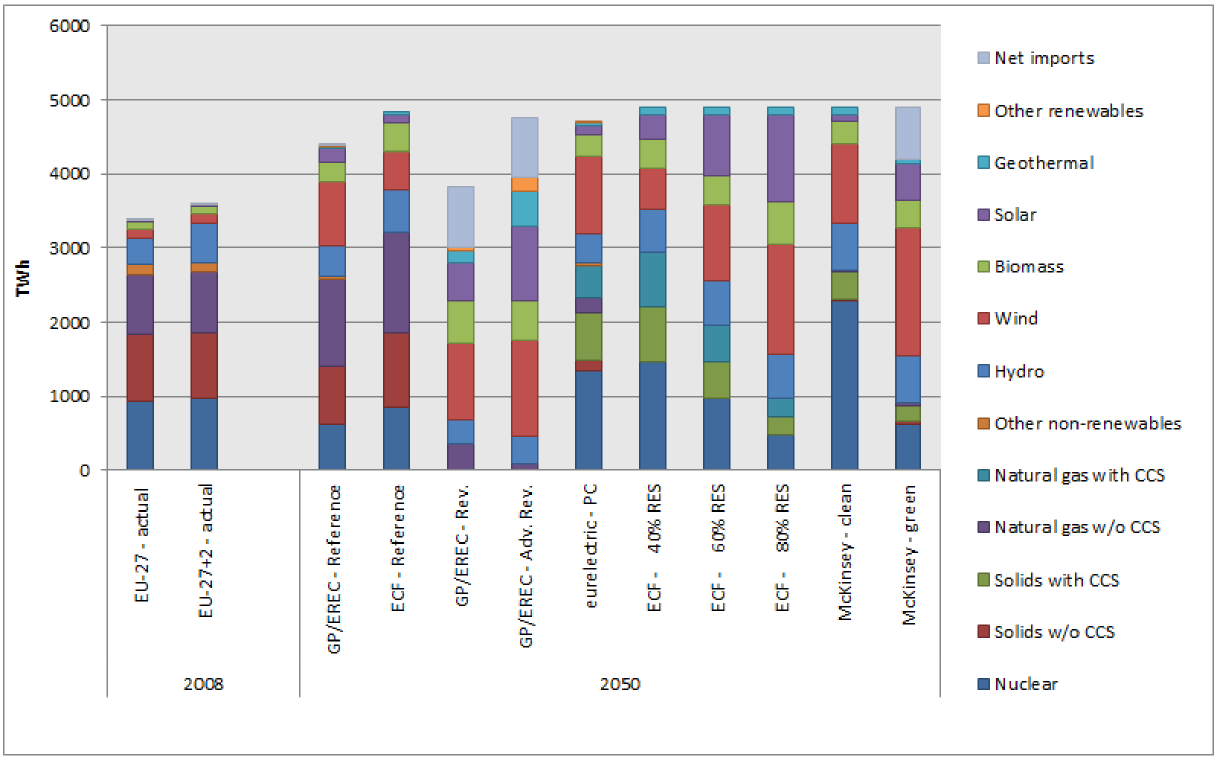
[4] Electricity generation in 2008 is given for both, EU-27 as well as EU-27 plus Norway and Switzerland, as this "EU-27 plus 2" region is analysed in the Roadmap 2050 (ECF 2010) scenarios.

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

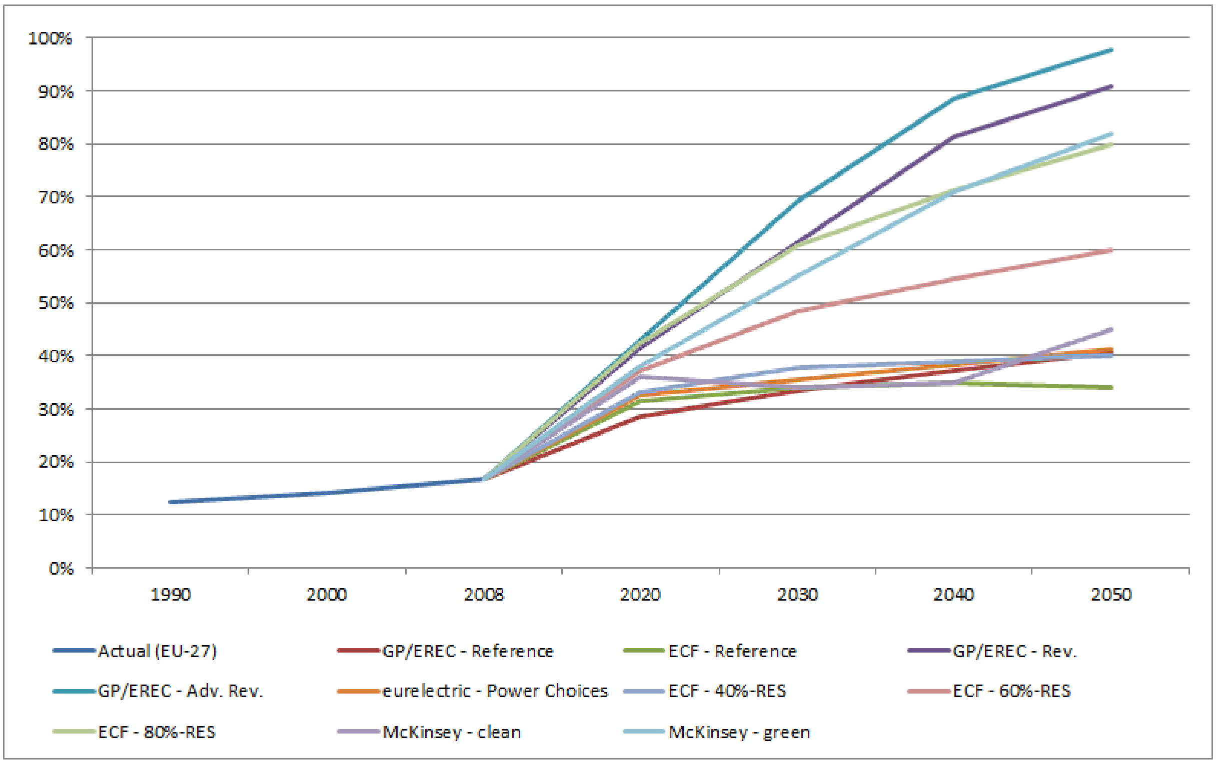


Source: Compiled from data provided by the given studies and for actual 2008 data by Eurostat (2010), Bundesamt für Energie (2010) and Statistics Norway (2010)

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.

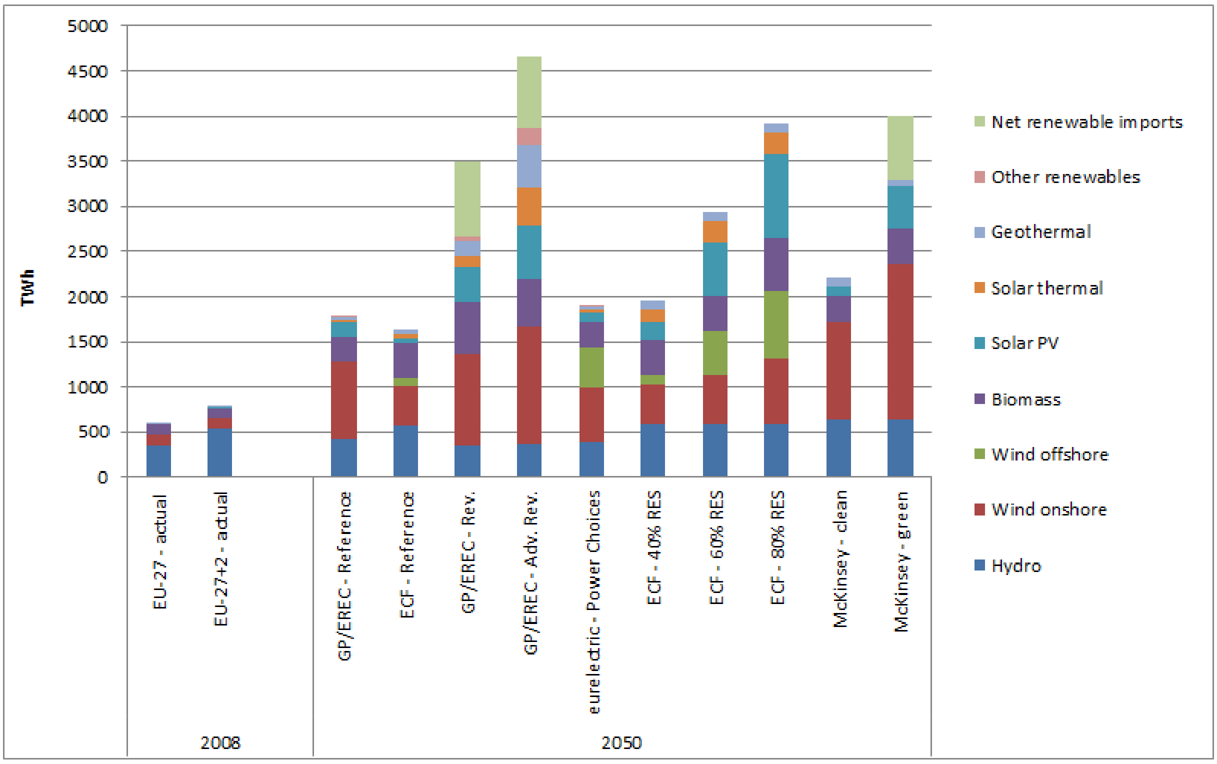
Figure 4 Development of the share of renewable energy sources in electricity generation (including net imports) in the different scenarios



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

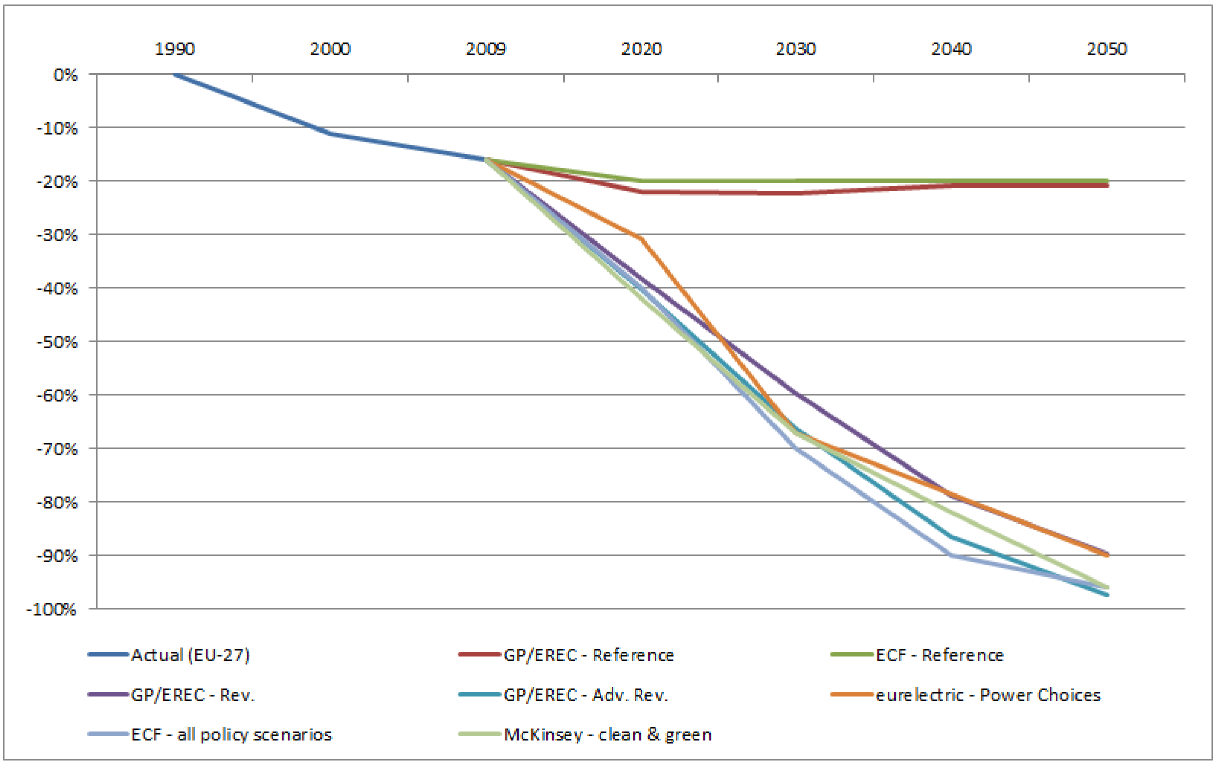


Source: Compiled from data provided by the given studies and for actual 2008 data by Eurostat (2010), Bundesamt für Energie (2010) and Statistics Norway (2010)

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

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[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]

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[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	+

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	++

++ = mandatory

+ = ideally included

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

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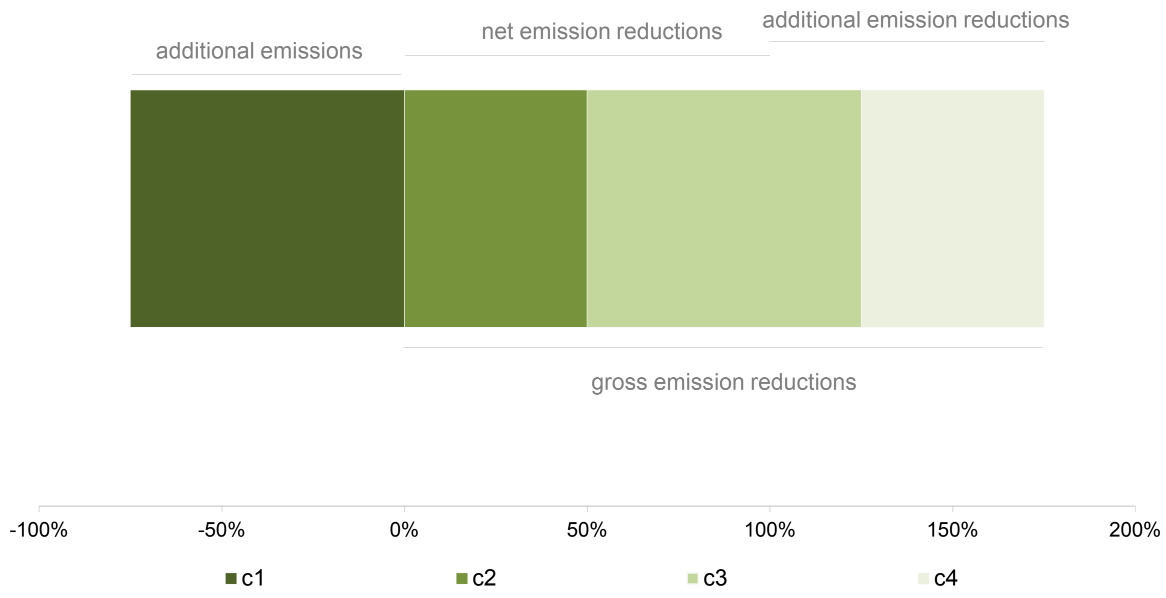
[7] Fuel input intensity = fossil fuel input per unit of electricity generated.

[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 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

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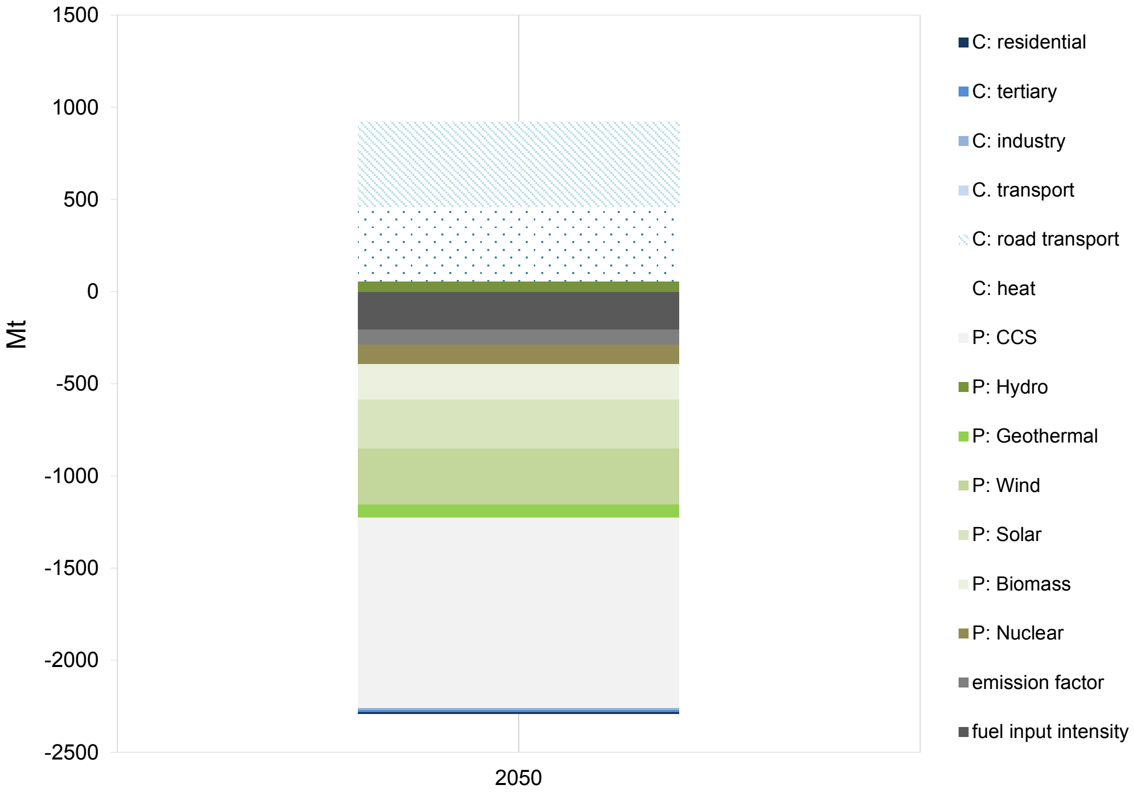
[9] Given that it was necessary to gap fill data, it is important to acknowledge that the values used in the decomposition analysis may not reveal the real effect based on the original data used in the study.

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

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).

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.

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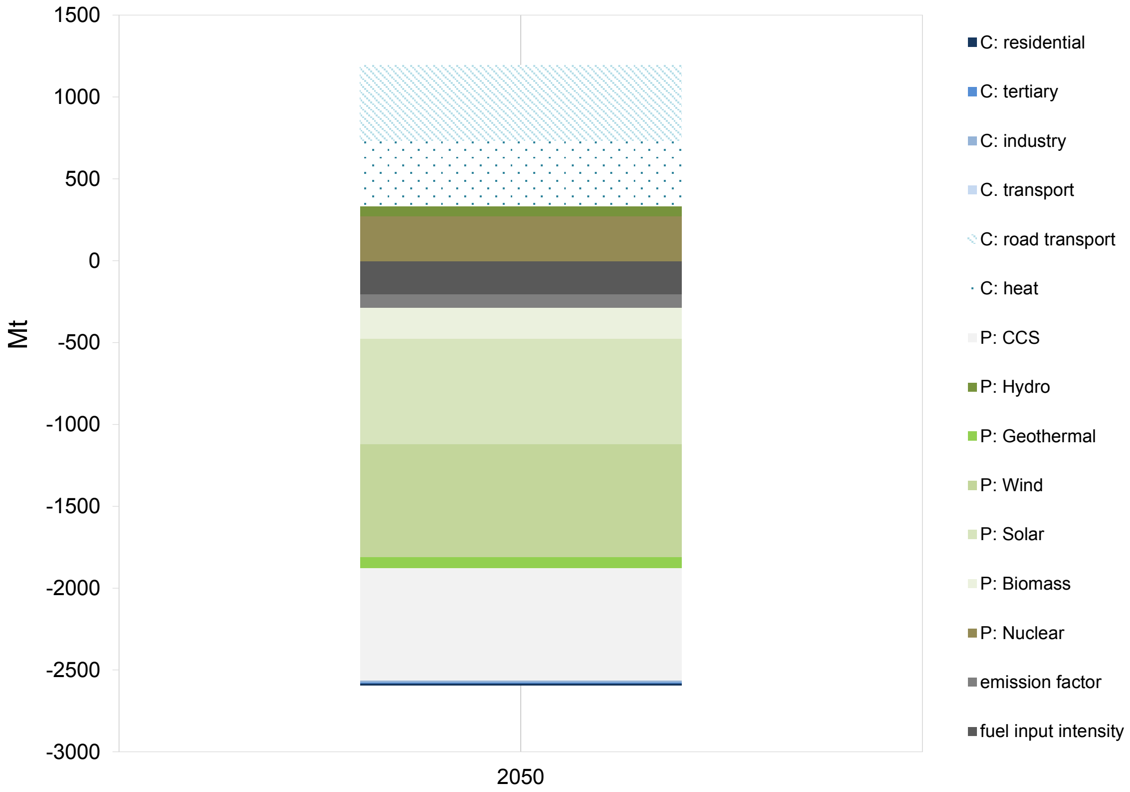
[12] New appliances add to emissions, as they are newly introduced into the market and did not yet exist in the base year.

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

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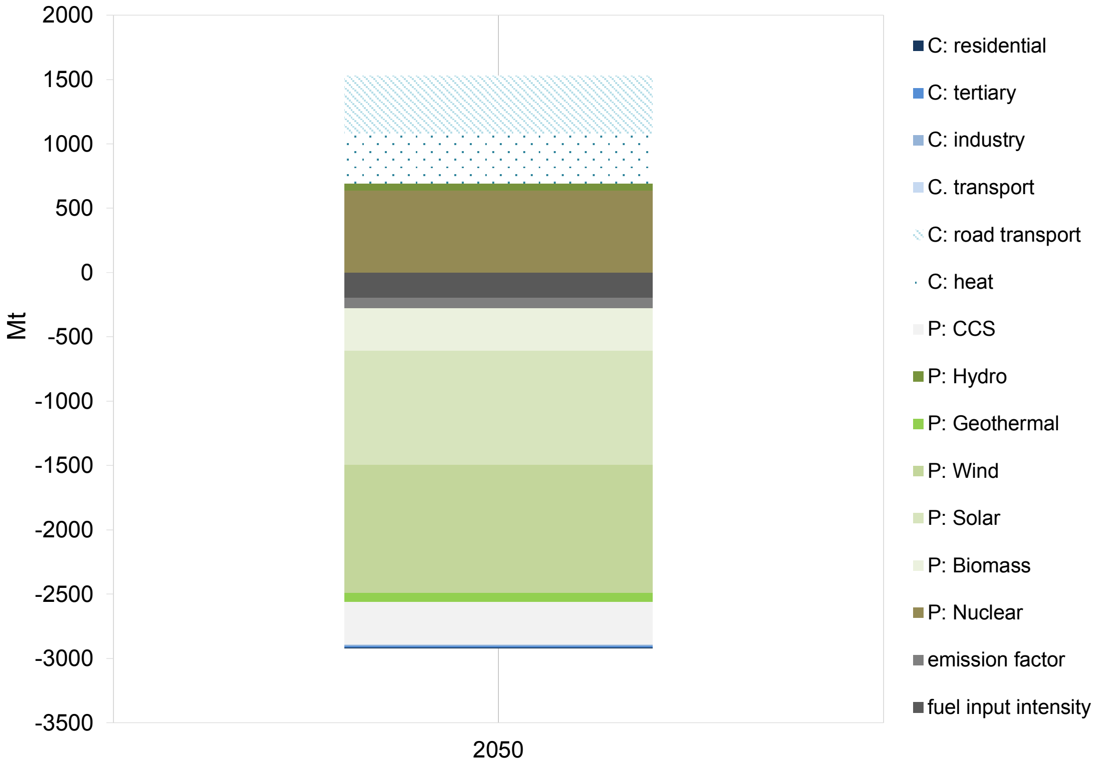
[13] New appliances add to emissions, as they are newly introduced into the market and did not yet exist in the base year.

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. Electricity sector CO_2 emissions in this scenario are reduced by 95% until 2050 compared

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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.

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% and 8% increase in the emissions of the transport and industrial sector respectively by 2050

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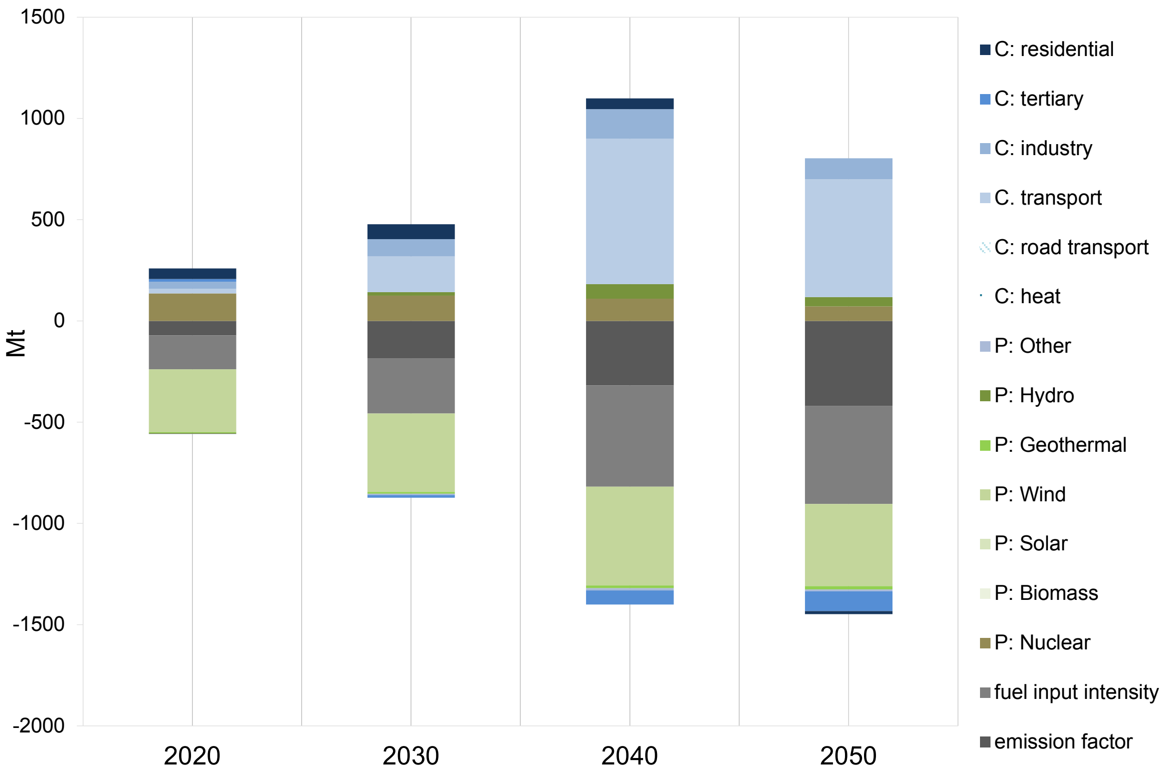
[15] Especially towards the end of the scenario period (i.e. by 2040 and 2050) the electricity generation from (only) fossil fuels in power plants cannot fully explain the CO2 emissions as provided within the study. Our calculations indicate that the emissions provided within the study may include a 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

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

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

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.

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

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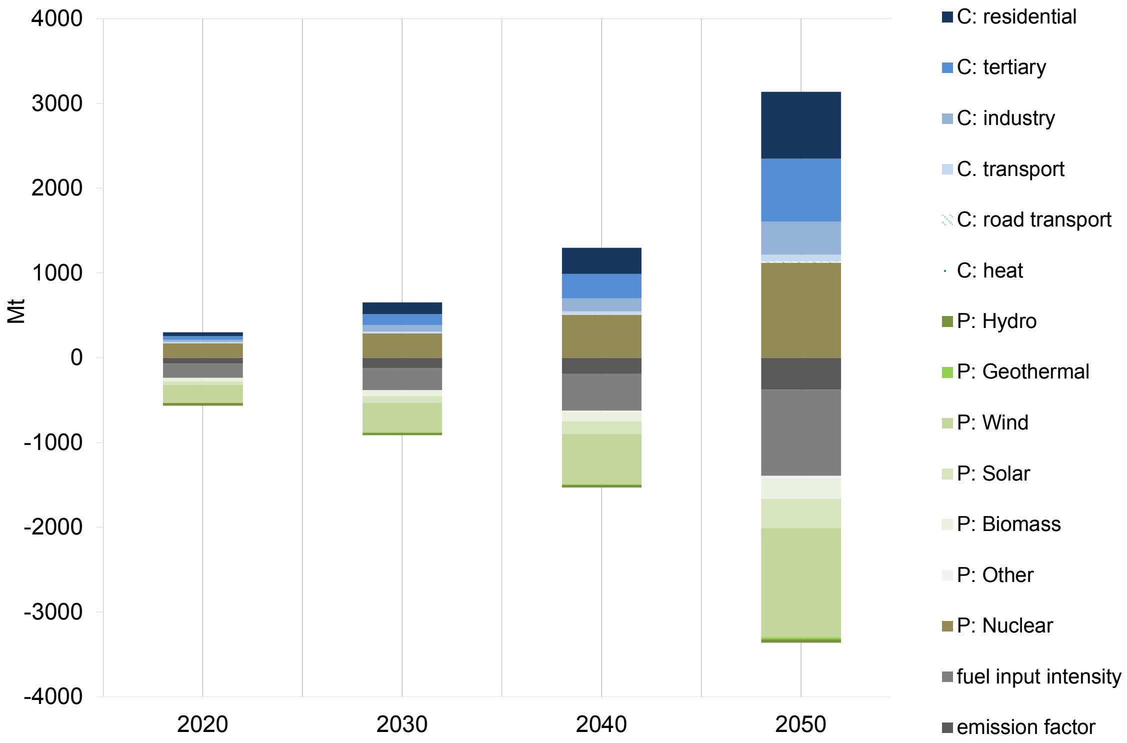
[17] Note that the relative contributions of individual effects appear to be very large in Table 10. This is the case because the overall (or net) emission reductions compared to the base year are relatively small, at just over 200 Mt throughout the course of the reference scenario. As the contributions 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.

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

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[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%

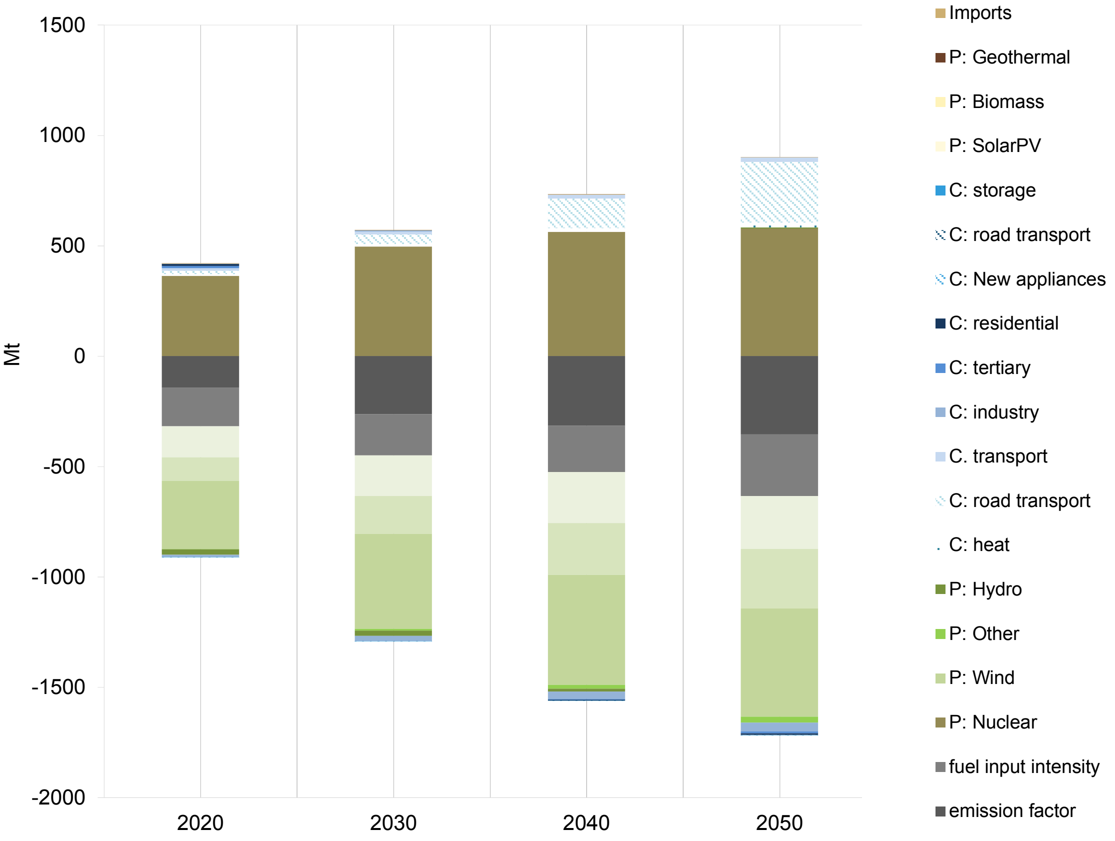
Source: Results from the decomposition analysis

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

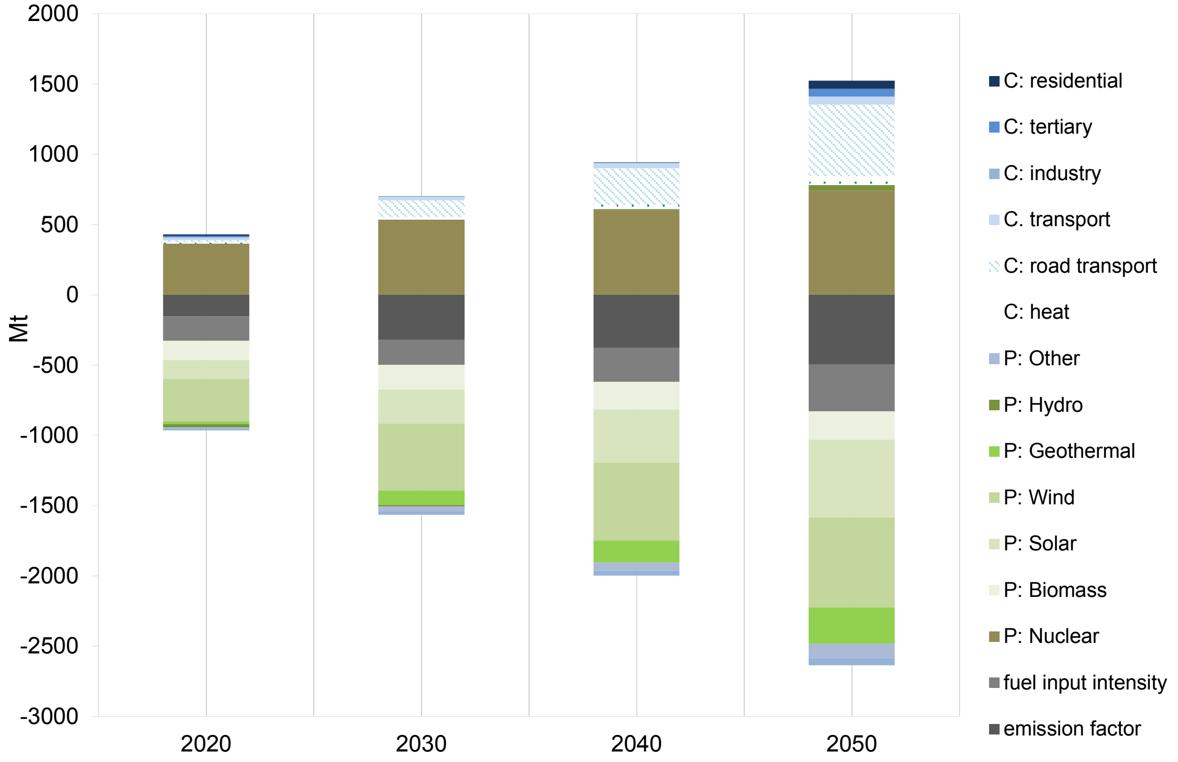
Causal factor	2020	2030	2040	2050
Consumption side				
C: traditional appliances	-5%	-1%	-1%	-8%
C: residential	-2%	0%	0%	-4%
C: tertiary	-2%	0%	0%	-4%
C: industry	2%	2%	3%	4%
C. transport	-4%	-3%	-3%	-4%
C: New appliances	-4%	-14%	-23%	-40%
C: road transport	-3%	-13%	-21%	-36%
C: heat	-1%	-2%	-2%	-5%
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]

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.

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

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.

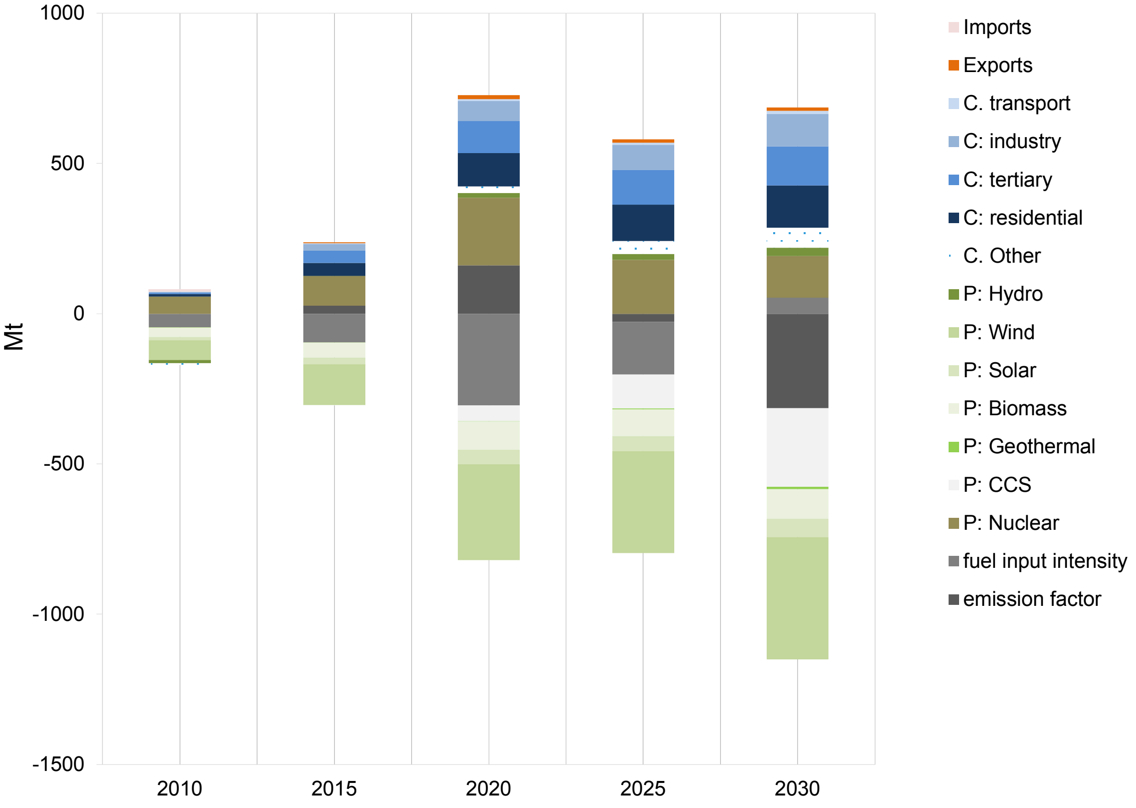
The emission reductions attributed to CCS (56% by 2030) do not exceed the emission reduction effect of renewable energies. More nuclear power is used in 2030 (1087 TWh in 2030 compared to 998 in 2005) than in the base year, the additional emissions caused by the share of nuclear power utilized decrease 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

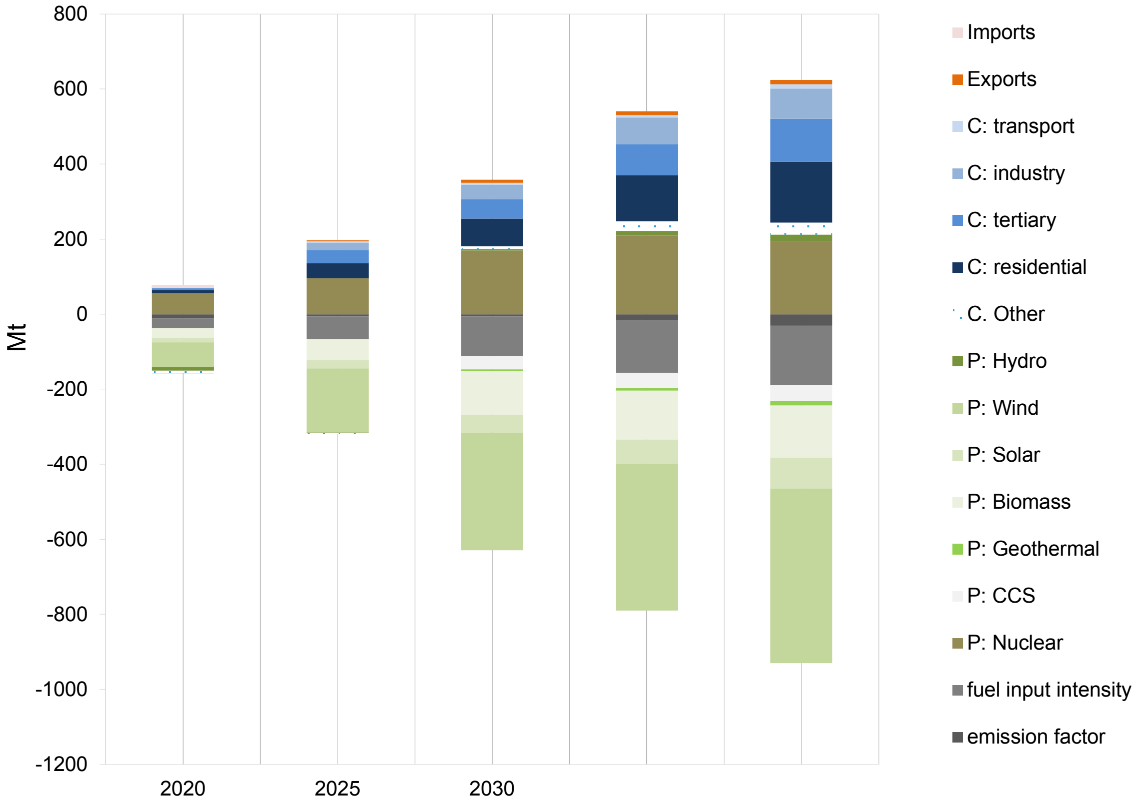
According to the decomposition analysis the increased amount of electricity consumption across all sectors contributes to increasing emissions compared to the base year for all periods considered.

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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Power Sector Decarbonisation: Metastudy

WP 2.3

Existing decarbonisation studies on specific EU Member States

Berlin, Wuppertal, 31.10.2011

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Content

1 Introduction

This paper presents a qualitative and a quantitative analysis on relevant EU member state studies focussing on future pathways of decarbonisation.

The selected studies are:

- Germany: Blueprint Germany (WWF, 2009a)
- Germany: Pathways Towards a 100% Renewable Electricity System (SRU, 2011)
- UK: 2050 Pathways Analysis (DECC, 2010)
- Sweden: Swedish long-term low carbon scenario (Jenny Gode, Särnholm, L. Zetterberg, Arnell, & T. Zetterberg, 2010)

These three studies have been chosen due to their general importance in the discourse on the topic. The qualitative analysis of these studies covers the following areas of interest: *general background information, thematic background, methodology, scenarios / pathways presented, infrastructural changes within the power system, discussion and recommendation of relevant policies, brief quantitative overview*. For ease of reference the structure of the qualitative summaries follow the same lines as the summaries in WP 2.1.

The quantitative comparison of the studies' pathways provides a) a looking glass into how the pathways are characterised and b) a comparison to the pathway characteristics of the other studies considered. This comparison focuses on data that is relevant for a decarbonised future electricity sector. The quantitative comparison is complemented by the in-depth analysis of selected scenarios.

The in-depth analysis locates which causal factors contribute how much to the actual emission reductions achieved in a scenario and is based on the decomposition methodology documented in WP 1.2. 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. Not all of the given studies provided all information necessary. Thus only a set of scenarios from is being presented in the concluding chapter.

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 three studies based on a standardised summary (Chapter 2). An individual analysis of selected scenarios with the decomposition approach follows in Chapter 3. This chapter also includes a documentation of gap filling efforts for those studies that did not provide enough data for a decomposition analysis. The paper ends with a conclusion (Chapter 4). The Annex provides further insights into recent German energy policy scenarios.

WP 2.3 thus functions as a looking glass: it provides insights into individual decarbonisation pathways of specific EU member states and sheds light into the similarities and differences that underlie these studies.

2 Introduction to scenario studies and general comparison of their scenarios

2.1 Introduction of scenario studies

Among others, these three different scenario studies on EU Member States have been released during the last two years. Before comparing crucial characteristics of potential future electricity sectors laid out by these studies, each study is introduced along the same lines as the EU-wide studies have been introduced in WP 2.1.

2.1.1 Germany: Blueprint Germany

General Information

'Blueprint Germany', commissioned by World Wide Fund for Nature Germany (WWF Germany) was published in October 2009 and conducted by Prognos AG, Öko-Institut and Dr. Ziesing.

Thematic background

The study evaluates the technical feasibility of Germany achieving a GHG reduction of 95% below 1990 levels by 2050. Beyond that, it assesses the impact which such a reduction target will have on Germany's economic structure and how lifestyle and consumption patterns may need to change.

Methodology

The PROGNOS bottom-up, modular, energy model system has been used to determine energy consumption by sector. Furthermore, the PROGNOS model for European power plant fleet was utilised to determine the German power plant fleet. The future development of this fleet is based on annual power demand and the development of peak load. The use of conventional power plants within the model is based on marginal cost logic (i.e. merit order), whereas renewables contribute to power generation in accordance with their available capacity (it is assumed financial subsidies ensure cost effectiveness). By 2050 all conventional power stations which are currently operating will no longer do so.

Scenarios/pathways

Two scenarios are developed to inform policy decision making: a reference scenario and an innovation scenario. Both of these scenarios are split into a variation with and without CCS. Data shared by all scenarios are socio-economic, energy prices and climate data.

The Reference Scenario describes and projects a world as we know it, with changes based on current demographic and technological change. The economy will develop more into a service-oriented economy, with knowledge-based and highly specialised efficient products. Energy and climate policies will remain within the boundaries defined today. Efficiency measures are assumed to be implemented if the respective calculations show immediate pay-offs. In the Innovation Scenario, the world will not change unrecognisably from the world in the Reference Scenario; however avoiding the impact of climate change is now considered a high priority, now that an international consensus on climate protection has been achieved. Emissions trading will play a major role in this context. All consumption sectors must deliver ambitious emission reductions by applying energy efficiency measures and in some cases extensive technical changes, which may lead to additional costs for the economy.

Infrastructural changes within the German power system

To achieve the target of reducing emissions by 95 % below 1990 levels by 2050, a significant increase in electricity production based on renewable energies will be required. In order to integrate a higher share of fluctuating renewable energies into the electricity system it will be necessary for electricity production plants to increase capacity factors and to achieve a higher degree of dispatchability. These should be incentivised by the German Renewable Energy Sources Act (RESA) via the setting of the electricity feed-in tariff.

The design of the electricity market is of key importance to the future market integration of renewable energies. In order to avoid price volatility in the electricity market following the integration of a higher share of fluctuating feed-in from renewable technologies, it is essential that the market price for electricity is no longer determined according to supply and demand for each hour of the day at the national level. Instead it will be necessary to ensure the availability of storage capacity either directly via storage technologies or indirectly via a large scale network of integration.

The incorporation of decentralised energy production options, such as large-scale optimisation of consumption and load, requires a new, improved level of network optimisation for transfer and distribution networks. There will be no alternative to intelligent load management, particularly when there are significant shares of electric mobility, which is regarded as crucial to achieving emission reductions in passenger cars without using substantial quantities of biomass. It is envisaged that innovation programmes for the development of biofuels (i.e. to ensure that total demand for biofuels can be covered by second generation biofuels in 2020) and the commercialisation of CCS (i.e. pilot plants should be built for the industrial sectors up to 2020 and carbon storage sites need to be tested) will be designed to achieve the ambitious emissions.

Discussion and recommendation of relevant policies

Three areas of action have been identified in order to achieve the long-term target of reducing emissions to 95 % below 1990 levels by 2050. These areas of action for encouraging the necessary infrastructural changes in the European / German energy system include the following:

- Strategic targets are set for total emission reductions below 1990 levels (i.e. 40 % by 2020, 60 % by 2030, 80 % by 2040 and 95 % by 2050), energy productivity (i.e. 2.6 % per annum improvement) and the share of renewable energy technologies within total primary energy consumption (i.e. 20 % by 2020, 35 % by 2030, 55 % by 2040 and 75 % by 2050) to provide, on an abstract level, key directions for the necessary re-organisation of the energy system.

- Implementation strategies are put forward in the study for overcoming the fact that emission reductions in different sectors have different levels of potential, time requirements and time windows for implementation. Therefore, it is acknowledged that certain reduction potentials will be linked with other complementary actions (i.e. the electrification of passenger cars is linked to the de-carbonisation of electricity production and development of sophisticated electricity distribution networks) and this needs to be considered in policy making decisions.
- Instrumentation strategies are referred to in the study as the implementation of policy instruments to support the low carbon transition. General policy instruments viewed as important include a significant price for GHG emissions (i.e. improving the EU ETS and carbon taxation), regulatory approaches to support low carbon technology (i.e. the use of CCS should be made compulsory from 2030 onwards for process-related industrial emissions) and regulatory provisions to prevent the ‘lock-in’ of capital and energy-intensive technologies (i.e. from 2025 onwards room heating in new buildings will need to be either zero energy or plus energy standard).

Quantitative Overview

Table 1 provides insights into the data collected for tier 1 of the common roster of data and information.

Table 1 Blueprint Germany: Quantitative overview

	base year	2020				2030				2050			
	2005	**R**	**R CCS**	**I**	**I CCS**	**R**	**R CCS**	**I**	**I CCS**	**R**	**R CCS**	**I**	**I CCS**
Electricity consumption													
· Absolute (in TWh/a)	517	492	492	423	423	474	474	370	370	472	472	330	330
· Change vs. base year	-	-5%	-5%	-18%	-18%	-8%	-8%	-28%	-28%	-9%	-9%	-36%	-36%
Share in electricity generation													
· Fossil (non-CCS)	63%	60%	60%	54%	54%	62%	58%	38%	40%	60%	41%	3%	4%
· Fossil CCS	0%	0%	0%	0%	0%	0%	4%	0%	4%	0%	19%	0%	20%
· Nuclear	26%	6%	5%	6%	6%	0%	0%	0%	0%	0%	0%	0%	0%
· Renewables	10%	30%	31%	36%	36%	33%	35%	54%	47%	34%	36%	75%	62%
Power sector CO_2 emissions													
· Absolute (in Mt CO_2)	344.00	279	279	225	225	256	241	134	137	234	175	14	23
· Change vs. base year		-19%	-19%	-35%	-35%	-19%	-30%	-61%	-60%	-32%	-49%	-96%	-93%
· Change vs. 1990		-22%	-22%	-37%	-37%	-22%	-32%	-62%	-62%	-34%	-51%	-96%	-94%
General													
· GDP (in billion $€_{2000}$)	2124	2457				2598				2981			
· Population (in millions)	82.5	79.8				78.6				72.2			
Fuel prices (in $€_{2007}$/GJ)													
· Oil	6.45	11.94				14.93				25.08			
· Hard coal	1.60	2.27				2.82				4.75			
· Natural gas	4.72	8.61				10.83				18.33			
Modelling approach	PROGNOS bottom-up, modular, energy model system PROGNOS model for European power plant fleet												
Geographical coverage	Germany												

Source: Compiled from (WWF, 2009a) .

2.1.2 UK: 2050 Pathways Analysis

General information

The "2050 Pathways Analysis" was published in July 2010 by the Department of Energy and Climate Change (DECC) in cooperation with HM Treasury, other departments and relevant stakeholders. Since March 2011 an update of the "2050 Pathway Analysis – Response to the Call of Evidence" is available online. DECC has been established in 2008 for safeguarding the energy and climate change policy of the UK's government. The main area of focus of the report is the UK.

Thematic background

The 2050 Pathway Analysis represents a diverse and interactive simulation and discussion platform. It has been published as a Call for Evidence which aims to present several options to consider some of the choices and trade-offs which the UK will have to make for reaching the goal of reducing its greenhouse gas emissions by at least 80% by 2050, relative to 1990 levels. It is emphasized, that this analysis is not considered to present a single feasible pathway. Furthermore it is important to note, that the report is based on physical limits and does not reveal concrete cost optimisation forecasts. The second version of the 2050 Pathways Analysis presents further pathway options and describes the adjustments that have and have not been made and the reasons therefore. The analysis itself is not considered to be a completed report but rather a work in transition which offers grass roots for further discussions and scenario development.

A consolidated version implying more detailed information regarding some possible cost developments that integrates all existing pathways with updated information in a single document is announced to published during the summer 2011. For the future it is planned to update the Calculator annually, assuring to constantly provide most up to date data and regarding current technical and scientific developments.

Methodology

An online 2050 Pathways Calculator was especially developed for evaluating the data for each pathway. The Calculator provides original current UK data and ‘a range of four different future trajectories, which aim to reflect the whole range of potential futures that might be experienced in each sector. The trajectories are defined by factors such as the lead time and build rate of new infrastructure, improvements and changes in technology, levels of behavioural and lifestyle change, changes in fuel choices, and structural changes such as the shape of industry.’ (2050 Pathways Analysis Response p.3) The Calculator is available on the website of DECC and gives the public the opportunity to create their own pathway and to participate in the discussion of how to reduce greenhouse gas emissions by at least 80% by 2050.

All pathways are built up in three steps:

1. The range of plausible trajectories to 2050 for each sector is set out.
2. Trajectories are combined across all sectors form pathways to 2050 for the UK.
3. Pathways which are successful in a) meeting the 80% reduction target, b) safeguarding that supply is meeting demand and c) guaranteeing a secure energy system, are selected.

The first part of the 2050 Pathway Analysis gives an introduction and then describes the six pathways and the Reference Case Pathway in detail. The second part presents a sector by sector approach which provides an outlook on what changes and possibilities there are within the scope of emissions and energy system.

Data regarding economic growth (GDP: 2.5% per annum), population growth (0.5% per annum), technical potential, roll-out rates land availability and ecological sensitivity are assumed to be identical in all pathways, including the reference case. Alongside emissions from the supply sector, use of energy, emissions from agriculture, waste, industrial processes, carbon capture technologies, land use, land use change and forestry, emissions from international aviation and shipping have also been examined.

Scenarios / pathways

The pathways are meant to show a broad range of choices and aim to give policy makers as well as scientific institutes and organizations or any interested private person profound examples for discussions, how the 80% reduction goal could be met. Only the Reference Case Pathway won't meet the 80% goal, with an approximated reduction of about 16% from 1990 levels.

Besides a Reference Case Pathway with almost no attempt to decarbonise and no significant development within the new technologies sector, there are six exemplary pathways within the first edition of the 2050 Pathway Analysis. *Pathway Alpha* represents a case with a largely balanced effort across all sectors. *Pathway Beta* shows a development where there is no carbon capture and storage technology implied within electricity generation. *Pathway Gamma* simulates a scenario where no new nuclear plants will be built. *Pathway Delta* is a pathway in which only minimal new renewable electricity capacity can be built. *Pathway Epsilon* forecasts, what could happen if supplies of bioenergy were limited and finally, *Pathway Zeta* examines what little behaviour change on the part of consumers and businesses could imply. For a more detailed description of the pathways please refer to p. 17-30 of the 2050 Pathway Analysis.

In the updated Analysis version from March 2011 further seventeen pathways, highlighting different development scenarios, are presented. Pathway 1 represents a revised version of Pathway Alpha. Due to three refinements the overall emissions are slightly higher compared to the former Pathway Alpha. The other sixteen pathways represent highly ambitious scenarios that tend to reach 'high-high' levels in different sectors.

Infrastructural changes within the UK power system

According to the report, transforming the economy of Great Britain requires 'a coalition of citizens, business, and the energy industry' ((DECC, 2010), p.4).

A summary of common messages from the July 2010 analysis pathways is reflected in the March 2011 version ((DECC, 2010), p.10):

- Ambitious per capita energy demand reduction is needed
- A substantial level of electrification of heating, transport and industry is needed
- Electricity supply needs to be decarbonised, while at the same time it may need to double
- A growing level of variable renewable generation increases the challenge of balancing the electricity grid
- Sustainable bioenergy is a vital part of a low carbon energy system
- Reduction in emissions from agriculture, waste, industrial processes and international transport will be necessary by 2050
- There will be an on-going need for fossil fuels in our energy mix, although their precise long term role will depend on a range of issues such as the development of carbon capture and storage.

Discussion and recommendation of relevant policies

The 2050 Pathway Analysis does not give advises for specific policy decisions, it rather offers an overview on possibilities what might be feasible by 2050 and thereby opens the floor for further discussions.

As advising body, DECC uses the arguments and messages which are generated with the Pathway Analysis for further development of new policies (e.g. 'Green Deal' a new Energy Bill in December 2010; the Electricity Market Reform White Paper, published in July 2011 and advises for the UK's fourth carbon budget)

Quantitative overview

The following table provides an overview of some of the key figures of the reference case (RCP) and the Pathway Alpha scenario (PA).

Table 2 UK Pathways Analysis 2050: Quantitative Overview*

	base year	2020		2030		2050	
	2007	RCP	PA	RCP	PA	RCP	PA
Electricity consumption							
· Absolute (in TWh/a)	342	385.00	394.00	422.80	499.00	532.30	660.50
· Change vs. base year	-	13%	15%	24%	46%	56%	93%
Share in electricity generation							
· Fossil (non-CCS + CCS)	82%	82%	67%	87%	36%	99%	28%
· Fossil CCS							
· Nuclear	15%	6%	11%	2%	21%	0%	30%
· Renewables	3%	12%	22%	12%	43%	1%	42%
Power sector CO_2 emissions							
· Absolute (in Mt CO_2)	191	168	127	145	13	207	-80
· Change vs. base year	-	-12%	-34%	-24%	-93%	8%	-142%
· Change vs. 1990	-	-17%	-38%	-29%	-94%	2%	-139%
General							
· GDP (in current billion €)	1,912	2,569		3,211		5,017	
· Population (in millions)	61.0	66.5		70.6		76.8	
Fuel prices (in €/GJ)							
· Oil	n.s.	15.49		17.40		n.s.	
· Hard coal	n.s.	3.10		3.10		n.s.	
· Natural gas	n.s.	76.30		84.15		n.s.	
Modelling approach	2050 Pathways Calculator, developed by DECC , can be used online to develop own pathway http://2050-calculator-tool.decc.gov.uk/						
Geographical coverage	UK focus, it also includes trajectories for potential international imports of bioenergy and electricity						

Source: Compiled from data in (DECC, 2010) and (DECC, 2011).

*GDP and population data for 2007 according to UK's Office for National Statistics (ONS); for the following years the growth rates provided in the study were applied to calculate GDP and population development.

2.1.3 Sweden: Swedish long-term low carbon scenario

General information

The study entitled, Swedish long-term low carbon scenario, was completed by the Swedish Environmental Research Institute in December 2010.

Thematic background

The aim of the study is to develop and elaborate on energy scenarios, which are associated with low carbon economic growth. The measures proposed in the four energy scenarios referred to in the study will considerably reduce the consumption of fossil fuels in the Swedish economy by 2050. Depending upon whether or not the scenarios include the use of CCS, the reduction in carbon dioxide emissions below 2005 levels is expected to range from 72% to 79% by 2050.

Methodology

The methodology applied in the decarbonisation study involves firstly establishing the baseline projection of energy demand in 2050 for industrial, residential and service and transport sectors. The authors of the study extrapolate the energy demand projections for 2030 used by the Swedish Energy Agency to 2050 energy demand values for the end using sectors. Secondly, measures to reduce fossil fuel utilisation and carbon dioxide emissions are identified (i.e. fuel shift, CCS) and then the energy demand in 2050 following the implementation of these measures for the end using sectors is calculated to derive the decarbonisation scenarios.

Scenarios / pathways

The study focuses on the development of an energy scenario that minimises the use of fossil fuels and it is envisaged by the authors within the main scenario (Biofuels 2050) that fossil fuel consumption is substituted with biofuel use. For example, in the transport sector it is assumed that 50% of the liquid and gas fuels are converted to biofuels. However, in order to account for the uncertainty associated with the potential of bioenergy in 2050 an alternative scenario (Fossil Fuels + bio CCS 2050) is also considered in the study. In contrast to the Biofuels 2050 scenario, the Fossil Fuels + bio CCS 2050 scenario assumes that no biofuels are used in the transport sector and that the energy demand is met via fossil fuels. In order to reach the same emissions level as the Biofuels 2050 scenario, the Fossil Fuels + bio CCS 2050 scenario assumes that extensive capture and storage on biogenic carbon dioxide from stationary plants (i.e. pulp and paper mills) is implemented on a large scale. Given the uncertainty about the future development of CCS technology, both of these scenarios are assessed with the inclusion and exclusion of CCS.

Infrastructural changes within the Swedish power system

The current production of electricity in Sweden (i.e. 150 TWh), which is primarily provided by a combination of hydro, nuclear and combined heat and power, would be almost sufficient to meet the expected electricity demand in 2050 (i.e. energy efficiency improvements will offset increased electricity demand from economic growth). However, in the event that nuclear power is phased out, there will be a need for the new production of approximately 75 TWh of electricity. Given that the study is exploratory in nature, how this additional electricity demand will be met (i.e. the energy mix) and the infrastructure change required is not specified. The authors acknowledge that assumptions such as an increase in electric mobility and a shift of goods transported by road to rail will require ‘massive investments’ in infrastructure, although an analysis of the feasibility of these assumptions was beyond the scope of the study.

Discussion and recommendation of relevant policies

The study provides several important recommendations to ensure that the Swedish economy follows a low carbon pathway. It is evident that a key recommendation is that the end using sectors need to implement policy measures to reduce their utilisation of fossil fuels. For example, the Biofuels 2050 scenario in the study envisages a complete transformation of the transport sector converting fossil fuel use to biofuel use. A similar substitution from fossil fuel use to biofuel use is recommended for the industrial sector (i.e. use of biofuels in cement ovens) to reduce process related emissions. The use of bio CCS in the pulp and paper mill provides an additional abatement option to reduce process emissions.

The study highlights that there may be a potential shortfall in electricity generation in 2050 if nuclear power is phased out. Therefore a further analysis into how this additional electricity demand will be met needs to be investigated in the near future.

Quantitative overview

Table 3 provides an overview of the data in tier 1 of the common roster of data and information. The years 2010 to 2030 have not been listed since the study originally listed the values for 2050 for the scenarios only. Data in between was either not available (production side) or projected from until 2030. Thus, the real scenario data from the study only refers to 2050 values. Please refer to Section 3.4.1 for a further explanation of the data situation and gap-filling.

Table 3 Swedish long-term low carbon scenario: quantitative overview[1]

	base year	**2050**	
	2005	**Biofuels 2050**	**Fossil Fuel + BECCS**
Electricity consumption			
· Absolute (in TWh/a)	131	141.00	N/A
· Change vs. base year	-	8%	N/A
Share in electricity generation			
· Fossil (non-CCS)	N/A	N/A	N/A
· Fossil CCS	0%	0%	0%
· Nuclear	45%	N/A	N/A
· Renewables / non-fossil	47%	89%	89%
Power sector CO_2 emissions			
· Absolute (in Mt CO_2)	59	17	37
· Change vs. base year	-	-71%	-37%
· Change vs. 1990	N/A	N/A	N/A
General			
· GDP (in current billion €)	298.4	364.5	
· Population (in millions)	9.0	10.6	
Fuel prices (in $€_{2008}$/GJ)			
· Oil	N/A	N/A	
· Hard coal	N/A	N/A	
· Natural gas	N/A	N/A	
Modelling approach	Extrapolation of energy demand projections for 2030 by Swedish Energy Agency to 2050 for the end using sectors. Identification of easures to reduce fossil fuel utilisation and carbon dioxide emissions. Then the energy demand in 2050 following the implementation of these measures for the end using sectors is calculated to derive the decarbonisation scenarios		

Source: Compiled from (Jenny Gode et al., 2010) and (Energimyndighet, 2009).

The electricity generation values for the scenarios including CCS (i.e. Biofuels 2050 + CCS, Fossil fuels + BECCS 2050 + CCS) are not explicitly stated in the study. Electricity consumption in these scenarios can be assumed to be identical to the corresponding scenario without CCS. Thus, Table 3 does not contain additional information on the scenarios with CCS. It should be summarized however that in the options with CCS the CO_2 emissions in 2050 are assumed to be 12 Mt in both of the additional scenarios.

2.1.4 SRU - Pathways Towards a 100% Renewable Electricity System[2]

General information

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[1] For the Fossil fuels + BECCS scenario, no value was indicated for electricity demand from the residential & services sectors. The data most likely stems from(J Gode & Jarnehammar, 2007) , which has been made available to us recently but written in Swedish, so the data could not yet be retrieved.

[2] Wege zur 100% erneuerbaren Stromversorgung

The special report "Pathways Towards a 100% Renewable Electricity System" by the German Advisory Council on the Environment (SRU)[3] was published in January 2011. Members of the SRU are appointed by the German government, but the SRU independently determines the focus and scope of its reports. It consists of seven university professors from different environment-related disciplines and provides analysis and policy recommendations for current environmental topics.

Thematic background

In order to reach its goal to reduce greenhouse gases by 40% relative to 1990 levels until 2020 and by at least 80% by 2050, Germany will have to rapidly decarbonise its electricity sector. The report aims at informing political decision makers about the technical, economic and political feasibility of moving towards 100% of renewable electricity generation by 2050. The report was published after the German government had adopted its energy concept in 2010. However, German policy has since changed as a response to the nuclear accident at the Fukushima power plant and a new energy package was adopted in July 2011.

Methodology

This report only considers the electricity sector. In a first step German electricity demand in 2050 is determined on the basis of results of previous studies (such as (Barthel et al., 2006; Enquete-Kommission, 2002; Nitsch, 2008; UBA, 2009; WWF, 2009b)). Subsequently, the REMix model of the German Aerospace Centre (DLR)[4] is used to determine the cost optimized energy mix for the defined levels of electricity demand and net imports. This model is based on a geo-information system that charts the potential of all renewable energy sources and storage facilities in Germany, Europe and North Africa using a high resolution grid.

Assumptions on costs of electricity generation technologies are based on research by the DLR, while forecasts of GDP and population growth and energy price levels are taken from a study commissioned by the German Environmental Agency (Nitsch, 2008). The matching between demand and supply is calculated in hourly intervals. Finally, taking into account characteristics of the existing power plant fleet, a pathway is sketched along which the electricity sector needs to evolve in order to achieve the 100% renewable electricity goal by 2050.

Scenarios / pathways

Three groups of scenarios are analysed: German energy self sufficiency (scenario group 1); a regional network involving Germany and Scandinavia (scenario group 2); and a Europe-North African network (scenario group 3). Those scenarios are further differentiated by allowing for 15% net import of electricity vs. 0% net import and by relatively low (509TWh) vs.

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[3] Sachverständigenrat für Umweltfragen

[4] Deutsches Zentrum für Luft- und Raumfahrt

relatively high (700 TWh) electricity demand in 2050. Detailed results were provided for the two scenarios deemed most relevant: A regional network with Denmark and Norway, 0% net electricity imports and a demand of either 509 TWh (2.1.a) or 700 TWh (2.1.b) in 2050. Quantitative results of those two scenarios are displayed in Table 4 below.

Infrastructural changes within the European power system

The authors favour an electricity network between Germany, Denmark and Norway, as the most realistic and cost-efficient option.

In order to tap into storage capacity in Norway, an extension of the electricity grid and storage facilities (pumped and compressed air storage) will be necessary. Furthermore, links from offshore wind farms to shore will have to be constructed. With respect to generation facilities, conventional power plants (with an assumed average lifetime of 35 years) will subsequently be replaced by renewable electricity generation capacity, which will have to increase at an average rate of 6 GW and 8 GW per year by 2020 for scenarios 2.1.a and 2.1.b respectively.

In all scenarios, wind energy, particularly from offshore wind turbines, will expand rapidly. The use of solar energy differs across scenarios as it depends on the cost of electricity and hence final demand and the share of electricity that is imported. Biomass use accounts for no more than 7% of electricity demand, largely owing to land use conflicts and the relatively high cost of this energy resource. Neither new nuclear plants nor fossil-fuel plants with CCS will be constructed, only a number of gas turbines.

Discussion and recommendation of relevant policies

The authors highlight the importance of energy efficiency improvements in facilitating the transition to 100% renewable electricity supply and suggest introducing a cap on electricity consumption and a White Certificates Scheme. The German government will also need to support capacity expansion of renewable energy sources. To this end, the authors propose extending Germany’s Renewable Energy Act (EEG) and rendering it more cost-efficient, e.g. scaling-up support for offshore wind power, while reducing support for photovoltaic energy. At the same time, the phase-out of conventional power plants has to be designed in a socially acceptable manner and could be accompanied by measures targeting negatively affected regions (e.g. by building up the relevant supply sectors in those regions). Furthermore, grid extension should be accelerated by providing investment incentives and shortening planning procedures.

Moreover, policy certainty should be created by translating long-term goals into law at the national and EU level, e.g. a reduction goal of 80-95% compared to 1990 levels by 2050 and a reform of the EU ETS with a view to making it more efficient. In order to be able to adopt those laws, it will be crucial to generate wide-spread public support as well as party consensus on those goals.

Finally, proactive foreign policy in the energy domain is advocated in order to facilitate links with Scandinavia and potentially North Africa.

Quantitative overview

The following table provides an overview of some of the key figures of the study's two main scenarios.

Table 4 Wege zur 100% erneuerbaren Stromversorgung: Quantitative Overview

	base year	**2020**		**2030**		**2050**	
	2008	**2.1.a**	**2.1.b**	**2.1.a**	**2.1.b**	**2.1.a**	**2.1.b**
Electricity consumption*							
· Absolute (in TWh/a)	542	533	587	525	625	509	700
· Change vs. base year		-2%	8%	-3%	15%	-6%	29%
Share in electricity generation							
· Fossil (non-CCS)	62%	41%	39%	28%	24%	0%	0%
· Fossil CCS	0%	0%	0%	0%	0%	0%	0%
· Nuclear	23%	7%	7%	0%	0%	0%	0%
· Renewables	14%	51%	54%	72%	76%	100%	100%
Power sector CO$_2$ emissions							
· Absolute (in Mt CO$_2$)							0
· Change vs. base year							-100%
· Change vs. 1990							-100%
General							
· GDP (in billion €$_{2000}$)		2,763	2,763	3,130	3,130	3,600	3,600
· Population (in millions)		81	81	79	79	75	75
Fuel prices (in €$_{2005}$/GJ)							
· Oil		12.70	12.70	15.67	15.67	19.70	19.70
· Hard coal		5.33	5.33	6.89	6.89	9.85	9.85
· Natural gas		10.67	10.67	13.79	13.79	18.52	18.52
Modelling approach	Backcasting from a goal of 100% renwables, taking into account renewables potential and calculating cost-efficient alternative using the REMix Model						
Geographical coverage	Germany						

Note: Gross electricity demand (however, by 2050 gross and net demand will be nearly identical, since there is virtually no own consumption of renewable energy plants).

Source: Compiled by the authors based on data provided in the study.

2.2 General comparison of scenarios

The following scenario comparison includes all the scenarios of the three 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 four scenarios from the Blueprint Germany study
    - Reference without CCS
    - Reference with CCS
    - Innovation without CCS
    - Innovation with CCS

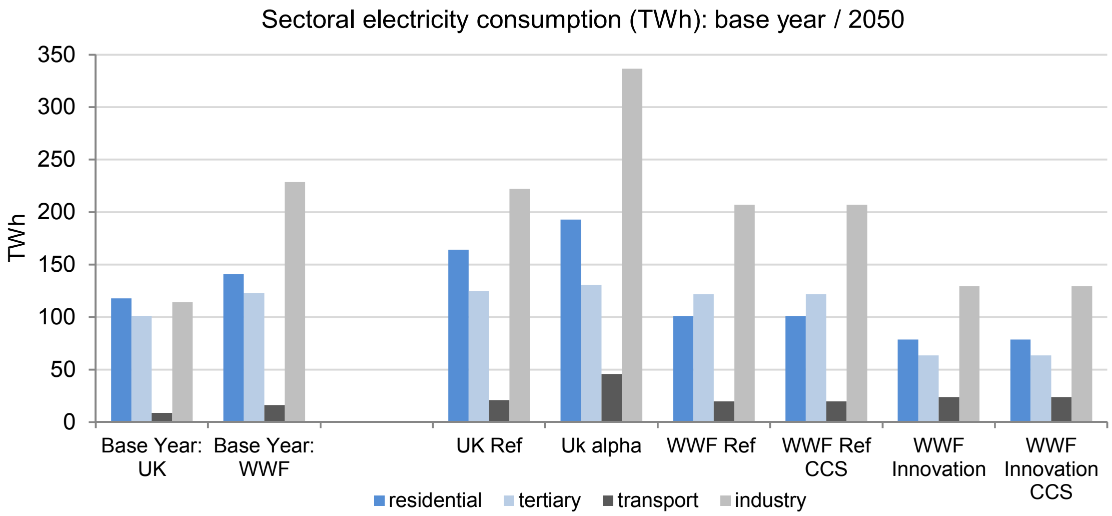
- two scenarios from the 2050 Pathways Analysis
    - Reference
    - Pathway Alpha

The reference scenario and the low carbon scenarios of the study by the Swedish Environmental Research Institute (2010) do not provide sufficiently detailed data to be included in the following comparisons.

2.2.1 Electricity demand by sectors

Figure 1 shows the electricity demand by sector in the studies' base years (2005 for the scenarios in Blueprint Germany and 2007 in the scenarios in the 2050 Pathway Analysis) and in the year 2050.

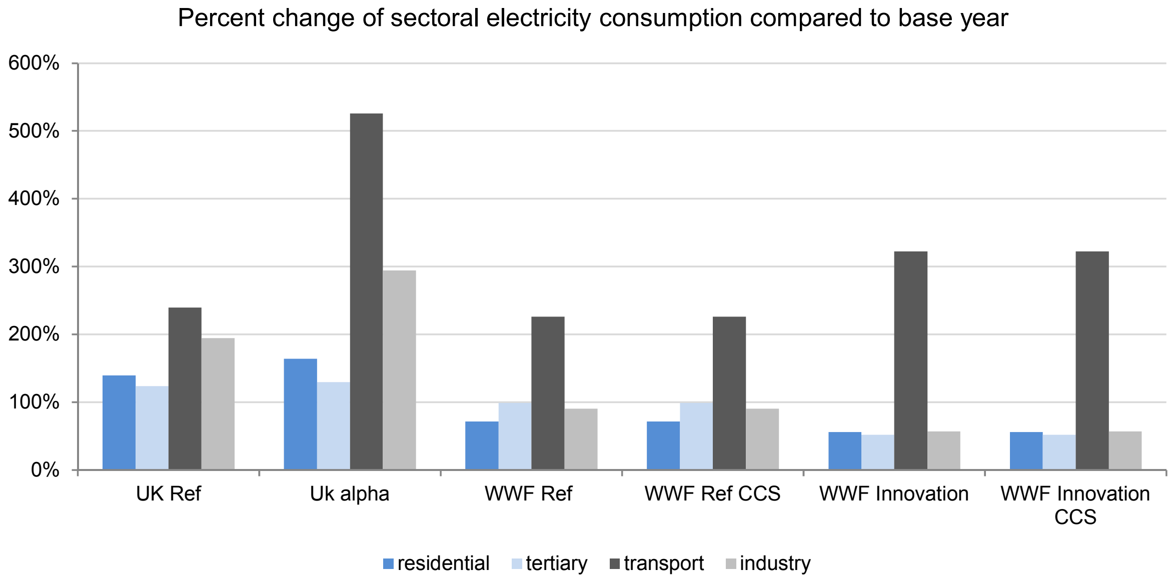
Figure 1 Electricity demand in the base year and in 2050



Source: compiled from (WWF, 2009a), (DECC, 2010, 2011) ,

The scenarios considered from the 2050 Pathway Analysis study (Reference, Pathway Alpha) are associated with an increase in electricity demand for the residential, commercial, industry and transport sectors. Under the Pathway Alpha scenario the electricity consumption of residential (193 TWh), tertiary (131 TWh), industry (337 TWh) and transport (46 TWh) sectors increases considerably by 2050. The increased consumption of electricity in all sectors by 2050, which is equivalent to an increase ranging from 129% (tertiary) to 526% (transport) compared to the base year (Figure 2), reflects the fact that the Pathway Alpha scenario assumes that the majority of industry, heating and transport uses will be powered by electricity from low carbon sources[5].

Figure 2 Relative change in electricity consumption in 2050



Source: compiled from (WWF, 2009a), (DECC, 2010, 2011),

The scenarios analysed from the Blueprint Germany study (Reference with/without CCS, Innovation with/without CCS) are associated with a decrease in electricity demand for residential, tertiary and industry sectors. The Innovation with/without CCS scenario assumes that the electricity demand of residential (79 TWh), tertiary (64 TWh), industry (129 TWh) and transport (24 TWh) sectors all decline by 2050. The decreased consumption of electricity in these sectors by 2050, which is equivalent to a decrease ranging from 52% (tertiary) to 57% (industry) compared to the base year (Figure 2), reflects the fact that the Innovation with/without CCS assumes ambitious improvements in energy efficiency in the residential, tertiary and industry sectors.

The increase of electricity demand by 2050 in the transport sector for all of the scenarios in the Blueprint Germany and 2050 Pathway Analysis studies underlines the importance of the electrification of road transport as a means of decarbonising the economy of both Germany and the UK. The Pathway Alpha scenario envisages that by 2050 the electricity demand of the transport sector will increase by 526% compared to the base year, which is significantly higher than the increase in electricity consumption assumed in the Innovation with/without CCS scenario (322%). Given that both scenarios expect a progressive shift to electric

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[5] (DECC, 2010) p. 18

vehicles by 2050 the difference may be partially explained by divergent assumptions about passenger transport mobility between 2005 and 2050. The Innovation with/without CCS scenario assumes that passenger mobility in 2050 will decline by 8% compared to the base year[6] whereas the Pathway Alpha scenario expects continued growth in passenger mobility, which only begins to slow after 2035[7].

2.2.2 Electricity supply by sources

Figure 3 shows electricity generation by sources in 2050 in both reference and all policy scenarios compared to the base year of the scenarios. In line with the overall goal of all the studies' policy scenarios, electricity generation in 2050 is based 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.

In the base year of the Blueprint Germany study the majority of electricity supply was generated from fossil fuel combustion (365 TWh), followed by nuclear (151 TWh) and a minor contribution from renewables such as wind (27 TWh) and hydro power (20 TWh). Both the Reference with/without CCS and the Innovation with/without CCS envisage a radically different electricity mix to the present situation in Germany. The phase out of nuclear power is expected in all of the scenarios considered in the Blueprint Germany study. The main differences occur with regard to the utilisation of fossil fuels and the rate of renewable energy penetration by 2050.

The WWF reference scenario without CCS assumes that electricity production from fossil fuel combustion declines slightly from the base year (311 TWh) with a considerable increase in electricity provided by renewables between the base year and 2050 (Figure 4). The WWF reference scenario with CCS scenario includes the same supply of electricity from renewables as in the previous scenario, with the only difference being that CCS produces 100 TWh of electricity. This subsequently reduces the electricity required from fossil fuel combustion (212 TWh) to meet the overall demand in 2050. The WWF innovation scenario without CCS envisages a substantial reduction in electricity supply from fossil fuel consumption in 2050, with renewables meeting the electricity 'gap'. The majority of the electricity in 2050 is supplied by wind energy (291 TWh) followed by considerable contributions from biomass (41 TWh), geothermal (35 TWh), solar (28 TWh) and hydro power (25 TWh).

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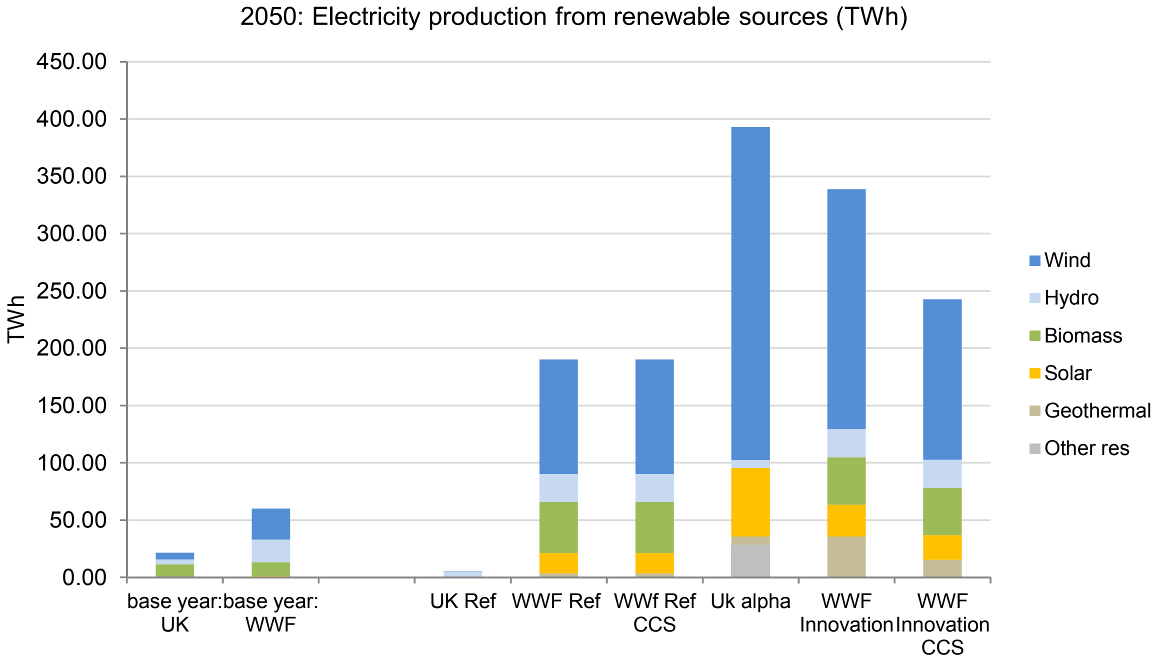
[6] (WWF, 2009a), p. 206

[7] (DECC, 2010), p. 63

Figure 3 Electricity Generation by source in base year and 2050



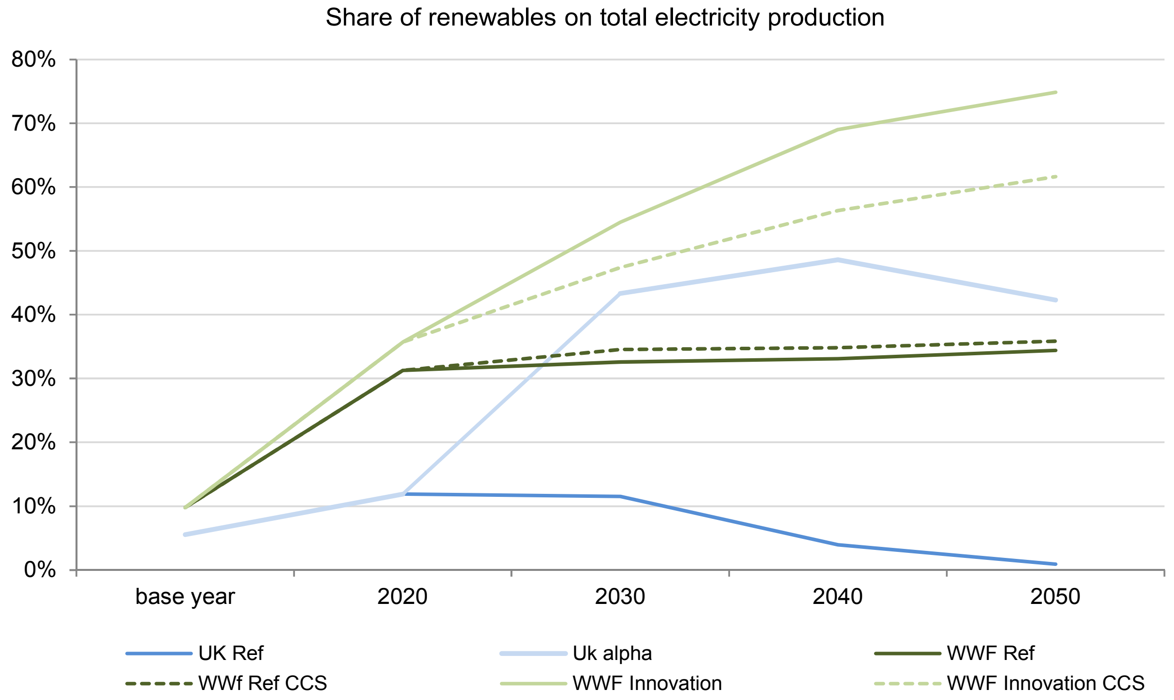
Source: compiled from (WWF, 2009a), (DECC, 2010, 2011)

In the base year of the 2050 Pathway Analysis study the majority of electricity supply was generated from fossil fuel combustion (310 TWh), followed by nuclear (58 TWh) and a minor contribution from renewables such as wind (6 TWh) and hydro power (4 TWh). The Reference and Pathway Alpha scenarios envisage alternative high and low carbon futures for the UK economy with considerable differences in the use of fossil fuel to generate electricity supply in 2050.

The Reference scenario assumes that by 2050 electricity production from fossil fuel combustion increases from the base year (580 TWh). The scenario envisages that the share of renewable energy in total electricity production will decline between 2020 and 2050, which may be due to the increasing deployment of CCS technology (Figure 4).

In contrast, the Pathway Alpha scenario outlines an alternative electricity mix in 2050 that is completely independent of fossil fuels. Renewables are expected to significantly contribute to the electricity mix in 2050 under the Pathway Alpha scenario with wind energy the dominant technology (291 TWh). It is interesting to note that wind energy provides the most electricity in 2050 for all of the scenarios considered in this analysis. In addition to renewables, nuclear power (275 TWh) and CCS technology (262 TWh) also contribute to the electricity supply in 2050 (Figure 3). The investment in a new generation of nuclear power stations represents a major difference between the Pathway Alpha scenario and the scenarios considered in the Blueprint Germany study, however given the higher electricity demand in 2050 envisaged in the Pathway Alpha scenario a more diverse electricity mix may be necessary to ensure energy security.

Figure 4 Development of the share of renewable energy sources in electricity generation in the different scenarios

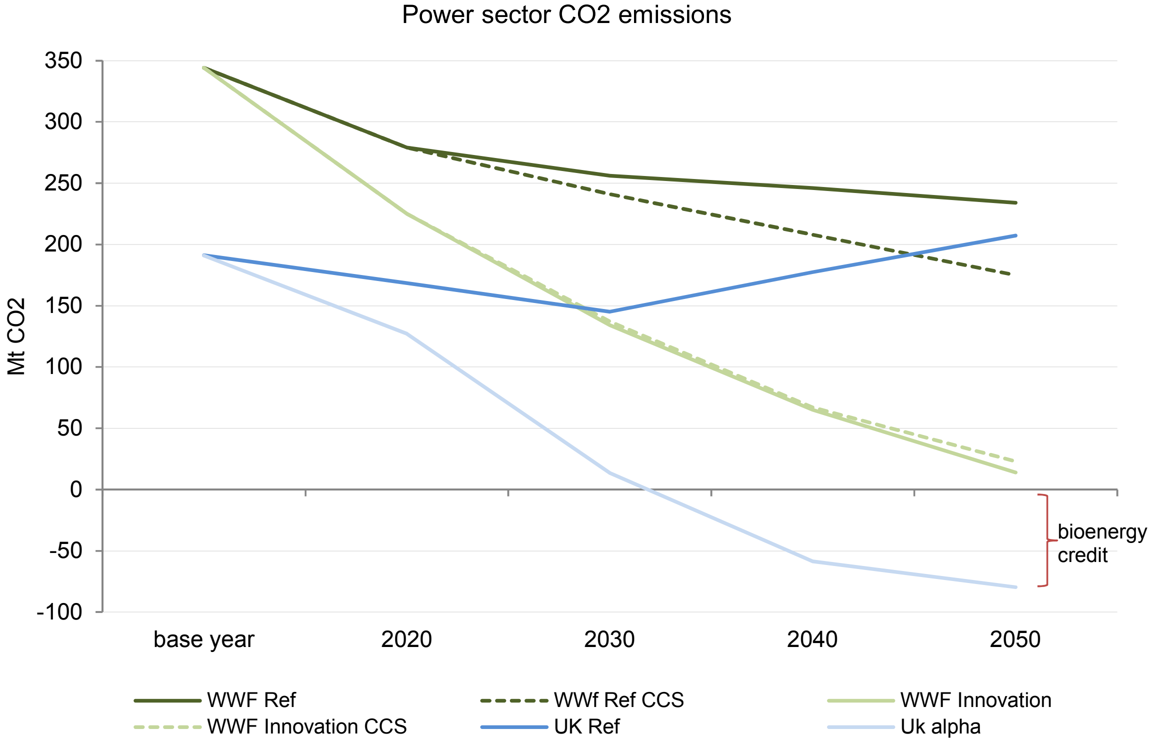


Source: compiled from (WWF, 2009a) and (DECC, 2010) and (DECC, 2011).

2.2.3 Electricity sector CO_2 emissions

The electricity sector CO_2 emission reductions for all scenarios between the base year and 2050 are illustrated below in Figure 5. The WWF reference with/without CCS scenario provides a CO_2 reduction in the power sector of -32% and -49% respectively below the base year. Figure 5 shows that the pathways for both WWF reference scenarios experience sharp emission reductions until the year 2020. During the period between 2020 and 2050, the WWF reference without CCS scenario reduces CO_2 emissions at a slower rate compared to the more linear rate of reduction under the WWF reference with CCS scenario. The WWF innovation with/without scenario achieves a CO_2 reduction in the power sector of -96% and -93% respectively below the base year. In contrast to the WWF reference scenarios, the rate of CO_2 emission reduction is steeper for the WWF reference scenarios reflecting the more ambitious measures within these scenarios to improve energy efficiency and increase the supply of electricity by renewables (Figure 5).

Figure 5 Power sector emission pathways



Source: compiled from (WWF, 2009a) and (DECC, 2010) and (DECC, 2011).

The Reference scenario in the 2050 Pathway Analysis study represents the only scenario considered in this general comparison to experience higher CO_2 emissions (i.e. 8% increase) in 2050 compared to the base year (Figure 5). CO_2 emissions decline steadily until 2030 in the reference scenario, however after the phase out of nuclear power CO_2 emissions increase considerably until the year 2050. In contrast, the Pathway Alpha scenario achieves a full decarbonisation of the power sector by 2050. The rate of emission reduction increases considerably after 2020 with the increasing deployment of CCS technology and investment in nuclear power and renewables (Figure 5). It is important to note, that as a consequence of bio-energy crediting[8] the CO_2 emissions become 'negative' after 2035 enabling the Pathway Alpha scenario to achieve a full decarbonisation. If bio-energy crediting is not considered then the scenario achieves a CO_2 emission reduction of 91% below the base year in 2050.

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[8] The definition of bioenergy crediting is not clear within the 2050 Pathway Analysis, and therefore clarification will be required before these results can be fully interpreted.

3 Individual analysis of the studies

3.1 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 a specific set of data. 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 that is considered to be essential for the decomposition analysis has been gap filled.

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 along the lines of tables and figures. The interpretation of the values found in these will be explained here in more detail.

Table 5: Causal factors and their contributions to emission changes (Mt), and their contribution to net emission reductions (%)

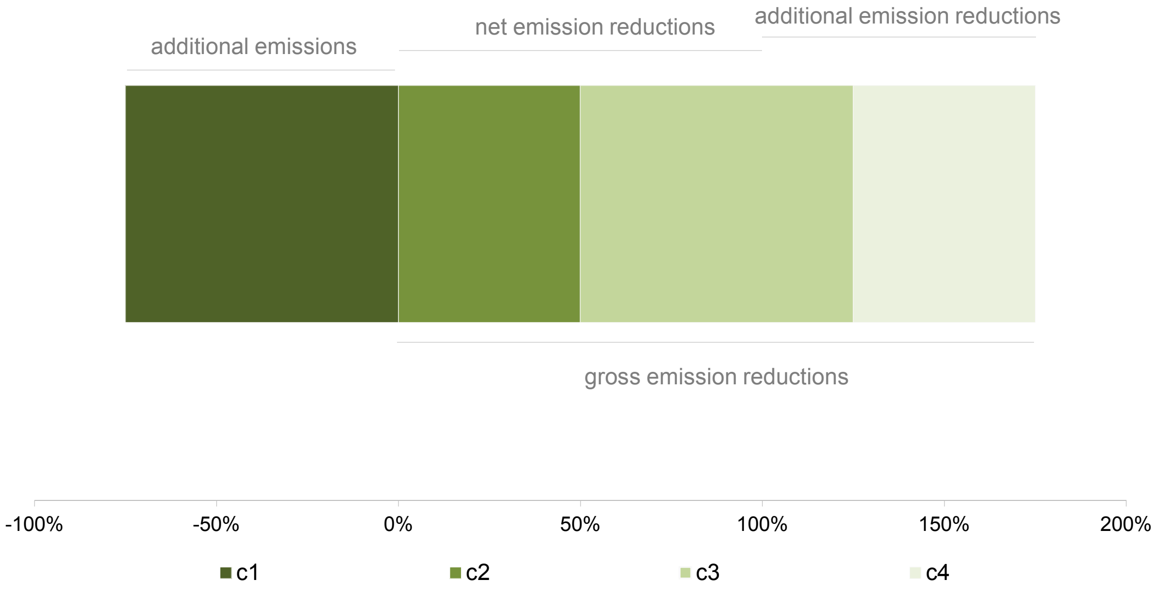
causal factor	Mt	%
c1	75	-75%
c2	-50	50%
c3	-75	75%
c4	-50	50%

Source: Author's own

The results of the decomposition analysis will be presented in the format of the table above for all of the decarbonisation scenarios considered in this metastudy. The emission change attributed to each causal factor (i.e. consumption, production, emission factor and fuel input intensity) will be presented either in terms of 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 6 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 6 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 Blueprint Germany

3.2.1 Data situation and gap-filling

The data provided in (WWF, 2009a) is very detailed and well documented throughout the study. Gap-filling was only necessary on a minimal level to account for differences between total consumption and supply of electricity.

Tier 1 data was readily available from the study. Tier 2 data was nearly completely available spread across various tables throughout the study. The availability of tier 2 data is displayed by Table 6.

Table 6: Blueprint Germany: data availability for tier 2 data

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

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

Source: compiled from (WWF, 2009a).

Data was available for all datasets indicated with a cross for the base-year (2005) and the years 2020, 2030, 2040, 2050. Slight differences between total consumption and total supply of electricity have been found at a few instances, but these did not exceed a magnitude of (10 TWh) within the reference scenario without CCS and the innovation scenario without CCS[9]. The sources for this difference could not be located within the study itself[10].

To account for this fact and to equalize demand and supply of electricity completely for enabling the decomposition analysis – the difference has been attributed to the category *other consumption* in tier 2 which also holds information on conversion- and transmission losses. The difference was always found on the consumption side, i.e the individual components of consumption did not add up to total production of electricity.

3.2.2 Decomposition analysis for selected scenarios

The decomposition analysis has been accomplished for 3 of 4 scenarios considered in this study: the reference scenario without CCS and the innovation scenario without CCS, and the reference scenario with CCS.

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[9] In the reference scenario with CCS the largest difference between demand and supply has been 78 TWh in 2050. We included this scenario, since the difference in the previous years was much smaller.

[10] Regarding the innovation scenario with CCS a discrepancy between the values of electricity consumption and electricity production was found, which was too high than to be accounted for in the category other consumption.

Reference Scenario without CCS

The reference scenario describes and projects a world as we know it, with changes based on current demographic and technological change. The economy will develop more into a service-oriented economy, with knowledge-based and highly specialised efficient products. Energy and climate policies will remain within the boundaries defined today. Efficiency measures are assumed to be implemented if the respective calculations show immediate pay-offs. Table 7 and Figure 7 summarize the results from the decomposition analysis regarding the reference scenario. While Table 8 displays the relative emission reduction contribution of the causal factors considered, Figure 7 presents the absolute emission changes that each of the causal factors exhibits compared to the base year CO_2 emissions.

Results are listed for each of the years considered in the study and refer to the base year always (and not to the previous year).

Table 7: Blueprint Germany / Reference scenario without CCS: Relative emission reduction contributions compared to the base year (2005).

Causal factor	2020	2030	2040	2050
Consumption side				
C: traditional appliances	16%	26%	25%	30%
C: residential	9%	15%	18%	20%
C: tertiary	7%	3%	-4%	1%
C: industry	2%	9%	12%	11%
C. transport	-1%	-2%	-2%	-2%
C: New appliances	0%	-1%	-4%	-9%
C: road transport	0%	-1%	-4%	-9%
C: storage	-9%	-7%	-8%	-7%
C. Other	10%	8%	9%	8%
Exports	8%	6%	5%	5%
Production Side				
P: Renewables	172%	148%	134%	122%
P: Hydro	8%	7%	7%	6%
P:Wind	89%	80%	74%	67%
P: Wind onshore	40%	36%	32%	29%
P: Wind offshore	49%	44%	42%	39%
P: Solar	21%	18%	16%	15%
P: SolarPV	21%	18%	16%	15%
P: CSP	0%	0%	0%	0%
P: Biomass	51%	41%	34%	30%
P: Geothermal	3%	2%	3%	3%
P: Other	0%	0%	0%	0%
P: Nuclear	-164%	-158%	-142%	-123%
P: Other storage output	13%	12%	11%	11%
Imports	0%	6%	8%	9%
P: CCS	0%	0%	0%	0%
Intensities				
fuel input intensity	65%	84%	86%	77%
emission factor	-10%	-23%	-25%	-22%

Source: Results from the decomposition analysis.

On the consumption side it can be observed that new appliances in road transport add to emissions rather than to emission reductions: they are newly introduced into the market and did not yet exist in the base year and thus constitute additional emissions. The same holds true for electricity consumption from storage. Traditional appliances, however, deliver emission reductions compared to the base year due to the change of consumption patterns and due to efficiency improvements. These emission reductions increase from 16% in 2020 to 30% in 2050 (Table 7). By 2050 emission reductions of 33 Mt compared to the base year are achieved by the change of consumption patterns and energy efficient improvement of traditional appliances.

With regards to the production of electricity, it is evident that the increasing share of renewables in electricity production contributes to emission reductions. Figure 7 shows that emission reduction contribution from renewables increases in absolute terms from 111 Mt in 2010 to 134 Mt in 2050. It is assumed that imported electricity in the scenario, which will increase from 5 TWh in 2030 to 10 TWh in 2050, is only supplied by renewable sources of energy. As these imports are categorized as being from CO_2 free generation sources they trigger emission reductions as outlined in Table 7. Exports also provide positive contributions to emission reductions as the reference scenario assumes that from 2010 onwards no electricity will be exported.[11] Electricity generation from storage increases and is methodologically assumed to be categorized as a non-emitting source of electricity generation. Thus the effect on emission reductions is positive, while relatively constant in its share.

Fuel input intensity is simply the fossil fuel input divided by the production output. If the fuel input intensity decreases then emissions will be reduced as fossil fuels are used more effectively (i.e. fuel switching, efficiency improvements). In the reference without CCS scenario the fuel input intensity variable contributes positively to emission reductions due to both improvements in the efficiency of conventional power plants over time and a decline in the amount of electricity generated by these power plants by 2050. In 2050 the decreased fuel input intensity contributes around 84 Mt to emission reduction (Figure 7).

In the given scenario the emission factor increases and contributes additional emissions rather than emission reductions: In 2050, 234 Mt CO_2 are emitted by the power sector in total with a fuel input of 2283 PJ. The emission factor has slightly increased and thus adds emissions as the decomposition analysis reveals. It is likely that the phase out of nuclear power and the exclusion of CCS technology in the scenario contributes to this increase in emission factor due to the 'gap' in electricity production being replaced in part by electricity produced from fossil fuels, which would therefore produce additional emissions that would otherwise have been omitted.

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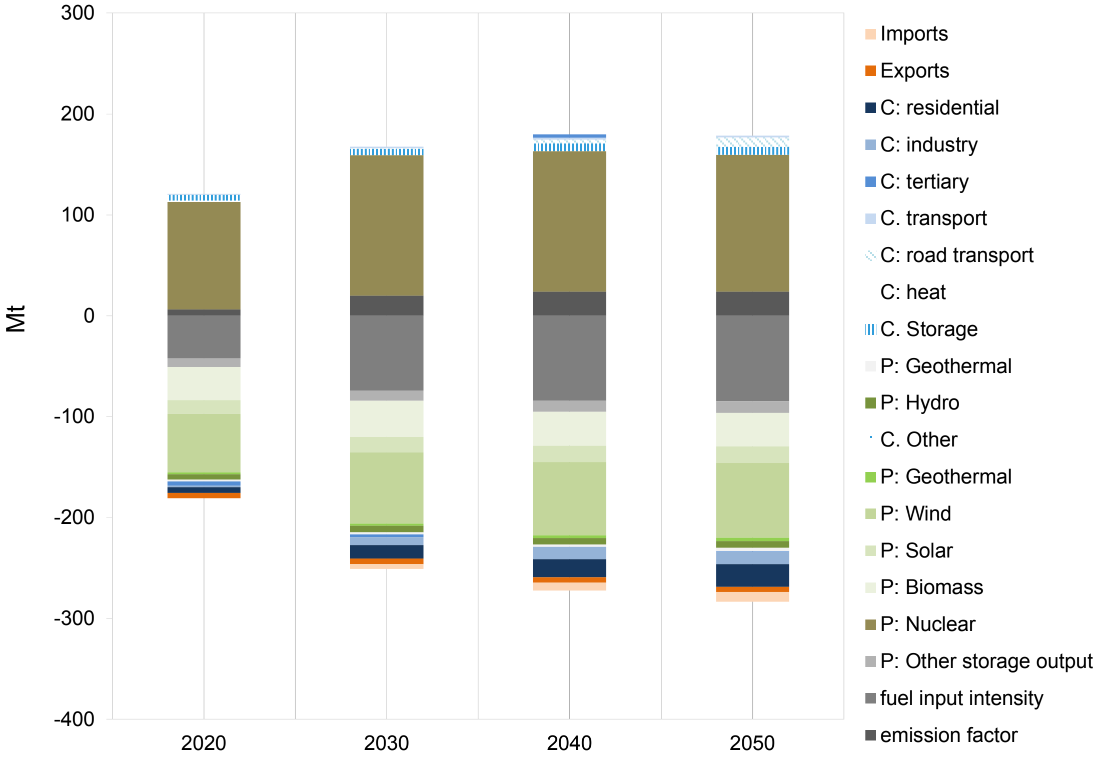
[11] As mentioned in WP 1.2., exports are accounted for on the demand side under the following assumption: exports relate to electricity **consumed** by consumers abroad, while imports are accounted for on the production side as they reflect electricity **produced** abroad.

Figure 7: Blueprint Germany / reference without CCS scenario: absolute emission changes compared to the base year in 2020, 2030, 2040, 2050..[12]



Source: results from decomposition analysis

Innovation Scenario without CCS

In the innovation scenario the world will not change unrecognisably from the world in the reference scenario; however avoiding the impact of climate change is now considered a high priority, now that an international consensus on climate protection has been achieved. Emissions trading will play a major role in this context. All consumption sectors must deliver ambitious emission reductions by applying energy efficiency measures and in some cases extensive technical changes, which may lead to additional costs for the economy. Table 8 and Figure 8 display the results of the decomposition analysis in relative and absolute terms respectively.

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[12] Figure 7 depicts the absolute emission changes compared to the base year that each of the causal factors exhibits in the reference scenario without CCS. C: indicates consumption areas, while P: indicates production technologies. Pattern-filled segments reflect consumption areas of new appliances.

Table 8: Blueprint Germany / innovation scenario without CCS: relative emission reduction contributions of the causal factors compared to the base year (2005).

Causal factor	2020	2030	2040	2050
Consumption side				
C: traditional appliances	39%	32%	31%	46%
C: residential	5%	6%	8%	13%
C: tertiary	11%	8%	7%	13%
C: industry	24%	19%	16%	21%
C. transport	0%	-1%	-1%	-2%
C: New appliances	0%	-1%	-3%	-6%
C: road transport	0%	-1%	-3%	-6%
C: storage	-4%	-5%	-7%	-17%
C. Other	4%	3%	2%	3%
Exports	4%	2%	1%	2%
Production Side				
P: Renewables	106%	90%	88%	128%
P: Hydro	7%	4%	4%	4%
P:Wind	55%	56%	59%	83%
P: Wind onshore	26%	17%	15%	20%
P: Wind offshore	28%	39%	44%	63%
P: Solar	12%	10%	9%	12%
P: SolarPV	12%	10%	9%	12%
P: Biomass	31%	16%	11%	14%
P: Geothermal	2%	3%	5%	16%
P: Nuclear	-80%	-53%	-40%	-52%
P: Other storage output	8%	9%	11%	22%
Imports	0%	7%	12%	21%
P: CCS	0%	0%	0%	0%
Intensities				
fuel input intensity	31%	19%	10%	20%
emission factor	-8%	-2%	-5%	-68%
relative emission reduction compared to base year	**35%**	**61%**	**81%**	**96%**

Source: Results from the decomposition analysis.

In the innovation scenario without CCS the consumption of electricity by new appliances in the heat market and electric mobility add to emissions (19.8 TWh). This is to be expected as these appliances are newly introduced into the market and did not previously exist in the base year and therefore constitute additional emissions. In contrast, traditional appliances contribute to emission reductions due to changing consumption patterns and improvements in energy efficiency. In 2050 these add up to 151 Mt compared to the base year, which is more than three times as much as in the reference scenario (compare Table 7) and can be explained by the strong energy efficiency improvements assumed to be achieved in this scenario.

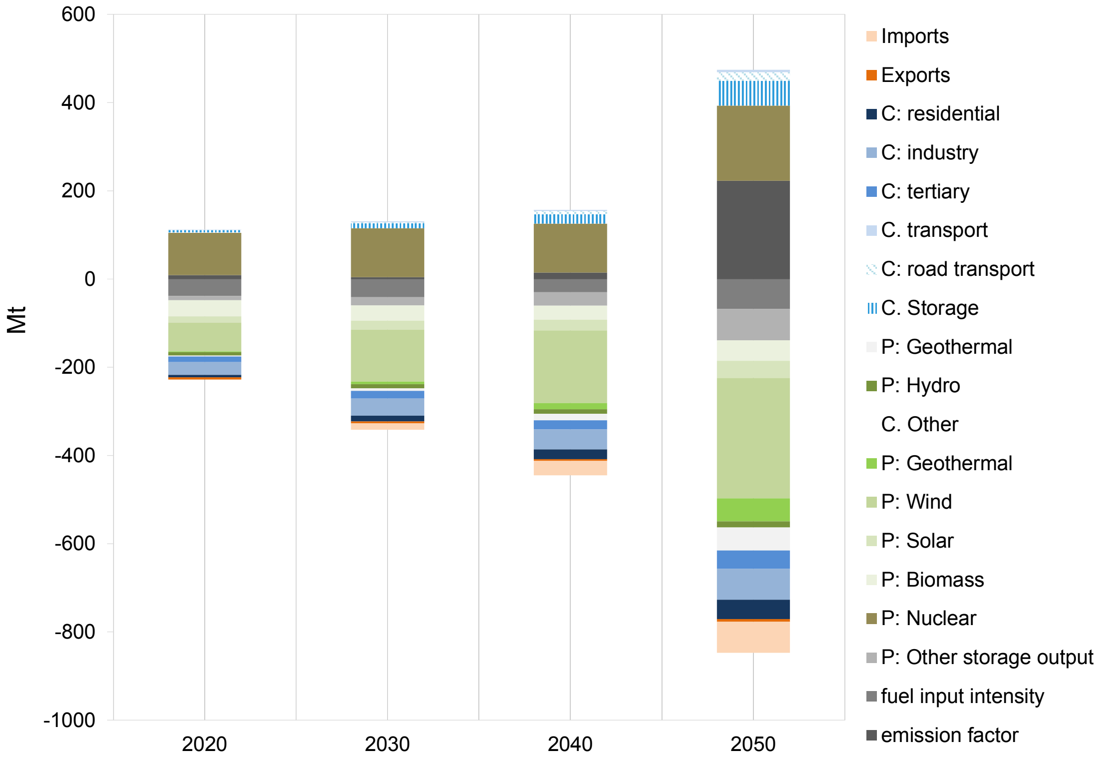
With regards to the production of electricity, it is evident that the increasing share of renewables in electricity production contributes considerably to emission reductions. Figure 8 shows that emission reduction contribution from renewables increases in absolute terms from 125 Mt in 2010 to 424 Mt in 2050. Based upon the assumption that electricity will only be imported from renewable energy sources (i.e. 15 TWh in 2030 increasing to 48 TWh in 2050) it is expected that these CO_2 free imports of electricity will also trigger emission reductions. Electricity exports provide further contributions to emission reductions as the innovation scenario assumes that from 2010 onwards no electricity will be exported. Electricity generation from storage increases and is methodologically assumed to be categorized as a non-emitting source of electricity generation. In the innovation scenario storage capacities are expanded more strongly than in the baseline scenario, thus the contribution to emission reductions from electricity generation storage increases.

The innovation scenario assumes that nuclear power is phased out in Germany, thus the phase out of nuclear electricity generation needs to be substituted by other electricity generation sources and in turn the phase out contributes additional emissions rather than emission reductions.

The fuel input intensity contributes to emission reductions as in the future time steps the efficiency of conventional power plants increases while at the same time less electricity is generated by these power plants. In 2050 decreased fuel input intensity contributes around 67 Mt to emission reduction (Figure 8). Interestingly the contribution of fuel input intensity to emission reductions is lower in this scenario than the reference scenario without CCS. Given the intermittent nature of renewable energy sources, back up electricity generation provisions (i.e. from fossil fuel) are required to ensure a reliable and secure power supply. As a consequence, it is likely that a scenario with a higher share of renewables will result in fossil fuels being used less efficiently as a provider of back up electricity generation and therefore the combustion process will not necessarily be optimised.

In the given scenario, the emission factor increases, and contributes additional emissions rather than emission reductions: In 2050 14 Mt CO_2 are emitted by the power sector at a fuel input of 95 PJ.

Figure 8: Blueprint Germany / innovation scenario without CCS: absolute emission changes compared to the base year in 2020, 2030, 2040, and 2050.



Source: Results of decomposition analysis

Reference Scenario with CCS

The reference scenario with CCS follows along the same lines as the reference scenario. It differs in that it exploits CCS technology. Table 9 and Figure 9 summarise the results from the decomposition analysis regarding the reference scenario. Results are listed for each of the years considered in the study and refer to the base year always (and not to the previous year).

Table 9 Blueprint Germany / Reference Scenario with CCS: relative emission reduction contributions of the causal factors compared to the base year (2005).

Causal factor	2020	2030	2040	2050
Consumption side				
C: traditional appliances	16%	21%	17%	19%
C: residential	9%	12%	12%	13%
C: tertiary	7%	3%	-2%	0%
C: industry	2%	7%	8%	7%
C. transport	-1%	-1%	-1%	-1%
C: New appliances	0%	-1%	-3%	-5%
C: road transport	0%	-1%	-3%	-5%
C: storage	-9%	-6%	-5%	-5%
C. Other	10%	7%	6%	-18%
Exports	8%	5%	4%	3%
Production Side				
P: Renewables	172%	121%	89%	65%
P: Hydro	8%	6%	4%	2%
P:Wind	89%	66%	49%	36%
P: Wind onshore	40%	29%	21%	14%
P: Wind offshore	49%	36%	28%	22%
P: Solar	21%	14%	11%	8%
P: SolarPV	21%	14%	11%	8%
P: Biomass	51%	33%	23%	16%
P: Geothermal	3%	2%	2%	2%
P: Nuclear	-165%	-129%	-94%	-79%
P: Other storage output	13%	9%	7%	6%
Imports	0%	6%	5%	5%
P: CCS	0%	19%	41%	46%
Intensities				
fuel input intensity	65%	67%	53%	78%
emission factor	-10%	-19%	-20%	-14%
relative emission reduction compared to base year	**19%**	**30%**	**40%**	**49%**

Source: Results from decomposition analysis

With regards to consumption it can be observed that new appliances in the heat market add to emissions rather than to emission reductions: they are newly introduced into the market and did not yet exist in the base year and thus constitute additional emissions. The same holds true for electricity consumption from storage. Traditional appliances, however, due to efficiency improvements exhibit increasing absolute amounts of emission reductions that in 2050 add up to 33 Mt compared to the base year, which is in the same magnitude as in the reference scenario without CCS.

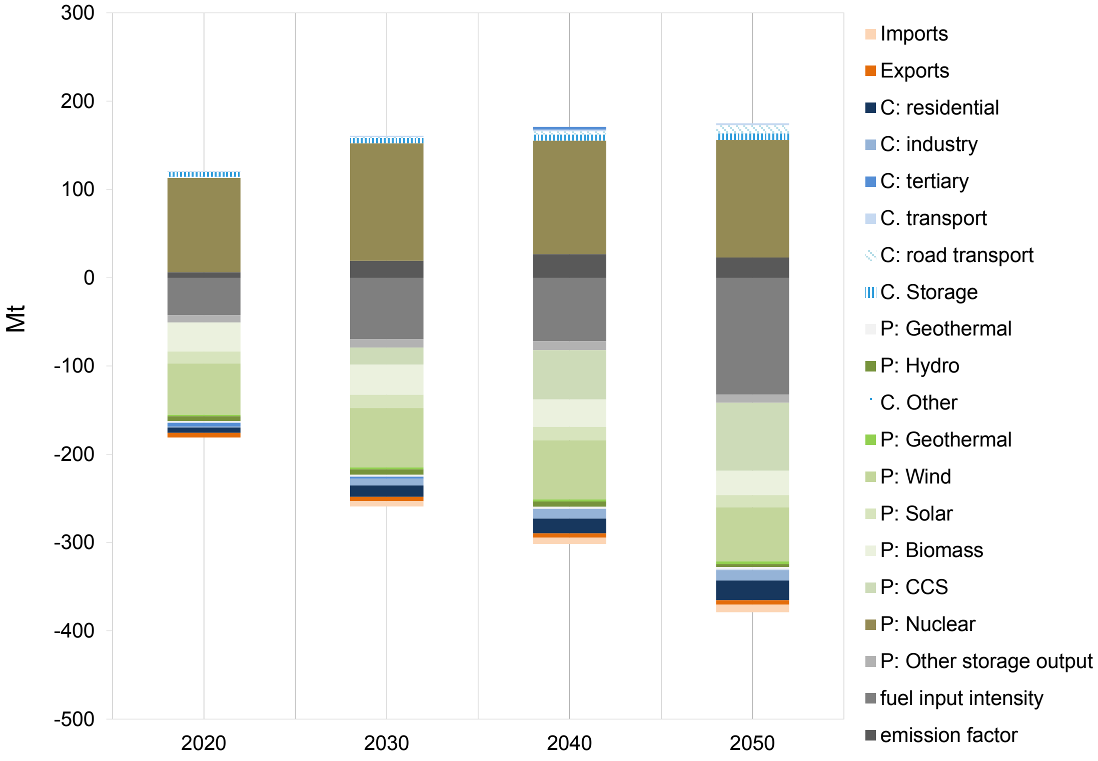
Interestingly the production of electricity by renewable energies contributes steadily to emission reductions (111 Mt in 2010, 109 Mt in 2050). This represents a clear difference from the reference scenario without CCS and demonstrates the effect that the inclusion of CCS technology in the energy mix exhibits on the role of renewables. As in all scenarios considered in this study electricity will be imported solely from renewable energy sources is assumed and imports increase from 6 TWh starting in 2030 to 10 TWh in 2050. As these imports are categorized as being from CO_2 free generation sources they trigger emission reductions, which remain at a nearly constant scale throughout the considered years (around

5-6%). Exports of electricity also result in emission reductions as the reference scenario with CCS assumes that from 2010 onwards no electricity will be exported any longer. Electricity generation from storage increases and is methodologically assumed to be categorized as a non-emitting source of electricity generation. In the reference scenario with CCS emission reductions achieved due to storage technology in electricity generation remains nearly constant.

The reference scenario with CCS assumes that nuclear power is phased out in Germany, thus the phase out of nuclear electricity generation needs to be substituted by other electricity generation sources and in turn the phase out contributes to additional emissions of 132 Mt by 2050 compared to the base year (Figure 9).

Fuel input intensity contributes to emission reductions as in the future time steps the efficiency of conventional power plants increases while at the same time less electricity is generated by these power plants. In 2050 decreased fuel input intensity contributes around 132 Mt to emission reduction (Figure 8). Given the intermittent nature of renewable energy sources, back up electricity generation provisions (i.e. from fossil fuel) are required to ensure a reliable and secure power supply. The emission factor increases and contributes additional emissions rather than emission reductions. In 2050 175 Mt CO_2 are emitted by the power sector at a fuel input of 1709 PJ.

Figure 9 Blueprint Germany / Reference scenario with CCS: absolute emission changes compared to the base year in 2020, 2030, 2040, and 2050.



Source: Results from decomposition methodology

3.3 2050 Pathways Analysis

3.3.1 Data situation and gap-filling

Data provided within the scope of the 2050 Pathway Analysis is quite broad. However, data given within the report itself concentrates mainly on energy overall. The only relevant information available for tier 1 and 2 are data for electricity generation within most sectors in part two of the 2010 version and the remark that GDP with an annual growth rate of 2,5% and population with an average annual growth rate of 0,5% apply for all pathways.

Alongside with the second version of the analysis report a calculator spreadsheet of the updated Online Calculator 2050 version with detailed and complex data information has been published. This spreadsheet offers a comprehensive set of relevant data. Electricity generation data is only given as gross numbers.

Regarding general data like base-year (2007) and 2010 statistics the analysis report mainly refers to the UK's Office for National Statistics (ONS). The spreadsheet directly offers copies of all relevant datasets within various chapters.

Fuel Input: Currently we could only locate data on primary input reserves. Gap-filling this crucial data by making estimated calculations is prone to errors and has thus been omitted at this point.

Fuel Prices: Within the 2010 report a vague cost assumption for fuel prices in a range between low and high-high (applicable to all pathways with no given concrete directions) is given for the years 2010, 2020, 2030 and 2040. For the data presented within this study cost assumptions in the middle range have been chosen. The upcoming third version of the 2050 Pathways Analysis is supposed to give some more detailed information regarding the cost analysis.

General: The fact that the original 2050 Pathway Analysis and the updates are presented separately in Version 2 provide a challenge to obtain an overall impression of the relevance of changes. Besides the acknowledgements on the changes within each sector, 16 new pathways are presented and only an updated version of *Pathway Alpha*, which is now referred to as *Pathway One* is given. Even though the changes are described as minor, the lack of an updated 'summary of the selection of levels and trajectories for the different pathways' (*Beta to Zeta*) makes a further data analysis of those pathways impossible.

The third version of the 2050 Pathways Analysis is announced to be published in summer 2011 and promises to deliver more details on cost development. Furthermore, it may provide a merged version including all pathways in a consolidated single report.

3.3.2 Decomposition analysis

Following a review of the study and the analysis of the data availability (see previous section) it was evident that the necessary information to complete a decomposition analysis was unfortunately not available. This is mainly due to the fuel input not being available. The comprehensive set of data – given fuel input was available – would allow for a decomposition analysis with focus on the production side, as data on electricity demand is available on sectoral level (no distinction between traditional and new appliances possible).

3.4 Swedish long-term low carbon scenario

3.4.1 Data situation and gap filling

The analysis of the energy mix in 2050 was beyond the scope of (see , (Jenny Gode et al., 2010) p.39). Despite a value for electricity generation from hydro power in 2050 (68 TWh), the only further indication of electricity generation technologies was into the category "Nuclear, wind, increased hydro, solar, and wave power" and into CHP (both industry and district heating networks). For CHP however, it was not possible to derive from the study the mix of fuel input used for electricity purposes only. Thus, we were unable to account and attribute the remaining 8% (2005) and the remaining 11% (2050) of electricity production to the roster. The values provided by the study are (2005, 2050 respectively): 11.9 TWh, 16.3 TWh in the Biofuels 2050 scenario and 11.9 TWh and 18.2 TWh in the Fossil fuels + BECCS scenario. The common roster of data and information has been gap-filled were possible:

Base year values for electricity demand have been readily available from the study and were cross checked with the data given in (Energimyndighet, 2009) . This holds true for all end-using sectors. Values for population have been retrieved from (Statistics Sweden, 2011) and then extrapolated based on the information given in the study (17% increase by 2050). GDP values have been retrieved from (Energimyndighet, 2009) and extrapolated to 2050 by using the assumption in the study that GDP grows by 2.25% annually.

2050 values were readily available from the study for electricity demand by the various end-using sectors for the Biofuels 2050 scenario. These have been extrapolated by the authors from the base-year and intermediate values provided in (Energimyndighet, 2009) .

For the Fossil fuels + BECCS scenario however, no value was indicated for electricity demand from the residential & services sectors. We assume that this data stems from (J Gode & Jarnehammar, 2007), which is not available to us. Thus, for the moment no electricity consumption in 2050 for the Biofuels 2050 scenario is indicated.

Intermediate values for electricity consumption (except for the residential and services sector[13]) have been gap-filled for 2010, 2020, 2030 from (Energimyndighet, 2009) as this source was listed to be the base for the scenarios (p. 12 (Jenny Gode et al., 2010)).

3.4.2 Decomposition analysis

Following a review of the study and the analysis of the data availability it was evident that the necessary information to complete a decomposition analysis was unfortunately not available. For example, the fossil fuel input associated with the production of electricity from CHP was not provided explicitly in the study. Furthermore, it was beyond the scope of the study to

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[13] Electricity consumption in 2030 from the residential and services sector stem from (Jenny Gode & Jarnehammar, 2007) , which has been made available to us recently but is written in Swedish.

determine the contribution of nuclear, wind, increased hydro, solar and wave power in 2050, so that these electricity generation sources were bundled into a single category. Given that the majority of Sweden's electricity supply is generated from non-fossil sources and that essential data required for the decomposition analysis was not available, it was decided that the study would currently not be suitable for further analysis. However, tier 1 information was collected as stringently as possible and is summarised in Table 3.

3.5 SRU - Pathways Towards a 100% Renewable Electricity System

3.5.1 Data availability and gap filling

Data has been documented in various tables and figures and has been retrieved from the study itself. There has been no detailed breakdown of electricity consumption regarding neither end-use sectors nor a distinction between traditional and new appliances. The production side of electricity however, has been documented in detail for the base year and 2050. Thus a decomposition analysis has been deemed possible, but due to the data availability the focus of decomposition is thus more detailed on the power production side. Data for electricity related CO_2 emissions in 2005 has been gap filled by (UBA, 2011a), and primary energy input has been retrieved from (AGEB, 2005).

3.5.2 Decomposition Analysis

Scenario 2.1.a

Scenario 1a belongs to scenario group 1 which sketches a scenario of German energy self-sufficiency within a regional network with Denmark and Norway. This scenario exhibits with no net imports and relatively low (509TWh) electricity demand in 2050. Table 10 displays the results of the decomposition analysis.

Table 10: SRU 2.1.a: Relative emission reduction contributions of causal factors

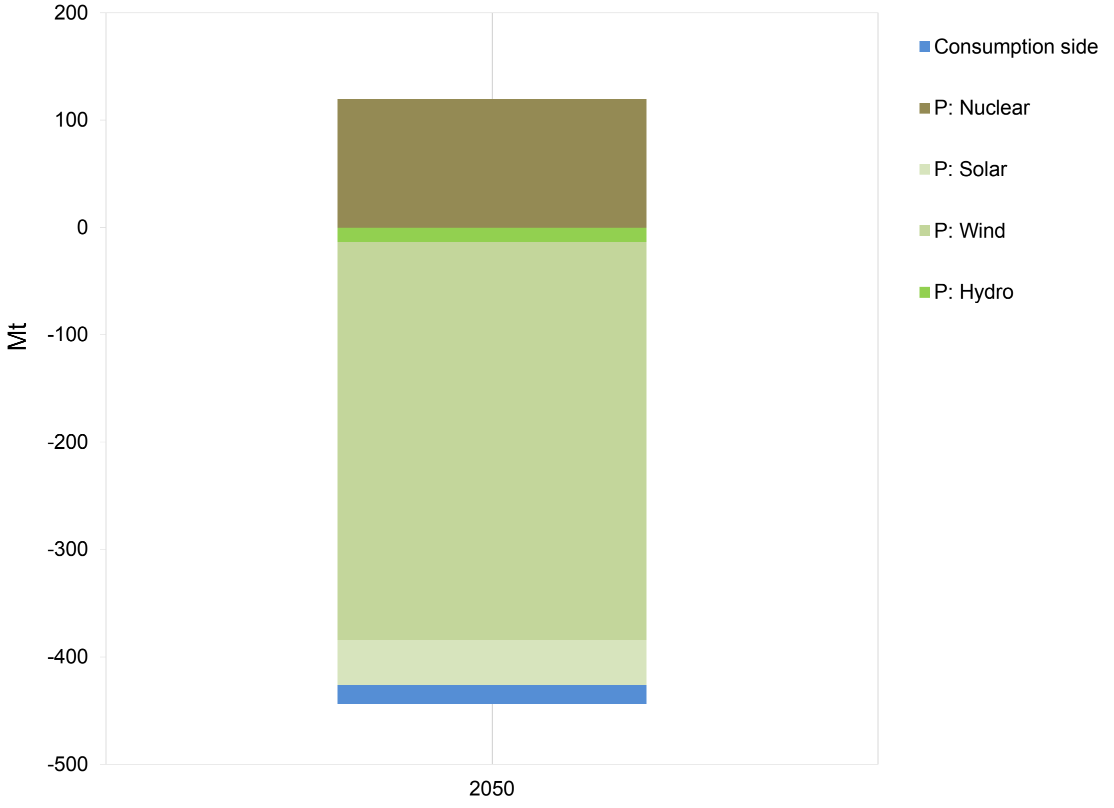
Causal factor	2050
Consumption side	5%
C: Consumption	6%
C. Other	-0.28%
Production Side	95%
P: Renewables	131%
P: Hydro	4%
P:Wind	114%
P: Solar	13%
P: Nuclear	-37%
relative emission reduction compared to base year	100%

Source: results from decomposition analysis

The scenario 2.1a assumes a slight decrease in electricity consumption (542TWh in the base year and 509TWh in 2050), thus the consumption side accounts for a slight share of emission reductions in the magnitude of 18TWh in 2050. On the production side renewable energies contribute towards emission reductions in the magnitude of 131% which is partially compensating the additional emissions produced by the phase out of nuclear power. Additional emissions in this scenario are solely based on the phase out of electricity generation by nuclear technology. In total these additional emissions are compensated for by the slight decrease in electricity consumption and the production of electricity from renewable energy sources.

The production of electricity is assumed to be fully decarbonized by 2050, which means that no emissions are produced and no fuel input that produces emissions is utilized. There is thus no contribution of fuel input intensity and emission factor to emission reductions as they ceased to be causal factors of emissions by 2050. Figure 10 demonstrated the absolute contributions to emission changes by the causal factors considered in the 2.1a scenario.

Figure 10 SRU/ 2.1.a: absolute emission changes in 2050 compared to the base year



Source: results from decomposition analysis

Scenario 2.1.b

Scenario 2.1.b belongs to scenario group 1 which sketches a scenario of German energy self- sufficiency within a regional network with Denmark and Norway. This scenario exhibits no net imports and relatively high (700TWh) electricity demand in 2050.

Table 11:

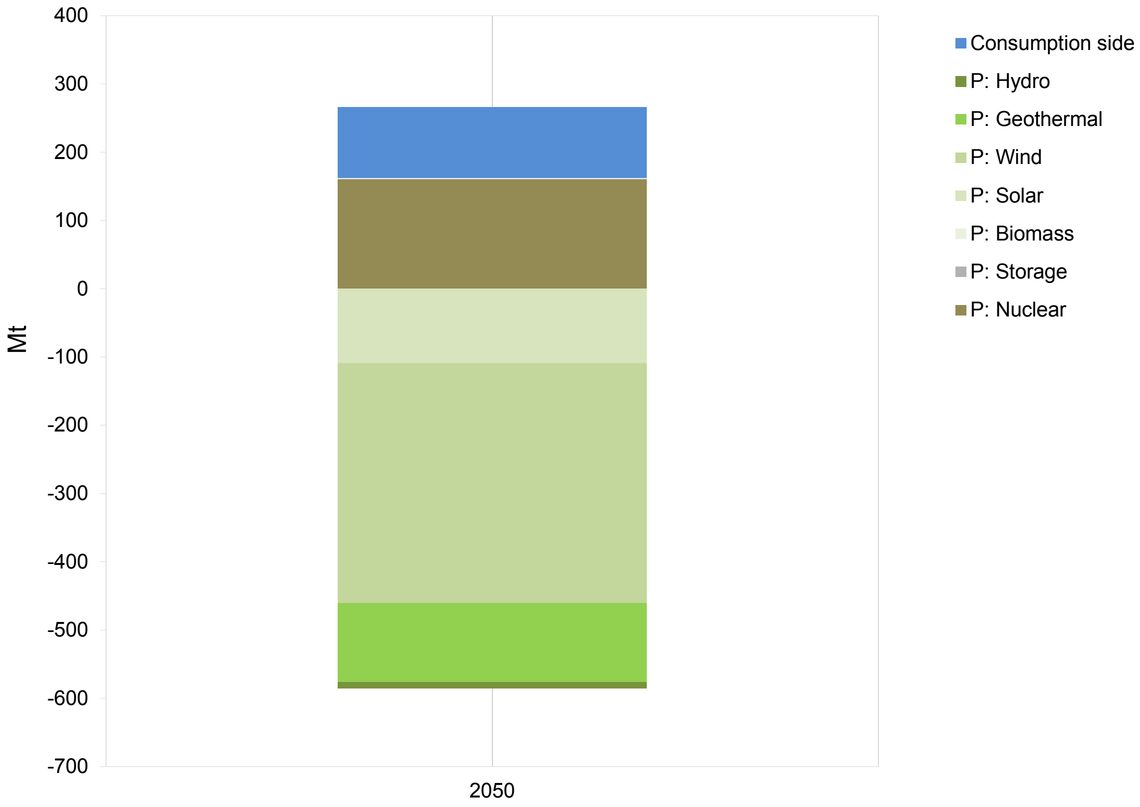
Causal factor	2050
Consumption side	-32%
C: Consumption	-37%
C. Other	-0.3%
Exports	5.3%
Production Side	132%
P: Renewables	180%
P: Hydro	3%
P:Wind	109%
P: Solar	34%
P: Biomass	-0.4%
P: Geothermal	36%
P: Nuclear	-49%
P: Storage	1%
relative emission reduction compared to base year	100%

Source: results from decomposition analysis

In contrast to scenario 2.1a, scenario 2.1.b assumes an increase in electricity consumption (542 TWh in the base year and 700 TWh in 2050), thus the consumption side accounts for additional emissions in the magnitude of 104 Mt CO_2 (including exports and other consumption) in 2050 compared to the base year. On the production side renewable energies contribute to emission reductions of 180% which compensates for the additional emissions produced by the phase out of nuclear and the additional emissions triggered by higher electricity consumption. Electricity generation from wind contributes the most to emission reductions (352 Mt), followed by solar. Interestingly, biomass produces slight additional emissions (but in the magnitude close to zero) despite its absolute growth. This is can be explained by the fact that its actual share in electricity generation slightly decreases by 2050.

The production of electricity is assumed to be fully decarbonized by 2050, which means that no emissions are produced and no fuel input that produces emissions is utilized. There is thus no contribution of fuel input intensity and emission factor to emission reductions as both these factors ceased to be causal factors of CO_2 emissions. Figure 11 displays the absolute emission changed produced by the causal factors considered in the SRU 2.1b scenario.

Figure 11: SRU 21b: absolute emission changes in 2050 compared to the base year



Source: results from decomposition analysis

4 Comparison of analysis results and conclusions[14]

The decarbonisation pathways considered in this analysis present alternative views on how emission reductions can be achieved in both Germany and the UK by 2050. The extent to which these economies can be fully decarbonised will depend upon the implementation of policies to promote energy efficiency and support the development of low carbon technologies for electricity production. The more ambitious scenarios within both the Blueprint Germany and the 2050 Pathway Analysis study imply that CO_2 emission reductions in excess of 90% compared to the base year are feasible under a policy framework that facilitates such a low carbon transition in both countries. The CO_2 emission reductions in the electricity sector for each of the scenarios considered in the analysis are a:

- 96% in the WWF Innovation w/o CCS scenario;
- 94% in the WWF Innovation w CCS scenario;
- 51% in the WWF Reference w CCS scenario;
- 34% in the WWF Reference scenario:
- 8% in the UK Reference Case Pathway;
- 142% in the UK Pathway Alpha
- 100% in the SRU 2.1a scenario
- 100% in the SRU 2.1b scenario

The Pathway Alpha scenario apparently exceeds a target of zero emissions in 2050 due to bioenergy crediting, which leads to negative emissions of -80 Mt. Since the definition is not clear within the 2050 Pathway Analysis study, clarification will be required before these results can be fully interpreted. Not considering the bioenergy credits, the Pathway Alpha would be characterized by CO_2 emission reductions of 91% - near full decarbonisation. Interestingly the various scenarios within these two studies envisage contrasting approaches to delivering a decarbonised economy with regards to projection trends for electricity consumption and the adoption of different technologies to enable the necessary CO_2 emission reductions.

The comparison of sectoral electricity demand illustrates that the two studies compared differ in their assumption about how the sectoral electricity demands will evolve in the future. While the WWF scenarios all project decreasing demand in the residential, tertiary and industry sector, the two UK scenarios considered show increasing demand throughout all sectors. The transport sector is a sector that seems to be agreed upon about a future increase of electricity consumption due to increasing electrification in this sector. The different projection trends of electricity consumption demonstrate two distinct pathways for achieving a low carbon economy. While the emphasis of all of the WWF scenarios is on a reduction in electricity consumption through energy efficiency improvements and a restructuring of

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[14] Please refer to the Appendix for detailed information on the SRU scenarios in a framework of other German orientied studies.

industry, the Pathway Alpha scenario depends upon the electrification of many aspects of the economy to maintain existing living standards without increasing emissions. Such widespread electrification will inevitably increase electricity consumption considerably. Further research will be required to ascertain how robust the assumptions of both studies are with regards to electricity consumption in 2050.

Despite these fundamental differences in projection trends for electricity demand in 2050, the scenarios in both studies rely upon a considerable increase in renewables to provide electricity in the future. In the case of the Blueprint Germany study, the assumption to phase out nuclear power requires this electricity provision to be replaced by renewables in order to achieve the decarbonisation targets. Whereas in the 2050 Pathway Analysis study, the growth in renewables is required to simply contribute to increasing electricity consumption as more and more applications are electrified (i.e. mobility, heating ect.) Renewable energy sources for electricity generation therefore play a major role in all scenarios that consider a movement towards a decarbonised economy. It is worthwhile to point out that in the two studies that are comparable electricity generation from wind makes up the largest share of renewable energy production in the future. Given the wind energy resources available to both countries and the maturity of the renewable technology this is to be expected.

The findings of the general comparison of the scenarios were further complemented by the results of the decomposition analysis. Although insufficient data was available to complete the decomposition analysis for the 2050 Pathway Analysis, the decomposition analysis of the Blueprint Germany study and the SRU study provided important insights that confirmed the results that can be obtained by a direct comparison of “primary data” and can complement these results through an actual quantification of emission reduction contributions. For example, the decomposition analysis attributed an increase in electricity consumption by the transportation sector as a causal factor producing additional emissions in the WWF scenarios (Table 12). The magnitude of these additional emissions however is determined by the level of electrification assumed in a given scenario. In this case the innovation scenario exhibits larger additional emissions than the reference scenarios in which electrification is following a slower trend.

It is evident from the decomposition anaylsis for both the WWF and SRU studies that the energy mix in 2050 plays an important role in the emissions trajectory of all scenarios. For example, the phase out of nuclear energy produces additional emissions that need to be compensated via other measures to ensure that the emissions target in each scenario is achieved. The deployment of renewable energy is a vital measure in all scenarios to reduce emissions by 2050, however interestingly the decomposition analysis of the WWF study has demonstrated that the benefits of using the non-CO_2 electricity producing technology may be slightly reduced by the need to use back up fossil fuel plants more inefficiently. In contrast, the SRU study assumes that decarbonisation of the power system is not dependent upon fossil fuels for back up energy supply. This conflict demonstrates the value of such an analysis by identifying the similarities and importantly the differences between scenarios, challenging the robustness of the author’s assumptions and quantifying the emissions change associated with all of the causal factors to provide transparent information to facilitate political decision making.

Table 12 Absolute emission contributions of causal factors in selected decomposed scenarios

	Scenario				
Causal factor	WWF Ref	WWF Ref CCS	WWF Innov	SRU 2.1.a	SRU 2.1.b
Consumption side	**-29.92**	**10.65**	**-91.87**	**-17.77**	**103.53**
C: traditional appliances	-33.13	-32.52	-150.54	-18.68	119.66
C: residential	-22.53	-22.11	-44.10	N/A	N/A
C: tertiary	-0.62	-0.61	-41.95	N/A	N/A
C: industry	-12.01	-11.79	-69.98	N/A	N/A
C. transport	2.03	1.99	5.49	N/A	N/A
C. New appliances	9.36	9.18	19.80	N/A	N/A
C: road transport	9.36	9.18	19.80	N/A	N/A
C. Storage	7.86	7.72	55.75	N/A	N/A
C. Other	-8.95	31.24	-10.53	0.91	0.91
Exports	-5.05	-4.96	-6.35	0.00	-17.04
Production side	**-19.88**	**-70.93**	**-394.84**	**-306.23**	**-427.53**
P: Renewables	-133.74	-109.07	-424.01	-425.85	-584.09
P: Hydro	-6.51	-3.54	-13.90	-13.73	-8.97
P: Wind	-74.02	-61.01	-273.06	-370.55	-351.73
P: Solar	-16.30	-13.94	-38.84	-41.57	-108.94
P: Biomass	-33.36	-27.52	-46.41	0.00	1.30
P: Geothermal	-3.55	-3.07	-51.81	0.00	-115.75
P: Nuclear	135.43	132.92	170.20	119.62	160.06
P: Hydrogen	0.00	0.00	0.00	0.00	0.00
P: SNG	0.00	0.00	0.00	0.00	0.00
P: Other storage output	-11.70	-9.34	-71.37	0.00	-3.50
Imports	-9.87	-8.52	-69.65	0.00	0.00
P: CCS	0.00	-76.91	0.00	0.00	0.00
Intensiies	**-60.20**	**-108.73**	**N/A**	**N/A**	**N/A**
fuel input intensity	-84.36	-132.09	-67.14	N/A	N/A
emission factor	24.17	23.36	223.85	N/A	N/A
total emission reduction compared to base year	**110.00**	**169.00**	**330.00**	**324.00**	**324.00**

Source: Results from decomposition analysis.

The study has revealed that the datasets used to determine these decarbonisation pathways are not always fully transparent with the reports often failing to provide essential data for a decomposition analysis. The analysis of scenarios from various studies during the course of this project has shown several issues that can provide insights into future research needs and documentation standards to improve the interpretability of data from studies. Several points should be highlighted.

- Documentation of data and assumptions various significantly between studies, even if the scope of the studies can be seen as being very similar to each other.
- A minimum of data is required to provide the means of a standardized comparison between studies and scenarios. A future standard on data documentation for a specific type of studies may be a viable approach in order to ensure comparability, interpretability and further analysis of such studies. Given the urgency with which the decarbonisation efforts are being approached within the EU policy context, such a minimum standard would help to give this process the momentum it deserves.

5 Annex A: Excursus on Germany: Analysis of the future development of the German electricity sector in various recent German energy policy scenarios

5.1 Introduction

The objective of this project is to compare and analyse European energy scenarios regarding the long-term development of the European electricity systems. As the number of scenario studies for the whole of Europe is limited and as a number of studies are available for individual European countries, this work package takes a look at some of these individual countries. One of them is Germany, which has the biggest and perhaps most important electricity market within Europe. In this Annex a number of recent energy scenarios for Germany are compared in regard to the development of the electricity system described in these scenarios.[15] This is done with the goal of evaluating how far scenario studies on individual countries support some of the main findings so far extracted from the analysis of European energy scenarios.

This Annex will start by briefly introducing the six different energy scenario studies used in this scenario comparison. Afterwards some selected scenarios will be evaluated based on how electricity demand and electricity supply as well as electricity sector CO_2 emissions develop in the coming decades. The focus will be on the situation in the year 2050.

5.2 Scenario Studies

5.2.1 Energy Scenarios for an Energy Concept of the Federal Government

The scenario study „Energy Scenarios for an Energy Concept of the Federal Government" has been commissioned and released in 2010 by the German Federal Ministries of Economics (BMWi) and the Federal Ministry of Environment (BMU) as a basis for its energy concept finalised in autumn of 2010. The study has been prepared by a consortium consisting of the Institute for Energy Economics at Cologne University (EWI), the Institute of Economic Structures Research (GWS) and Prognos. In addition to a reference scenario four different policy scenarios were developed, which differ in regard to how many years of additional operating time is allocated to Germany's nuclear reactors (on top of the original phase-out law of 2002). For the policy scenarios the German government had defined various targets: They had to be compatible with a 40% greenhouse gas (GHG) emission reduction by 2020 and an 85% reduction by 2050 (versus 1990 emissions). Furthermore, the share of primary energy was stipulated to reach at least 50% by the middle of the century. An important objective of the policy scenarios was to highlight the effects of different assumptions about the operating time of Germany's nuclear power plants. For the following

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[15] As those scenarios found in the study commissioned by have already been discussed extensively in the main part of this report, they are not included in the comparison of this Annex.

comparison the study's "Scenario I B" has been chosen, as in that policy scenario the nuclear plants' operating time is only increased by four years, which is closest to the decision for a complete phase out until 2022 that has meanwhile (after the accidents in Japan's Fukushima-Daiichi nuclear power plant) been made.[16]

5.2.2 Lead Scenario 2010

The scenario study "Long-term scenarios and strategies for the expansion of renewable energy in Germany while taking into account the development in Europe and globally" (short: "Lead Study 2010") was commissioned by the German Federal Ministry of Environment (BMU). It was completed in 2010 and released in early 2011. The study was developed by the National Research Center for Aeronautics and Space (DLR), the Fraunhofer-Institute for Wind Energy and Energy System Technology (Fraunhofer IWES) and the Engineering Bureau for New Energies (IfnE). The study's main objective is to show how Germany's energy-related CO_2 emissions can be reduced by 85% until 2050 (compared to 1990 emissions). The study regards the growth in renewable energy as a central element for reaching this target and focuses on how these sources of energy develop throughout the course of the scenario. Nuclear power phase out is completed by 2025 and no use of CCS technology is assumed. The study focuses on describing one scenario (Base Scenario 2010 A), which will be included in the following comparison. Two additional "Base Scenarios" are developed and briefly described. In one of these two scenarios the market share of electric vehicles in total individual mobility is assumed to grow to 66% by 2050 (compared to 33% in the Base Scenario 2010 A), while in the other scenario an extension of the operating times of Germany's nuclear power plants by an average of 12 years is assumed to reflect the intentions of the German government at that time.

5.2.3 Energy Future 2050

The study Energy Future 2050 was released in 2009 and has been commissioned by the four big energy utilities in Germany, EnBW, EON, RWE and Vattenfall. The study has been prepared by the Research Center for Energy Economics (FfE). The main objective of the study is to describe the most likely development of the German energy system under different conditions.[17] For this purpose three different scenarios are developed. Scenario 1 is a reference case and describes how the energy system could evolve if its main drivers were to remain unchanged compared to the recent past. Scenario 2 and Scenario 3 assume considerably stronger energy efficiency improvements over time. In addition, Scenario 3 includes behavioural changes which reduce energy demand. Furthermore in Scenario 3 the operating times of each existing nuclear power plant is assumed to reach 60 years and some additional nuclear power plants are built until 2050. Scenario 3 is the most ambitious scenario in this study regarding CO_2 emission reductions and will be included in the following scenario comparison.

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[16] No policy scenario was developed in the study that assumes no extension of operating times for nuclear power plants beyond the operating times stipulated in the original phase out law of 2002.

[17] In contrast to most other energy scenario studies discussed here, this study does not formulate in advance a certain CO_2 or GHG emission reduction target for the year 2050.

5.2.4 Climate Protection: Plan B 2050

This study (Greenpeace, 2009), also released in 2009, has been commissioned by Greenpeace Germany and has been prepared by EUtech Energy & Manangement. Apart from a reference scenario one policy scenario is developed. This so called "Plan B" scenario will be included in the following scenario comparison. The main objective of this scenario is the reduction of domestic GHG by 90% until the middle of the century (compared to 1990 levels). No use of CCS technology is assumed and the scenario phases out nuclear power by 2015. Unlike policy scenarios of most other studies, no net electricity imports (from renewable sources) are assumed by 2050 to help realize deep cuts in CO_2 emissions. Instead all electricity demand is met by domestic renewable energy sources.

5.2.5 100% renewable electricity supply by 2050

The German Advisory Council on the Environment (SRU) has released a comprehensive study in early 2011 which developed different scenarios within several scenario families describing how Germany could by 2050 achieve an electricity system that is completely based on renewable energy sources. The first scenario family describes an autonomous electricity supply which does not at all rely on exchanging electricity with other countries. The second scenario family assumes that Germany conducts electricity trade with Denmark and Norway, while the third scenario family assumes that electricity is traded within all of Europe and Northern Africa. In all three cases scenario *families* are described, as each time two scenarios are developed, differing in electricity demand (509 TWh/a versus 700 TWh/a in 2050). Using an electricity model from DLR, for each scenario context the cheapest fully-renewable electricity system is determined for the year 2050. In the following scenario comparison two of this study's scenarios, both assuming electricity trade with Denmark and Norway, will be included: Scenario 2.1.a, which assumes low electricity demand and no *net* imports of electricity and Scenario 2.2.b, which assumes high electricity demand up to 15% of net electricity imports.

5.2.6 Energy Target 2050

The study "Energy Study 2050: 100% Electricity from Renewable Sources" has been conducted by the German Federal Environment Agency (UBA) and has been released in 2010. The study describes in three different scenarios how Germany can supply 100% of its electricity demand by renewable sources by 2050. One of the scenarios, called Regional Network, relies mainly on domestic renewable potential and electricity transmission within Germany. In the scenario International Large-Scale Technology, Germany's electricity supply in 2050 is based to some extent on the large-scale exploitation of renewable energy potentials in Germany, other European countries and Northern Africa. The third scenario on the other hand, called Local-Self-Sufficient, describes a scenario in which individual regions within Germany realise a self-sufficient electricity supply by 2050. This scenario requires the available technological and ecological potentials of the various renewable energy sources to be almost completely exploited in many regions and it also requires realising the available efficiency potential to the full extent. As only the Regional Network scenario is described in detail in the scenario study, this scenario will be considered in the following comparison.

5.3 Comparison and analysis of the development of the German electricity sector in the various scenarios

5.3.1 Electricity demand

Compared to recent years, electricity demand in Germany in 2050 is lower in most of the scenarios analysed (see Table 13). Only in the Base Scenario 2010 A a slight increase of 5% is observed. In the other scenarios demand in 2050 is between 4% (Scenario 3) and 24% (Scenario I B) lower than in 2005, 2007 or 2008.[18] Looking at the different sectors, the highest agreement is in the household sector, where all but one scenario assume a similar and significant decline in electricity demand (by between 36 and 49%). In the other scenario (Network of Regions) electricity demand also declines, but only by 18%. In the tertiary sector most scenarios assume a decline by about 20%, while one scenario (Scenario 3) assumes that electricity demand will be reduced by a little more than half. Significant uncertainties concerning the future development of electricity demand are in the industry sector, where some scenarios assume a decline in demand by up to about 40%, while one scenario (Scenario 3) assumes a *growth* in electricity demand by almost 50%. In the transport sector all scenarios agree that electricity demand will increase significantly.[19] However, while it increases in most scenarios by about 300%, growth is limited to 50% in Scenario 3 and is as high as 519% in Plan B. In Plan B electric vehicles are assumed to dominate individual passenger transportation by 2050, while the dissemination of electric cars in Scenario 3 is limited.

Table 13 Change (in %) in final electricity demand in four sectors between 2005/2007/2008 and 2050 in various scenarios

	Household	Tertiary	Industry	Transport	TOTAL
Network of Regions (UBA 2010)	-18%	-24%	-17%	329%	-7%
Scenario I B (BMWi 2010)	-39%	-20%	-39%	292%	-24%
Scenario 3 (EnBW et al 2009)	-49%	-52%	48%	50%	-4%
Base Scenario 2010 A (BMU 2010)	-36%	-19%	-13%	326%	5%
Plan B (Greenpeace 2009)	-46%	-22%	-22%	519%	-12%

Source: Own table, data based on energy scenario studies quoted.

5.3.2 Electricity supply

The following two figures show German electricity supply in the various scenarios for the years 2030 and 2050 (compared to actual data from 2010). Mainly due to the assumed improvements in energy efficiency, all scenarios assume that less electricity generation is needed in 2030 compared to today. However, the scenarios differ in the extent of the decline. Looking at electricity generation used domestically (i.e. accounting for net imports and net

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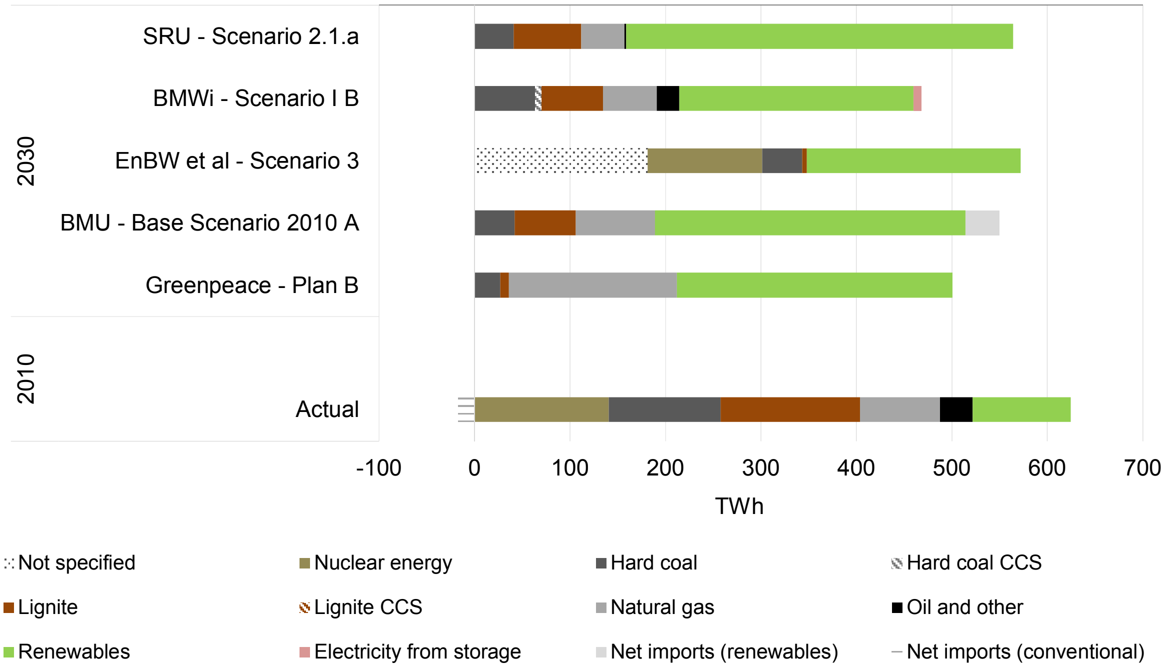
[18] For each scenario the change in electricity demand was calculated by comparing the demand in 2050 with the demand of the base year, which was either 2005, 2007 or 2008.

[19] The main reason for growth in electricity demand in the transport sector is the expected trend in increasing shares of partly or fully electric vehicles.

exports), the decline until 2030 is between 6% (in Scenario 3) and 23% (in Scenario I B). There's also a clear trend towards a higher contribution of renewable energy sources to electricity generation. This contribution at least doubles (Scenario 3) and in one scenario (Scenario 2.1.a) even almost triples compared to 2010. In line with the old phase-out law of 2002 as well as the recent phase-out decision by the current federal government, nuclear power is no longer used in most of these scenarios in 2030. The only exception is Scenario 3, in which nuclear power in 2030 contributes almost the same amount of electricity as in 2010.

Figure 12 Electricity generation by source (including net electricity imports) in 2010 (actual) and in 2030 in various scenarios

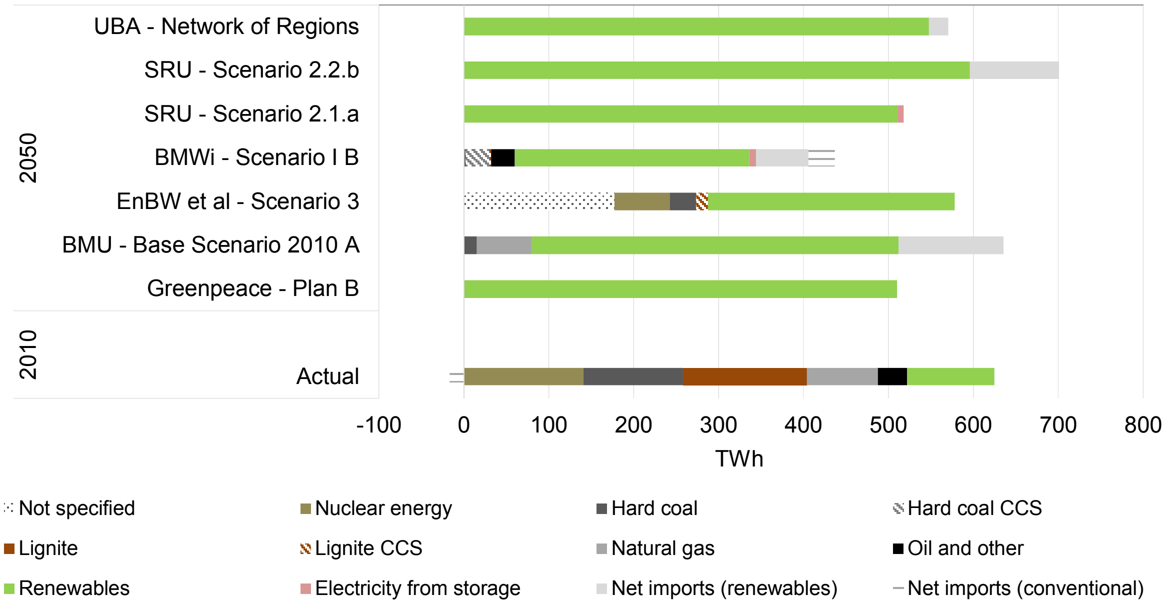


Source Own figure, data based on energy scenario studies quoted and for actual data on (AG Energiebilanzen, 2011)

While electricity generation from hard coal and lignite is significantly lower in all scenarios in 2030 compared to today (-49 to -86%), generation from natural gas is only slightly lower in most scenarios and even considerably higher in one of the scenarios (Plan B). The main reason for this change in relevance of these types of fossil fuels is the fact that specific CO_2 emissions of electricity generation based on natural gas is much lower than specific emissions of electricity generation based on hard coal or lignite. Furthermore, natural gas power plants are more flexible to adjust to the growing contribution from fluctuating renewable energy sources than lignite power plants. In one of the scenarios (Base Scenario 2010 A) by 2030 some contribution from renewables-based electricity generation from abroad is already assumed.

In line with the differing assumptions about the development of electricity demand (see Table 13), the amount of electricity generation by the middle of the century varies considerably in all the scenarios. Electricity generation (including imports) in 2050 is between about 440 TWh (Scenario I B) and 700 TWh (Scenario 2.2.b). That is equivalent to ranging from a 28% decline to a 15% rise in electricity generation compared to today. By 2050 hard coal and lignite are entirely or largely phased out in the electricity sector in those scenarios that do not assume the use of CCS technology for fossil fuel power plants. Even in the two scenarios which use CCS coal power plants, considerably less electricity is generated from coal than today (at least 83% less). The contribution of renewable energy sources to electricity generation (including imports of electricity from renewable sources) increases significantly in all scenarios, by at least 182% (Scenario 3) and by up to 580% (Scenario 2.2.b). In two scenarios (Scenario 2.2.b and Base Scenario 2010 A) over 100 TWh of electricity from renewable sources are imported in 2050, while only in three of the seven scenarios (Scenario 2.1.a, Scenario 3 and Plan B) analysed no net imports of electricity are assumed in 2050.

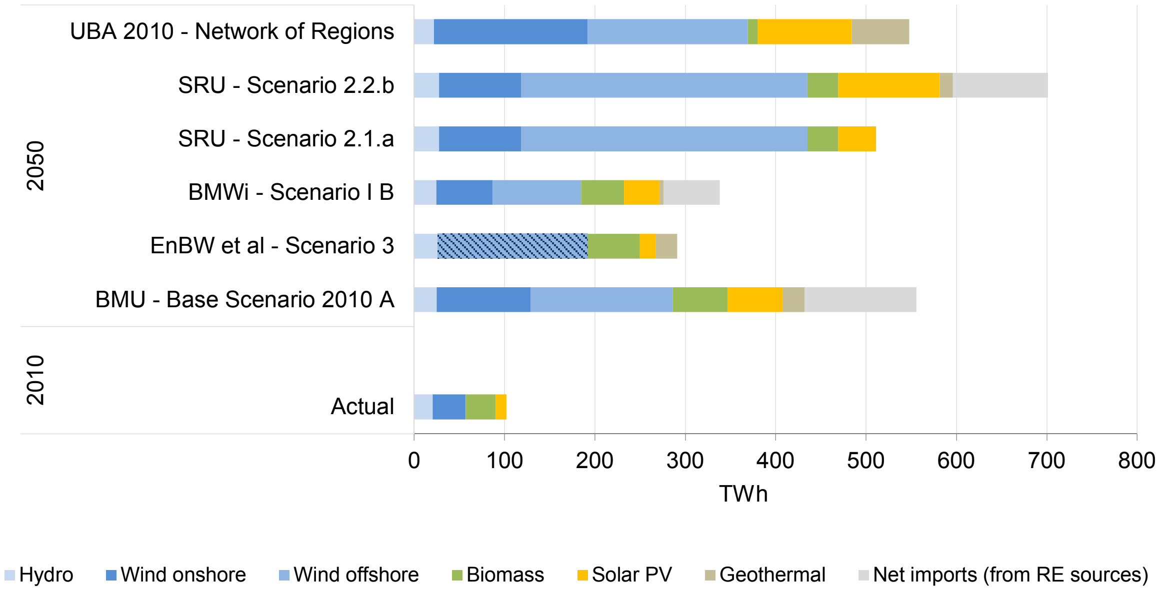
Figure 13	Electricity generation by source (including net electricity imports) in 2010 (actual) and in 2050 in various scenarios



Source:	Own figure, data based on energy scenario studies quoted and for actual data on (AG Energiebilanzen, 2011)

Figure 14 takes a closer look at electricity generation from renewable sources in 2050 according to the various scenarios. It is apparent that all scenarios see wind energy as Germany's most important source for renewable electricity in the future. While all scenarios see a considerable potential for increased electricity production from onshore wind energy (about 2 to 5 times the generation of 2010), the scenarios see an even bigger potential in offshore wind energy. However, expectations about the realisable potential of offshore wind power until 2050 vary considerably. Its contribution in the middle of the century varies from 98 TWh/a (Scenario I B) to 317 TWh/a (Scenario 2.2.b and Scenario 2.1.a). Electricity generation from biomass is increased to some extent in most scenarios. However, some scenarios (especially Network or Regions) limit the use of biomass for electricity generation as the sustainable potential of biomass use is limited and biomass might play an important role in mitigating CO_2 emissions in the transport sector. Due mainly to cost considerations the future expansion of solar PV and geothermal power plants is limited in most scenarios. However, in a few scenarios electricity generation from solar PV is increased five-fold (Base Scenario 2010 A) to ten-fold (Scenario 2.2.b) until 2050 compared to 2010 generation.

Figure 14 Renewable energy sources in electricity generation (including net electricity imports from renewable sources) in 2010 (actual) and in 2050 in various scenarios



Source: Own figure, data based on energy scenario studies quoted and for actual data on (AG Energiebilanzen, 2011) . Note: (EnBW, e.on Energie, Power, & Europe, 2009) do not provide separate numbers for onshore and offshore wind. To account for this, the corresponding segment is visualized with dashes.

Figure 15 shows the development of the share of renewable energy sources in meeting gross electricity demand in Germany (including net imports). In most scenarios the share reaches 37 to 40% by 2020 and 86 to 100% in 2050, up from 17% in 2010. In Scenario I B the share of renewables in 2050 is just below 80%. The only scenario with a considerable lower share of renewables is Scenario 3. This scenario, which also uses CCS power plants and new nuclear plants by the middle of the century, reaches only 50% in the share of renewables in 2050.[20]

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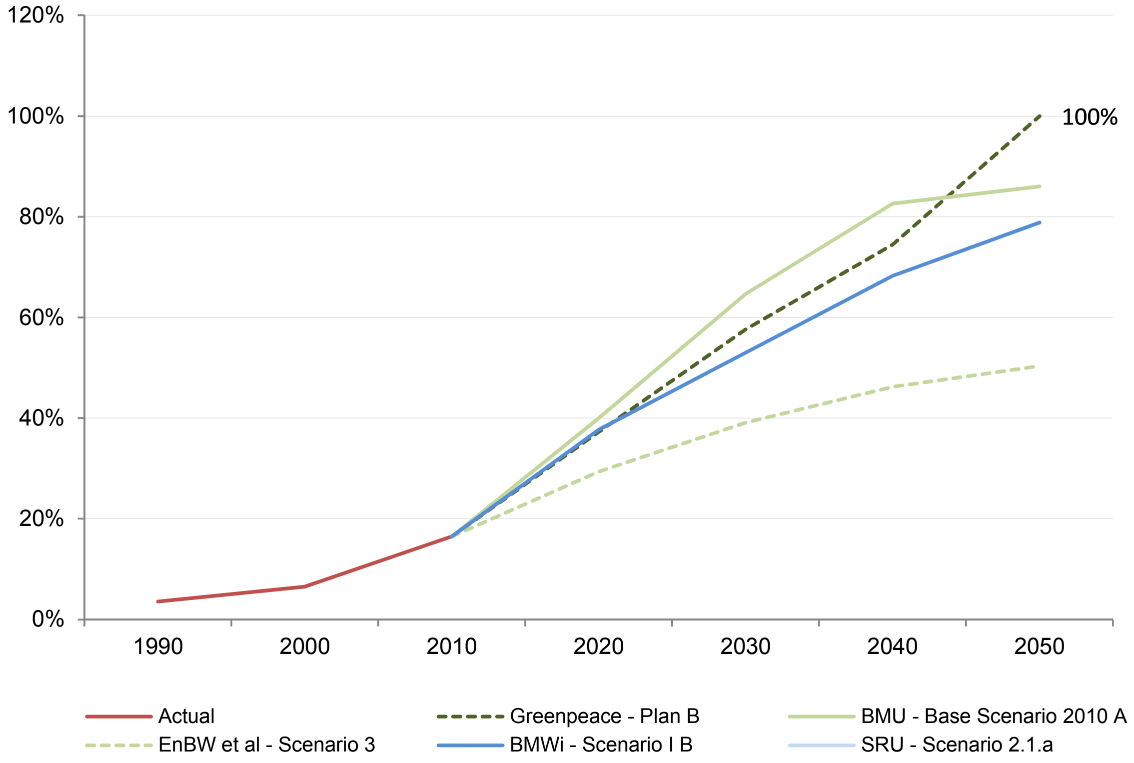
[20] However, as there is a considerable share of electricity generation from CHP plants, whose fuel source is not revealed by the study, the share could actually be a bit higher (depending on whether biomass is used in CHP and if so, to what extent).

Figure 15 Development of the share of renewable energy sources in meeting electricity demand (including net electricity imports) from 1990 to 2010 (actual) and until 2050 in various scenarios

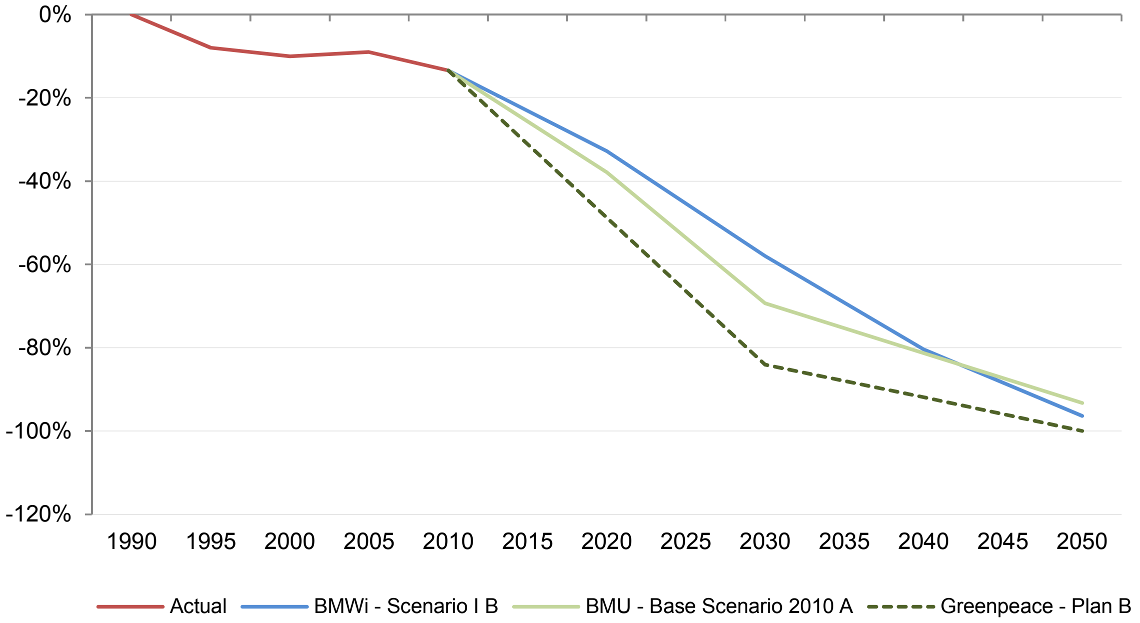


Source: Own figure, data based on energy scenario studies quoted and for actual data from (BMU, 2011)

5.3.3 Electricity sector CO_2 emissions

Finally, Figure 16 shows the development of CO_2 emissions in the electricity sector in those scenarios, which provide this information. In these three scenarios electricity sector CO_2 emissions are reduced by at least 93% and by up to 100% by 2050 (compared to 1990 levels).

Figure 16 Development of electricity sector CO_2 emissions from 1990 to 2010 (actual) and until 2050 in various scenarios



Source: Own figure, data based on energy scenario studies quoted and for actual data on (UBA, 2011b)

5.4 Conclusion

There may be few, if any other European countries in which so many extensive energy scenario studies have been developed over the past few years. A comparison of many of these studies' scenarios shows many similarities and some differences in electricity demand and supply. Among the similarities are the following findings:

- By far-reaching efficiency improvements electricity demand can be reduced or at least stabilised at today's level until 2050 despite growing importance of "new" electricity-using technologies.
- Renewable energy sources will quickly increase their market share in electricity generation, reaching in most scenarios 85 to 100%.
- Expanding the use of wind energy (and integrating it into the electricity system), especially offshore wind energy, is a prerequisite for reaching high shares of renewables in the coming decades.
- CCS will likely either play no role or only a very limited role in electricity supply in Germany until the middle of the century.
- Through efficiency improvements and renewable energy expansion, CO_2 emissions in the electricity sector can be reduced quickly and by about 95 to 100% until 2050 (compared to 1990 levels). The electricity sector can thus play a major role in reducing energy system CO_2 emissions.

Some major differences among the scenarios are as follows:

- There is no consensus on how electricity demand will change compared to today in each sector (perhaps apart from the household sector).
- The role of some renewable energy technologies (especially solar and geothermal) in future electricity supply is still unclear, mainly due to large uncertainties about technology cost developments in the future.
- Most of these findings (both similarities and differences) are very similar to the respective findings so far within this project on European energy scenarios as well as to the findings of the analysis of the scenarios commissioned by WWF (2009) in the main part of this report.

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Information for Policy Makers 1

Decarbonisation Scenarios leading to the EU Energy Roadmap 2050.

SEFEP working paper 2012

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23rd January 2012

smart energy
for europe platform

This report has been commissioned by the Smart Energy for Europe Platform (SEFEP).

Table of Contents

List of Figures

List of Tables

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About SEFEP

SEFEP, the Smart Energy for Europe Platform, is an independent, non-profit organisation founded by the European Climate Foundation and the Stiftung Mercator. Based in Berlin, SEFEP offers a platform to stimulate cooperation and synergies among all European actors who aim to build a fully de-carbonised, predominantly renewable power sector.

Summary

With growing concerns about climate change, energy import dependency and increasing fuel costs, a political consensus has formed in Europe in recent years about the need to transform the way we supply and consume energy. However, there is less political consensus on the specific steps that need to be taken in order to achieve a future sustainable energy system. Questions about which technologies should be used to what extent and how fast changes in the energy system should be instituted are being discussed on the European Union as well as on the Member State level.

Energy scenarios are seen as a helpful tool to guide and inform these discussions. Several scenario studies on the European energy system have been released in recent years by stakeholders like environmental NGOs and industry associations. A number of these studies have recently been analysed by the Öko Institut and the Wuppertal Institute within an ongoing project commissioned by the Smart Energy for Europe Platform (SEFEF). The project aims to advance the debate on the decarbonisation of the energy system in the European Union as well as the EU Member States during the course of 2012 and to make contributions to the scientific literature on this topic. Analysis within the project focuses on the development of the electricity system, as this system today is the main source for CO_2 emissions and is widely regarded to be the key system to any future decarbonisation pathway. The paper at hand presents the results of an in-depth analysis and a comparison of six mitigation scenarios from three important scenario studies released since 2009 by Greenpeace, EURELECTRIC and the European Climate Foundation (ECF) respectively. A decomposition method is applied to show the extent to which technologies and strategies contribute to CO_2 emission reductions in the individual scenarios.[1]

The authors conclude that there are a few technologies and strategies in the electricity sector, which are key in any mitigation pathway. This consensus especially concerns the need for stronger improvements in energy efficiency to reduce future increases in electricity demand and the rapid deployment of renewable energy technologies, especially onshore and offshore wind. Disagreements in the scenarios analysed mostly deal with the two mitigation options Carbon Capture and Storage (CCS) and nuclear energy. The level of public acceptance towards these technologies, their future costs (especially compared to renewable energy technologies) and in the case of CCS also the technological feasibility is assessed differently in the scenario studies considered here. Despite the differences in the scenarios, the analysis makes clear that political action is needed today to ensure that there will be no delays in the transition towards a sustainable energy system. One reason for this is because major infrastructural changes are required in regard to the electricity grid and any such measures (especially building storage facilities and new transmission lines) are characterised by considerable lead times. The same holds true for the more controversial and uncertain mitigation option of CCS, which would require a significant pipeline infrastructure and ready-to-use CO_2 storage sites. As long as uncertainty about such key infrastructural changes remains, investments will likely not be sufficient to realise any ambitious mitigation pathway.

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[1] In a next step within the SEFEP funded project a similar analysis will be conducted for the scenarios developed within the European Commission's Roadmap 2050 study, which was released in December 2011.

1. Introduction

At the UN climate conference in Cancún in December 2010, all Parties expressed support for a target to limit global warming to a maximum of 2°C above pre-industrial levels, which is generally considered to be the threshold for global temperature rise to prevent the catastrophic consequences of climate change. The European Council subsequently reconfirmed in February 2011 that the objective of the European Union (EU) is to reduce greenhouse gas emissions (GHGs) by 80 to 95 % below 1990 levels by 2050.[2] Although the EU is already committed to GHG emission reductions of at least 20 % below 1990 levels by 2020 as part of the Energy and Climate Package[3], longer-term policies are now required to ensure that the ambitious reduction target for 2050 is achieved. The European Commission has therefore published a 'Roadmap for moving to a competitive low-carbon economy in 2050'[4], providing guidance on how the EU can decarbonise the economy.

The process around this document which finally led to the EU Energy Roadmap 2050[5], published in December 2011, is based on economic modeling and scenario analysis, which considers how the EU can move towards a low carbon economy assuming continued global population growth, increasing global GDP and by varying trends in terms of international climate action, energy and technological development.[6] The outcome of the analysis is a recommendation that the EU should reduce GHG emissions by 80 % below 1990 levels by 2050 and that this target is technically feasible and financially viable using proven technologies if strong incentives (i.e. carbon pricing) exist. The cost efficient pathway to achieve the 2050 target calls for domestic GHG reductions below 1990 levels of 25 % in 2020, 40 % in 2030 and 60 % in 2040 and this would require an additional annual investment of €270 billion for the next 40 years. This is equivalent to 'an additional investment of 1.5 % of EU GDP per annum on top of the overall current investment representing 19 % of GDP in 2009.'[7] The extent and timing of these GHG reduction targets are differentiated by sector reflecting the different abatement potentials that exist within the EU (Figure 1).

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[2] European Council (2011): Conclusions – 4 February 2011. http://www.consilium.europa.eu/uedocs/cms_data/docs/pressdata/en/ec/119175.pdf

[3] The objective of the Energy and Climate Package is to reduce GHGs by at least 20% by 2020 relative to 1990 emission levels, increase the share of renewable energy in meeting final energy demand in the EU to 20% and to reduce energy consumption by 20% compared to projected trends. See the annex for more information on how these policy objectives are to be achieved.

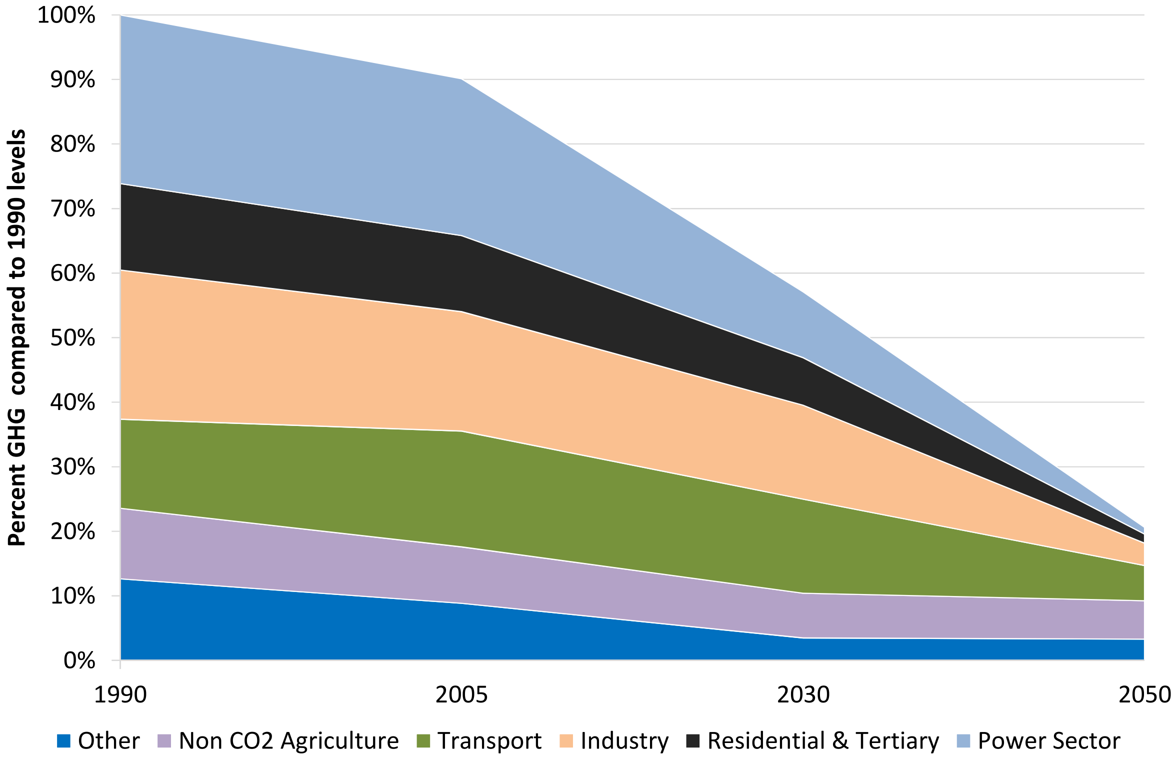
[4] COM (2011): A Roadmap for moving to a competitive low carbon economy in 2050. 112 final.

[5] COM(2011) 885/2.

[6] COM (2011): A Roadmap for moving to a competitive low carbon economy in 2050. 112 final.

[7] COM (2011): A Roadmap for moving to a competitive low carbon economy in 2050. 112 final.

Figure 1 EU Roadmap 2050 decarbonisation pathway



Source: COM (2011) and adapted by Öko-Institut / Wuppertal Institut (2012)

As part of the development of the EU Energy Roadmap 2050, the impact assessment accompanying the communication[8] included a stakeholder consultation whereby a selection of decarbonisation studies up until the year 2010 were reviewed in order to compare different views on how the EU can decarbonise its economy. For example, a decarbonisation scenario may differ based upon the use of technologies to generate electricity (i.e. renewable energy, nuclear and CCS) or may also differ due to how energy is used (i.e. rates of consumption and efficiency improvements). The objective of this policy paper is to provide a quantitative analysis of the similarities and differences of the decarbonisation scenarios for three studies that were previously analysed qualitatively by the European Commission. The decomposition scenarios analysed in this policy paper include:

- Greenpeace, European Renewable Energy Council (2010). *Energy revolution - a sustainable world energy outlook*: Energy Revolution and Advanced Energy Revolution Scenario.
- ECF (2010). *Roadmap 2050 - A practical guide to a prosperous, low-carbon Europe. Technical analysis:* 40%, 60% and 80% RES scenarios.

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[8] COM (2011) Impact assessment accompanying document to the Communication entitled ‘A Roadmap for moving to a competitive low carbon economy in 2050’. SEC (2011) 288 final. Brussels.

- Eurelectric (2009). *Power Choices. Pathways to carbon-neutral electricity in Europe by 2050*: Power Choices Scenario.

The scenarios considered in this policy paper advocate a 'shared vision' for a decarbonised power sector in 2050 with a similar level of ambition with regards to CO_2 emission reductions in 2050. However, the scenarios under consideration have different views on the technology mix and levels of energy consumption and these differences are reviewed in Section 2. To provide further insights into the similarities and differences between the decarbonisation scenarios a decomposition analysis is completed in Section 3. The added value of this decomposition analysis is the ability to attribute the CO_2 emission reductions from a decarbonisation scenario to important causal factors such as the increase of wind power in the energy mix. The cost assumptions underlying these decarbonisation scenarios are considered in Section 4. The implications of the similarities and differences identified between all of the decarbonisation scenarios will then be discussed in Section 0 focusing especially on the timing of political action needed to realise the decarbonisation pathways. The paper concludes with Section 6.

In December 2011, the final EU Energy Roadmap 2050[9] was published and additional scenarios have been produced and simulated based on the PRIMES model. These scenarios will be subsequently analysed in a future policy paper.

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[9] COM(2011) 885/2.

2. Shared vision of a decarbonised Europe

Differences between the scenarios can be explained by differences in key assumptions, like those on future technology and fuel costs (see Section 4) as well as by different modelling approaches (see the Annex). In some scenarios explicit normative assumptions have a direct and significant effect on the evolution of the energy system. For example in the Greenpeace scenarios the use CCS technology is ruled out and the use of nuclear power is phased out, as the organization does not see these two mitigation options as sustainable solutions. At the same time the ECF Roadmap 2050 scenarios set a fixed share for renewable energy sources in electricity generation in 2050 of 40 %, 60 % and 80 % respectively. The following section provides an overview of the similarities and differences between the decarbonisation scenarios considered in this policy paper with regards to emission trajectories, electricity consumption and electricity supply projections until the year 2050.

2.1 Emission trajectories

The decarbonisation scenarios all achieve CO_2 emission reductions in the power sector of at least 90 % below 1990 emission levels by 2050. The bullet point list below illustrates the hierarchy of ambition (i.e. emission reductions below 1990 levels by 2050) for the decarbonisation scenarios:

- Greenpeace: Advanced Energy Revolution Scenario (- 97 %)[10]
- ECF Roadmap 2050: 40 % RES, 60 % RES and 80 % RES Scenarios (- 96 %)[11]
- Greenpeace: Energy Revolution Scenario (- 90 %)[12]
- Eurelectric: Power Choices Scenario (- 90 %)[13]

Some studies that develop decarbonisation pathways first establish a reference scenario (i.e. emissions development without climate action). According to the reference scenarios in both the Greenpeace and ECF Roadmap 2050 studies, CO_2 emissions would decline to a level of roughly 20 % below their respective base years by 2020. However, afterwards CO_2 emissions in both scenarios stagnate so that by 2050 CO_2 emissions would still be only about 20 % lower than in 1990. The CO_2 emission-reducing effects of higher contributions of renewable energy sources and lower shares of coal in electricity generation are largely offset in these reference scenarios by growing electricity production (Figure 2).

The CO_2 emission reduction pathways in all of the decarbonisation scenarios illustrated in Figure 2 are similar. However, in comparison to the other pathways the Power Choices scenario exhibits slower CO_2 emission reductions until 2020 followed by 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 in the study is not assumed to be commercially available until 2025. The ECF Roadmap 2050 decarbonisation scenarios, especially the ECF 40 % and ECF 60 % scenarios also use CCS to a significant extent. Here CCS is assumed to be progressively available from 2020 onwards. Although all

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[10] Hereafter: Greenpeace Adv. Rev.

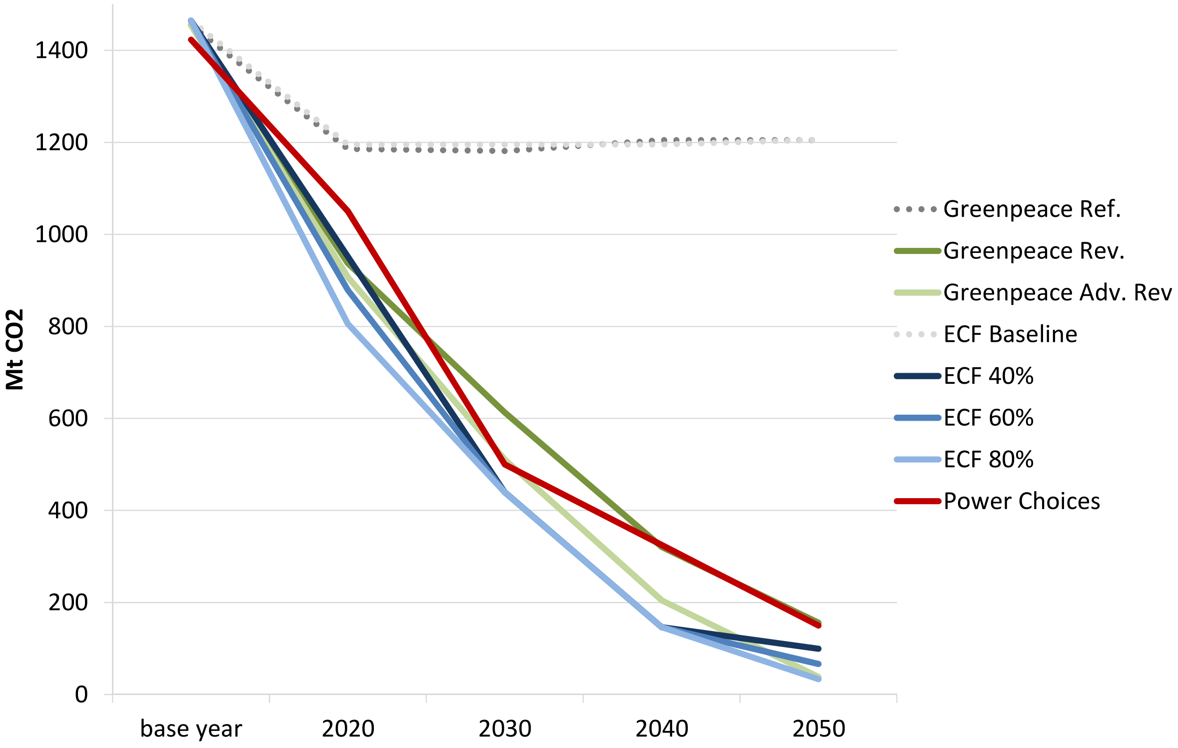
[11] Hereafter: ECF 40%, ECF 60%, ECF 80%.

[12] Hereafter: Greenpeace Rev.

[13] Hereafter: Power Choices

of the decarbonisation scenarios share a 'similar vision' with regards to the level of CO_2 emission reductions by 2050; the extent to which electricity is consumed and the means of supplying electricity differ considerably between them.

Figure 2 CO_2 emission trajectories for reference and decarbonisation scenarios



Note: A systematic overview about scenario assumptions with respect to crucial factors influencing the emission pathways can be found in Table 6 in Annex 8.3

Source: Öko-Institut / Wuppertal Institut (2012)

2.2 Electricity consumption

The change in electricity demand between the base year and the year 2050 for four sectors (i.e. residential, tertiary, transport and industry) are shown in Figure 3[14]. There is a general consensus among the decarbonisation scenarios that total electricity demand will increase in the coming decades. By 2050 electricity demand will have increased between 21 % (Greenpeace Rev. scenario)

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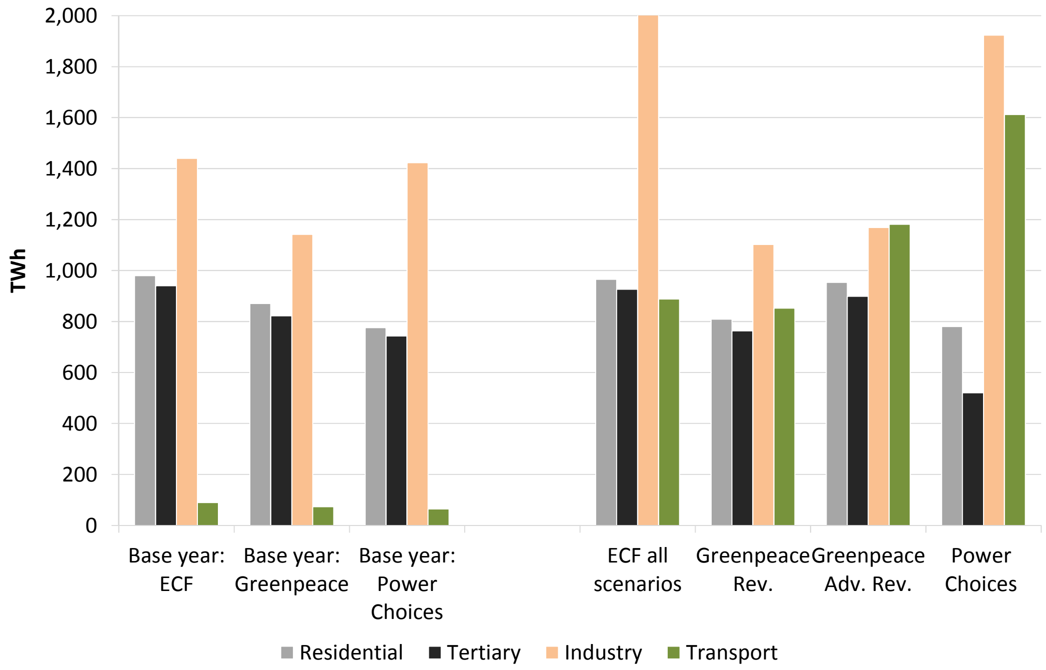
[14] The base year is defined as the year in which values of key variables are provided based on historical values. It provides the base for the first modeled year in each of the scenarios. The base year for the Eurelectric (i.e. Power Choices) and ECF Roadmap 2050 studies is 2005, whilst the Greenpeace study refers to 2007 as the base year.

and 61 % (Power Choices scenario) compared to their respective base years.[15] It is also assumed in all of the decarbonisation scenarios that the transport sector will experience a significant increase in electricity demand due to the growth in the use of electric vehicles. Compared to the respective base years an 11-fold (Greenpeace Rev. scenario) to 24-fold (Power Choices scenario) increase in electricity demand in the transport sector is envisaged. However there is much uncertainty in regard to the development of electricity demand in the remaining sectors. For example, the Greenpeace Rev. scenario assumes ambitious energy efficiency improvements whilst also limiting the fuel shift towards electricity, resulting in a reduction in electricity demand compared to the base year of 7 % for the residential and tertiary sectors and 4 % for the industrial sector in 2050 (Figure 3). In contrast, the Power Choices scenario foresees a significant increase in the electricity demand of the industrial sector in 2050 (i.e. 35 % increase compared to the base year).

Figure 3 A comparison of the electricity consumption between the base year and the year 2050 for the decarbonisation scenarios



Source: Öko-Institut / Wuppertal Institut (2012)

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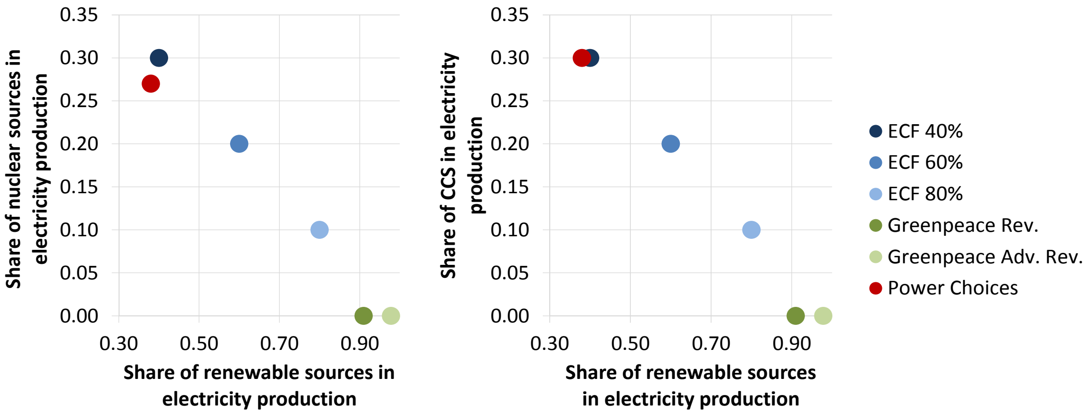
[15] It is important to acknowledge the opposing factors on future electricity demand of energy efficiency improvement in end user appliances on the one hand and the electrification of industrial processes and transportation on the other hand. Reference scenarios are provided in sufficient detail for the Greenpeace and ECF Roadmap 2050 studies and 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 due to these opposing factors cancelling each other out.

2.3 Sources of electricity production

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 for the decarbonisation scenarios. Given that nuclear power is phased out and CCS is not seen as a viable or desirable technology in both the Greenpeace Rev. and Greenpeace Adv. Rev. scenarios; the electricity supply is based on 91 % and 98 % renewable energy sources in 2050 respectively and this includes electricity imports (Figure 4). The rest is supplied by natural gas power plants. In contrast, the Power Choices scenario and the ECF 40 % scenario from the ECF Roadmap 2050 study rely to a significant extent on nuclear power, which will account for 30 % and 27 % respectively of electricity generation in 2050 (Figure 4). CCS coal and natural gas power plants are also used to a significant extent in the Power Choices scenario and the ECF 40 % scenario from the ECF Roadmap 2050 study, providing 30 % of electricity supply in 2050 in both decarbonisation scenarios.

Figure 4 Share of electricity from renewable sources compared to the share of electricity from nuclear energy / CCS electricity generation for the decarbonisation scenarios by 2050



Source: Öko-Institut / Wuppertal Institut (2012)

All of the individual factors described in this section (i.e. the sources of consumption and production of electricity), despite their different (e.g. technical) nature, have one characteristic in common: their level of use/non-use triggers changes in CO_2 emissions over time. The decomposition analysis in 3 uses this common denominator as a metric to derive the effect that each of these individual factors has on emission changes in a given decarbonisation scenario.

3. Comparison of decarbonisation scenarios

The overview in the previous section outlined the important similarities and differences with regards to the overall timing of CO_2 emission reductions, technologies deployed and rates of electricity consumption. However, this analysis is unable to attribute emission changes to the specific changes to the electricity system advocated in all of the decarbonisation scenarios. The objective in the following is therefore to quantitatively analyse all of the decarbonisation scenarios based upon decomposition techniques in order to determine how the causal factors drive changes in emissions.

3.1 Methodology

A decomposition analysis requires an equation that describes the influence of several causal factors on the observed changes of a variable of interest (i.e. CO_2 emissions). According to the decomposition equation developed for this policy paper[16], the total amount of CO_2 emissions can be determined by the electricity consumption in the various sectors[17] which is being supplied, by the electricity production from a mix of different technologies[18] that differ in their need for fossil fuels[19] (e.g. old coal plants need more coal than new ones, wind farms need no fossil fuel) which in turn will have different emission factors[20], implying differing CO_2 emissions per energy unit (i.e. gas less than coal). An in-depth description of the decomposition equation is provided in the background document accompanying this policy paper entitled WP 1.2: Comparison Methodologies. Input data from all of the decarbonisation scenarios were collected and supplemented with transparent gap-filling techniques to ensure that the decomposition equation could be successfully executed.[21] Based upon the Laspeyres decomposition method, the isolated effect of a causal factor on the CO_2 emissions of the power sector in 2050 was calculated by changing the value of a causal factor to its scenario value in 2050 whilst ensuring that the remaining causal factors remain at their base year value. By replicating this calculation for all the causal factors, the outcome of the decomposition analysis is to attribute changes in emissions to changes in the consumption of electricity, the production of electricity from different technologies, the fossil fuel input and the different emission factors associated with the use of different fossil fuels.[22]

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[16] $E_t = C_t(1-\pi_t^{\,f})\frac{I_t}{P_t^{fos}}\frac{E_t}{I_t}$

[17] In the decomposition equation this is referred to as 'electricity consumption',C_t , which is defined as the consumption of electricity from various sectors at time step *t*.

[18] In the decomposition equation this is referred to as 'electricity production', $1-\pi_t^{\,f}$, which is defined as the share of production from CO_2 emitting electricity generation technologies at time step *t.*

[19] In the decomposition equation this is referred to as 'fuel input intensity', I_t/P_t^{fos}, which is defined as the fossil fuel input per unit of electricity production at time step *t*.

[20] In the decomposition equation this is referred to as 'emission factor', which is defined as the CO_2 emissions per unit of fossil fuel input at time step *t*, E_t/I_t.

[21] See *WP 2.2. Quantitative analysis of existing EU-wide studies* (hereafter WP 2.2.).

[22] The extent to which we can attribute the observed changes in the variable of interest to the explanatory factors depends upon the size of the residual from the decomposition. The residual occurs due to the 'mixed effect' of explanatory factors interacting with one another to contribute to the observed change in the variable of interest. The residual has been distributed to the causal factor proportional to their contribution to overall CO_2 emission changes. See also WP 1.2.

3.2 Results

The results of the decomposition analysis in the year 2050 are presented in Figure 5 (top) along with the respective electricity generation mix of the decarbonisation scenarios (bottom).

The coloured bars in Figure 5 (top) for each decarbonisation scenario represent the CO_2 **emission change** from the base year due to different causal factors, which can either positively or negatively contribute to CO_2 emissions. For example, Figure 5 (top) shows that additional CO_2 emissions would result from a phase out or the reduced use of nuclear power as illustrated by the negative brown segment while additional deployment of renewable energies (i.e. the positive green segment) would result in CO_2 emission reductions. The **net emission reduction** delivered by each decarbonisation scenario (i.e. actual emission reductions) is determined by subtracting the **additional emissions** (i.e. negative segments) from the **gross emission reductions** (i.e. positive segments).[23]

The coloured bars in Figure 5 (bottom) for each decarbonisation scenario represents the absolute contribution of an electricity generating technology, which is measured in TWh, in supplying electricity. For example, the absolute contribution of wind energy in supplying the total electricity of a decarbonisation scenario in the year 2050 is illustrated by the purple segment. It is important to acknowledge that the total electricity demand varies between the decarbonisation scenarios due to the different assumptions with regard to electricity consumption, which were previously discussed in Section 2.

Figure 5 demonstrates the relationship between changes in emission levels (compared to the base year) and changes in the electricity generation mix that are associated with the different decarbonisation scenarios by the year 2050. For example, the rapid deployment of renewable energy technology (excluding imports) envisaged in the Greenpeace Adv. Rev. scenario represents 81 % of the electricity generation mix and is responsible for 121% (57% of the gross emission reductions by causal factors)[24] of emission changes by 2050. However, the absence of nuclear power in the electricity generation mix of the Greenpeace Adv. Rev. scenario in 2050 is reflected by additional emissions of 45 % that need to be offset by additional emission reductions (i.e. deployment of renewables, imports). The Greenpeace Adv. Rev. scenario is dependent upon considerable electricity imports, which represent 17 % of the electricity generation mix and account for 31 % (14 % of the gross emission reductions by causal factors) of emission changes by 2050.

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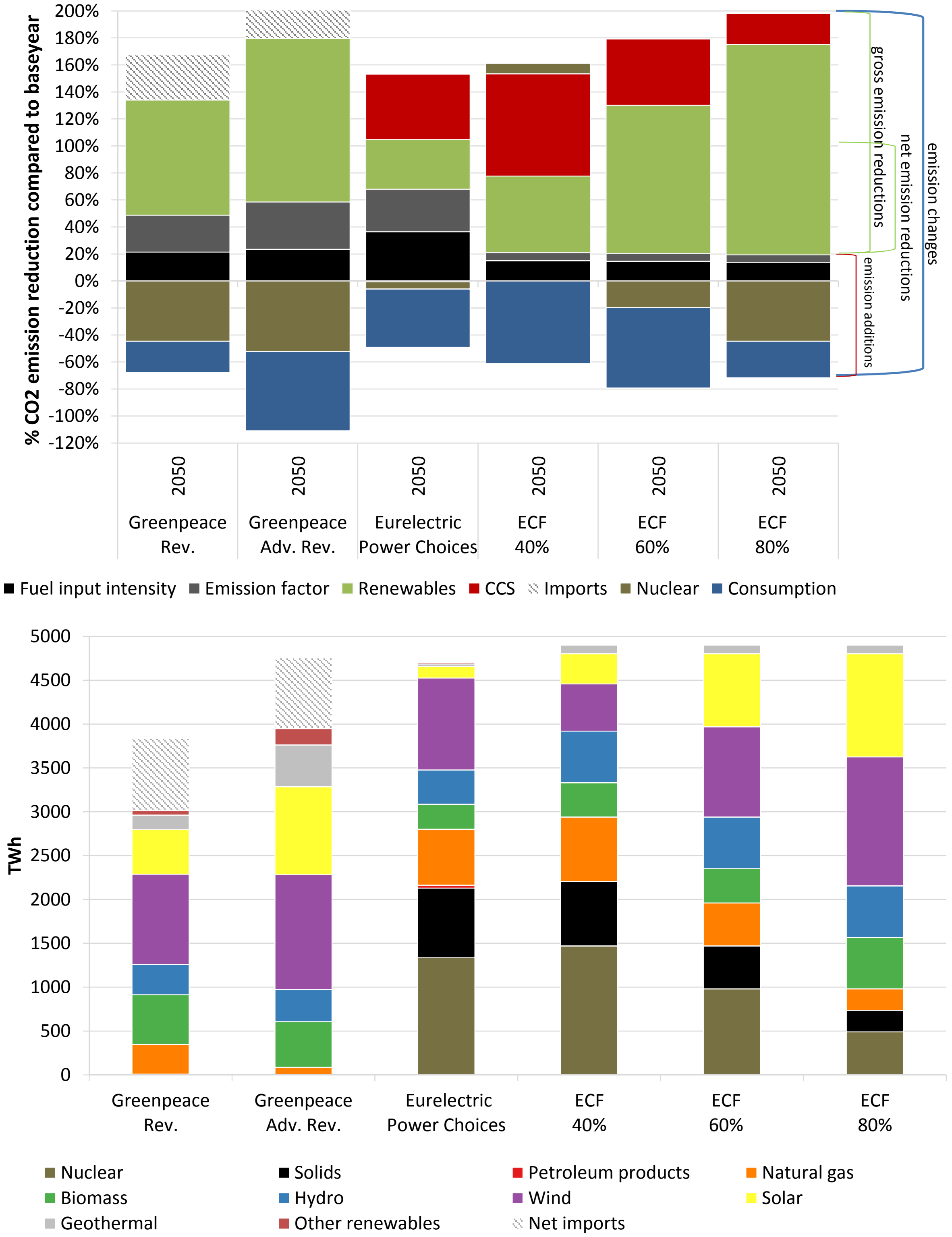
[23] The positive part of each column in Figure 5 (top) represents the gross emission reductions achieved by the causal factors. The positive part of each column is longer than the actual emission reductions achieved because additional emissions triggered by factors depicted in the negative part of each column need to be compensated for in order to reach the emission goal of each scenario which is equal to the net emission reductions achieved.

[24] The value in the bracket represents the share of that causal factor’s emission reduction on the gross emission reductions achieved by the causal factors. These shares are illustrated in the Annex for each scenario. Hereafter all brackets following text on emission changes will refer to the share of that causal factor’s contribution on gross emission reduction achieved by the causal factors.

Figure 5 Overview of the contribution of different causal factors to emission changes in 2050 compared to the base year (top) accompanied by the electricity generation mix within the different scenarios (bottom)



Source: Öko-Institut / Wuppertal Institut (2012)

In contrast, ECF 40 % is the only decarbonisation scenario analysed whereby nuclear energy contributes to emission reductions in 2050, accounting for 30 % of the electricity generation mix (Figure 5). With the exception of the Greenpeace decarbonisation scenarios, which are not supportive of the commercialisation of CCS, the remaining decarbonisation scenarios all expect that the deployment of CCS technology will deliver considerable emission reductions by 2050. For example, CCS technology accounts for around 30 % of the electricity generating mix by 2050 in the Power Choices scenario contributing to emission change of 48 % (29% on gross emission reductions) relative to the base year (Figure 5). It is evident that all of the decarbonisation scenarios will require major changes in the energy system (i.e. transmission lines for offshore wind and imports, pipelines for CCS), which will be associated with long lead times that need to guide the timing of political action in order to realise these ambitious decarbonisation scenarios.

Table 1 Decomposition results of CO$_2$ emission reduction in 2050 for the decarbonisation scenarios.

	Greenpeace Rev	Greenpeace Adv. Rev.	ECF 40 % RES	ECF 60 % RES	ECF 80 % RES	Eureletcric Power Choices
	Million tonnes of CO2					
Residential cons.	8	-59	8	8	8	16
Tertiary cons.	8	-55	8	8	8	98
Industry cons.	40	51	12	12	12	-104
Transport cons.	-21	-57	1	1	1	-582
Road transport cons.	-275	-509	-461	-460	-446	
Heating cons.	-21	-64	-404	-402	-390	
Other cons.	-2	-3	0	0	38	-44
Wind use	489	641	307	687	1000	406
Solar use	271	551	264	644	884	50
Biomass use	240	205	192	191	334	53
Geothermal use	87	259	70	70	68	16
Hydro use	-5	-41	-58	-58	-56	-46
Other RES use	27	102	0	0	0	9
Sum RES use	1109	1716	775	1534	2228	488
Nuclear use	-579	-739	106	-276	-637	-71
CCS use	0	0	1033	686	333	643
Hydrogen use	0	10	0	0	0	0
Storage cons.	-38	-140	0	0	0	0
Import	437	436	0	0	0	-8
Fuel input intensity	279	333	205	205	199	485
Emission factor	354	495	82	81	79	419

Note: Negative values reflect emission additions, while positive values reflect emission reductions.

Source: Öko-Institut / Wuppertal Institut (2012)

The results of the decomposition analysis are illustrated further in Table 1, which outlines the absolute reduction in CO$_2$ emissions between the base year and 2050 attributed to each causal factor measured in million tonnes of CO$_2$. The CO$_2$ emission reduction is either negative and thus characterised by additional emissions (i.e. red shading) or is positive and characterised by emission reductions (i.e. green shading). It is important to acknowledge that the emission changes in one scenario are not directly comparable with another scenario as this would require the results to be normalised to account for differences in the base year. However, the trends that emerge from the scenarios decomposition analysis are clear.

All of the decarbonisation scenarios analysed in this policy paper assume that electricity consumption will increase considerably for road transport and heat applications by 2050. This is due to the envisaged growth in new electric appliances (i.e. electric mobility, heat pumps), reducing CO_2 emissions by switching from other fuels to low carbon electricity. This trend is dependent however upon political action, which will be necessary to facilitate the commercialisation of new appliances such as electric vehicles, which are currently too expensive for a widespread diffusion. For example, political action may consist of public investments in infrastructural developments (i.e. charging points) and tax subsidies to lower the capital costs associated with purchasing electrical vehicles. As a consequence of the increase in electricity consumption for both road transport and other new appliances used for heating in 2050, additional CO_2 emissions will be generated within the electricity system.[25] It is therefore essential that political action is taken in parallel to transform the energy system so that low carbon technology is primarily used to generate electricity. It is important to acknowledge that efficiency improvements in traditional applications in the residential, tertiary, industry and transport sectors will not nearly offset the increase in electricity consumption from the new appliances by 2050 as well as additional electricity consumption caused by GDP growth in any of the decarbonisation scenarios, given the base year's electricity mix.

The decomposition analysis demonstrates that an increase in the share of electricity generated from renewable technology will result in considerable emission reductions by 2050. All of the decarbonisation scenarios envisage that wind energy will account for the largest share of electricity generation from renewables in 2050. There is also a general consensus that an increase in solar and biomass energy will greatly contribute to emission reductions in 2050. The increasing deployment of renewables in all of the decarbonisation scenarios assumes that the cost of electricity generation will reduce over time (see Section 4); however political action in the form of market deployment policies as well as public investment in the research and development of renewable technologies will be necessary for these cost assumptions to materialise. Policy makers also need to address the existing barriers to the deployment of renewables (i.e. planning permission, capital costs) that considerably increase lead times. Infrastructural investments in transmission grids and storage technology will be necessary in the longer term to overcome issues concerning both the distribution of electricity and the intermittency of supply.[26]

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[25] Given that the decomposition analysis only calculates the 'isolated effect' of a causal factor, the emissions reduction from an increase in consumption is negative (i.e. additional emissions) as the energy mix remains the same as in the base year. The residual of the decomposition accounts for 'mixed effects' such as an increase in electricity consumption and an increase in the share of renewables in the energy mix and is distributed proportionally to each causal factor, so that the mixed effects are accounted for.

[26] The power system model applied in the ECF study provides sufficient temporal and spatial resolution to properly take into account the fluctuating nature of these sources. The model endogenously decides on least-cost strategies to deal with the fluctuation, choosing for example between building additional storage capacity, applying demand response measures or building additional transmission

There is agreement amongst the decarbonisation scenarios that CO_2 emissions will be reduced by 2050 as a consequence of an increase in the average conversion efficiency of the remaining fossil fuel plants (i.e. an improvement in the fuel input intensity) and due to the fossil fuel input becoming cleaner (i.e. an improvement in the emission factor by fuel switch from coal to gas). All of the decarbonisation scenarios expect the average conversion efficiency of fossil fuel plants and the cleanliness of the fossil fuel input to improve by 2050.[27] The increasing efficiency of fossil fuel consumption and the switch from coal to gas envisaged in these decarbonisation scenarios may be further encouraged by reducing the subsidies associated with fossil fuel use and by setting CO_2 taxes to increase the cost of fossil fuel use.

In order to provide policy makers with further insights into the importance of the timing of political action between 2020 and 2050 to reduce CO_2 emissions; Figure 5 (top) is extended in Figure 6 to show how the different causal factors contribute to CO_2 emission change at various time horizon intervals (i.e. 2020, 2030, 2040 and 2050) always compared to the base year. The emissions relative to the base year are illustrated in Figure 6 by the dark green line for each decarbonisation scenario, which demonstrates that in all scenarios the gross emission reductions offset the additional emissions so that the power sector is nearly fully decarbonised by 2050.

Although all of the scenarios achieve an almost fully decarbonised power sector in Europe by 2050, the combinations of causal factors differ between the decarbonisation scenarios, which influence the overall timing of CO_2 emission reductions. For example, the Greenpeace Adv. Rev. scenario depends primarily upon the deployment of renewable energy to reduce CO_2 emissions maintaining a high contribution to CO_2 emission reductions (i.e. in excess of 100 %) throughout the 2020 to 2050 period. In contrast, the contribution of renewable energies to emission reductions in the Power Choices scenario declines throughout the 2020 to 2050 time frame and is progressively substituted by the emergence of CCS technology (i.e. illustrated by the red bars in Figure 6). The rate at which CO_2 emission reductions occur between 2020 and 2050 in these scenarios reflect their different use of abatement measures. For example, initially the rate of CO_2 emission reductions in the Greenpeace Adv. Rev. scenario is higher than in the Power Choices scenario.

However, with the commercialisation of CCS technology the rate of CO_2 emission reductions increases significantly in the Power Choices scenario between 2030 and 2040. This presumes that major breakthroughs in technological development and costs of CCS technology will be realised in the coming 10 to 20 years and that there will be sufficient public acceptance for CO2 pipelines and storage facilities in Europe.

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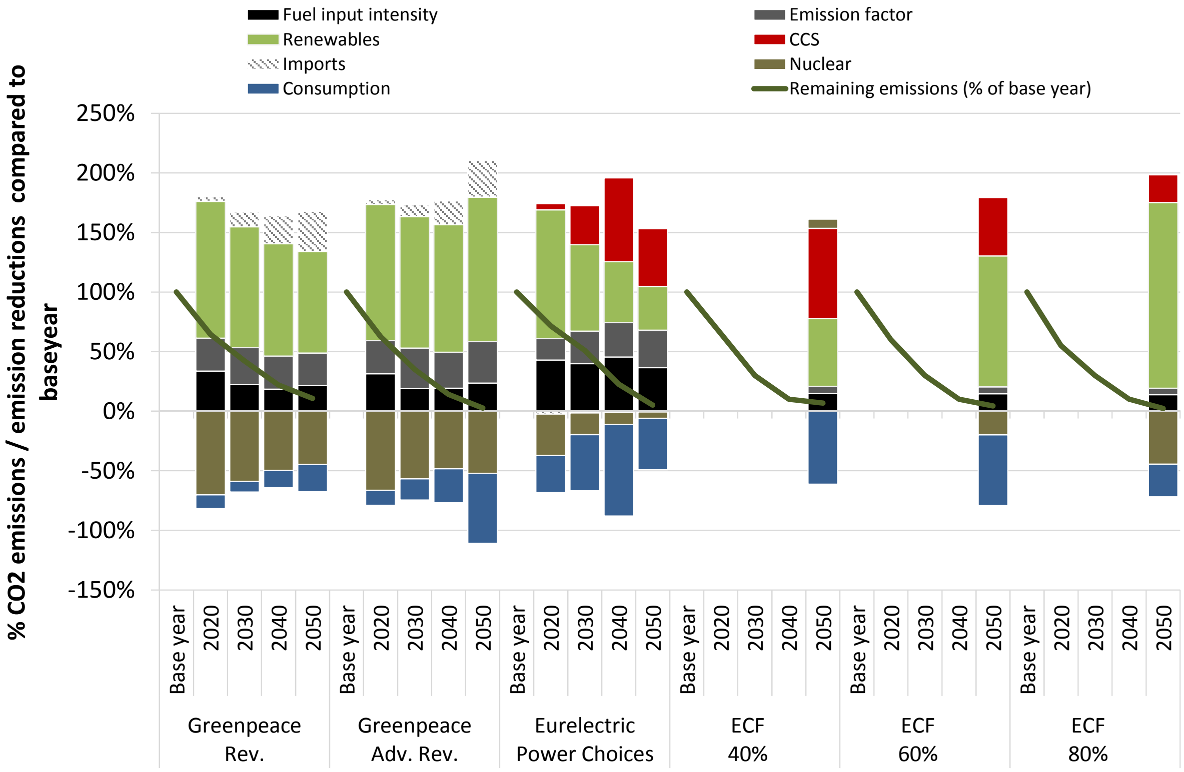
lines. The models used in the other two studies are not explicit power system models and do not have a comparable level of spatial and temporal resolution.

[27] A biomass correction factor was applied to the CO_2 emissions output of the Power Choices scenario in 2050 so that the fuel input intensity and emission factors positively contributed to emission reductions. The CO_2 emissions reported in the study in relation to fuel input yielded a fuel mix too emission intense, given the fuel switch also reported in the study. It was thus assumed that biomass emissions were included in the reported CO_2 emissions. Assuming that 20 % of biomass emissions are non-neutral these were subtracted from the total energy sector CO_2 emissions provided.

Figure 6 Overview of the contribution to emission change from the base year of different causal factors in the decarbonisation scenarios between 2020 and 2050



Source: Öko-Institut / Wuppertal Institut (2012)

With the exception of the ECF 40 % scenario, the remaining decarbonisation scenarios envisage that the role of nuclear power in the production of electricity will decline between 2020 and 2050 resulting in additional CO_2 emissions by 2050. The phase out of nuclear power may result in additional CO_2 emissions because it would need to be replaced by alternative sources of electricity production that may – under specific circumstances - be more CO_2 intensive. However, as Figure 6 demonstrates, the deployment of renewable energies alone in all scenarios is more than sufficient to offset additional emissions associated with a decrease in the use of nuclear energy. The consumption of electricity (i.e. illustrated by the blue segment in Figure 6) in 2050 increases in all decarbonisation scenarios compared to the base year and therefore also contributes to additional CO_2 emissions that need to be offset by CO_2 emission reductions contributed by other causal factors (i.e. renewables, fuel switching from coal to gas, improvements in the combustion efficiency of fossil fuel plants etc.).

4. Cost assumptions of the scenarios

All of the decarbonisation scenarios considered in this metastudy are characterised by a similar level of ambition (i.e. to reduce CO_2 emissions by at least 90 % by 2050), yet it is evident that the combination of abatement measures to deliver these CO_2 emission reductions vary. To a certain extent, the difference between decarbonisation scenarios can be explained by the setting of normative targets for the deployment of specific technologies.[28] For example, the use of nuclear power plants and CCS technology has not been considered in the Greenpeace scenarios due to sustainability concerns. However, even within such pre-defined constraints the cost assumptions of various power generation technologies are still a key driving factor influencing the structure of electricity supply in all of the decarbonisation scenarios.[29] The aim of this section is to provide a transparent comparison of the various assumptions (i.e. fossil fuel price, capital expenditure and electricity generation costs) applied in these decarbonisation scenarios regarding the cost development of the various power generating technologies until 2050.

4.1 Fossil fuel prices

The fossil fuel prices assumed within the ECF Roadmap 2050 scenarios are much lower than those in the Greenpeace scenarios (Table 2). Fossil fuel prices in the ECF Roadmap 2050 scenarios rise moderately between 2015 and 2030 and stay flat in the following two decades, prices still remain lower than they were on average in the year 2008, when crude oil for example sold at 80 $€_{2005}$/barrel. In contrast, the fossil fuel prices assumed in the Greenpeace scenarios increase considerably, with crude oil reaching 124 $€_{2005}$/barrel in 2030 (remaining flat thereafter) and the natural gas price more than doubling between 2008 and 2050, increasing from 9 $€_{2005}$/GJ (2008) to 22 $€_{2005}$/GJ (2050).

Table 2 Fossil fuel import prices (in €2005) in the ECF Roadmap 2050 and Energy Revolution scenarios in 2015, 2030 and 2050

		Crude oil import price (€2005/barrel)	Natural gas import price (€2005/GJ)	Hard coal import price (€2005/tonne)
ECF Roadmap 2050	2015	55	6	57
	2030	73	9	69
	2050	73	9	69
Greenpeace Energy Revolution	2015	92	12	96
	2030	124	16	118
	2050	124	22	143

Source: Öko-Institut / Wuppertal Institut (2012)

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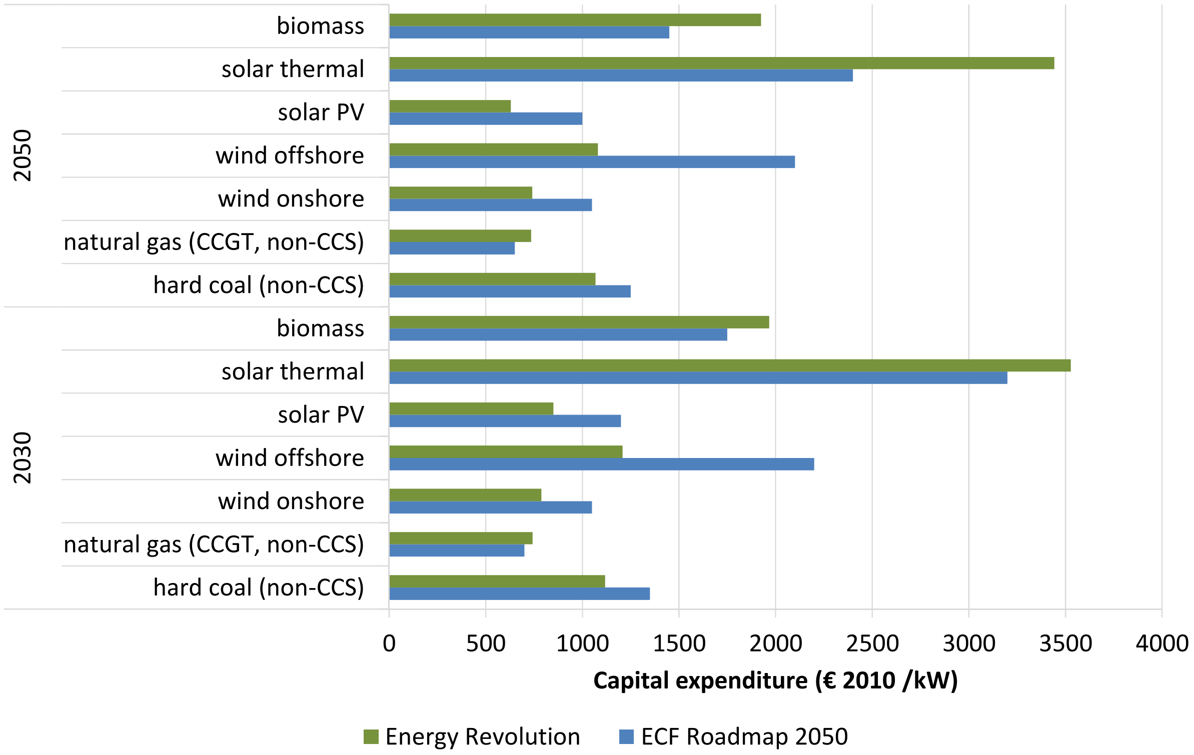
[28] This is also explicitly the case for all the ECF Roadmap 2050 policy scenarios. The ECF Roadmap 2050 scenarios have been developed by explicitly prescribing varying shares of renewables, nuclear and CCS technologies to be reached by 2050. In the Power Choices scenario no such technology-specific requirements are pre-defined.

[29] See the Annex on the energy models used in the studies for further information about the importance of cost assumptions in the scenarios.

4.2 Capital expenditure

The capital expenditure for all conventional fossil fuel power plant technology is expected to moderately decrease between 2030 and 2050 in both the ECF Roadmap 2050 and Energy Revolution studies (Figure 7)[30]. When these capital expenditure assumptions are compared to the respective base year of each study, it is evident that non-CCS natural gas power plants[31] becomes 13 % cheaper between 2010 and 2050 in the ECF Roadmap 2050 study and 9 % cheaper between 2007 and 2050 in the Energy Revolution study. Although there is a general consensus that the capital expenditure for renewable technology will decrease at a faster rate than experienced by more mature fossil fuel technologies, the scale of this capital expenditure development differs between the studies. For example, while specific investments costs for onshore wind plants decrease by about 40 % in the Energy Revolution study between 2007 and 2050, they are reduced by only about 10 % in the ECF Roadmap 2050 for the 2010 to 2050 time horizon. In contrast, the ECF Roadmap 2050 study foresees more potential to reduce investment costs in solar thermal and biomass power plants until 2050.

Figure 7 Capital expenditure (in €2010/kW) for various fossil and renewable energy technologies in the ECF Roadmap 2050 and Energy Revolution scenarios in 2030 and 2050



Source: Öko-Institut / Wuppertal Institut (2012)

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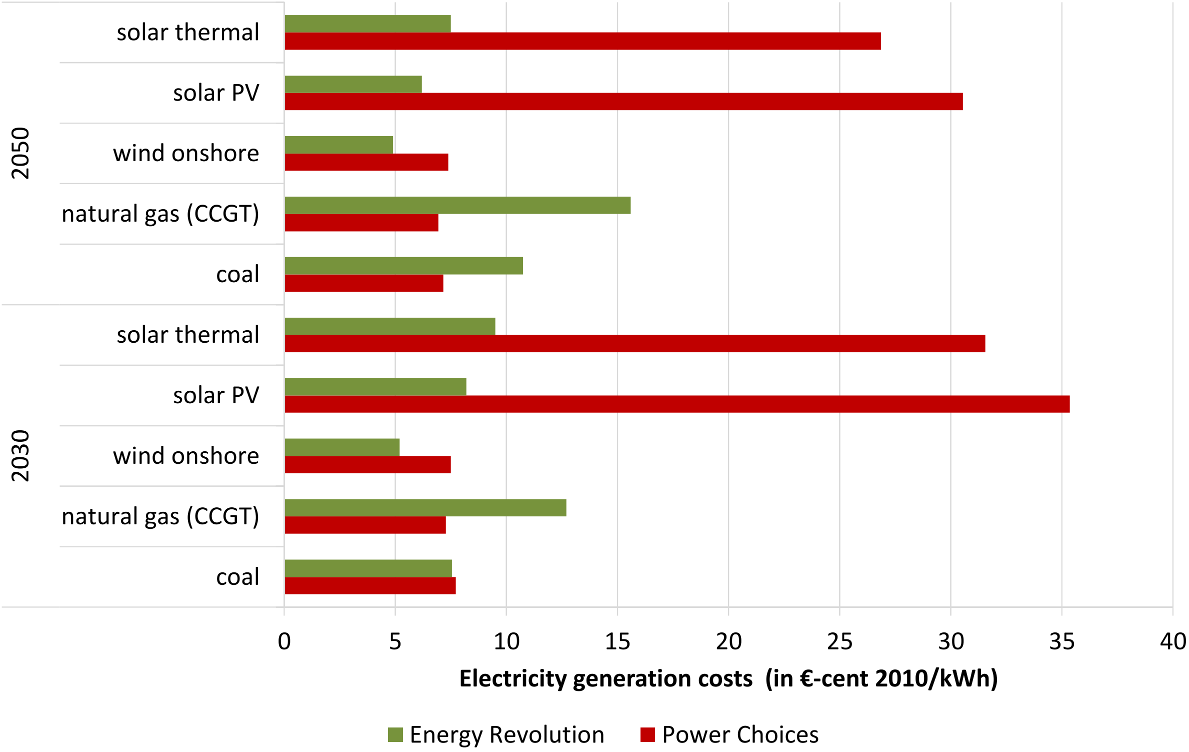
[30] No figures for capital expenditure are provided by the Power Choices study.

[31] Capital expenditure for natural gas CCS plants is assumed to decrease by 35 % from 2020 to 2050 in the ECF Roadmap 2050 study. No comparison is possible as no such plants are built in the Energy Revolution scenarios.

4.3 Electricity generation costs

The electricity generation costs for some fossil and renewable technologies between the Power Choices and the Energy Revolution scenarios in 2030 and 2050 are outlined in Figure 8.[32] While in the Energy Revolution study generation costs of fossil technologies are assumed to increase (as increasing fossil fuel and CO_2 prices overcompensate moderately falling technology costs), they slightly decrease over time in the Power Choices scenario. These opposing trends lead to considerably different coal and natural gas generating costs by the middle of the century. Even more pronounced are the differences between the two studies in respect to the generating costs of renewables. Here cost reductions are much more dramatic in the Energy Revolution study than in the Power Choices study, leading to drastically different generating costs especially for solar PV and solar thermal power plants. By 2050, solar PV generating costs are about 1/5th in the Energy Revolution scenarios and solar thermal generating costs about 1/3rd of the costs in the Power Choices scenario.

Figure 8 Generation costs (in €-cent2010/kWh) for various fossil and renewable energy technologies in the Power Choices and Energy Revolution scenarios in 2030 and 2050



Source: Öko-Institut / Wuppertal Institut (2012)

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[32] No figures for electricity generation costs are provided in the Roadmap 2050 study. Fossil fuel costs provided for the Power Choices scenario are at a CO_2 price of 30 $€_{2008}$/t. The CO_2 price is assumed to increase to over 40 $€_{2008}$/t in 2050, but no generation costs are given for higher CO_2 costs.

As the relative costs of different technologies are the key criteria determining which technologies are deployed and to what extent[33], there is no doubt that the energy system described in the Power Choices scenario would look very different if the cost assumptions of the Greenpeace study had been used instead. The share of fossil fuels would be lower while the share of renewables would be higher. However, as no explicit sensitivity analysis has been performed and documented in the Power Choices study (or in the other studies analysed), it is not possible to quantify the effects that changes in relative costs would have. Due to the combination of high importance of technology costs and – as shown – high uncertainty about their future development, such sensitivity modelling would be highly valuable and is sorely missing from the available scenario studies, including the EU's Energy Roadmap 2050 (despite the reference scenario where high and low energy import prices have been assumed besides the reference scenario as such).

4.4 Cost assumptions on nuclear power

Unfortunately the cost development of nuclear power cannot be directly compared between the scenarios: The Energy Revolution study does not provide any data on nuclear power as this technology is phased out in the study's policy scenarios and the figures provided by the Power Choices study on the one hand (generation costs) and the ECF Roadmap 2050 on the other hand (capital expenditure) cannot be directly compared. However, in the two latter studies nuclear power costs are assumed to remain virtually stable in the coming decades: In the Power Choices study generation costs are assumed to decline slightly from 4.5 €-cents_{2005}/kWh in 2020 to 4.4 €-cents_{2005}/kWh in 2050 while capital expenditure in the ECF Roadmap 2050 study is reduced from about 3,000 $€_{2010}$ to about 2,900 $€_{2010}$ per kWh.

4.5 Explanation of the difference in cost assumptions

An explanation for the difference in the cost assumptions applied by the decarbonisation scenarios involves the concept of learning rates, which suggests that the specific cost of a technology declines faster the more the technology is deployed. Given that the deployment of renewables is highest in the Energy Revolution scenarios, it is to be expected that their specific costs are the lowest of the decarbonisation scenarios. Although the effect of learning rates on the long-term technology costs are taken into account by all of the decarbonisation scenarios, the transparency of how these learning rates are applied is currently insufficient. For example, no specific learning rates are provided by the Power Choices study and the learning rates assumed in the Energy Revolution and the ECF Roadmap 2050 studies are not easily comparable for a variety of reasons, one being differences in technology classifications.

Not all cost differences between the scenarios can be explained by learning rates. For example, differences in conventional fossil fuel generation costs are not so much due to different assumptions on capital costs but rather on (very) different assumptions on the future development of fuel prices. In addition some of the cost/capital expenditure assumptions in the scenarios are already today

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[33] See the Annex for a discussion on how non-cost factors can influence the development of the energy system in energy models.

clearly outdated, which may result in the cost reduction potential of abatement measures being underestimated.[34]

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[34] An extreme example is the cost assumptions for PV in the Power Choices scenario: In 2010 in Germany the remuneration of one kWh from a new PV plant fed into the public grid was between 28 and 39 €-cents_{2010} (depending on the system's size and its location) according to the country's Renewable Energy Law. In the Power Choices scenario generation costs for 2010 are given by 45 €-cent_{2005}/kWh (50 €-cent_{2010}/kWh) and they only decline slightly to 44 €-cent_{2005}/kWh (49 €-cent_{2010}/kWh) in 2020.

5. Window of opportunity for political action

The window of opportunity for political action to prevent runaway climate change is rapidly closing as high-carbon energy generation facilities continue to be built around the world, resulting in an emissions 'lock in' effect that reduces the likelihood of limiting global temperature rise to 2°C (likely requiring stabilization of atmospheric levels of greenhouse gases at no more than 450 ppm of CO_2 equivalent). According to the IEA (2011), a continuation of current trends in energy generation will result in 90 % of the available 'carbon budget' until 2035 being used up by 2015 already.[35] Political action at both the international and national level is therefore urgently required to incentivise low-carbon investments in order to decarbonise the world's energy generation. The purpose of this section is to provide further guidance on the timing of this political action from the European perspective by identifying the windows of opportunities for implementing important abatement measures that can be divided into the following categories:

- Existing abatement measures (i.e. renewable energies, fuel switching etc.)
- Key innovations (i.e. CCS technology, electric mobility etc.)

The outcome of the decomposition analysis outlined in Section 3 is re-organised in Table 3 and Table 4 following the above distinction between the evolutionary development of existing measures and the key innovations that require breakthroughs in technology to deliver the CO_2 emission reductions envisaged in the decarbonisation scenarios. Furthermore, the contribution of the causal factors to overall CO_2 emission changes is presented in relative terms to enable a better comparison between the decarbonisation scenarios and to complement Figure 5 and Figure 6.

The dark green shaded row in Table 3 illustrates that the deployment of renewable energy plays a central role throughout the 2020 to 2050 period in all of the decarbonisation scenarios; however there is a greater level of consensus on the short term contribution to CO_2 emission reductions than in the longer term. The narrow range of the contribution of renewable energy to CO_2 emission changes in 2020 between the decarbonisation scenarios (i.e. 108 % to 115 % relative to the base years) reflects the renewable energy target set within the EU Climate Package. However it is important that policy makers are aware of the potential for delays in the lead times that are associated with the deployment of renewable technologies and to legislate accordingly in order to ensure that this policy target is achieved by 2020. In the longer term, the contribution of renewable energy to CO_2 emission changes in 2050 is less certain ranging from 37 % to 156 % (which accounts for 24 and 77% gross emission reductions) relative to the respective base years of the decarbonisation scenarios in Table 3. The divergent range reflects the emergence of CCS as an additional abatement measure in the longer term.

In all of the decarbonisation scenarios it is expected that improving the efficiency of fossil fuel plants and switching to cleaner fuel inputs (i.e. from coal to gas) will result in CO_2 emission reductions consistently throughout the 2020 to 2050 time period for all decarbonisation scenarios (Table 3). In order to encourage these improvements, political action will be required that progressively increases

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[35] IEA(2011): World Energy Outlook 2011.

the cost of carbon until the year 2050 through the implementation of a range of policy instruments (i.e. environmental taxes, emissions trading). Furthermore, the dark red shaded row in Table 3 demonstrates that the majority of the decomposition scenarios expect the role of nuclear power to decline by 2050, which will result in additional emissions that will need to be offset by introducing policies aimed at encouraging the rapid deployment of alternative sources of low carbon electricity generation (see column *RES use*) and improvements in energy efficiency.

Table 3 The contribution of existing abatement measures to CO_2 emission change compared to the base year of each scenario between 2020 and 2050.

		Resid. cons.	Tertiary cons.	Industry cons.	Road tr. cons.	RES use	Nuclear use	Emission factor	Fuel input intensity
Greenpeace Rev	2020	-2%	-2%	2%	-2%	115%	-70%	28%	34%
Greenpeace Adv		-2%	-2%	2%	-4%	114%	-66%	28%	31%
Power Choices		-13%	-4%	-9%	-6%	108%	-35%	18%	43%
Greenpeace Rev	2030	0%	0%	3%	-2%	101%	-59%	31%	22%
Greenpeace Adv		0%	0%	2%	-3%	110%	-57%	34%	19%
Power Choices		-11%	2%	-13%	-26%	73%	-18%	27%	40%
Greenpeace Rev	2040	0%	0%	3%	-2%	94%	-50%	28%	19%
Greenpeace Adv		0%	0%	3%	-3%	107%	-48%	30%	19%
Power Choices		-5%	6%	-13%	-65%	51%	-10%	29%	46%
Greenpeace Rev	2050	1%	1%	3%	-2%	85%	-45%	27%	21%
Greenpeace Adv		-4%	-4%	4%	-4%	121%	-52%	35%	24%
Power Choices		1%	7%	-8%	-44%	37%	-5%	32%	37%
ECF 40% RES		1%	1%	1%	0%	57%	8%	6%	15%
ECF 60% RES		1%	1%	1%	0%	110%	-20%	6%	15%
ECF 80% RES		2%	1%	1%	1%	156%	-45%	5%	14%

Note: Positive values reflect emission reductions, negative values correspond to emission additions. A detailed breakdown on shares of causal factors on gross CO_2 emission reductions in each scenario can be found in the Annex.

Source: Öko-Institut / Wuppertal Institut (2012)

The commercialisation of CCS technology in the medium term is expected to contribute in several decarbonisation scenarios considerably to CO_2 emission reductions towards the end of the 2020 to 2050 time horizon. For example, the deployment of CCS technology will account for 70 % of emission changes (29.3 % of gross CO_2 emission reductions) in 2040 according to the Power Choices scenario and 76% of emission changes (45.2% of gross CO_2 emission reductions) in the 40% RES scenario. A potential vulnerability to the realisation of these scenarios is the potential reliance on a single technology which is not yet in a commercial state. The assumption that CCS technology will become financially viable in the medium term, depends upon the level of investment in research and development that is provided to deliver the technological breakthroughs that are necessary. Therefore, decarbonisation scenarios dependent upon CCS technology for emission reductions rely upon the development of an abatement technology that is highly uncertain.

In contrast the Greenpeace scenarios exclude CCS technology due to environmental concerns and instead opt to import low-carbon electricity from outside of Europe; however this abatement measure will also require investments to develop international transmission infrastructure increasingly from 2030 onwards and is connected to several, e.g. political and financial uncertainties. Finally, the rising electricity demand over time for new appliances such as electric vehicles and heat pumps (Table 4) presents policy makers with the challenge of decarbonising the power sector by 2050 to prevent electric vehicles from contributing to CO_2 emissions in the future. Given the dependency of these new appliances on a low carbon electricity grid, political action is urgently required now to ensure that these key innovations can be increasingly utilised from 2020 onwards to reduce CO_2 emissions.

Table 4 The contribution of key innovations to CO_2 emission change compared to the base year of each scenario between 2020 and 2050.[36]

		Road transport cons.	Heating cons.	Storage cons.	CCS use	Imports
Greenpeace Rev.	2020	-3%	-2%	-3%	0%	4%
Greenpeace Adv. Rev.		-3%	-1%	-3%	0%	4%
Power Choices		0%	0%	0%	5%	-2%
Greenpeace Rev.	2030	-5%	-1%	-3%	0%	12%
Greenpeace Adv. Rev.		-13%	-2%	-3%	0%	10%
Power Choices		0%	0%	0%	33%	-1%
Greenpeace Rev.	2040	-12%	-2%	-3%	0%	23%
Greenpeace Adv. Rev.		-21%	-2%	-5%	0%	20%
Power Choices		-12%	0%	0%	70%	-1%
Greenpeace Rev.	2050	-21%	-2%	-3%	0%	34%
Greenpeace Adv. Rev.		-36%	-5%	-10%	0%	31%
Power Choices		0%	0%	0%	48%	-1%
ECF 40% RES		-34%	-30%	0%	76%	0%
ECF 60% RES		-33%	-29%	0%	49%	0%
ECF 80%RES		-58%	-31%	0%	23%	0%

Note: Positive values reflect emission reductions, negative values correspond to emission additions. A detailed breakdown on shares of causal factors on gross CO_2 emission reductions in each scenario can be found in the Annex.

Source: Öko-Institut / Wuppertal Institut (2012)

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[36] The Power Choices scenario does not differentiate electricity consumption between traditional appliances and new appliances (i.e. road transport and heat) and therefore these additional CO2 emissions from the new appliances are accounted for in the residential, tertiary, industry and transport figures shown in Table 4.

6. Conclusion

This paper identifies robust corridors where political action is urgently required in order to deliver the 'shared vision' set out in the decarbonisation scenarios. Given that the window of opportunity for political action to prevent the 'lock in' of carbon intensive technologies in the power sector is time limited, it is essential that political action is taken within the next decade to implement the CO_2 emission reductions associated with 'key innovations' that were identified in the decomposition analysis and discussed in Section 5. Further political debate will be necessary to decide upon the more controversial elements of decarbonisation (i.e. the deployment of nuclear power and CCS technology in the energy mix) and this policy paper challenges the robustness of decarbonisation scenarios that are dependent on assumptions associated with high levels of uncertainty (i.e. commercialisation date of CCS). The following six key issues have been identified previously and are summarised into several bullet points here:

1. **Energy efficiency improvements will play a key role**
   Significant efficiency improvements are vital in order to limit CO_2 emission increases through the increase in electricity consumption resulting from economic growth and electrification of various energy services (especially transportation) to an appropriate level. However, while there is agreement in all scenario studies that faster improvements in energy efficiency are essential to limit future growth in electricity demand, there is no consensus in which sectors such improvements can be reached best and most economically. This is an area where further research is very much needed. Enhancements of the decomposition method would be needed to separately account for changes in efficiency.

2. **E-mobility will play a large role in decarbonising transport**
   There is a shared understanding that electricity will be pivotal in helping the transport sector reduce its CO_2 emissions. In all scenarios electricity will have a large share in individual transportation by 2050, while the share of public transportation (which mostly uses electricity) is also expected to increase in most scenarios. In order for e-mobility to deliver CO_2 emission reductions in all aspects the electricity generation mix needs to change at the same time, otherwise emissions reduced by avoiding emissions from fuel combustion in cars would re-enter the system through the electricity mix.

3. **Renewables will be most important electricity supply option, but further cost reductions needed**
   All scenarios analysed assume that all renewable energy technologies combined will be the most important mitigation option in electricity supply. The scenarios also agree that of all renewable sources, wind (onshore and offshore) will be the single most important one. While no technological breakthroughs are required to realise these visions, continued innovation and cost reductions are essential for some of the renewable technologies, especially for solar PV, offshore wind, solar thermal and (important in some scenarios) geothermal energy. Challenges associated with the fluctuating nature of especially wind and

solar energy are not addressed sufficiently in some of the scenario studies and should be high on the political and scientific agenda.

4. **Uncertainty regarding the future role of nuclear and CCS**
   The biggest differences in the electricity supply of the scenarios analysed are the two abatement options nuclear power and CCS. Social acceptance for both of these technologies is lacking in many European countries, making scenarios with high use of these technologies vulnerable in this regard. Most scenarios see a declining role for nuclear power in the coming decades. The technological and economic viability of the large-scale use of CCS technology is as of yet unproven. A high reliance on electricity from CCS power plants can only be reconciled with very ambitious CO2 reduction targets (e.g. 95% or more) when CCS capture rates of around 99% can be realized technologically. If CCS is seen as a worthwhile option for the future, political assistance in the form of research, development and deployment support as well as a clear legislative framework for CO_2 transport and storage is needed in the short term. High-renewable scenarios indicate that power sector CO_2 reductions of 90 % and more by 2050 (compared to 1990) may be possible without relying either nuclear power or CCS technology. Furthermore, there are indications that those scenarios relying to a large degree on nuclear and CCS power plants are underestimating the cost reduction potential of renewable energy technologies.

5. **The issue of energy policy timing is crucial in changing the energy system**
   As chapter 3 has shown, in all scenarios large-scale, centralised technologies (especially CCS, nuclear power and/or off-shore wind) play a major role in achieving a low carbon electricity system. However, these technologies exhibit longer lead times and high investments, both leading to higher risks in an environment that is difficult to predict. Therefore political decisions are needed in the short term to reduce uncertainty for investors and to facilitate the transformation process in the electricity sector. Specific tasks include measures to prepare the electricity grid infrastructure for a quickly growing share of fluctuating energy sources (supporting storage technologies, making sure the electricity grid is transformed in a timely manner). If CCS is regarded as a desirable future option in the European electricity system, financial support for research and development as well as the planning of pipelines and storage sites is needed, considering the long lead times involved. Adapting the regulatory framework of the energy system will itself have considerable lead times, so political action even for the post-2020 development is required very soon.

6. **Need for greater transparency in energy scenarios**
   If the transparency of decarbonisation studies regarding data reporting increased and conformed to a European-wide standard this would add value for further utilisation of the data by the European Commission and others. A blank data roster sheet is provided in the annex, which suggests how data and accompanying assumptions could be reported in a standardised way.

7. References

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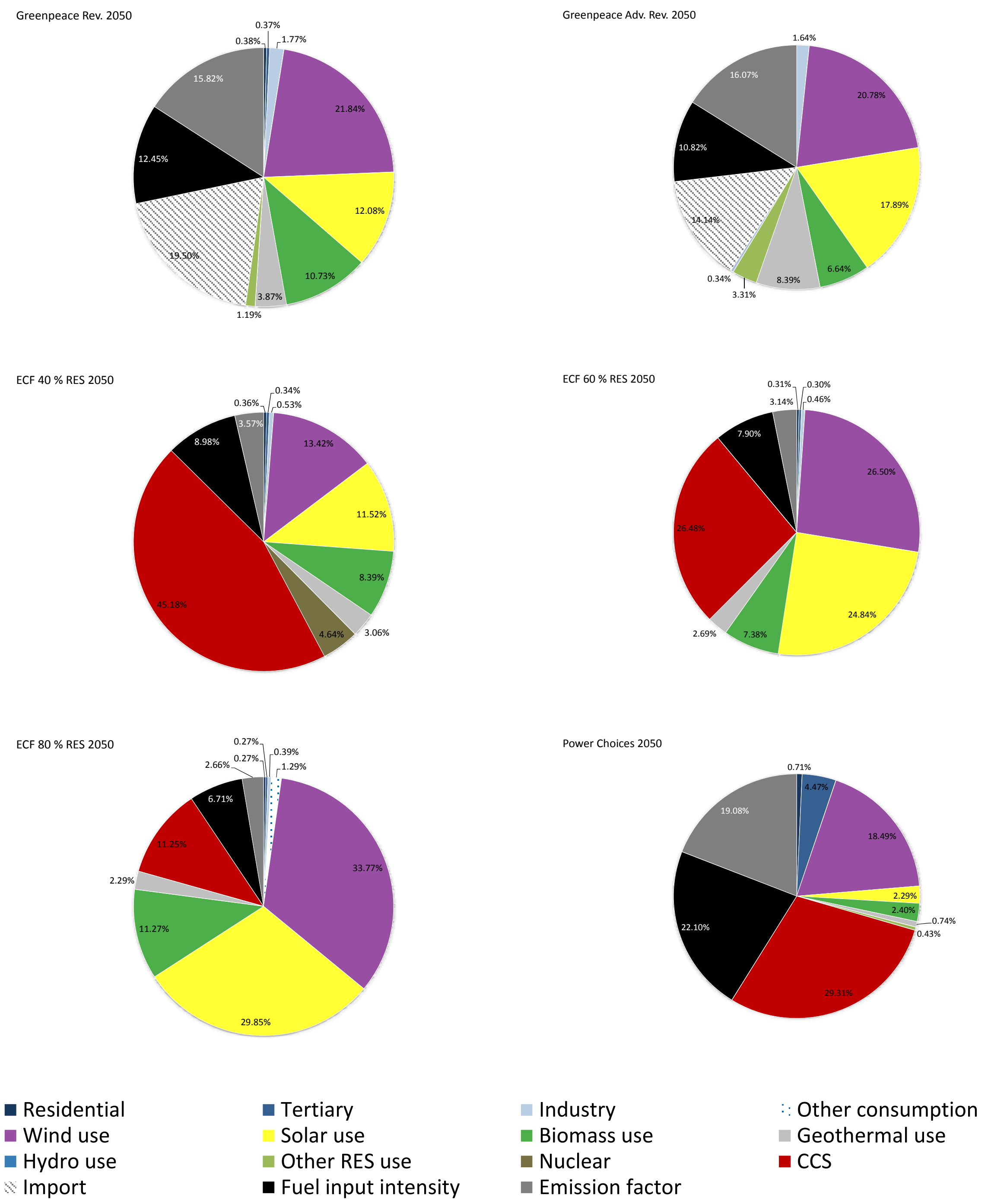
8. Annex

8.1 Shares of causal factors on gross CO_2 emission reductions in each scenario

Figure 9 Shares of causal factors on gross emission reductions in 2050.



Note: These figures exemplify the positive parts of Figure 5 and Figure 6. The positive parts of these graphs show those causal factors that contribute to emission reductions. The sum of these emission reductions are the gross emission reductions that are necessary to compensate for the additional emissions depicted in the negative part of the graph. The gross emission reductions have been set in relation to each of the causal factor to determine that causal factor's share on gross emission reductions.

Source: Öko-Institut, Wuppertal Institut (2012)

8.2 Climate Policies in the EU

In December 2008, the European Union (EU) adopted a comprehensive energy and climate package to further enhance the international reputation of the EU as a leader on climate policy. The objective of the energy and climate package is to reduce greenhouse gases (GHGs) by at least 20 % by 2020 relative to 1990 emission levels, increase the share of renewable energy in meeting the EU's final energy demand to 20 % and to reduce energy consumption by 20 % compared to projected trends.

An essential policy instrument to achieve these climate policy objectives is the Emissions Trading System (ETS), which was introduced in 2005 (Directive 2003/87/EC) and regulates over 11 000 installations that are responsible for almost half of the GHG emissions emitted in the EU. The ETS is based upon the principle of cap and trade, which can be briefly summarized as follows:

- A cap or limit on the total amount of particular GHG emissions that can be emitted is set for all factories, power plants or other installations participating in the EU ETS;
- Emission Unit Allowances (EUAs), which are equivalent to the emissions limit set under the cap, are distributed to the installations participating in the ETS;
- Installations are then required to surrender at the end of each year one EUA for each tonne of GHG which they have emitted;
- The ability to trade allowances enables installations that do not have enough allowances to cover their emission level for a compliance period by purchasing allowances on the market. In contrast, installations with a surplus of allowances can sell these on the market.
- These transactions creates a price per tonne of GHG that provides the financial incentive for installations to either reduce their level of emissions to sell their allowance surplus on the market or to buy allowances if this is more cost effective than reducing their own emissions.

The third trading phase of the EU ETS will commence in 2013 with the introduction of an EU wide cap on emissions, which will reduce at an annual rate of 1.74 % to ensure that the EU achieves a -21 % reduction in the ETS sector relative to 2005 emission levels (Directive 2009/29/EC). Emissions from sectors not covered by the ETS (i.e. buildings, transport and agriculture) are subject to the Effort Sharing Decision (406/2009/EC), which obliges the Member States to ensure that collectively non-ETS emissions are reduced by -10 % below 2005 levels by 2020. If the policies are fully implemented in both directives, it is envisaged that the EU objective of an economy wide reduction of -20 % below 1990 emission levels will be achieved by 2020.

National binding targets have been set for each Member State to ensure that the average renewable share across the EU reaches 20 % by 2020 (Directive 2009/28/EC). Given that the starting point, the renewable energy potential and the energy mix varies for each Member State, the EU target of 20 % was translated to individual targets that ranged from a renewables share of 10 % in Malta to 49 % in

Sweden. If these national binding targets are achieved then the EU objective of increasing the share of renewable energy in meeting the EU’s final energy demand to 20 % will also be achieved by 2020. To ensure that the energy efficiency objective is also achieved by 2020 the European Commission recently proposed new legislation (COM (2011) 370 Final) to obligate Member States to establish energy saving schemes.

8.3 Energy models used in the studies considered

The three studies analysed in this paper use energy models to develop their scenarios. Energy models consist of a more or less detailed mathematical representation of the energy system. They are used (among other purposes) to develop and analyse possible future developments of the energy system. Many different types of energy models exist and they are used depending on the purpose of the analysis. The following table gives a brief overview of the models used in the three scenario studies discussed in this paper.

Table 5 Models used in the studies considered

Scenario study	**Name of the model**	**Type of the model**
Greenpeace (2010)	MESAP/PlaNet	Simulation model
ECF (2010)	Referred to as „power system analysis model“	Simulation model (partial optimisation)
Eurelectric (2010)	PRIMES	Partial market equilibrium model

The Greenpeace study uses the simulation model MESAP/PlaNet. Simulation models aim to mirror actual energy market transactions by simulating the behaviour of market actors. Energy demand and supply in these models is not only driven by market prices, but also by other factors like risk aversion and information deficits. The Greenpeace study only models the supply side, while assumptions are made beforehand about the development of energy demand, based on expected growth in energy services as well as on studies evaluating the potential for efficiency improvements.

Simulation models generally give modellers a significant amount of freedom to influence the development of the energy system. In these models it can be assumed, for instance, that certain policy interventions or widespread changes in preferences lead to very different decisions by market actors than in the past. In this way the alternative scenarios in the Greenpeace study assume that adequate policies are in place to ensure that a swift decrease of fossil fuels in the power sector (as well as in the rest of the energy system) will take place. Therefore assumptions about the development of costs of various supply technologies are not necessarily as crucial as in other models.

The study by Eurelectric uses the PRIMES model, which was developed by E3MLab of the National Technical University of Athens. PRIMES is a so called partial equilibrium model which determines the market equilibrium by finding the price of each energy fuel that matches the supply and demand of energy. Energy demand and energy supply are modelled simultaneously so for example an increase in electricity prices would (ceteris paribus) lead to lower electricity demand.

The ECF study uses a power system model, which minimizes annual electricity production cost while maintaining the required level of system reliability. However, no overall optimisation takes place, as the deployment levels of renewables, CCS and nuclear are predetermined in each scenario.

In all energy models the development of the (relative) costs of competing technologies and resources can be seen as a key input parameter that has a major influence on how the energy system develops. In the models used in the three scenario studies the development of technology costs and fuel costs are provided exogenously (that is, they are not derived from the model). Other key assumptions influencing energy system development are those about changes in policy and consumer preferences and of course – in those models that deal with energy supply only – the assumption about how energy demand will develop. Those models that endogenously determine energy demand require additional assumptions, like changes in population, in per capita GDP and in demand-side efficiency.

While the studies provide at least some information on the cost assumptions made (see Chapter 4), there is insufficient information on what other factors determine developments in energy supply and (if modelled) energy demand and how these factors change over time.

However, some key assumptions that are not (directly) cost-related are explicitly made within the studies and have a major influence on how the energy system and thus emission trajectories evolve in the respective scenarios. The following table summarizes a number of these key assumptions for the various scenarios and may serve as a complement to Figure 2.

Table 6 Key assumptions of the studies considered that influence the decarbonisation pathways

Study	**Scenarios**	**Key assumptions (apart from costs)**
Greenpeace (2010)	• Energy Revolution • Adv. Energy Revolution	• EU CO_2 emissions reduced by 80% (Energy Revolution) / 95% (Adv. Energy Revolution) below 1990 levels by 2050 • Technical efficiency potential realised to a large extent • Increasing use of electric vehicles and heat pumps leading to higher electricity demand • CCS not utilised • No new nuclear power stations built (nuclear power phased out completely by around 2040)
ECF (2010)	• 40%-RES • 60%-RES • 80%-RES	• European greenhouse gas emissions to be reduced by 80% below 1990 levels by 2050 • Adaption of more aggressive energy efficiency measures • Increasing use of electricity in road transport, industrial processes and heating leads to higher electricity demand • Share of renewables in power generation in 2050 set at 40, 60 and 80% respectively
Eurelectric (2009)	• Power Choices	• OECD power sector should become “virtually carbon-free” by 2050 • No explicit assumptions on the demand side (electricity demand modelled based on cost and GDP assumptions) • No key assumptions predetermining the electricity supply mix

8.4 Suggested standard for data reporting

Common roster of data and information

Metadata on the studies and modelling exercises

General information about study
Study title
Date published (month/year)
Source (URL, if available on internet)
Developed by
Institute(s)
Lead author(s)
Commissioning body/bodies
Context in which study was commissioned/prepared
Consideration of entire energy system (yes/no, only electricity)
Countries included in analysis (EU-27 or different scope?)

Scenarios
Reference scenario (yes/no)
Number of alternative scenarios
Scenario analysed here
Base year

Modelling approach
General modelling approach (if applicable)
Modelling approach for electricty sector
Important (external) model drivers

	base year	2010	2015	2020	2025	2030	2035	2040	2045	2050
Key socioeconomic assumptions										
Population (in million)										
Population (index, base year = 100)										
real GDP (in billion €$_{2008}$)										
real GDP (index, base year = 100)										

	base year	2010	2015	2020	2025	2030	2035	2040	2045	2050
Key targets, restrictions and assumptions										
Key targets (e.g. CO_2 emission reduction target)										
Key restrictions										
Construction of new nuclear power plants										
Construction of CCS power plants										
Assumptions about renewable energy potential										
Biomass share in whole energy system										
Biomass potential available to EU										
Assumptions about CCS storage capacity										

Electricity consumption

	base year	2010	2015	2020	2025	2030	2035	2040	2045	2050
Total electricity consumption (in TWh) EU-27										
Electricity consumption per country (in TWh) area under study										

	base year	2010	2015	2020	2025	2030	2035	2040	2045	2050
Electricity consumption per sector (in TWh)										
Residential										
Tertiary										
Industry										
Transport										

	base year	2010	2015	2020	2025	2030	2035	2040	2045	2050
Share of electricity consumption per sector										
Residential										
Tertiary										
Industry										
Transport										

	base year	2010	2015	2020	2025	2030	2035	2040	2045	2050
Electricity consumption from traditional appliances (in TWh)										
Residential										
Tertiary										
Industry										
Transport										
Electricity consumption from "new" appliances (in TWh)										
Road transport										
Heat market										
Electricity input for storage (in TWh)										
Pumped storage										
Compressed air storage										
Hydrogen production										
Battery storage										
Other types of storage										

Electricity consumption from power generation (in TWh)	base year	2010	2015	2020	2025	2030	2035	2040	2045	2050
Consumption for conversion										
Line losses										

Electricity supply data (in TWh)

	base year	2010	2015	2020	2025	2030	2035	2040	2045	2050
Net electricity generation per source (in TWh)										
Nuclear										

Fossil (CO2 emitting) energy sources										
Hard coal										
of which CCS										
Lignite										
of which CCS										
Natural gas										
of which CCS										
Oil										
Waste (non-biogenic)										
Renewable energy sources										
Hydro										
Wind										
of which onshore										
of which offshore										
Biomass										
of which from biogas										
of which from solid (including biogenic waste)										
Solar										
of which PV										
of which solar thermal										
Geothermal										
Ocean energy and other renewables										
Hydrogen (storage output)										
Synthetic natural gas (storage output)										
Output from other storage technology										

	base year	**2010**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Gross electricity generation per source (in TWh)										
Nuclear										
Fossil (CO2 emitting) energy sources										
Hard coal										
of which CCS										
Lignite										
of which CCS										
Natural gas										
of which CCS										
Oil										
Waste (non-biogenic)										
Renewable energy sources										
Hydro										
Wind										
of which onshore										
of which offshore										
Biomass										
of which from biogas										
of which from solid (including biogenic waste)										
Solar										
of which PV										
of which solar thermal										
Geothermal										
Ocean energy and other renewables										
Hydrogen (storage output)										
Synthetic natural gas (storage output)										
Output from other storage technology										
Power plants' own consumption of electricity										

	base year	**2010**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Net electricity generation from storage plants (in TWh)										

	base year	**2010**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Primary energy use for electricity generation by source (in PJ)										
Uranium										
Fossil fuel sources										
Hard coal										
Lignite										
Natural gas										
Oil										
Waste (non-biogenic)										
Renewable energy sources										
Biomass (including biogenic waste)										
Hydro										
Solar										
Wind										
Geothermal										
Ocean energy and other renewables										

Hydrogen

	base year	**2010**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Net electricity generation per country (in TWh)										
Austria										
Belgium										
Bulgaria										
Cyprus										
Czech Republic										
Denmark										
Estonia										
Finland										
France										
Germany										
Greece										
Hungary										
Ireland										
Italy										
Latvia										

Lithuania										
Luxemburg										
Malta										
Netherlands										
Poland										
Portugal										
Romania										
Slovakia										
Slovenia										
Spain										
Sweden										
United Kingdom										

	base year	2010	2015	2020	2025	2030	2035	2040	2045	2050
Export and import of electricity from outside Europe										
Export of electricity (in TWh)										
of which from renewable sources										
Import of electricity (in TWh)										
of which from renewable sources										
Net import of electricity (in TWh)										
of which from renewable sources										
Share of net imports in electricity consumption (in %)										

	base year	2010	2015	2020	2025	2030	2035	2040	2045	2050
Electricity generation from CHP and from decentralized sources										
Electricity generation from CHP (in TWh)										
of which small-scale CHP										
Share of CHP generation in electricity consumption (in %)										

Infrastructure data

	base year	2010	2015	2020	2025	2030	2035	2040	2045	2050
Power plant capacity (in GW)										
Nuclear										
Fossil energy sources										
Hard coal										
of which CCS										
Lignite										
of which CCS										
Natural gas										
of which CCS										
Oil										
Waste (non-biogenic)										
Renewable energy sources										
Hydro										
Wind										
of which onshore										
of which offshore										
Biomass										
of which biogas										
of which solid (including biogenic waste)										
Solar										
of which PV										
of which solar thermal										
Geothermal										
Ocean energy and other renewables										

	base year	2010	2015	2020	2025	2030	2035	2040	2045	2050
Storage capacity (in GW)										
Pumped storage plant										
Compressed air storage plant										
Hydrogen production plant										
Battery storage										
Other types of storage										

Information about power transmission network(s) ____________________

Information about power distribution network(s) ____________________

Information about system services (smart grids, DSM, etc.) ____________________

Assumptions and results of technologies' cost modelling

Description of cost modelling approach ____________________

Assumed learning curve (in % per doubling of capacity)	base year	2010	2015	2020	2025	2030	2035	2040	2045	2050
Nuclear										
Hard coal - without CCS										
Hard coal - with CCS										
Lignite - without CCS										
Lignite - with CCS										
Natural gas - without CCS										
Natural gas - with CCS										
Renewable technologies										
Hydro - general										
Hydro - small scale										
Hydro - large scale										
Wind - general										
Wind - onshore										
Wind - offshore										
Biomass - general										
Biomass - biogas										

Biomass - solid										
Solar PV										
Solar Thermal - general										
Solar Thermal - without storage										
Solar Thermal - with storage										
Geothermal										
Ocean energy										
Tidal energy										
Wave energy										
Hydrogen										

	base year	**2010**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Power plants' investment costs ($€_{2008}$ per kW)										
Nuclear										
Hard coal - without CCS										
Hard coal - with CCS										
Lignite - without CCS										
Lignite - with CCS										
Natural gas - without CCS										
Natural gas - with CCS										
Renewable technologies										
Hydro - general										
Hydro - small scale										
Hydro - large scale										
Wind - general										
Wind - onshore										
Wind - offshore										
Biomass - general										
Biomass - biogas										
Biomass - solid										
Solar PV										
Solar Thermal - general										
Solar Thermal - without storage										
Solar Thermal - with storage										
Geothermal										
Ocean energy										
Tidal energy										
Wave energy										
Hydrogen										

	base year	**2010**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Specific electricity generation costs (in €-cent$_{2008}$/kWh)										
Nuclear										
Hard coal - without CCS										
Hard coal - with CCS										
Lignite - without CCS										
Lignite - with CCS										
Natural gas - without CCS										
Natural gas - with CCS										
Renewable technologies										
Hydro - general										
Hydro - small scale										
Hydro - large scale										
Wind - general										
Wind - onshore										
Wind - offshore										
Biomass - general										
Biomass - biogas										
Biomass - solid										
Solar PV										
Solar Thermal - general										
Solar Thermal - without storage										
Solar Thermal - with storage										
Geothermal										
Ocean energy										
Tidal energy										
Wave energy										
Hydrogen										

	base year	**2010**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Assumed conversion efficiency of new plants (in %)										
Nuclear										
Hard coal - without CCS										
Hard coal - with CCS										
Lignite - without CCS										
Lignite - with CCS										
Natural gas - without CCS										
Natural gas - with CCS										
(Relevant) renewable technologies										
Biomass - biogas										
Biomass - solid										
Solar PV										
Hydrogen										

	base year	**2010**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Assumed average conversion efficiency of plants in stock (in %)										
Nuclear										
Hard coal - without CCS										
Hard coal - with CCS										
Lignite - without CCS										
Lignite - with CCS										
Natural gas - without CCS										
Natural gas - with CCS										
(Relevant) renewable technologies										

Biomass - biogas										
Biomass - solid										
Solar PV										
Hydrogen										

	base year	2010	2015	2020	2025	2030	2035	2040	2045	2050
Average full load hours of plants in stock (in hours/a)										
Nuclear										
Hard coal - without CCS										
Hard coal - with CCS										
Lignite - without CCS										
Lignite - with CCS										
Natural gas - without CCS										
Natural gas - with CCS										
Renewable technologies										
Hydro - general										
Hydro - small scale										
Hydro - large scale										
Wind - general										
Wind - onshore										
Wind - offshore										
Biomass - general										
Biomass - biogas										
Biomass - solid										
Solar PV										
Solar Thermal - general										
Solar Thermal - without storage										
Solar Thermal - with storage										
Geothermal										
Ocean energy										
Tidal energy										
Wave energy										
Hydrogen										

	base year	2010	2015	2020	2025	2030	2035	2040	2045	2050
World market prices for energy sources (in €$_{2008}$/GJ)										
Oil										
Natural gas										
Hard coal										
Uranium										

	base year	2010	2015	2020	2025	2030	2035	2040	2045	2050
CO2 price in (European) ETS (in €$_{2008}$/tCO2)										

Other key information

Interrelationship between electricity and other energy sectors ______________________

Policy measures assumed or deemed necessary ______________________

Reflections on uncertainties and robustness of results ______________________

	base year	2010	2015	2020	2025	2030	2035	2040	2045	2050
Electricity sector CO$_2$ emissions										
Total (in Mt of CO$_2$)										
Index (base year = 100)										
Index (1990 = 100)										

	base year	2010	2015	2020	2025	2030	2035	2040	2045	2050
Electricity sector CO$_2$ sequestration (in Mt of CO$_2$)										
Annual sequestration										
Cumulative sequestration										

Metastudy: Power Sector Decarbonisation

WP 3.1

Berlin, Wuppertal, 14.02.2012

Quantitative Analysis of scenarios from the EU's Energy Roadmap 2050

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Content

List of Figures

List of Tables

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 in total final energy demand to 20 % by 2020. Some 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 requirements of 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 to obtain 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 (some of) the underlying data, constrain the analysis and 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 scenarios with this method involves systematically disaggregating their overall emission reduction into contributions to emission reductions provided by the underlying causal factors (or components). This approach enables quantifying emission reductions on a disaggregated level and thus provides value added in increasing the transparency of modelling exercises.

While paper 2.2 of the project provides an in-depth analysis of selected studies released prior to the EU's Energy Roadmap 2050, this paper, WP 3.1, applies the same in-depth analysis to the scenarios described quantitatively in the Impact Assessment accompanying the Energy Roadmap 2050. For this analysis the seven main Energy Roadmap 2050 scenarios are considered. These are:

- Reference scenario
- Current policy initiatives scenario
- Energy efficiency scenario
- High renewable energy sources (RES) scenario
- Diversified supply technologies scenario
- Delayed CCS scenario
- Low nuclear scenario

All these scenarios are of general importance in the public discourse and relatively detailed data is available for each one of them.

Following this general introduction the paper at hand first provides an introduction of the scenarios and a general comparison of electricity demand and electricity supply across the scenarios (Chapter 2). An individual analysis of the scenarios with the decomposition approach follows in Chapter 3, while Chapter 4 compares the five decarbonisation scenarios using the decomposition results. The paper ends with a conclusion (Chapter 5).

2 Introduction to scenarios and general comparison

2.1 Scenarios from the EU's Energy Roadmap 2050

At the UN climate conference in Cancún in December 2010, all Parties expressed support for a target to limit global warming to a maximum of 2°C above pre-industrial levels, which is generally considered to be the threshold for global temperature rise to prevent the catastrophic consequences of climate change. The European Council subsequently reconfirmed in February 2011 that the objective of the European Union (EU) is to reduce greenhouse gas emissions (GHGs) by 80 to 95 % below 1990 levels by 2050. Although the EU is already committed to GHG emission reductions of at least 20 % below 1990 levels by 2020 as part of the Energy and Climate Package, longer-term policies are now required to ensure that the ambitious reduction target for 2050 is achieved. The European Commission has therefore published a 'Roadmap for moving to a competitive low-carbon economy in 2050' (European Commission 2011a), providing guidance on how the EU can decarbonise the economy.

The process around this document which finally led to the EU's Energy Roadmap 2050, published in December 2011, is based on economic modeling and scenario analysis, which considers how the EU can move towards a low carbon economy assuming continued global population growth, increasing global GDP and by varying trends in terms of international climate action, energy and technological development. The outcome of the analysis is a recommendation that the EU should reduce GHG emissions by 80 % below 1990 levels by 2050 and that this target is technically feasible and financially viable using proven technologies if strong incentives (i.e. carbon pricing) exist. The cost efficient pathway to achieve the 2050 target calls for domestic GHG reductions below 1990 levels of 25 % in 2020, 40 % in 2030 and 60 % in 2040 and this would require an additional annual investment of €270 billion for the next 40 years. This is equivalent to 'an additional investment of 1.5 % of EU GDP per annum on top of the overall current investment representing 19 % of GDP in 2009.' The extent and timing of these GHG reduction targets are differentiated by sector reflecting the different abatement potentials that exist within the EU.

The EU's Energy Roadmap 2050 was accompanied by an Impact Assessment (European Commission 2011c) which provides additional information underlying the assessment, specifically some key PRIMES modeling results of the 7 scenarios considered in the Energy Roadmap 2050.

The scenarios considered in the Roadmap were assessed with the PRIMES model, developed and run by E3MLab of the National Technical University of Athens. PRIMES is a partial equilibrium model that 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. In this exercise PRIMES is supported by more specialised models for projections regarding value added by branch of activity (GEM-E3 model) while for projections of world energy prices it makes use of PROMETHEUS, a fully stochastic world energy model. The scenarios considered in the EU's Energy Roadmap 2050 include two reference scenarios and five decarbonisation scenarios as summarised in Table 1.

Table 1 Summary of scenarios considered in the EU's Energy Roadmap 2050

Scenario	Characteristics
Reference scenario	The Reference scenario includes current trends and long-term projections on economic development (gross domestic product (GDP) growth 1.7% pa). The scenario includes policies adopted by March 2010, including the 2020 targets for RES share and GHG reductions as well as the Emissions Trading Scheme (ETS) Directive. For the analysis, several sensitivities with lower and higher GDP growth rates and lower and higher energy import prices were analysed.
Current Policy Initiatives Scneario (herafter: CPI scenario)	This scenario updates measures adopted, e.g. after the Fukushima events following the natural disasters in Japan, and being proposed as in the Energy 2020 strategy; the scenario also includes proposed actions concerning the "Energy Efficiency Plan" and the new "Energy Taxation Directive".
High energy efficiency scenario (herafter: Energy efficiency scenario)	Political commitment to very high energy savings; it includes e.g. more stringent minimum requirements for appliances and new buildings; high renovation rates of existing buildings; establishment of energy savings obligations on energy utilities. This leads to a decrease in energy demand of 41% by 2050 as compared to the peaks in 2005-2006.
Diversified supply scenario	No technology is preferred; all energy sources can compete on a market basis with no specific support measures. Decarbonisation is driven by carbon pricing assuming public acceptance of both nuclear and Carbon Capture & Storage (CCS).
High renewable energy sources scenario (herafter: high RES scenario)	Strong support measures for RES leading to a very high share of RES in gross final energy consumption (75% in 2050) and a share of RES in electricity consumption reaching 97%.
Delayed CCS scenario	Similar to Diversified supply technologies scenario but assuming that CCS is delayed, leading to higher shares for nuclear energy with decarbonisation driven by carbon prices rather than technology push.
Low nuclear scenario	Similar to Diversified supply technologies scenario but assuming that no new nuclear (besides reactors currently under construction) is being built resulting in a higher penetration of CCS (around 32% in power generation).

Source: (European Commission 2011b)

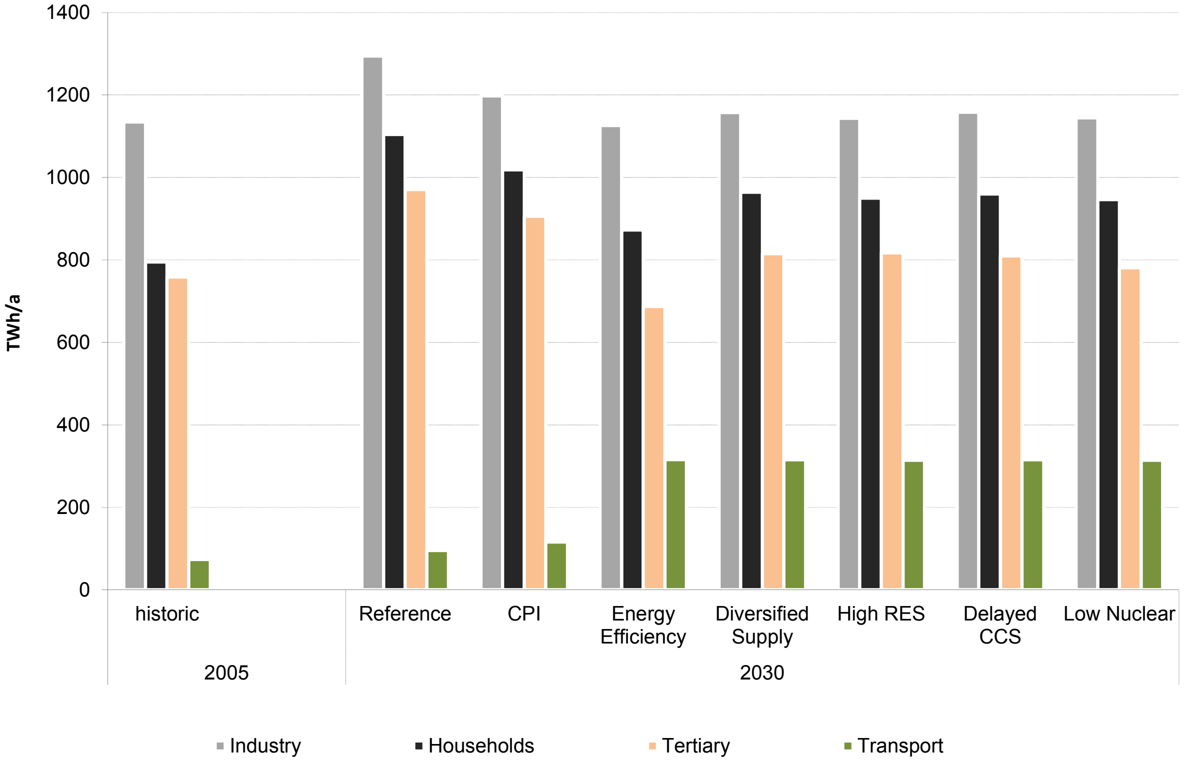
2.2 General comparison of scenarios

The following scenario comparison includes all the scenarios considered in the EU Energy Roadmap 2050. All of the scenarios are documented in the same fashion and provide information on how energy demand and supply will change up to the year 2050. In order to keep the comparison concise, the comparison will focus on the year 2050.

2.2.1 Electricity demand by sectors

Total electricity demand in the EU-27 increases until 2050 in all seven scenarios of the EU Energy Roadmap (see Figure 1). However, in the decarbonisation scenarios the increase is less pronounced than in the CPI and especially the Reference scenario. While electricity demand increases by 50% between 2005 and 2050 in the Reference scenario, the increase is between 16 and 31% in the decarbonisation scenarios. The lowest increase occurs in the Energy Efficiency scenario, where it is assumed that strong efficiency measures are implemented. Demand growth is also relatively low (+22%) in the High RES scenario, where higher generation costs and higher market prices are assumed to have a dampening effect on electricity demand.

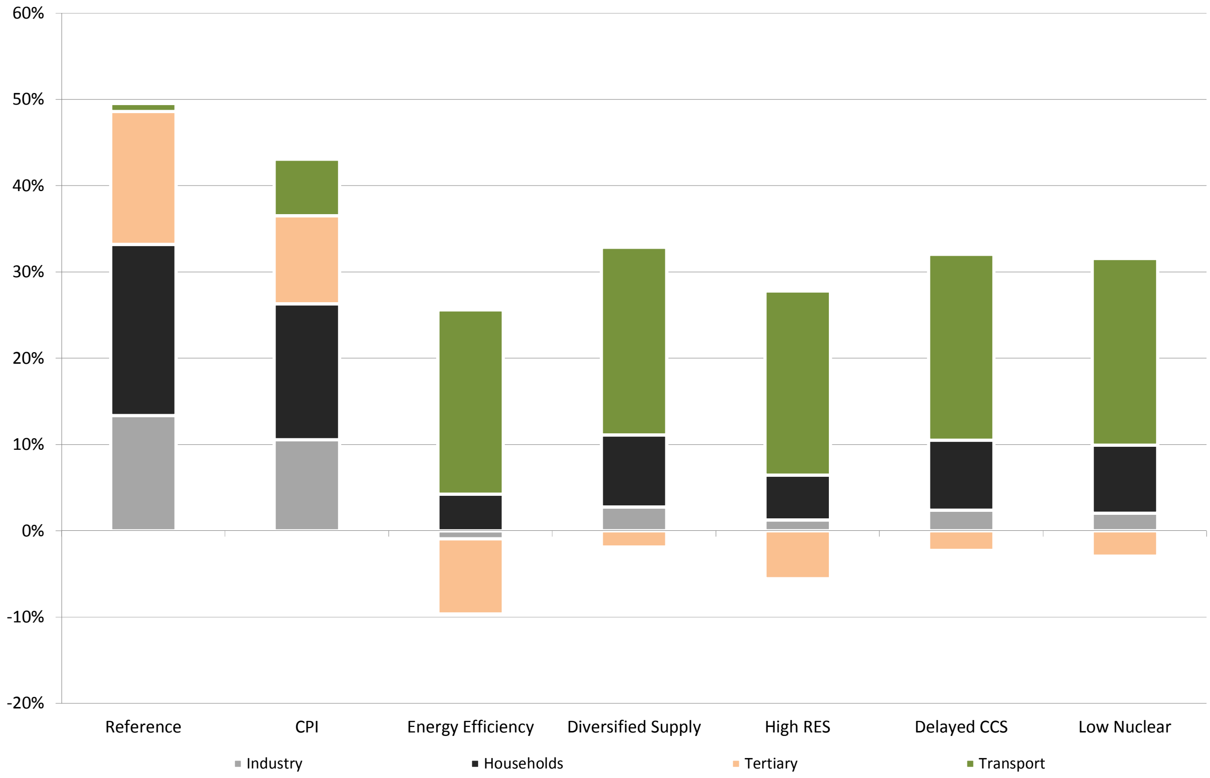
Figure 1 Electricity consumption (final energy demand) per sector in the EU-27 in 2005 and according to EU Energy Roadmap scenarios in 2050 (in TWh/a)



Source: (European Commission 2011c)

While considerable improvements in the efficient use of electricity are assumed in all of the decarbonisation scenarios (stronger so in the Energy Efficiency scenario), these improvements are overcompensated by additional demand for services requiring electricity. Some of that additional demand (for example in the case of electric cars and heat pumps) leads to lower non-electricity energy use and can thus help decarbonize the economy. Figure 2 highlights the relevance that a future widespread use of electric cars could have on electricity demand. The vast bulk of additional electricity demand in 2050 (compared to 2005) occurs in the transport sector. Without this additional demand (inter alia for heat pumps) electricity consumption would actually drop in the Energy Efficiency scenario and would be virtually flat in the High RES scenario, while it would increase only slightly in the other decarbonisation scenarios. Compared to a reference development, the EU Energy Roadmap sees considerable potential for reducing electricity demand in all of the three other sectors (tertiary, households and industry). Electricity demand in the tertiary sector in 2050 could even be considerably lower than in 2005.

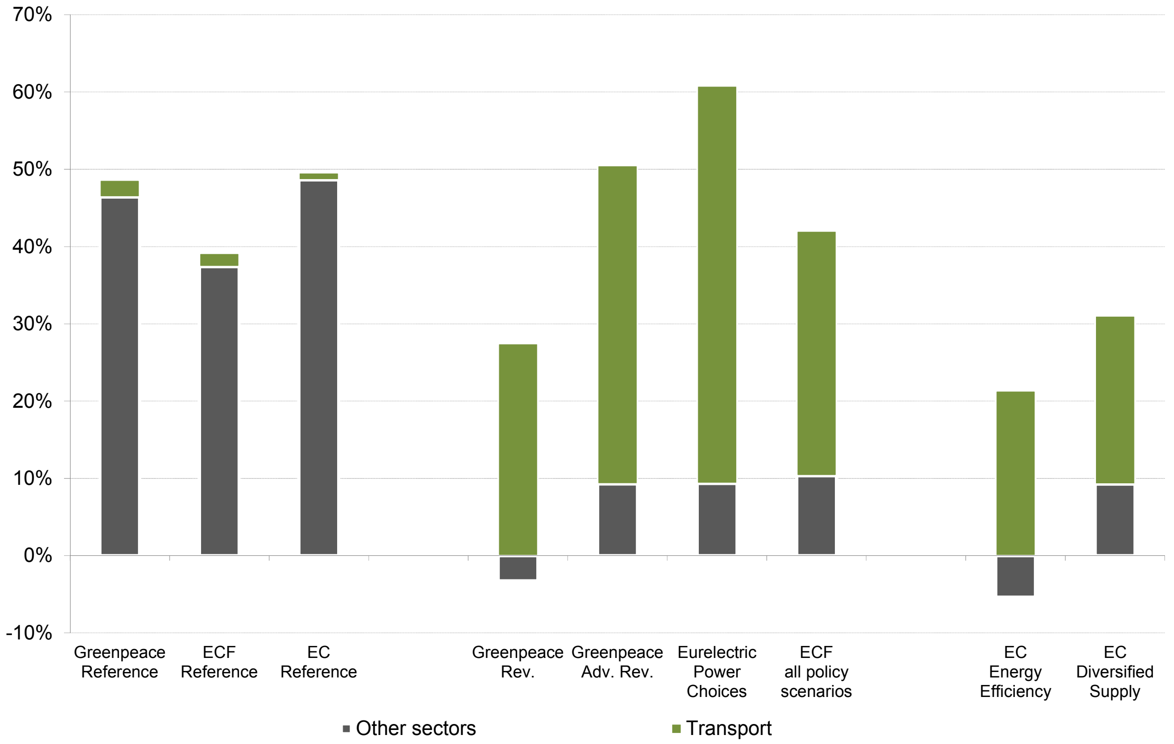
Figure 2 Change in final electricity demand in the EU-27 from 2005 to 2050 in the EU Energy Roadmap scenarios, differentiated by sectors



Source: (European Commission 2011c)

Previous European energy scenarios have made similar assumptions about the change in overall and sectoral electricity demand to be expected in any future decarbonised pathway. Figure 3 compares the changes in electricity demand between the base year and the year 2050 in three selected scenarios from the EU Energy Roadmap (Reference, Energy Efficiency and Diversified Supply) with two other reference and four other decarbonisation scenarios from previous scenario studies. All scenario studies see significant potential for efficiency improvements in the non-transport sectors compared to a business-as-usual development without strong efficiency measures. Realizing these efficiency potentials could enable demand increases in these sectors to remain low, at or below 10%. However, all scenarios expect electricity demand in the transport sector to increase dramatically, mostly due to the widespread introduction of full or hybrid electric cars. Compared to the policy scenarios of other studies, the decarbonisation scenarios of the EU Energy Roadmap are a little more conservative regarding the future electricity demand in the transport sector. Interestingly, as evidenced by electricity demand in the reference scenarios, without adequate policy support, none of the studies compared here expect electricity to play a much larger role in the transport sector in 2050 compared to today.

Figure 3 Change in final electricity demand in the EU-27 from 2005/2007 to 2050 in various scenarios, differentiated by the transport sector and the other sectors

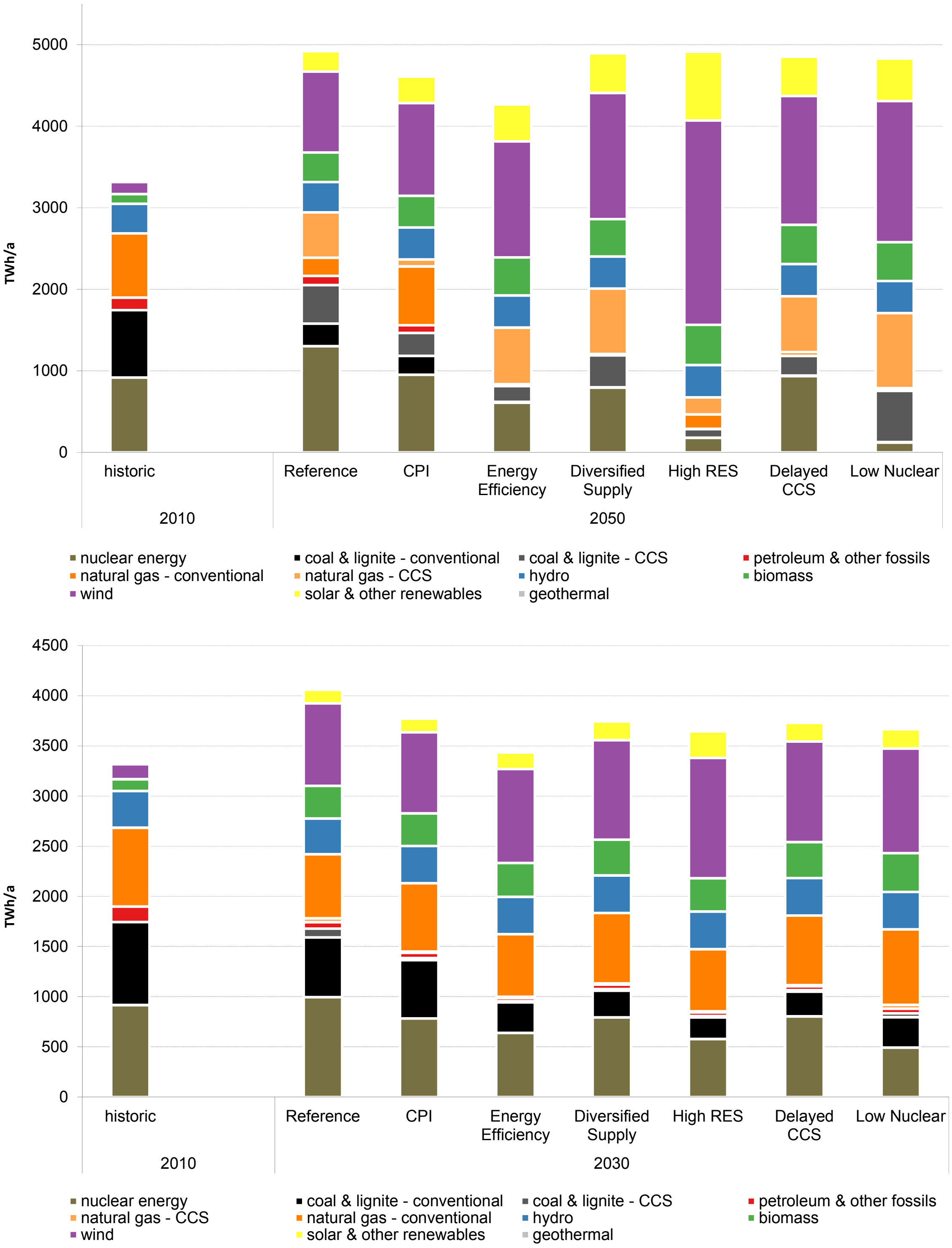


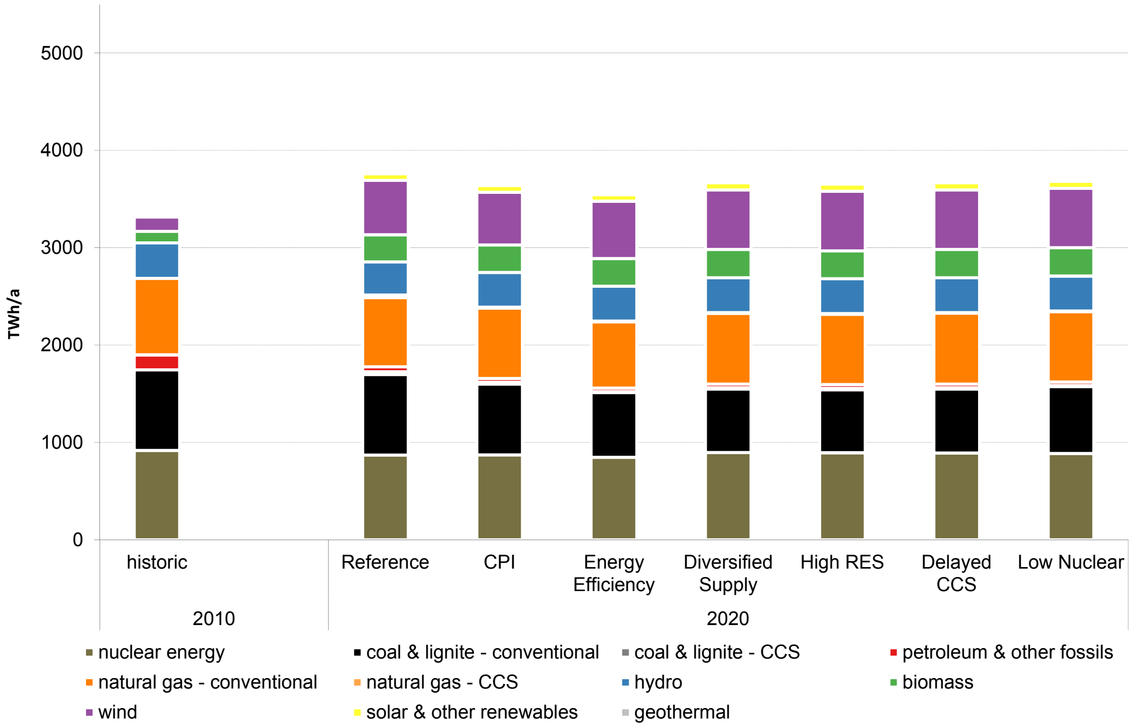
Source: (European Commission 2011c; Greenpeace International & European Renewable Energy Council 2010; eurelectric 2009; European Climate Foundation 2010)

2.2.2 Electricity supply in the EU Energy Roadmap scenarios

Figure 4 shows gross electricity generation by source in the EU-27 in the year 2010 according to Eurostat and in 2020, 2030 and 2050 according to the seven scenarios of the EU Energy Roadmap. In all scenarios a rising contribution of renewables is already apparent by 2020. Especially wind power but also electricity from biomass will increase considerably compared to today. Even in the reference scenarios the combined increase in electricity generation from renewables will more than offset the growing demand, enabling reductions in the use of nuclear energy and fossil fuels for electricity generation. Changes in the electricity supply between the two reference scenarios and the five decarbonisation scenarios are modest until 2020, owing to the long lead times of energy system changes and the fact that all scenarios assume that the EU's 2020 energy and climate targets are met. However, in the decarbonisation scenarios renewables are growing faster than in the two reference scenarios and the use of coal and lignite is already reduced by 16 to 20% in those scenarios compared to actual generation in 2010.

Figure 4: Gross electricity generation in the EU-27 by source in 2010 and according to EU Energy Roadmap scenarios in 2020/2030/2050 (in TWh/a)





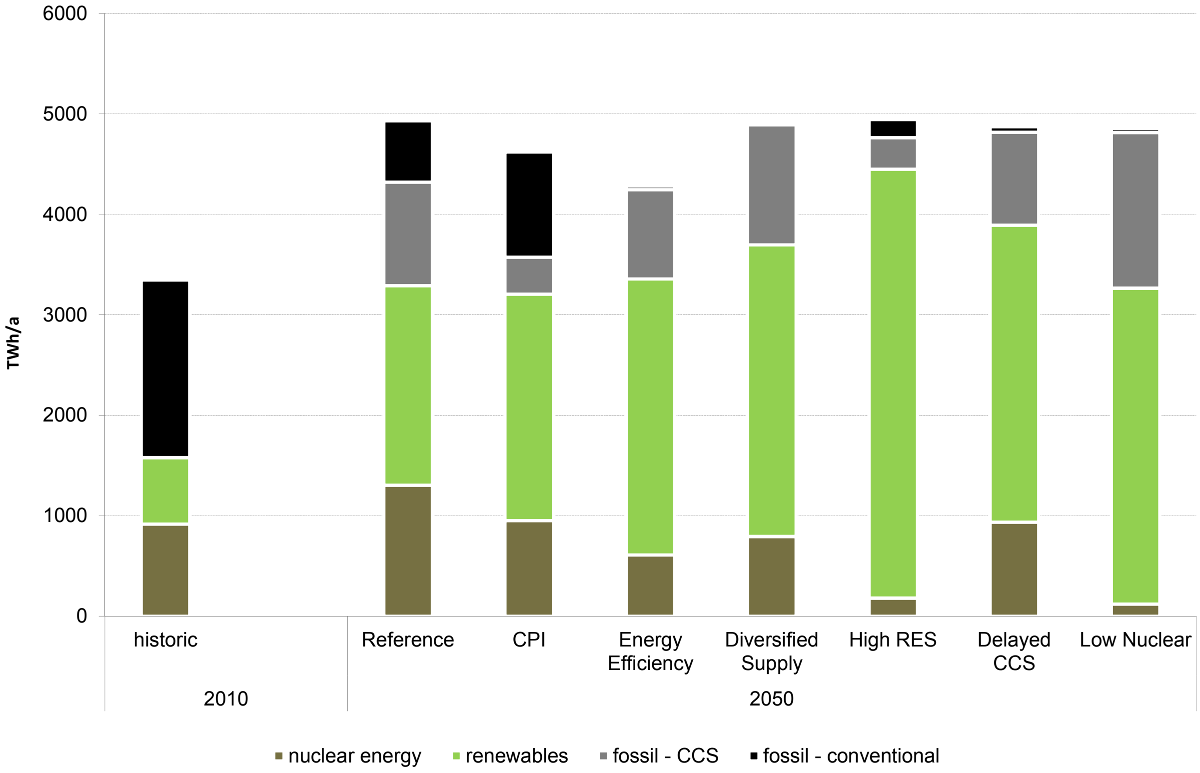
Source: (European Commission 2011c)

The trends observed until 2020 are mostly continued until 2030. Renewables further increase their relevance in the electricity system, reaching shares of just over 50 % in total gross electricity generation in all of the decarbonisation scenarios and 60 % in the High RES scenario. Wind is by far the most important renewable energy source in electricity generation, making up about half of all renewable generation in all of the scenarios in 2030. The share of coal and lignite is considerable reduced in all of the decarbonisation scenarios, as CCS technology in 2030 is still not widely deployed, having only a share of around 1% in most scenarios. The contribution of nuclear energy is also decreasing in all of the decarbonisation scenarios and is 12 % (Delayed CCS) to 46 % (Low nuclear) lower in 2030 than in 2010.

In 2050 renewables dominate the electricity system, holding shares in gross electricity generation of 59 % (Diversified Supply) to 86 % (High RES) in the decarbonisation scenarios. However, CCS power generation becomes an important element in the EU's power system, reaching shares of 19 % (Delayed CCS) to 32 % (Low Nuclear) in most decarbonisation scenarios. Only in the High RES scenario is CCS of little significance, contributing only 6 % by the middle of the century. Strong growth rates are assumed for CCS between 2030 and 2050. Wind remains by far the most important renewable source in electricity generation, but by 2050 the contribution of solar in the decarbonisation scenarios is of comparable size as that of biomass and hydro. The share of nuclear energy in 2050 is lower in all scenarios than today, falling from 27 % in 2010 to 26 % in the Reference and to only 2 % in the High RES and Low Nuclear scenarios.

Figure 5 emphasises the different roles of the three supply side mitigation options in the electricity sector in 2050 – renewables, CCS and nuclear energy.

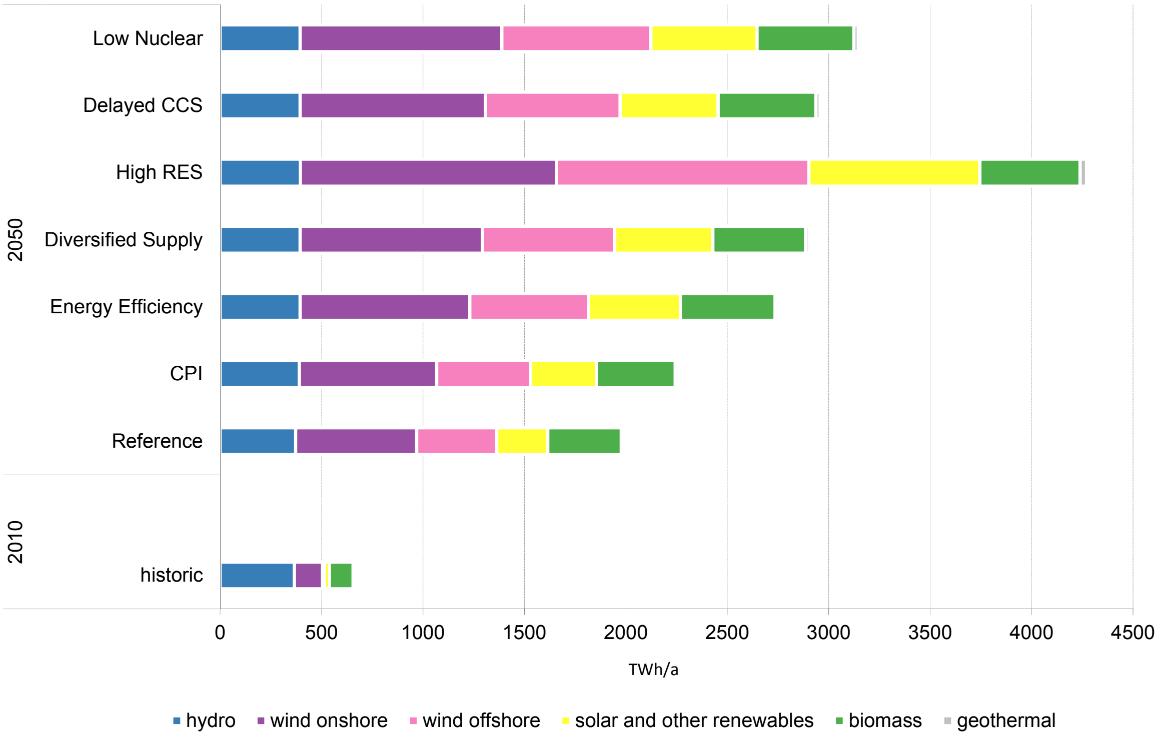
Figure 5 Gross electricity generation in the EU-27 by type of source in 2010 and according to EU Energy Roadmap scenarios in 2050 (in TWh/a)



Source: (European Commission 2011c)

Figure 6 takes a closer look at renewable electricity generation in the seven EU Energy Roadmap scenarios in 2050. The dominant role of wind power is apparent, so is the growing role of solar energy (which makes up more than 95 % of the category “solar and others”, which also includes tidal and wave energy). While in 2010 less than 10 % of Europe’s wind energy came from offshore plants, this share will considerably increase until 2050, reaching almost parity in the High RES scenario. While both solar and offshore wind power are assumed to remain relatively costly compared to exploiting onshore wind as well as hydro and biomass, their potential is large and they are therefore used to a much greater extent in the High RES decarbonisation scenario aiming for a high contribution from renewables.

Figure 6 Gross electricity generation from renewable sources in the EU-27 by type of source in 2010 and according to EU Energy Roadmap scenarios in 2050 (in TWh/a)



Source: (European Commission 2011c)

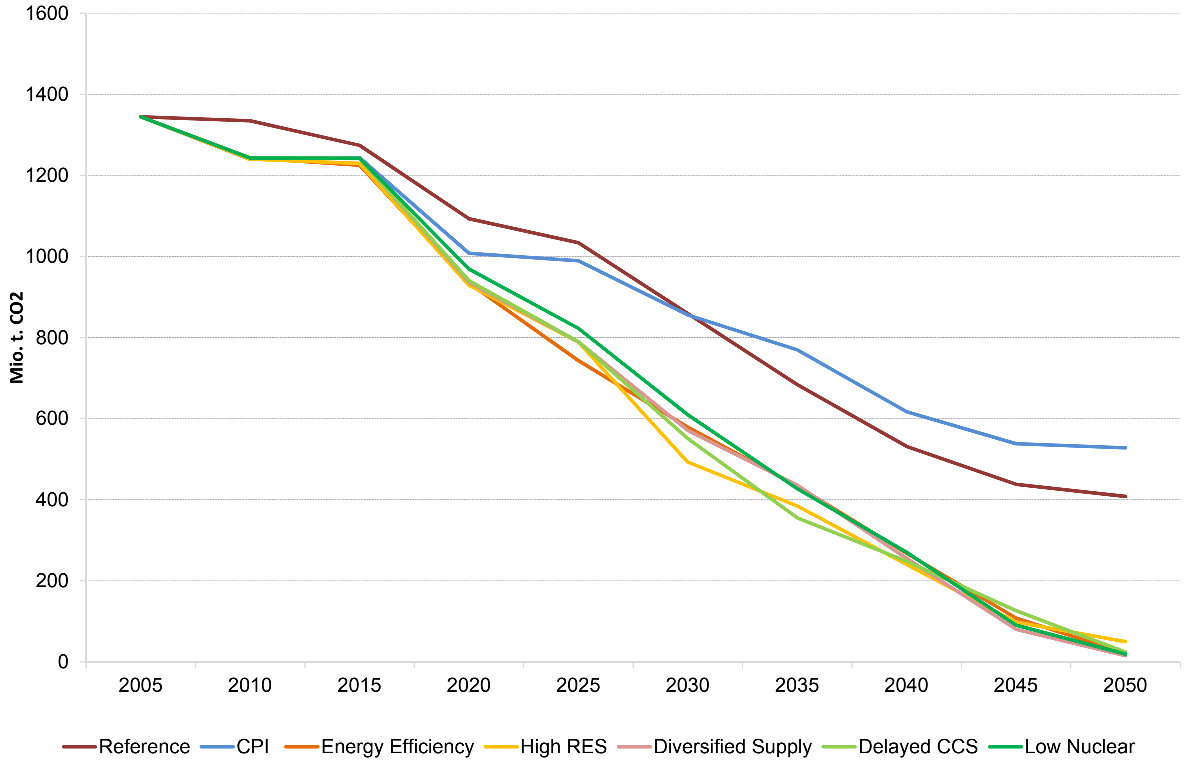
2.2.3 Electricity sector CO_2-emissions

The decarbonisation scenarios all achieve CO_2 emission reductions in the power sector of at least 96 % below 2005 emission levels by 2050. The bullet point list below illustrates the hierarchy of ambition in regard to the power sector (i.e. emission reductions below 2005 levels by 2050) for the decarbonisation scenarios:

- Diversified Supply (- 98.9 %)
- Low Nuclear (- 98.6 %)
- Energy Efficiency (- 98.4 %)
- Delayed CCS (- 98.2 %)
- High RES (- 96.3 %)

The EU Energy Roadmap 2050 provides a reference and a CPI scenario which expect CO_2 emissions to decline by 70 % and 61 % respectively below 2005 levels by 2050. Until 2030 the CPI scenario delivers more emission reductions than the reference scenario, reflecting additional measures adopted after March 2010. However, from 2030 onwards the reference scenario achieves greater CO_2 emission reductions than the CPI scenario and this may partly reflect the impact of a phase down in the use of nuclear energy following the political impact of the Fukushima disaster in 2011 (Figure 7).

Figure 7 Electricity sector CO_2-emission pathways in the different scenarios



Source: Data kindly provided by DG Energy

The emission development between 2020 and 2050 associated with the decarbonisation scenarios vary within a narrow range reflecting the different use of abatement options. All of the decarbonisation scenarios achieve the 2020 emissions target outlined in the Energy and Climate Package adopted by the EU in 2008. The Energy Efficiency scenario achieves power sector CO_2 emission reductions at the highest rate of all scenarios until 2025, reflecting the implementation of the key policy initiatives adopted by the EU. The High RES scenario delivers the greatest emission reductions of all the scenarios by the end of 2030 and is then subsequently surpassed by the Delayed CCS scenario by the end of 2035. The Diversified supply and Low nuclear scenarios are characterised by a steady rate of CO_2 emission reduction over the 2020 to 2050 time horizon and all decarbonisation scenarios ultimately reach approximately the same level of CO_2 emissions by 2050.

3 Individual Analysis with decomposition approach

3.1 Methodological notes

3.1.1 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 a specific set of data. 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 that is considered to be essential for the decomposition analysis has been gap filled.

3.1.2 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 along the lines of tables and figures. The interpretation of the values found in these will be explained here in more detail.

Table 2: Causal factors and their contributions to emission changes (Mt), and their contribution to net emission reductions (%)

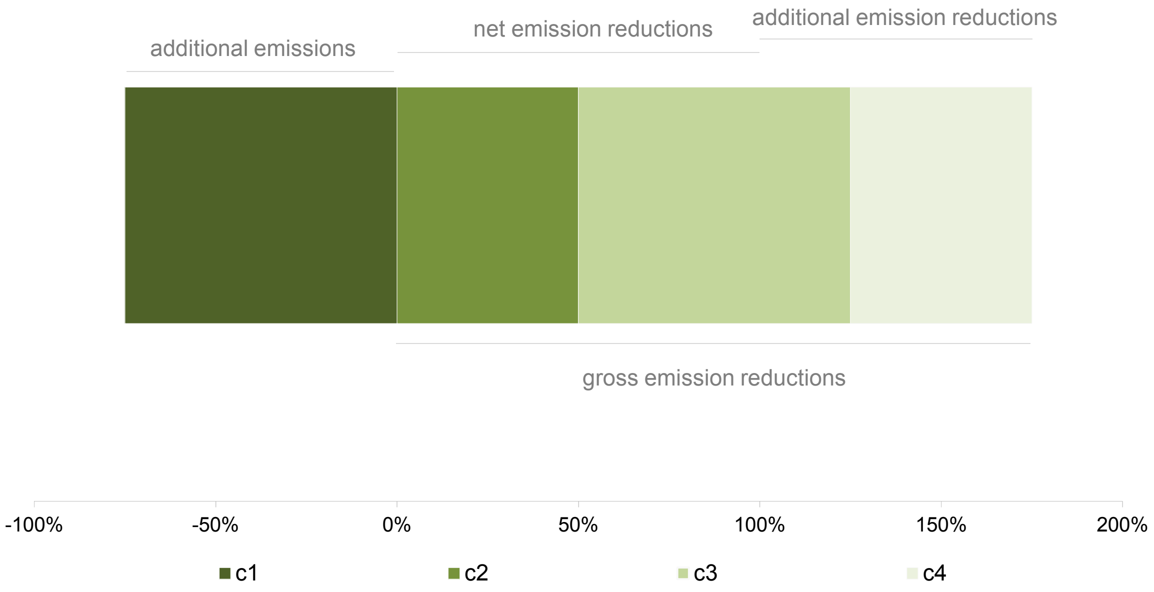
causal factor	Mt	%
c1	75	-75%
c2	-50	50%
c3	-75	75%
c4	-50	50%

Source: Author’s own

The results of the decomposition analysis will be presented in the format of the table above for all of the decarbonisation scenarios considered in this metastudy. The emission change attributed to each causal factor (i.e. consumption, production, emission factor and fuel input intensity) will be presented either in terms of 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 8 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 8 Schematics of net emission reductions, gross emission reductions, additional emission reductions and additional emissions[1]



Source: own representation

3.2 Decomposition Analysis

3.2.1 Data Availability

The data availability for all scenarios referred to in the EU Energy Roadmap 2050 is generally good. A comprehensive list of data is available in the Appendix of the accompanying Impact Assessment (European Commission 2011c). Further data was kindly provided to us by DG Energy in Excel format. This set of data contained more detailed information on power generation than the data appendix of the Impact Assessment and a further breakdown of CO_2 emissions in the power sector (for example distinguishing between power related CO_2 emissions excluding CO_2 emissions from district heating). The combined set of data served as an input to the decomposition analyses.

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[1] 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

However, both sets of data have a limited scope in terms of electricity consumption data. Most notably the data does not allow for a distinction between traditional and new appliances on the consumption side.

3.2.2 Gap Filling

Gap filling was only necessary to derive the CCS specific fuel input for the decomposition analysis. With the use of the given CCS share on electricity production and the overall fuel input, the fuel input for CCS has been determined as follows.

Using the scenario data available, we estimated how total electricity generation in CCS power plants would likely be separated between natural gas CCS plants on the one hand and hard coal plants on the other hand. This exercise had to be performed by the project team because this specific information (i.e. the share between natural gas and solids in CCS power generation) is important for performing a detailed decomposition approach and it is unfortunately not found within the EU Energy Roadmap 2050 publications.

However, gross electricity generation from CCS power plants (as a whole) are provided for each scenario and each 5-year step by the means of share of gross electricity generation. Apart from this CCS share and the figures on total gross electricity generation we used the available data on CO_2 emissions from the power sector on CO_2 captured and on natural gas and coal power station fuel input to estimate the approximate respective shares of natural gas and solids in total CCS power generation.

In order to do this, assumptions had to be made about the capture rate and the average conversion efficiencies of conventional natural gas power plants, conventional coal power plants, natural gas CCS power plants and coal CCS power plants respectively. These assumptions could be narrowed down using some of the available data, specifically the data on power sector fuel input and CO_2 emitted and captured. For example, using a trial & error method we concluded that the capture rate of both natural gas as well as coal CCS power plants is apparently assumed to be around 99 % by 2050 in at least some of the decarbonisation scenarios. As a consequence we assumed that in all decarbonisation scenarios the CCS capture rate increases from 90 % in the early CCS power plants in 2020 and 2030 to around 99 % by 2050. It is assumed to remain around 90 % in the two reference scenarios, namely the Reference and the CPI scenarios.

The data available also indicates that fossil power plant efficiencies reach very high levels by 2050. In our calculations we only achieve consistent results in most of the decarbonisation scenarios by assuming average gross efficiencies of 49 to 52 % for non-CCS coal and lignite power plants and around 61 % for natural gas power plants in 2050. Even more striking is the fact that by the middle of the century the average efficiency of CCS plants in the decomposition scenarios will have to be in a similar range, at 47 to 50 % for CCS coal and lignite power plants and around 58 % for CCS natural gas power plants. Until 2030 the average efficiencies are considerably lower, so new fossil power plants constructed after 2030 are apparently assumed to be highly efficient.

The 2050 assumptions would be highly optimistic regarding the CCS capture rate and fossil fuel plant efficiencies if the gap filling approach reflects the underlying assumptions of the scenarios correctly.

Using the capture rates and efficiencies (roughly) derived by getting fuel input and gross electricity output in line, total CCS electricity generation was divided between natural gas and coal power plants until the CO_2 emitted and the CO_2 captured matched the figures found in the EU Energy Roadmap 2050 publications (European Commission 2011c). For this exercise coal, natural gas and oil emission factors were assumed. For simplicity it was assumed that these factors do not change over time. The emission factors used are based on figures found in the IEA's World Energy Outlook 2009 (International Energy Agency 2009). They are as follows:

- For hard coal and lignite (average): 98.4 t CO_2/TJ
- For natural gas and other gases (average): 53-55 t CO_2/TJ
- For petroleum products (average): 78.8 t CO_2/TJ

The emission factor for natural gas and other gases was slightly adjusted from year to year and scenario to scenario within the range indicated to align the resulting CO_2 emissions occurring from the power sector fuel input with the sum of CO_2 emitted and CO_2 captured.

Using this approach we derived a growing share of natural gas CCS power plants in total CCS power generation over time. In the decarbonisation scenarios this share rises from 42 to 51 % in 2030 to 59 to 78 % in 2050.

While for most scenarios and years this method has led to consistent results (notwithstanding the very optimistic assumptions about the capture rate and plant efficiencies), there are a several exceptions where the installed capacity of some types of power plants could not be brought in line with the electricity generation expected from these plants, leading to capacity factors of over 100 %.[2]

3.2.3 Decomposition Analysis of EU Energy Roadmap 2050 Scenarios

Reference scenario

The Reference scenario defined in the EU Energy Roadmap 2050 (European Commission 2011b) is laid out to include current trends and long-term projections on economic development. The policies included in this scenario are those adopted by March 2010, thus they include the 2020 targets for renewable energy shares and GHG reductions and the ETS Directive. The relative emission change contributions of each of the causal factors in the

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[2] It would be of advantage if modelling assumptions/results on the average efficiencies of the various types of power plants as well as on the capture rate and the capacity factors were to be released by the modellers or the European Commission. This could clear up whether the mentioned inconsistencies are due to the method and assumptions we applied to derive the missing data or whether there are inconsistencies in the PRIMES modelling or the assumptions underlying the modelling. Furthermore this would remove uncertainties from the results of the decomposition analysis which relies on this data and which is reported as per scenario in Section 3.

decomposition analysis are presented in Table 3. Positive values reflect factors that in overall contribute to emission reductions, while negative factors can be viewed as emission drivers: their use or non-use contributes additional emissions, which in turn need to be offset by positive contributions. This is why percentages can be larger than 100%.

Table 3: EU Energy Roadmap / Reference scenario: Relative emission change contributions of causal factors

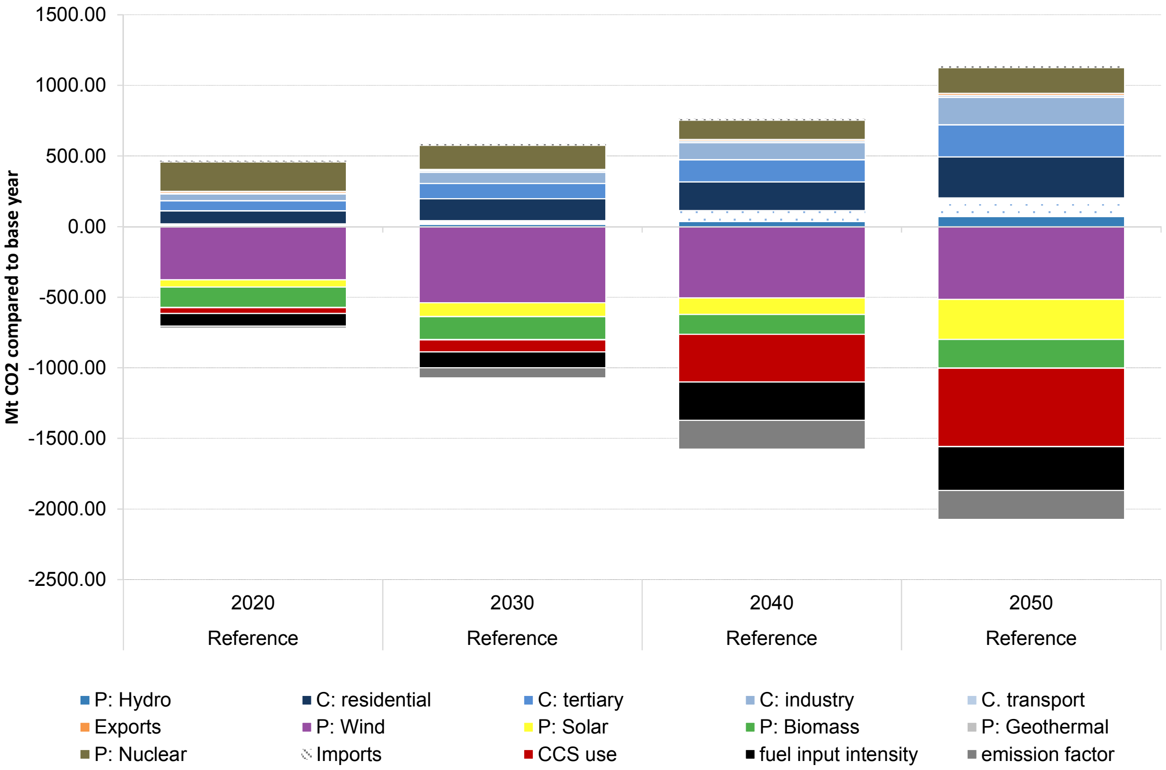
	2020	2030	2040	2050
Consumption				
Residential consumption	-37%	-32%	-25%	-31%
Tertiary consumption	-28%	-22%	-19%	-24%
Industry consumption	-19%	-17%	-15%	-21%
Transport consumption	-2%	-2%	-1%	-1%
Other consumption	-5%	-6%	-9%	-14%
Exports	-5%	-2%	-1%	-2%
Production Side				
Sum RES use	226%	162%	89%	99%
Hydro use	-3%	-3%	-4%	-8%
Wind use	150%	111%	62%	55%
Solar use	21%	20%	14%	30%
Biomass use	57%	34%	17%	22%
Geothermal use	0%	0%	0%	0%
Nuclear use	-83%	-35%	-17%	-19%
Imports	-4%	-2%	-1%	-1%
CCS use	17%	18%	42%	59%
Intensities				
fuel input intensity	35%	23%	33%	33%
emission factor	6%	15%	25%	22%

Source: results from decomposition analysis

The reference scenario describes the world with current trends and policies that have been adopted by March 2010. It can be observed that according to the decomposition analysis renewable energies provide a large factor to emission reductions, while their magnitude seems to fluctuate or decrease (in the case of wind). This may be explained by the increasing importance that CCS plays over time – its share on emission reduction contributions grows over time starting in 2020.

All consumption sectors seem to exhibit a growing demand for electricity, which implies additional emissions. In 2050 the residential sector exhibits the largest additional emissions in the consumption sectors, while growing electricity demand in transport only provides a small magnitude of additional emissions. An alternative view on the results summarised in the table above is given by Figure 9 which shows the absolute contribution to emission changes for the causal factors. Note that here positive values reflect additional emissions, while negative values reflect emission reductions.

Figure 9 EU Energy Roadmap 2050 / Reference scenario: Absolute emission changes in 2050 compared to the base year



Source: results from decomposition analysis

Current policy initiative scenario

This scenario updates the Reference scenario to include policy measures adopted after March 2010, e.g. the proposed Energy 2020 strategy. The scenario also includes proposed actions concerning the "Energy Efficiency Plan" and the new "Energy Taxation Directive" and individual Member State decisions on abandoning nuclear power.

The relative emission change contributions of each of the causal factors in the decomposition analysis are presented in Table 4. Positive values reflect factors that in overall contribute to emission reductions, while negative factors can be viewed as emission drivers: their use or non-use contributes additional emissions, which in turn need to be offset by positive contributions. This is why percentages can be larger than 100 %.

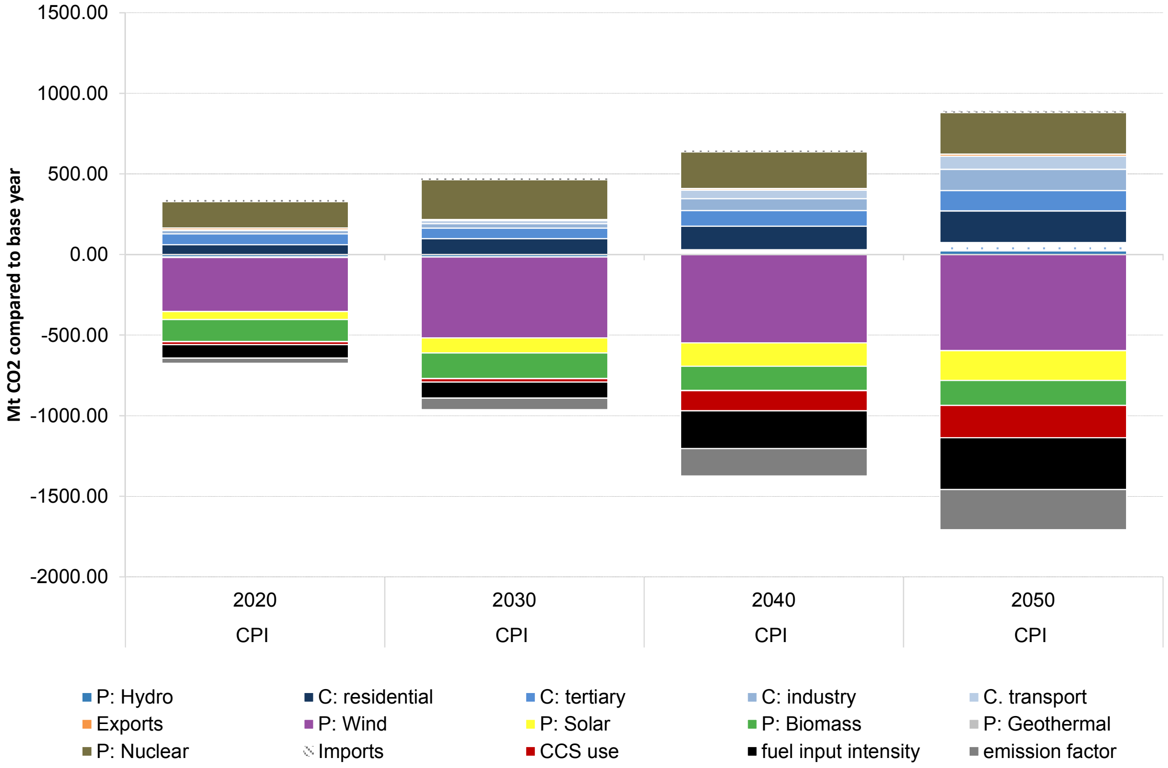
Table 4: EU Energy Roadmap 2050 / CPI scenario: Relative emission reduction contributions of causal factors

	2020	2030	2040	2050
Consumption				
Residential consumption	-18%	-20%	-20%	-24%
Tertiary consumption	-20%	-13%	-13%	-16%
Industry consumption	-6%	-6%	-10%	-16%
Transport consumption	-2%	-4%	-7%	-10%
Other consumption	1%	0%	-3%	-6%
Exports	-3%	-2%	-1%	-1%
Production Side				
Sum RES use	160%	157%	115%	112%
Hydro use	4%	3%	-1%	-3%
Wind use	100%	103%	75%	73%
Solar use	15%	19%	20%	23%
Biomass use	41%	33%	21%	19%
Geothermal use	0%	0%	0%	0%
Nuclear use	-49%	-50%	-31%	-32%
Imports	-3%	-2%	-1%	-1%
CCS use	6%	4%	17%	25%
Intensities				
fuel input intensity	25%	20%	32%	39%
emission factor	9%	15%	23%	31%

Source: results from decomposition analysis

The results are similar as for the reference scenario but differ with respect to the emission reductions achieved by the utilisation of CCS technology – this exhibits less electricity being generated from CCS technology than the reference scenario (compare Attachment 1 (European Commission 2011c)). Figure 10 visualises the absolute emission changes caused by the individual factors and one can observe the CCS contribution growing slower than in the reference scenario, while at the same time the emission reduction contribution from wind power does not fluctuate as in the Reference scenario but remains relatively stable, with a less strong contribution in 2050.

Figure 10 EU Energy Roadmap 2050 / CPI scenario: Absolute emission changes in 2050 compared to the base year



Source: results from decomposition analysis

Energy efficiency scenario

The energy efficiency scenario describes a world where there is political consensus and commitment to achieving high energy savings. This has consequences for the building sector in specific as it includes more stringent minimum requirements for appliances and new buildings, high renovation rates of existing buildings and the establishment of energy savings obligations on energy utilities. These commitments then trigger decreases in energy demand of 41 % by 2050 as compared to 2005-2006.

The relative emission change contributions of each of the causal factors in the decomposition analysis are presented in Table 5. Positive values reflect factors that in overall contribute to emission reductions, while negative factors can be viewed as emission drivers: their use or non-use contributes additional emissions, which in turn need to be offset by positive contributions. This is why percentages can be larger than 100 %.

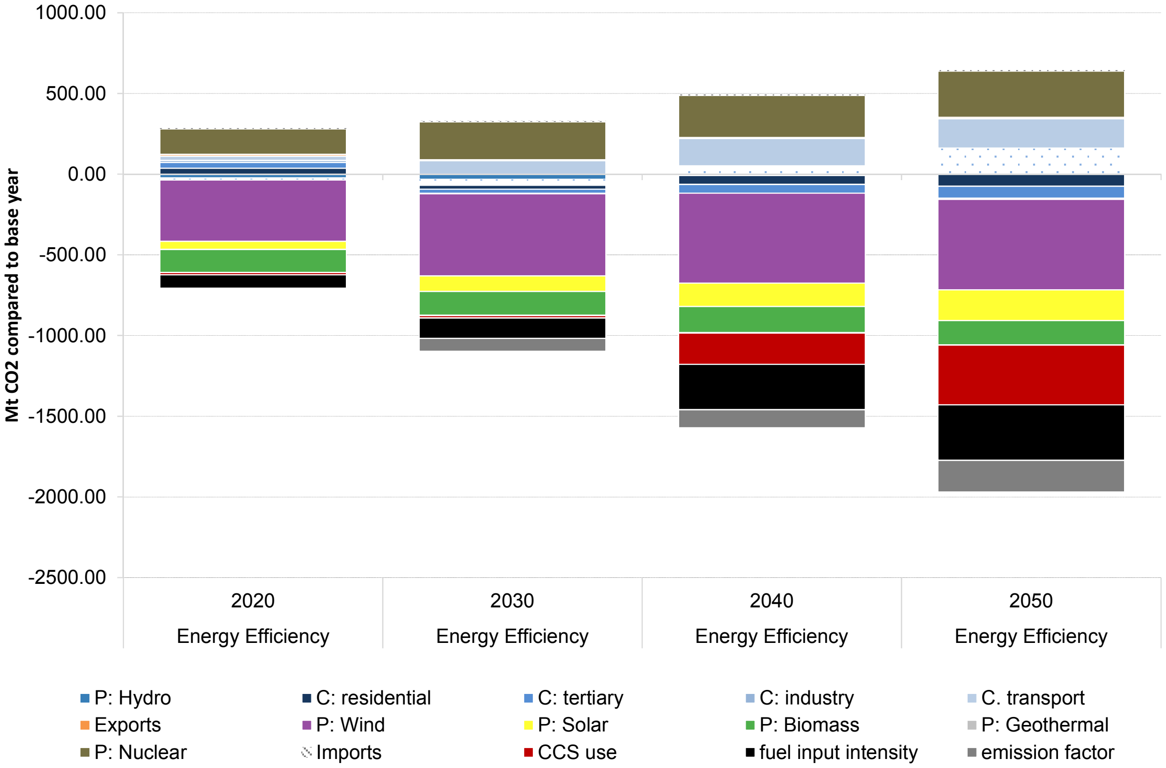
Table 5: EU Energy Roadmap 2050 / Energy efficiency scenario: Relative emission reduction contributions of causal factors

	2020	2030	2040	2050
Consumption				
Residential consumption	-9%	3%	5%	6%
Tertiary consumption	-9%	3%	5%	6%
Industry consumption	-3%	0%	0%	1%
Transport consumption	-7%	-11%	-16%	-14%
Other consumption	3%	5%	-5%	-12%
Exports	-3%	-1%	-1%	-1%
Production Side				
Sum RES use	146%	103%	81%	68%
Hydro use	6%	4%	1%	0%
Wind use	92%	67%	52%	42%
Solar use	12%	13%	13%	14%
Biomass use	35%	19%	15%	11%
Geothermal use	0%	0%	0%	0%
Nuclear use	-38%	-31%	-24%	-22%
Imports	-2%	-1%	-1%	0%
CCS use	3%	2%	18%	28%
Intensities				
fuel input intensity	20%	17%	26%	26%
emission factor	-2%	10%	10%	15%

Source: results from decomposition analysis

The results of the decomposition analysis are in line with the energy savings that are prescribed in this scenario. All consumption sectors, except the transport sector, provide slowly growing contributions to emission reductions starting after 2020, which is different from the Reference and CPI scenarios. The transport sector contributes negatively to emission reductions, i.e. triggers additional emissions (as in all other scenarios) since electric mobility will be utilised more and more (depending on the scenario assumption). Figure 11 exemplifies the results based on absolute emission changes triggered by the different causal factors.

Figure 11 EU Energy Roadmap 2050 / Energy efficiency scenario: Absolute emission changes in 2050 compared to the base year



Source: results from decomposition analysis

Diversified supply technologies scenario

The Diversified Supply Technologies scenario describes a world where there is no preference towards any specific electricity generation technology. It is assumed that all energy sources can compete on a market without any specific support measures provided for individual technologies. It is assumed that decarbonisation is driven by carbon pricing. Further it is assumed that there is public acceptance for both nuclear and Carbon Capture & Storage (CCS) technologies.

The relative emission change contributions of each of the causal factors in the decomposition analysis are presented in Table 6. Positive values reflect factors that in overall contribute to emission reductions, while negative factors can be viewed as emission drivers: their use or non-use contributes additional emissions, which in turn need to be offset by positive contributions. This is why percentages can be larger than 100 %.

Table 6: EU Energy Roadmap 2050 / Diversified supply scenario: Relative emission reduction contributions of causal factors

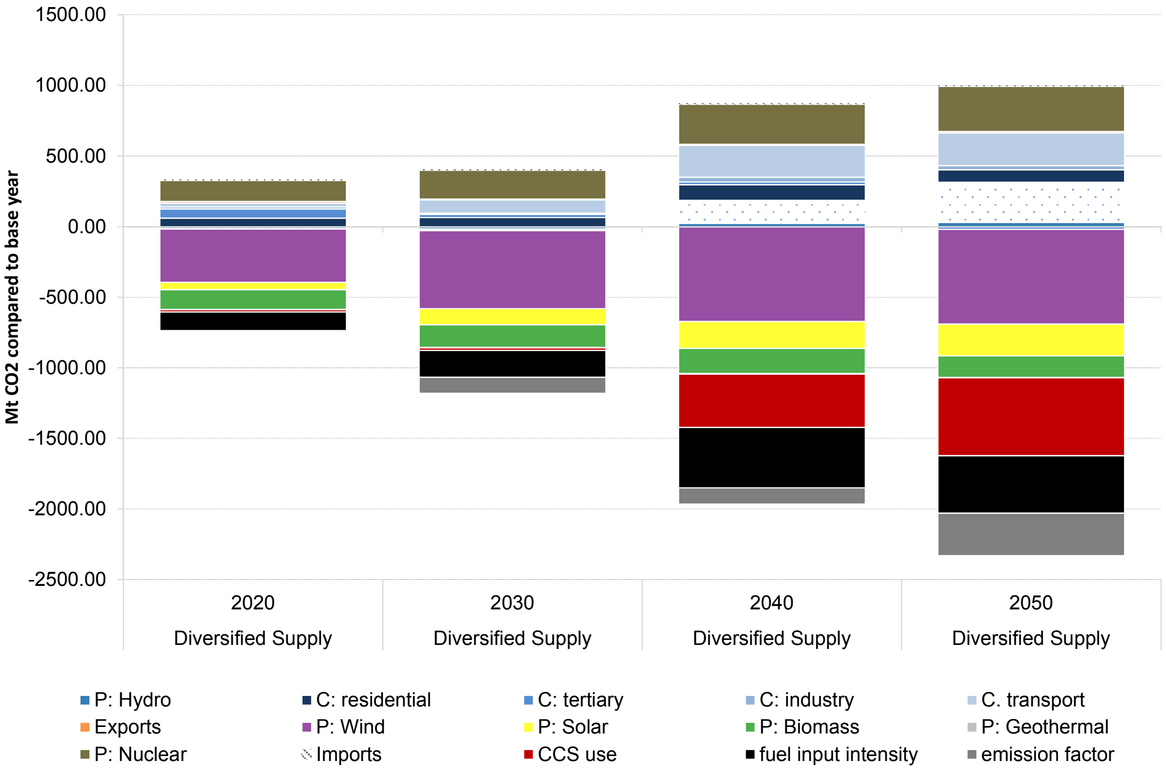
	2020	2030	2040	2050
Consumption				
Residential consumption	-15%	-8%	-10%	-7%
Tertiary consumption	-16%	-3%	-2%	2%
Industry consumption	-4%	-1%	-3%	-2%
Transport consumption	-6%	-12%	-21%	-17%
Other consumption	1%	2%	-15%	-21%
Exports	-3%	-1%	-1%	-1%
Production Side				
Sum RES use	143%	109%	94%	77%
Hydro use	3%	2%	-2%	-2%
Wind use	92%	71%	62%	50%
Solar use	13%	15%	17%	17%
Biomass use	35%	21%	16%	12%
Geothermal use	0%	1%	0%	0%
Nuclear use	-37%	-26%	-26%	-24%
Imports	-2%	-1%	-1%	-1%
CCS use	4%	2%	35%	41%
Intensities				
fuel input intensity	32%	24%	39%	31%
emission factor	2%	15%	11%	23%

Source: results from decomposition analysis

The results of the decomposition analysis show that the use of CCS technology contributes positively to emission reductions and this positive contribution grows over time. At the same time the decreased use of nuclear technologies (despite assumed public acceptance) triggers additional emissions which need to be offset by the portfolio of other generation technologies. Even if no generation technology is preferred in this scenario and the technologies compete on a market with no additional incentives, wind is one of the major contributors to emission reductions in this scenario; the largest among the renewable energy technologies.

All consumption sectors contribute additional emissions to the system. While these contributions grow weaker over time in all consumption sectors the additional emissions in the transport sector grow, mainly due to a growing use of electric mobility. Figure 12 provides insights into the absolute emission reductions triggered by the causal factors.

Figure 12 EU Energy Roadmap 2050 / Diversified supply scenario: Absolute emission changes in 2050 compared to the base year



Source: results from decomposition analysis

High Renewable energy sources scenario

The High RES scenario assumes strong support measures for renewable energy technologies, which leads to renewable energies exhibiting a large share in electricity consumption (reaching 97 % in 2050).

The relative emission change contributions of each of the causal factors in the decomposition analysis are presented in Table 7. Positive values reflect factors that in overall contribute to emission reductions, while negative factors can be viewed as emission drivers: their use or non-use contributes additional emissions, which in turn need to be offset by positive contributions. This is why percentages can be larger than 100 %.

Table 7: EU Energy Roadmap 2050 / High RES scenario: Relative emission reduction contributions of causal factors

	2020	2030	2040	2050
Consumption				
Residential consumption	-14%	-7%	-7%	-4%
Tertiary consumption	-15%	-3%	1%	4%
Industry consumption	-4%	0%	-2%	-1%
Transport consumption	-6%	-11%	-19%	-17%
Other consumption	2%	3%	-13%	-38%
Exports	-3%	-1%	-1%	-1%
Production Side				
Sum RES use	140%	120%	136%	125%
Hydro use	3%	3%	-1%	-2%
Wind use	91%	80%	91%	84%
Solar use	13%	19%	28%	30%
Biomass use	33%	17%	17%	13%
Geothermal use	0%	1%	1%	1%
Nuclear use	-35%	-37%	-48%	-46%
Imports	-2%	-1%	-1%	-1%
CCS use	4%	2%	7%	12%
Intensities				
fuel input intensity	32%	21%	30%	34%
emission factor	2%	14%	17%	32%

Source: results from decomposition analysis

The overall contribution of renewable energies to emission changes is highest in this scenario compared to the other decarbonisation scenarios, but interestingly the Reference and the CPI scenario both exhibit larger relative emission reductions provided by renewable energy use than the High RES scenario[3]. Figure 13 depicts the absolute contributions to emission changes in the high renewable energy sources scenario, which demonstrate the importance of renewable energies in this scenario and the relative small emission reduction contribution of CCS technology.

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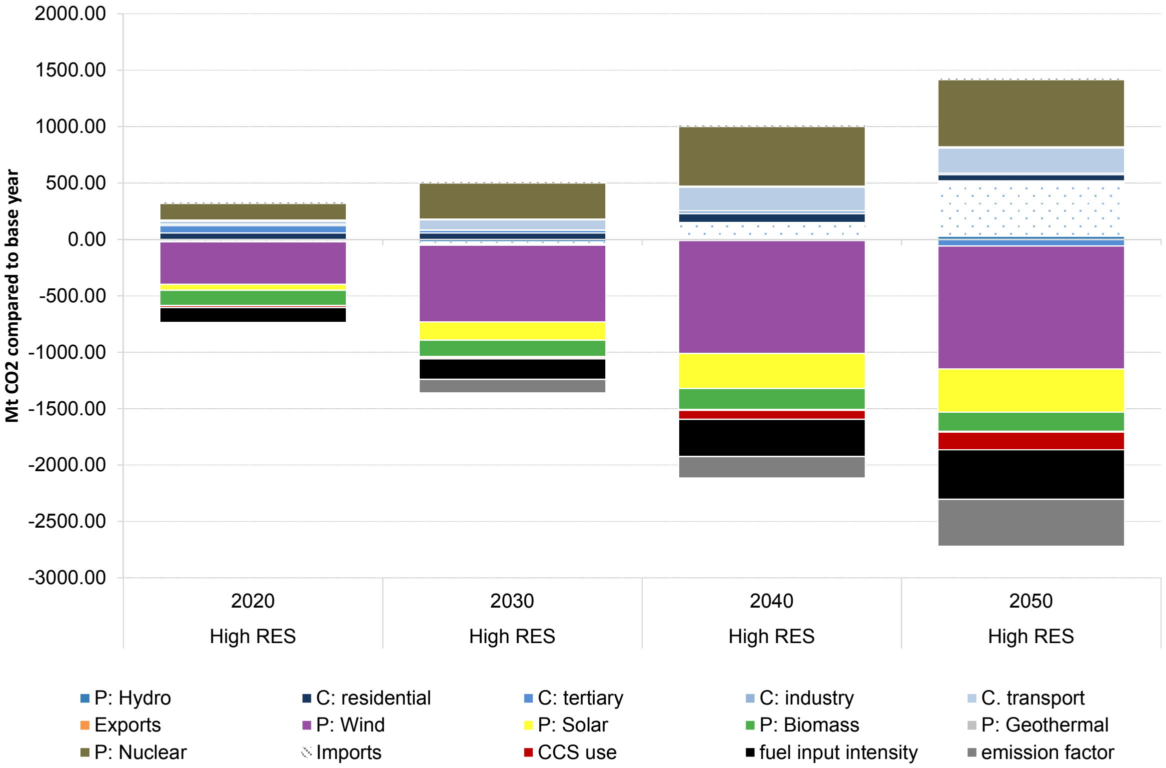
[3] This is visualised in the Appendix, where the shares of causal factors on gross CO_2 emission reductions in each scenario for 2050 are depicted.

Figure 13 EU Energy Roadmap 2050 / High RES scenario: Absolute emission changes in 2050 compared to the base year



Source: results from decomposition analysis

Delayed CCS scenario

This scenario describes a world which is similar to the Diversified Supply Technologies scenario but assumes that the introduction of CCS technology is delayed, which leads to higher shares of nuclear energy being used than in the other scenarios. Decarbonisation is being driven by carbon prices rather than through technology pushing measures.

The relative emission change contributions of each of the causal factors in the decomposition analysis are presented in Table 8. Positive values reflect factors that in overall contribute to emission reductions, while negative factors can be viewed as emission drivers: their use or non-use contributes additional emissions, which in turn need to be offset by positive contributions. This is why percentages can be larger than 100 %.

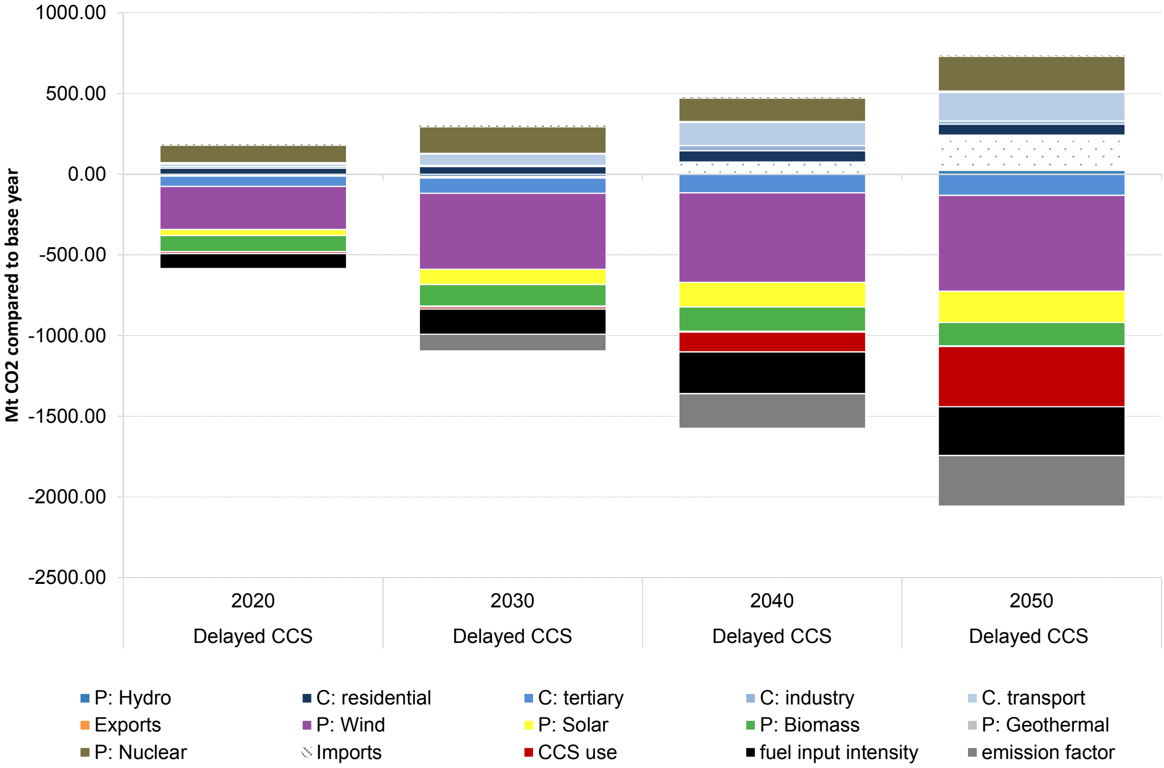
Table 8: EU Energy Roadmap 2050 / Delayed CCS scenario: Relative emission reduction contributions of causal factors

	2020	2030	2040	2050
Consumption				
Residential consumption	-9%	-6%	-6%	-5%
Tertiary consumption	16%	12%	11%	10%
Industry consumption	-2%	-1%	-3%	-1%
Transport consumption	-4%	-9%	-13%	-13%
Other consumption	1%	1%	-6%	-17%
Exports	-2%	-1%	-1%	-1%
Production Side				
Sum RES use	102%	90%	78%	69%
Hydro use	2%	2%	-1%	-2%
Wind use	66%	59%	51%	45%
Solar use	9%	12%	14%	15%
Biomass use	25%	17%	14%	11%
Geothermal use	0%	1%	0%	0%
Nuclear use	-27%	-21%	-13%	-16%
Imports	-2%	-1%	-1%	-1%
CCS use	3%	2%	11%	28%
Intensities				
fuel input intensity	23%	20%	24%	23%
emission factor	1%	13%	19%	24%

Source: results from decomposition analysis

On the consumption side the tertiary sector contributes a relatively stable amount to emission reductions, while all other sectors contribute to emission *additions*. The deployment of CCS is delayed in this scenario, which explains the relatively low shares of emission reductions contribution by CCS until 2040. Nuclear use on the other hand grows in absolute terms, but its relative amount on electricity generation decreases over time, which triggers additional emissions that need to be offset by the CO_2-free generation technologies among which wind provides the largest share of emission reductions. Figure 14 provides insights into the absolute emission changes triggered by each of the causal factors.

Figure 14 EU Energy Roadmap 2050 / Delayed CCS scenario: Absolute emission changes in 2050 compared to the base year



Source: results from decomposition analysis

Low nuclear scenario

The low nuclear scenario describes a world similar to the one in the Diversified Supply Technologies scenario but assumes that that no new nuclear power plants (besides reactors currently under construction) are being built. A higher penetration of CCS technology is the result (around 32 % in power generation in 2050).

The relative emission change contributions of each of the causal factors in the decomposition analysis are presented in Table 9. Positive values reflect factors that in overall contribute to emission reductions, while negative factors can be viewed as emission drivers: their use or non-use contributes additional emissions, which in turn need to be offset by positive contributions. This is why percentages can be larger than 100 %.

Table 9: EU Energy Roadmap 2050 / Low nuclear scenario: Relative emission reduction contributions of causal factors

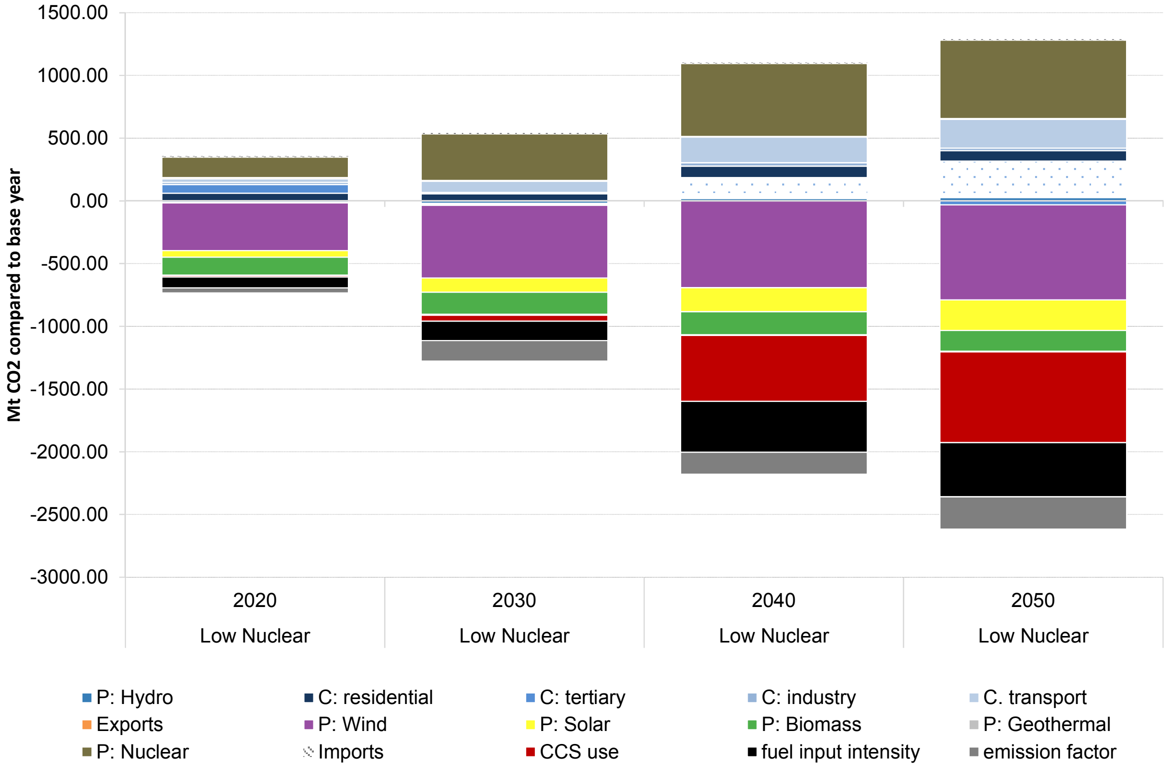
	2020	2030	2040	2050
Consumption				
Residential consumption	-16%	-8%	-9%	-6%
Tertiary consumption	-19%	-1%	0%	2%
Industry consumption	-5%	-1%	-2%	-2%
Transport consumption	-7%	-12%	-19%	-17%
Other consumption	1%	2%	-16%	-22%
Exports	-3%	-1%	-1%	0%
Production Side				
Sum RES use	157%	122%	98%	86%
Hydro use	3%	3%	-2%	-2%
Wind use	102%	79%	64%	57%
Solar use	14%	16%	18%	18%
Biomass use	38%	24%	17%	12%
Geothermal use	1%	1%	1%	0%
Nuclear use	-43%	-50%	-54%	-47%
Imports	-2%	-1%	-1%	-1%
CCS use	4%	6%	49%	55%
Intensities				
fuel input intensity	23%	21%	38%	33%
emission factor	11%	22%	16%	19%

Source: results from decomposition analysis

All consumption sectors contribute negatively, but decreasingly so, to emission reductions except the tertiary sector who starts to save emissions from 2040 on.

The declining importance of nuclear energy in electricity generation triggers additional emissions. These need to be offset by other sources. The main contributors to offsetting these additional emissions are according to the decomposition analysis renewable energies (wind as a forerunner), CCS and more efficient conventional power plants (“fuel input intensity”). The absolute emission changes triggered by each of the causal factors are depicted in Figure 15.

Figure 15 EU Energy Roadmap 2050 / Low nuclear scenario: Absolute emission changes in 2050 compared to the base year

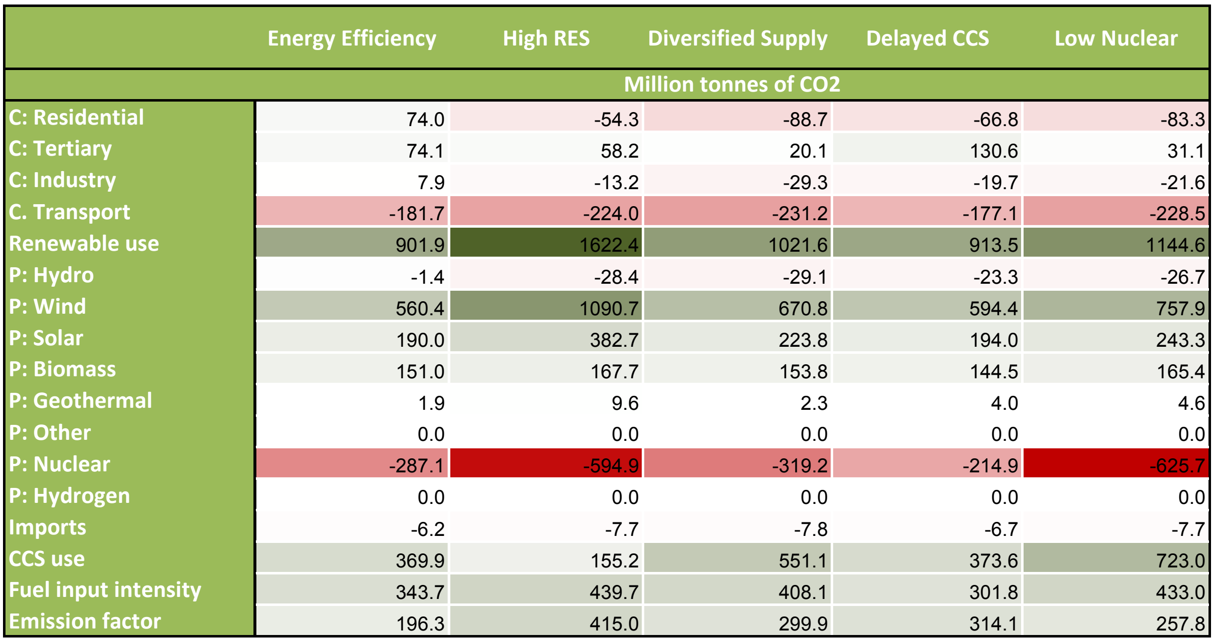


Source: results from decomposition analysis

4 Comparison of analysis results and conclusions

The results of the decomposition analysis are illustrated further in Table 10, which outlines the absolute reduction in CO_2 emissions between the base year and 2050 attributed to each causal factor measured in million tonnes of CO_2. The CO_2 emission reduction is either negative and thus characterised by additional emissions (i.e. red shading) or is positive and characterised by emission reductions (i.e. green shading).

Table 10 Decomposition results of CO_2 emission reduction in 2050 for the decarbonisation scenarios.



	Energy Efficiency	High RES	Diversified Supply	Delayed CCS	Low Nuclear
	Million tonnes of CO2				
C: Residential	74.0	-54.3	-88.7	-66.8	-83.3
C: Tertiary	74.1	58.2	20.1	130.6	31.1
C: Industry	7.9	-13.2	-29.3	-19.7	-21.6
C. Transport	-181.7	-224.0	-231.2	-177.1	-228.5
Renewable use	901.9	1622.4	1021.6	913.5	1144.6
P: Hydro	-1.4	-28.4	-29.1	-23.3	-26.7
P: Wind	560.4	1090.7	670.8	594.4	757.9
P: Solar	190.0	382.7	223.8	194.0	243.3
P: Biomass	151.0	167.7	153.8	144.5	165.4
P: Geothermal	1.9	9.6	2.3	4.0	4.6
P: Other	0.0	0.0	0.0	0.0	0.0
P: Nuclear	-287.1	-594.9	-319.2	-214.9	-625.7
P: Hydrogen	0.0	0.0	0.0	0.0	0.0
Imports	-6.2	-7.7	-7.8	-6.7	-7.7
CCS use	369.9	155.2	551.1	373.6	723.0
Fuel input intensity	343.7	439.7	408.1	301.8	433.0
Emission factor	196.3	415.0	299.9	314.1	257.8

Note: Negative values reflect emission additions, while positive values reflect emission reductions.

Source: Öko-Institut / Wuppertal Institut (2012), results from decomposition analysis.

All of the decarbonisation scenarios analysed in this policy paper assume that electricity consumption will increase considerably for road transport and heat applications by 2050. This is due to the envisaged growth in new electric appliances (i.e. electric mobility, heat pumps), which help to reduce CO_2 emissions by switching from other fuels to low carbon electricity. For example, a significant electrification of road transport is assumed in all of the decarbonisation scenarios, whereby 80 % of private passenger transport activity in 2050 will involve the use of plug-in hybrid or pure electric vehicles. This trend is dependent however upon political action, which will be necessary to facilitate the commercialisation of new appliances such as electric vehicles, which are currently too expensive for a widespread diffusion. For example, political action may consist of public investments in infrastructural developments (i.e. charging points) and tax subsidies to lower the capital costs associated with purchasing electrical vehicles. As a consequence of the increase in electricity consumption for both road transport and other new appliances used for heating in 2050, additional CO_2 emissions will be generated within the electricity system.

It is therefore essential that political action is taken in parallel to transform the energy system so that low carbon technology is primarily used to generate electricity. It is important to acknowledge that in all decarbonisation scenarios, including even the Energy efficiency scenario, improvements in the efficiency of traditional applications in the residential, tertiary, industry and transport sectors will not entirely offset the increase in electricity consumption from the new appliances by 2050 as well as additional electricity consumption caused by GDP growth in any of the decarbonisation scenarios, given the base year's electricity mix.

The decomposition analysis demonstrates that an increase in the share of electricity generated from renewable technology will result in considerable emission reductions by 2050. All of the decarbonisation scenarios envisage that wind energy will account for the largest share of electricity generation from renewables in 2050. There is also a general consensus that an increase in solar and biomass energy will greatly contribute to emission reductions in 2050.

The increasing deployment of renewables in all of the decarbonisation scenarios assumes that the capital expenditure cost of these technologies will reduce over time; however political action in the form of market deployment policies as well as public investment in the research and development of renewable technologies will be necessary for these cost assumptions to materialise. Policy makers also need to address the existing barriers to the deployment of renewables (i.e. planning permission, capital costs) that considerably increase lead times. Access to capital and the fast-tracking of planning applications for renewables will be essential for realising the High RES scenario, which assumes that the total RES capacity increases to over 1,900 GW by 2050 (this is more than eight times the current RES capacity). Infrastructural investments in transmission grids and storage technology will also be necessary in the longer term to overcome issues concerning both the distribution of electricity and the intermittency of supply.

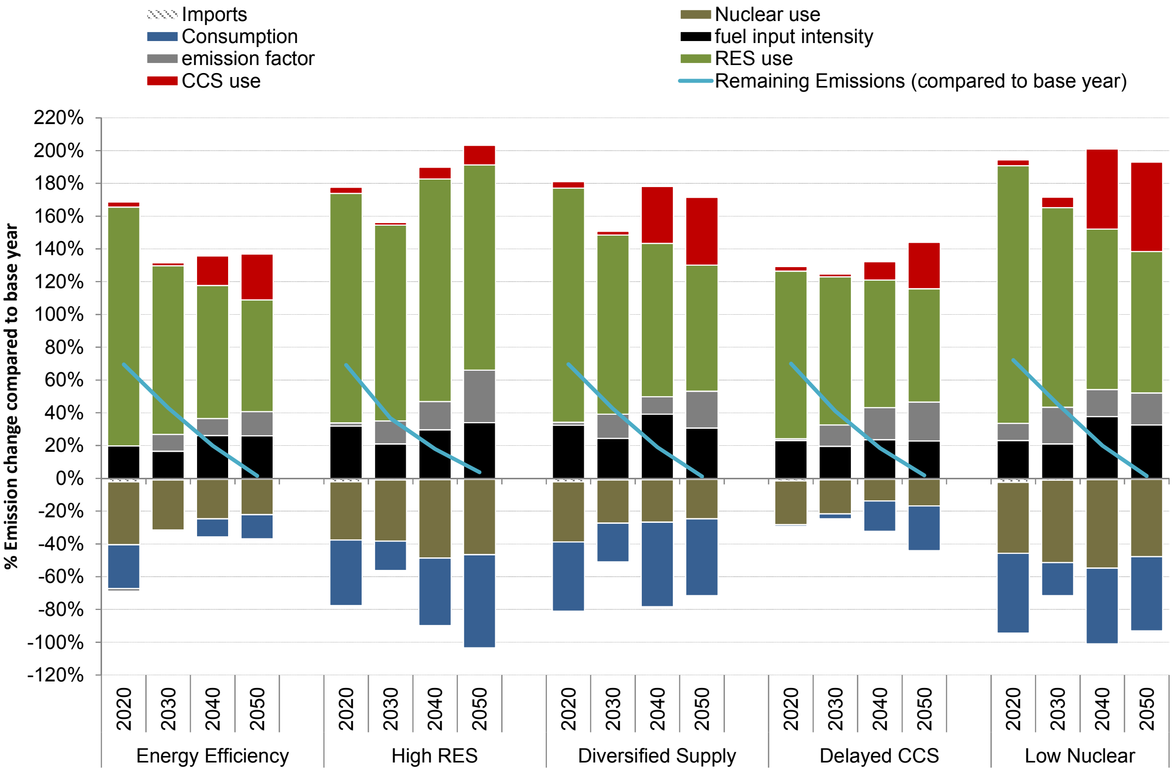
There is agreement amongst the decarbonisation scenarios that CO_2 emissions will be reduced by 2050 as a consequence of an increase in the average conversion efficiency of the remaining fossil fuel plants (i.e. an improvement in the fuel input intensity) and due to the fossil fuel input becoming cleaner (i.e. an improvement in the emission factor by fuel switch from coal to gas). All of the decarbonisation scenarios expect the average conversion efficiency of fossil fuel plants and the cleanliness of the fossil fuel input to improve by 2050. In particular, the Energy efficiency scenario is characterised by the lowest rate of primary energy consumption of all of the decarbonisation scenarios with a reduction of 16 % in 2030 and 38 % in 2050 compared to 2005 and reflects the effect of stringent energy efficiency policies such as 'an obligation that existing energy generation installations are upgraded to the BAT every time their permit needs to be updated'. The increasing efficiency of fossil fuel consumption and the switch from coal to gas envisaged in these decarbonisation scenarios may be further encouraged by reducing the subsidies associated with fossil fuel use and by setting CO_2 taxes to increase the cost of fossil fuel use.

The impact of nuclear energy use on emission change in all of the decarbonisation scenarios contributes to additional emissions by 2050. The political response of Member States such as Italy (i.e. abandoning substantial nuclear plans) and Germany (i.e. revision of nuclear policy) to the recent nuclear accident in Fukushima has been incorporated into the decarbonisation scenarios under consideration in this policy paper with lower expectations for the rate of nuclear penetration by 2050. For example, the share of nuclear use in the electricity generation mix declines to 3 % by 2050 in the Low nuclear scenario due to the underlying assumption that there is no new investment in nuclear capacity (except for plants currently under construction) and that after 2030 no decisions will be made to extend the lifetime of existing nuclear power plants. Even under the most ambitious scenario for the penetration of nuclear energy (i.e. the share of nuclear energy in the electricity mix is 18 % by 2050 in the Delayed CCS scenario) the causal factor nevertheless contributes to additional emissions. This partly reflects the fact that the share of nuclear energy declines in all scenarios compared to the base year.

All of the decarbonisation scenarios depend upon the emergence of CCS technology, albeit to varying extents, in order to reach the necessary level of emission reductions by 2050. It is assumed within the modelling exercise that the capital expenditure of CCS technology will be considerably reduced , especially until 2030, enabling the abatement technology to be highly utilised in the Low nuclear scenario. The use of CCS technology is only constrained by barriers relating to the potential for CO_2 storage and transport, which are reflected in the lower contribution of CCS technology to emission changes in 2050 (18 % of gross emission reductions) in the Delayed CCS scenario. In order to realise any of the decarbonisation scenarios, significant investment in CCS technology will be required to ensure the widespread penetration of this abatement option, which also needs to obtain support of the general public with regard to the financing and construction of dedicated CO_2 transport grids.

In order to provide policy makers with further insights into the importance of the timing of political action between 2020 and 2050 to reduce CO_2 emissions; Figure 16 shows how the different causal factors contribute to CO_2 emission change at various times (i.e. 2020, 2030, 2040 and 2050), always compared to the base year. The emissions relative to the base year are illustrated by the blue line for each decarbonisation scenario, which demonstrates that in all scenarios the gross emission reductions offset the additional emissions so that the power sector is nearly fully decarbonised by 2050.

Figure 16: Overview of the contribution to emission change from the base year of different causal factors in the decarbonisation scenarios between 2020 and 2050



Source: Öko-Institut / Wuppertal Institut (2012)

Although all of the scenarios achieve an almost fully decarbonised power sector in Europe by 2050, the combinations of causal factors differ between the decarbonisation scenarios, which influence the overall timing of CO_2 emission reductions. For example, the High RES scenario – as it name suggests – depends primarily upon the deployment of renewable energy to reduce CO_2 emissions. Therefore renewables maintain a high contribution to CO_2 emission change (i.e. in excess of 100 %) throughout the 2020 to 2050 period. In contrast, the contribution of renewable energies to emission reductions in all the remaining decarbonisation scenario declines throughout the 2020 to 2050 time frame and is progressively substituted by the emergence of either CCS technology (i.e. illustrated by the red segments) or improvements in energy efficiency. For example, the Energy efficiency scenario is characterised by both an increase in the efficiency rate of fossil fuel combustion and a decrease in electricity consumption throughout the 2020 to 2050 time horizon. The decline of nuclear energy use results in additional CO_2 emissions because it would need to be replaced by alternative sources of electricity production that may – under specific circumstances – be more CO_2 intensive. However, as Figure 16 demonstrates, the deployment of renewable energies alone in all scenarios is more than sufficient to offset additional emissions associated with a decrease in the use of nuclear energy.

5 Conclusions

This paper identifies robust energy system strategies followed within the different Energy Roadmap 2050 scenarios. For these strategies political action is urgently required in order to deliver the ‘shared vision’ that the European Commission is aiming for with its decarbonisation scenarios. Given that the window of opportunity for political action to prevent the ‘lock in’ of carbon intensive technologies in the power sector is time-limited, it is essential that political action is taken within the next decade to implement the ‘key innovations’ for CO_2 emission reductions that were identified in the decomposition analysis and discussed in Section 5. Further political debate will be necessary to decide upon the more controversial elements of decarbonisation (i.e. the deployment of nuclear power and CCS technology in the energy mix) and this policy paper challenges the robustness of decarbonisation scenarios that are highly dependent on assumptions associated with high levels of uncertainty (i.e. commercialisation date of CCS).

The following three robust energy system strategies have been identified by the analysis of the Energy Roadmap 2050 scenarios[4]:

- **Efficiency improvements critical**
  The decomposition analysis has shown that efficiency measures aimed at reducing the growth of electricity demand compared to a reference development are absolutely crucial to achieve the decarbonisation of the power system as envisioned in the policy scenarios. Efficiency improvements not only allow limiting electricity demand growth but also enable significant amounts of electricity to be used in the heating and especially the transport sector, thus "exporting" CO_2 emission reductions to these sectors – given supply side technologies in the power sector are decarbonised in parallel.
- **Renewables are most important supply side mitigation option, while the role of nuclear power will be limited**
  In all of the decarbonisation scenarios technologies using renewable energy sources are by far the most important supply-side mitigation option in the electricity system. The role of nuclear energy on the other hand will decrease in all of the decarbonisation scenarios.
- **Fluctuating electricity sources to capture major share in power generation within the next four decades**
  Of all renewable energy sources wind is by far the most important one for the decarbonisation of the electricity system. Robust growth in wind power is expected

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[4] These findings are largely in line with the respective findings of a previous analysis of other European energy scenarios conducted within this project (see SEFEP 2012). The main area of disagreement is in regard to nuclear power, as a few (pre-Fukushima) scenarios envision a more important role for this technology than the EU’s Energy Roadmap 2050 scenarios

already in the near-term as the technology, especially onshore wind, is relatively mature and among the most economically attractive low carbon electricity generation options. By 2050 wind onshore and offshore is responsible for more than 30 % of electricity generation in all of the decarbonisation scenarios and even for around 50 % in the High RES scenario. This also means that a large share of future electricity generation in Europe will be from fluctuating renewable energy sources (especially wind and solar PV). Policymakers should be aware of this and should prepare strategies early on for the electricity system to be able to deal with such a high share of fluctuating electricity supply.

In many of the decarbonisation scenarios **CCS technologies** also play an important role in reducing CO_2 emissions in the power sector. However, the High RES scenario indicates that the role of CCS may be limited when a high deployment of renewable technologies as well as their system integration will be successful. Even in the other scenarios, CCS is not expected to be deployed to any significant extent before 2030. This assumption about the relatively late relevance of CCS reflects current uncertainties about its technological viability and its economics, including infrastructure and CO_2 storage capacity. The high growth rate for CCS plants after 2030 and the assumed falling technology costs critically require both of these core CCS technology challenges to be solved by then, i.e. a significant technological maturity and sufficient public acceptance will be necessary.

Apart from the analysis of scenario results, the work within this project on the Energy Roadmap 2050 and on previous scenario studies has made it clear that the scenario studies themselves could be improved to further add to their relevance for energy policy making. Especially the following two issues should be addressed:

- **Need for greater transparency in scenario results**

  A few key assumptions, for example on specific generation costs and technological attributes (like the efficiencies of the various types of power plants and the capture rate assumed for CCS plants) as well as some key modelling results (like the amount of electricity generated in PV and CSP plants individually or in natural gas CCS and coal CCS plants) have not been made public and their availability would considerably help to analyse and better understand the reasons and implications of the differences in the seven Roadmap scenarios.
- **Sensitivity analyses could help explore effects of different technology price assumptions on electricity mix**

  It would prove useful if sensitivity analyses regarding crucial parameters were systematically applied to decarbonisation scenarios (for example capital cost assumptions). Such analyses would enable the exploration of capital cost corridors in which one or the other technology becomes economically viable.

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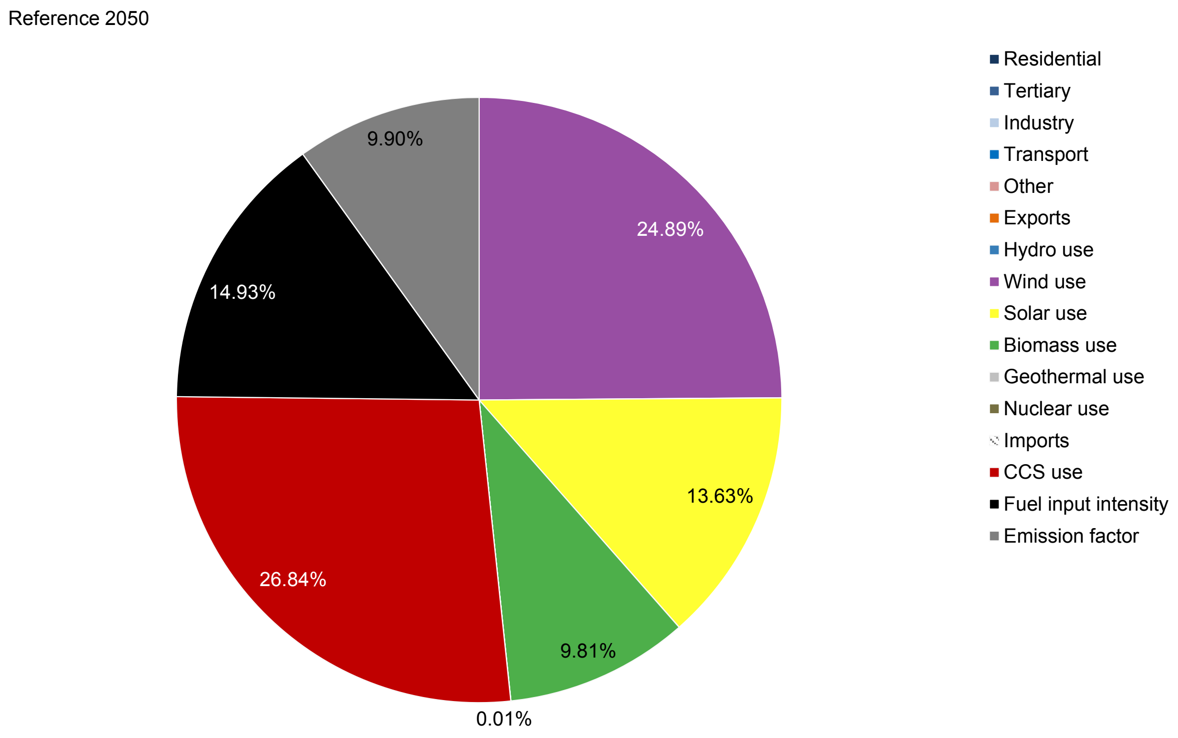
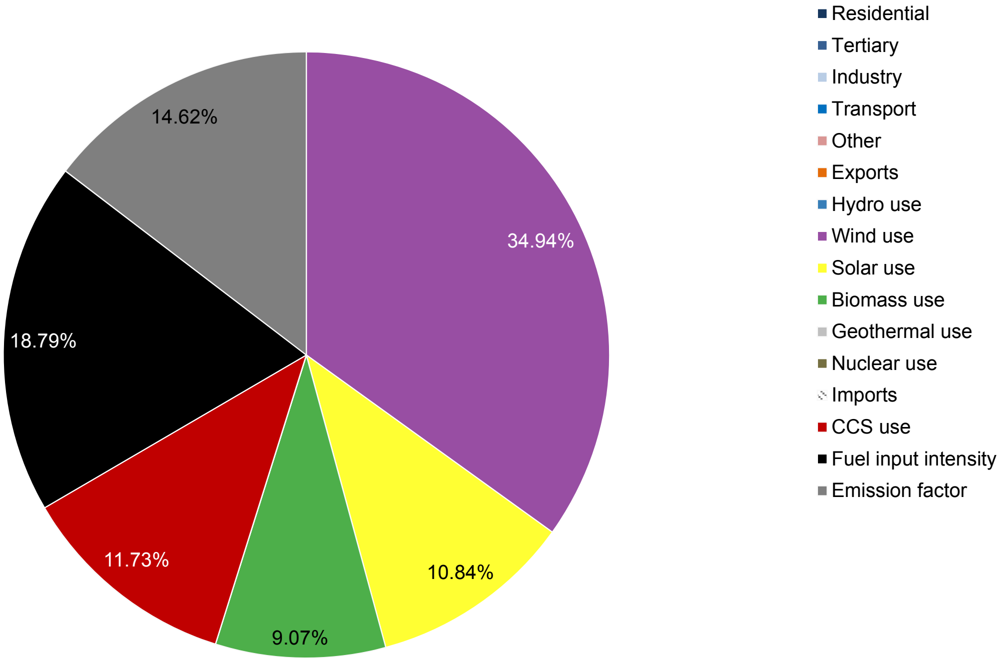
Appendix 1: Shares of causal factors on gross CO_2 emission reductions in each scenario

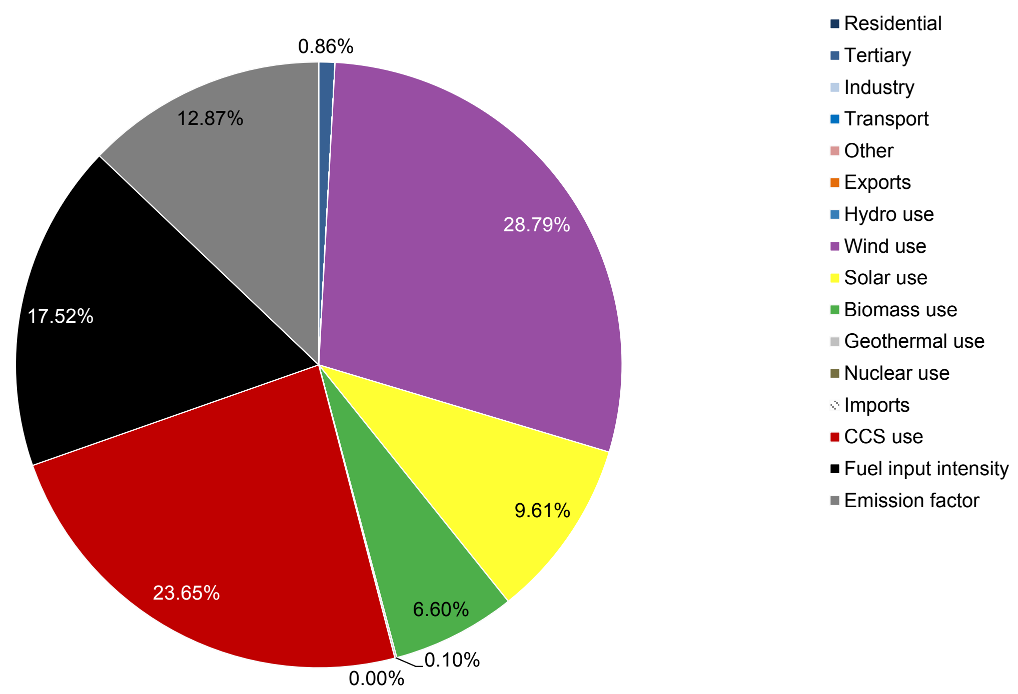
Figure 17 Shares of causal factors on gross CO_2 emission reductions in all EU Energy Roadmap 2050 scenarios for 2050.



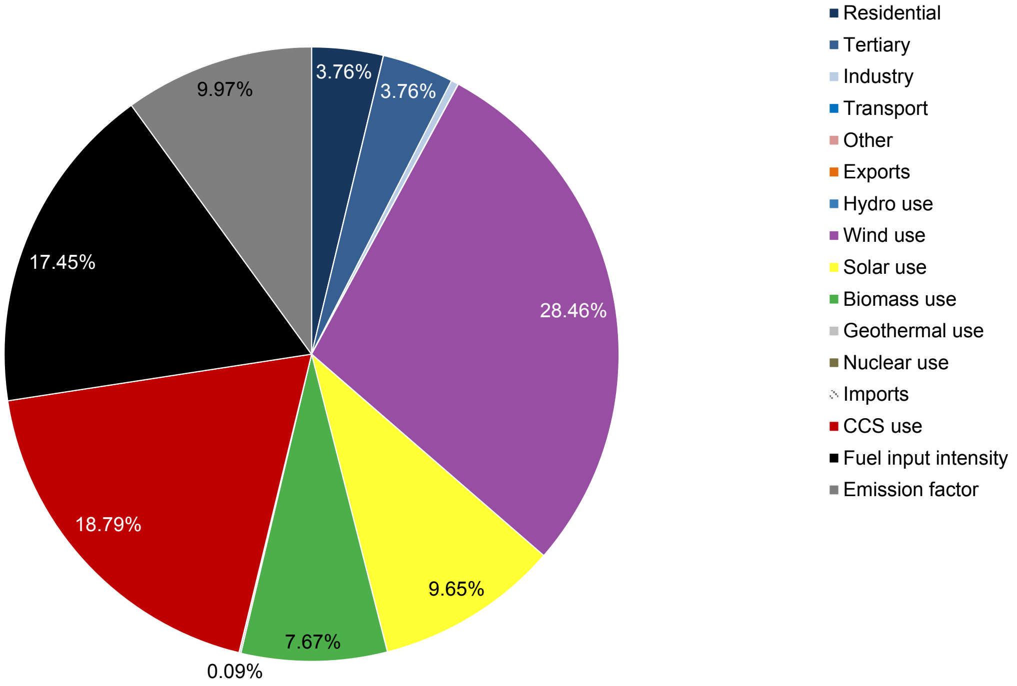
CPI 2050


14.62%
34.94%
18.79%
11.73%
10.84%
9.07%
Residential
Tertiary
Industry
Transport
Other
Exports
Hydro use
Wind use
Solar use
Biomass use
Geothermal use
Nuclear use
Imports
CCS use
Fuel input intensity
Emission factor

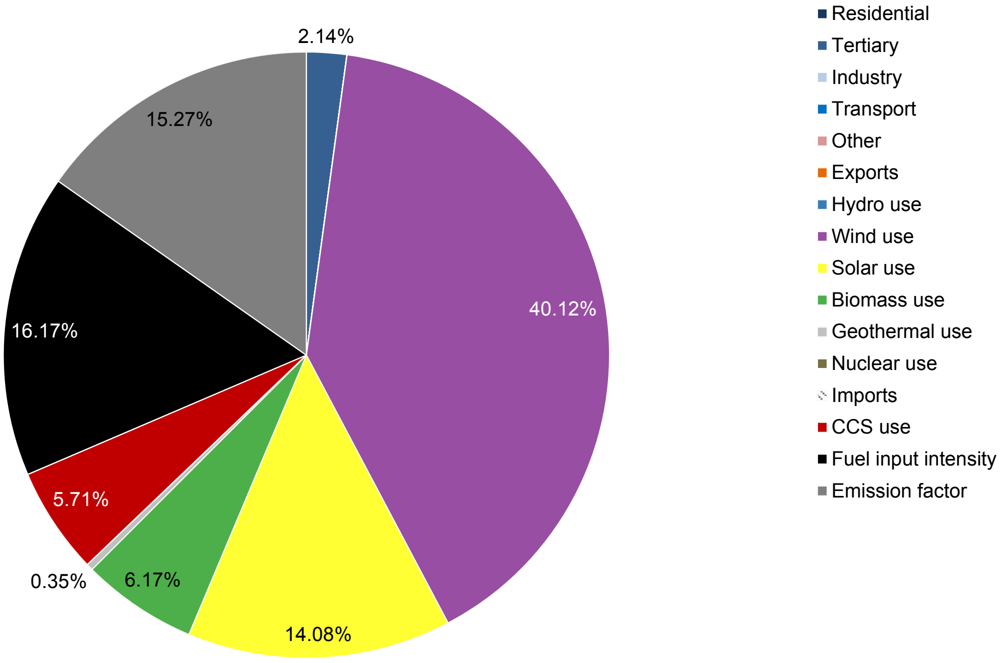
Diversified Supply 2050



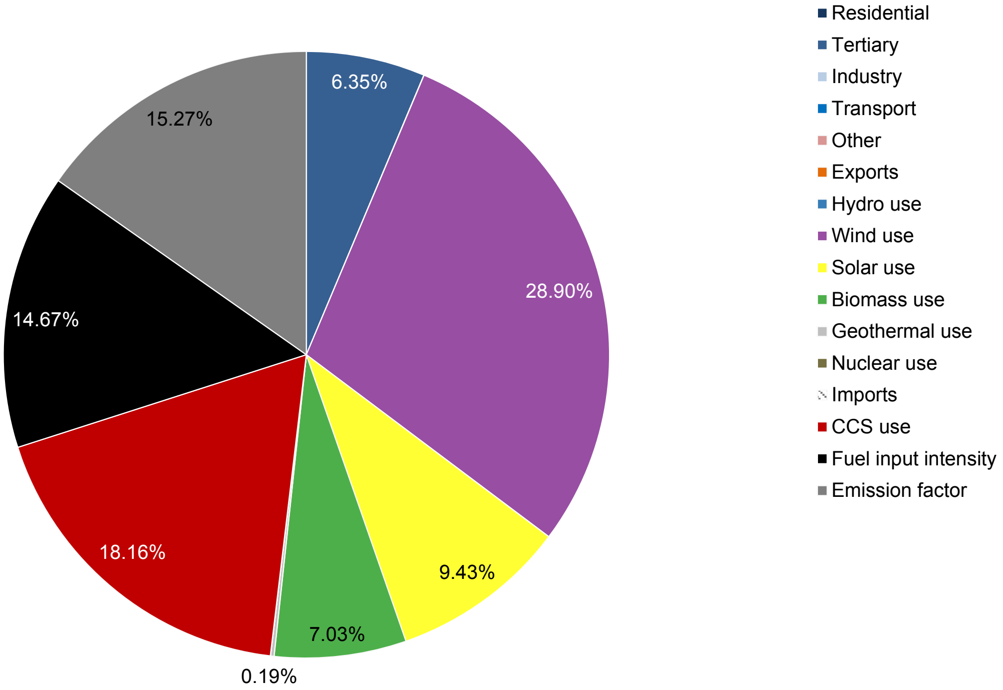
Energy Efficiency 2050

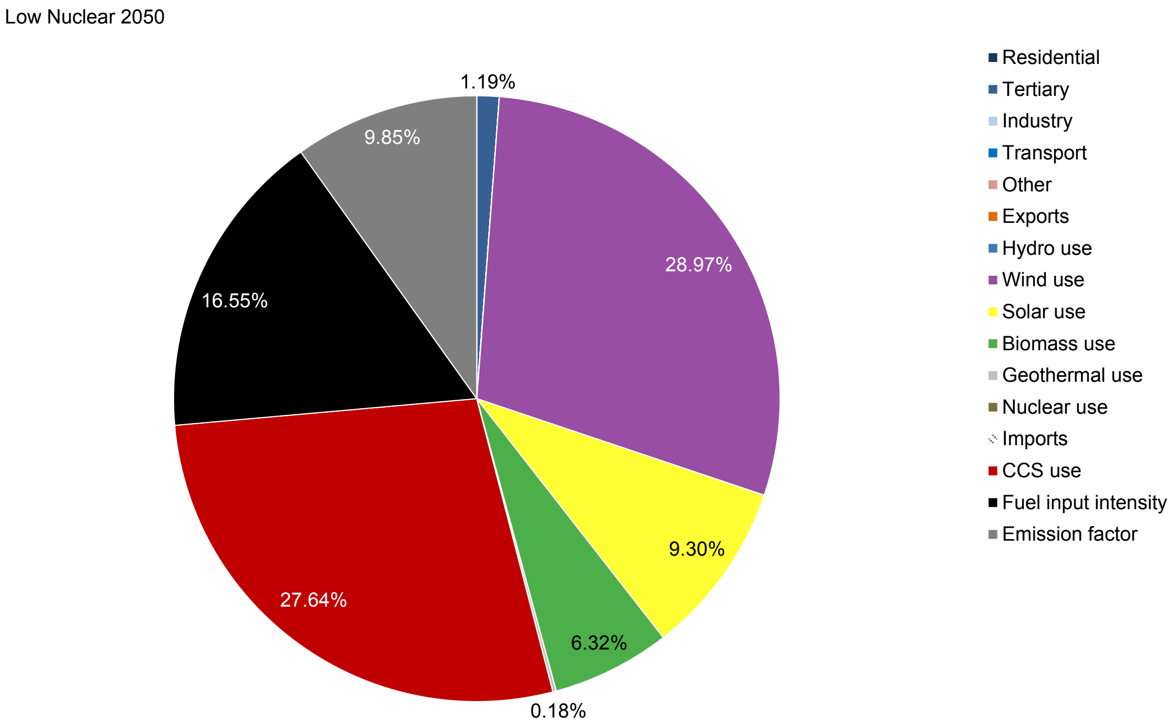


High RES 2050



Delayed CCS 2050





Source: Öko-Institut / Wuppertal Institute (2010), results of decomposition analysis.

Information for Policy Makers 2

Analysis of the EU's Energy Roadmap 2050 scenarios.

SEFEP working paper 2012

Authors

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May 2012

smart energy
for europe platform

This report has been commissioned by the Smart Energy for Europe Platform (SEFEP).

Table of Contents

List of Figures

List of Tables

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Dr. Felix Christian Matthes

Dr. Felix Matthes (Senior Staff) has been a Researcher at Öko-Institut since 1991. From 1991 to 1997 he was a senior scientist in the Energy and Climate Protection Division, from 1997 to 2008 he was the Coordinator of the division and since 2008 he has been Research Coordinator for Energy and Climate Policy. From 2002 to 2004 he served as Deputy Director of the Institute.

He has more than 17 years professional experience in research and consultancy, concentrating on energy and climate change issues. He has published numerous studies and publications on German and international energy policy, as well as on environment and climate policy. Key topics of his work include the design, the comparison and the implementation of emissions trading schemes, energy market modelling and technology-specific policies (e.g. regarding cogeneration, nuclear energy) as well as the comprehensive assessment and monitoring of energy and climate policy packages. His key topic of interest in recent years has been the implementation of the EU ETS, including the phase-in of auctioning in phase 2 and 3 of the scheme.

He has served as a member of the in-depth review teams for National Communications under the United Nations Framework Convention on Climate Change (UNFCCC) for several occasions. From 2000 to 2002 he was a Scientific Member of the Study Commission ‘Sustainable Energy in the Framework of Globalization and Liberalization” of the German Federal Parliament (German Bundestag). In 2007 and 2008 he was a visiting scientist at the Joint Program on the Science and Policy of Global Change of the Massachusetts Institute of Technology (MIT) in Cambridge, MA.

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About SEFEP

SEFEP, the Smart Energy for Europe Platform, is an independent, non-profit organisation founded by the European Climate Foundation and the Stiftung Mercator. Based in Berlin, SEFEP offers a platform to stimulate cooperation and synergies among all European actors who aim to build a fully de-carbonised, predominantly renewable power sector.

Summary

With growing concerns about climate change, energy import dependency and increasing fuel costs, a political consensus has formed in Europe in recent years about the need to transform the way we supply and consume energy. However, there is less political consensus on the specific steps that need to be taken in order to achieve a future sustainable energy system. Questions about which technologies should be used to what extent and how fast changes in the energy system should be instituted are being discussed on the European Union as well as on the Member State level.

Energy scenarios are seen as a helpful tool to guide and inform these discussions. Several scenario studies on the European energy system have been released in recent years by stakeholders like environmental NGOs and industry associations. A number of these studies have recently been analysed by the Öko-Institut and the Wuppertal Institute within an ongoing project commissioned by the Smart Energy for Europe Platform (SEFEF).[1] The project aims to advance the debate on the decarbonisation of the energy system in the EU as well as its Member States during the course of 2012 and to make contributions to the scientific literature on this topic. Analysis within the project focuses on the development of the electricity system, as this system today is the main source for CO_2 emissions and is widely regarded to be the key to any future decarbonisation pathway.

The paper at hand summarises the analyses accomplished based on scenarios developed within the recently released Energy Roadmap 2050 of the European Union. The Roadmap explores different energy system pathways, which are compatible with the EU's long-term climate targets. It is a highly influential publication and will play a significant role in determining what will follow the EU's 2020 energy agenda. The Roadmap's analysis is currently discussed by EU and Member States policymakers as well as by stakeholders throughout Europe. Consequently it was a logical step within the SEFEP funded project to take a closer look at the seven different scenarios developed within the EU's Energy Roadmap 2050. As in the previous analysis of earlier energy scenario studies (SEFEP 2012) the main tool used to analyse and compare the scenarios is a decomposition method applied to show the extent to which technologies and strategies contribute to CO_2 emission reductions in the respective scenarios.

The results of the Energy Roadmap 2050 analysis mirror many of the project's earlier findings from other scenario studies: Renewable energy technologies are the most important supply-side element in the electricity sector for ambitious decarbonisation within the next four decades and wind will be the major contributor within the renewables. At the same time considerable energy efficiency improvements compared to a reference development are needed to limit growth in electricity demand and to simultaneously enable a significant amount of electricity to be used in the transportation sector to help reduce CO_2 emissions in that sector. The scenarios also indicate that CCS can be an important mitigation technology within the European electricity system, but that its future availability and public acceptance is limited and its importance for successful decarbonisation can be considerably reduced if a strong deployment of renewables can be achieved in the future.

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[1] See (Sefep 2012).

1. Introduction

At the UN climate conference in Cancún in December 2010, nearly all Parties expressed support for a target to limit global warming to a maximum of 2°C above pre-industrial levels, which is generally considered to be the threshold for global temperature rise to prevent the catastrophic consequences of climate change. The European Council subsequently reconfirmed in February 2011 that the objective of the European Union (EU) is to reduce its greenhouse gas emissions (GHGs) by 80 to 95 % below 1990 levels by 2050.[2] Although the EU is already committed to GHG emission reductions of at least 20 % below 1990 levels by 2020 as part of the Energy and Climate Package[3], longer-term policies are now required to ensure that the ambitious reduction target for 2050 is achieved. The European Commission has therefore published a 'Roadmap for moving to a competitive low-carbon economy in 2050'[4], providing guidance on how the EU can decarbonise the economy.

The process around this document which finally led to the EU's Energy Roadmap 2050 (European Commission 2011b)[5], published in December 2011, which is based on economic modeling and scenario analysis, which considers how the EU can move towards a low carbon economy assuming continued global population growth, increasing global GDP and by varying trends in terms of international climate action, energy and technological development.[6] The outcome of the analysis is a recommendation that the EU should reduce its domestic GHG emissions by 80 % below 1990 levels by 2050 and that this target is technically feasible and financially viable using proven technologies if strong incentives (i.e. carbon pricing) exist. The cost efficient pathway to achieve the 2050 target calls for domestic GHG reductions below 1990 levels of 25 % in 2020, 40 % in 2030 and 60 % in 2040 and this would require an additional annual investment of €270 billion for the next 40 years. This is equivalent to 'an additional investment of 1.5 % of EU GDP per annum on top of the overall current investment representing 19 % of GDP in 2009.'[7] The extent and timing of these GHG reduction targets are differentiated by sector reflecting the different abatement potentials that exist within the EU (Figure 1).

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[2] European Council (2011): Conclusions – 4 February 2011. http://www.consilium.europa.eu/uedocs/cms_data/docs/pressdata/en/ec/119175.pdf

[3] The objective of the Energy and Climate Package is to reduce GHGs by at least 20 % by 2020 relative to 1990 emission levels, increase the share of renewable energy in meeting final energy demand in the EU to 20 % and to reduce energy consumption by 20 % compared to projected trends. See the annex for more information on how these policy objectives are to be achieved.

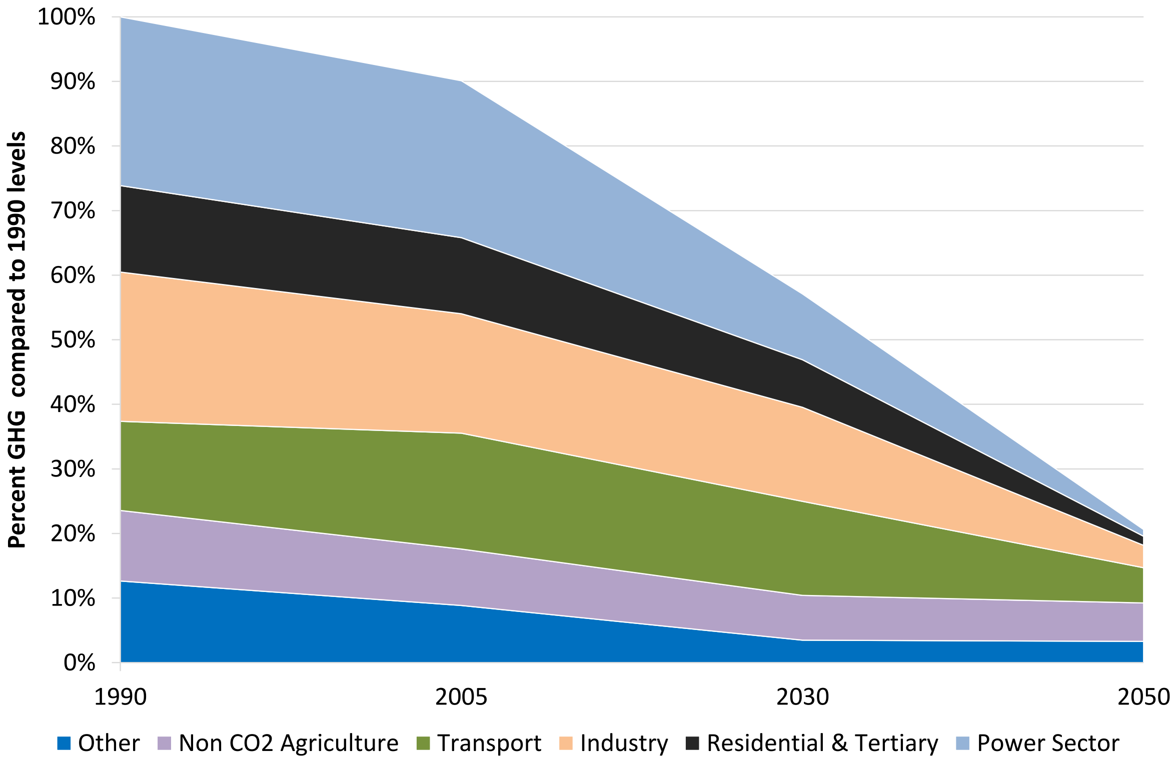
[4] COM (2011): A Roadmap for moving to a competitive low carbon economy in 2050. 112 final.

[5] COM (2011) 885/2.

[6] COM (2011): A Roadmap for moving to a competitive low carbon economy in 2050. 112 final.

[7] COM (2011): A Roadmap for moving to a competitive low carbon economy in 2050. 112 final.

Figure 1 EU Roadmap 2050 decarbonisation pathway



Source: (European Commission 2011a) and adapted by Öko-Institut / Wuppertal Institute (2012)

In December 2011, the final Energy Roadmap 2050[8] was published containing several scenarios based on the PRIMES model. The decarbonisation scenarios considered in the EU's Energy Roadmap 2050 reflect different views on how the EU can decarbonise its economy. For example, a decarbonisation scenario may differ based upon the use of technologies to generate electricity (i.e. renewable energy, nuclear and CCS) or may also differ due to how energy is used (i.e. rates of consumption and efficiency improvements). The objective of this policy paper is to provide a quantitative analysis of the similarities and differences of the following decarbonisation scenarios outlined in the EU's Energy Roadmap 2050:

- **Energy efficiency**: The scenario 'is driven by a political commitment of very high primary energy savings by 2050 and includes a very stringent implementation of the Energy Efficiency plan'. [9]

- **Diversified supply technologies:** All energy sources compete on a market basis in this scenario 'with no specific support measures for energy efficiency and renewables and assumes acceptance of nuclear and CCS as well as solution of the nuclear waste issue'. [10]

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[8] COM(2011) 885/2.

[9] SEC(2011) 1565/2.

- **High RES:** The scenario aims at 'achieving a higher overall RES share and very high RES penetration in power generation, mainly relying on domestic supply'.[11]

- **Delayed CCS:** The scenario 'follows a similar approach to the Diversified supply technologies scenario but assumes difficulties for CCS regarding storage sites and transport while having the same conditions for nuclear' as the Diversified supply technologies scenario.[12]

- **Low nuclear:** The scenario 'follows a similar approach to the Diversified supply technologies scenario but assumes that public perception of nuclear safety remains low and that implementation of technical solutions to waste management remains unsolved leading to a lack of public acceptance'.[13] The same conditions exist for CCS as in the Diversified supply technologies scenario.

The scenarios considered in this policy paper advocate a 'shared vision' for a decarbonised power sector in 2050 with a similar level of ambition with regards to CO_2 emission reductions in 2050. However, the scenarios under consideration have different views on the technology mix and levels of energy consumption and these differences are reviewed in regard to the electricity sector in Section 2. To provide further insights into the similarities and differences between the decarbonisation scenarios a decomposition analysis is completed in Section 3. The added value of this decomposition analysis is the ability to attribute the CO_2 emission reductions from a decarbonisation scenario to important causal factors such as the increase of wind power in the energy mix. The cost assumptions underlying these decarbonisation scenarios are considered in Section **Error! Reference source not found.**. The implications of the similarities and differences identified between all of the decarbonisation scenarios will then be discussed in Section 5 focusing especially on the timing of political action needed to realise the decarbonisation pathways. The paper concludes with Section 6.

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[10] SEC(2011) 1565/2.
[11] SEC(2011) 1565/2.
[12] SEC(2011) 1565/2.
[13] SEC(2011) 1565/2.

2. Shared vision of a decarbonised Europe

2.1 Emission trajectories

The decarbonisation scenarios all achieve CO_2 emission reductions in the power sector of at least 96 % below 2005 emission levels by 2050. The bullet point list below illustrates the hierarchy of ambition in regard to the power sector (i.e. emission reductions below 2005 levels by 2050) for the decarbonisation scenarios:

- Diversified supply (- 98.9 %)
- Low nuclear (- 98.6 %)
- Energy efficiency (- 98.4 %)
- Delayed CCS (- 98.2 %)
- High RES (- 96.3 %)

Many scenario studies that develop decarbonisation pathways first establish a reference scenario (i.e. emissions development without climate action). The EU's Energy Roadmap 2050 provides a reference[14] and a "Current Policy Initiatives" (CPI)[15] scenario which expect power sector CO_2 emissions to decline by 70 % and 61 % respectively below 2005 levels by 2050. Until 2030 the CPI scenario delivers more emission reductions than the reference scenario, reflecting additional measures adopted after March 2010. However, from 2030 onwards the reference scenario achieves greater CO_2 emission reductions than the CPI scenario and this may party reflect the impact of a phase down in the use of nuclear energy following the political impact of the Fukushima disaster in 2011 (Figure 2), reflected in the CPI but not the Reference scenario.

The emission development between 2020 and 2050 associated with the decarbonisation scenarios vary within a narrow range reflecting the different use of abatement options. All of the decarbonisation scenarios achieve the 2020 emissions target outlined in the Energy and Climate Package adopted by the EU in 2008. The Energy efficiency scenario achieves power sector CO_2 emission reductions at the highest rate of all scenarios until 2025, reflecting the implementation of the key policy initiatives adopted by the EU. The High RES scenario delivers the greatest emission reductions of all the scenarios by the end of 2030 and is then subsequently surpassed by the Delayed CCS scenario by the end of 2035. The Diversified supply and Low nuclear scenarios are characterised by a steady rate of CO_2 emission reduction over the 2020 to 2050 time horizon and all decarbonisation scenarios ultimately reach approximately the same level of CO_2 emissions by 2050 (Figure 2).

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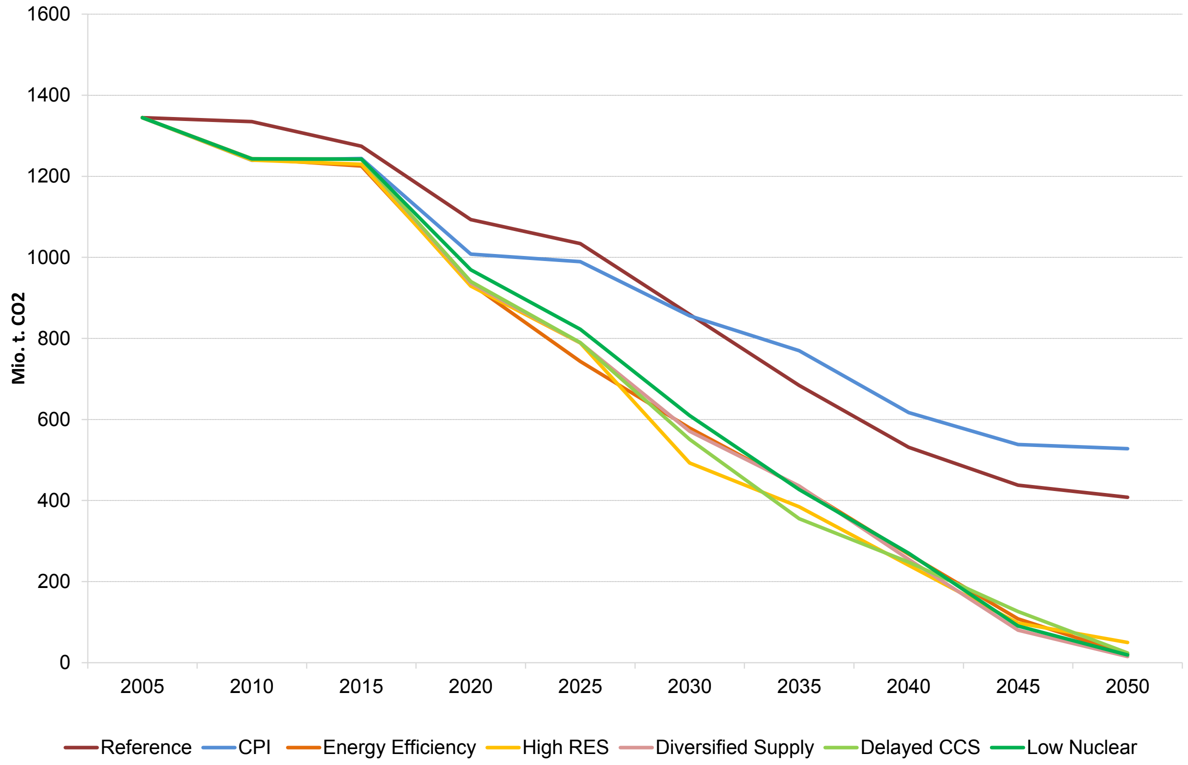
[14] 'The reference scenario includes current trends and long-term projections on economic development (GDP growth of 1.7 % p.a.). It takes into account rising fossil fuel prices and includes policies implemented by March 2010. The 2020 targets for GHG reductions and RES shares will be achieved but no further policies and targets after 2020 (besides the ETS directive) are modelled' (SEC (2011) 1565/2).

[15] The Current Policy Initiatives scenario also includes additional measures adopted after March 2010 in 'the area of energy efficiency, infrastructure, internal market, nuclear, energy taxation and transport. Technology assumptions for nuclear were revised reflecting the impact of Fukushima and the latest information on the state of play of CCS projects were included' (SEC (2011) 1565/2).

Figure 2 Power sector CO_2 emission trajectories for reference and decarbonisation scenarios



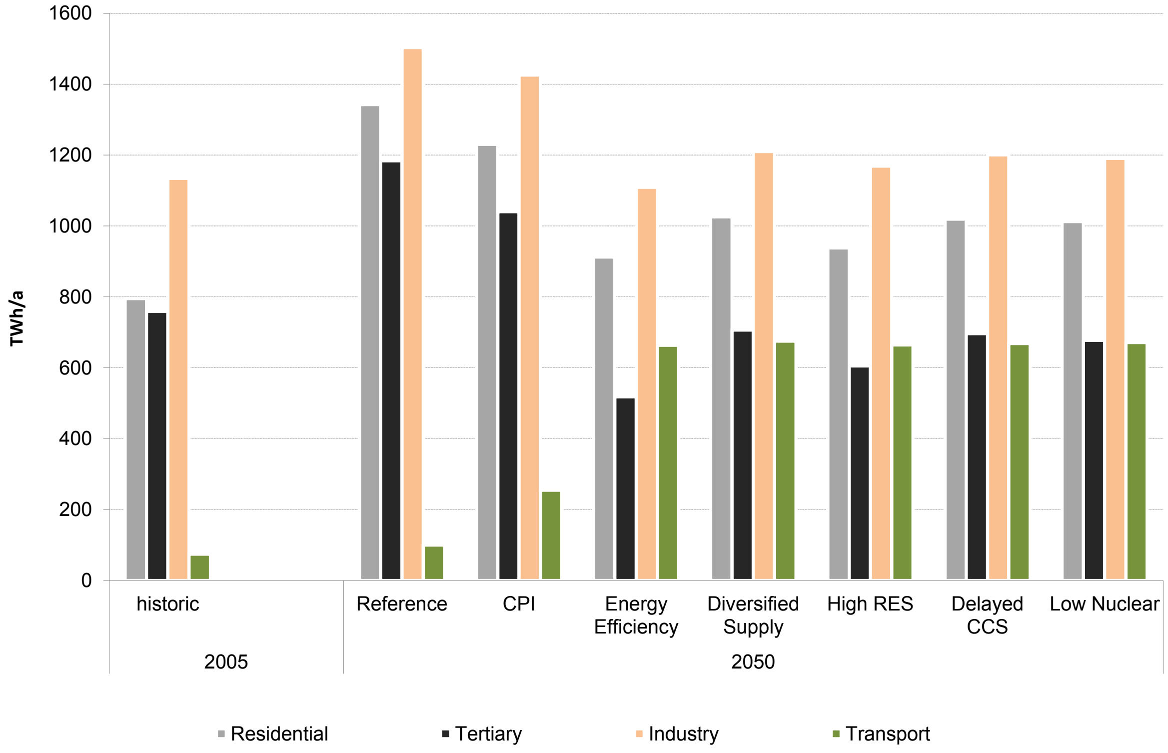
Source: Öko-Institut / Wuppertal Institute (2012), compiled from data kindly provided by DG Energy.

2.2 Electricity consumption

Total electricity demand in the EU-27 increases until 2050 in all seven scenarios of the EU's Energy Roadmap (Figure 3). However, in the decarbonisation scenarios the increase is less pronounced than in the CPI and especially the Reference scenario. While electricity demand increases by 50 % between 2005 and 2050 in the Reference scenario, the increase is between 16 and 31 % in the decarbonisation scenarios. The lowest increase occurs in the Energy efficiency scenario, where it is assumed that strong efficiency measures are implemented. Demand growth is also relatively low (+22 %) in the High RES scenario, where higher generation costs and higher market prices are assumed to have a dampening effect on electricity demand.

While considerable improvements in the efficient use of electricity are assumed in all of the decarbonisation scenarios (stronger so in the Energy efficiency scenario), these improvements are over compensated by additional demand for services requiring electricity. Some of that additional demand (for example in the case of electric cars and heat pumps) leads to lower non-electricity energy use and can thus help decarbonize the economy, but not the power sector as such if its supply technologies are not decarbonised in parallel. Figure 3 highlights the relevance that a future widespread use of electric cars could have on electricity demand. The vast bulk of additional electricity demand in 2050 (compared to 2005) occurs in the transport sector. Without this additional demand (inter alia for heat pumps) electricity consumption would actually drop in the Energy efficiency scenario and would be virtually flat in the High RES scenario, while it would increase only slightly in the other decarbonisation scenarios. Compared to a reference development, the EU's Energy Roadmap 2050 sees considerable potential for reducing electricity demand in all of the three other sectors (tertiary, households and industry). Electricity demand in the tertiary sector in 2050 could even be considerably lower than in 2005.

Figure 3 Electricity consumption (final energy demand) per sector in the EU-27 in 2005 and according to EU's Energy Roadmap scenarios in 2050 (in TWh/a)



Source: Öko-Institut / Wuppertal Institut (2012) compiled from data in European Commission (2011).

Previous European energy scenarios have made similar assumptions about the change in overall and sectoral electricity demand to be expected in any future decarbonised pathway. Figure 4 compares the changes in electricity demand between the base year and the year 2050 in three selected scenarios from the EU's Energy Roadmap 2050 (Reference, Energy efficiency and Diversified supply) with two other reference and four other decarbonisation scenarios from previous scenario studies.[16] All scenario studies see significant potential for efficiency improvements in the non-transport sectors compared to a business-as-usual development without strong efficiency measures. Realising these efficiency potentials could enable demand increases in these sectors to remain low, at or below 10 %. However, all scenarios expect electricity demand in the transport sector to increase dramatically,

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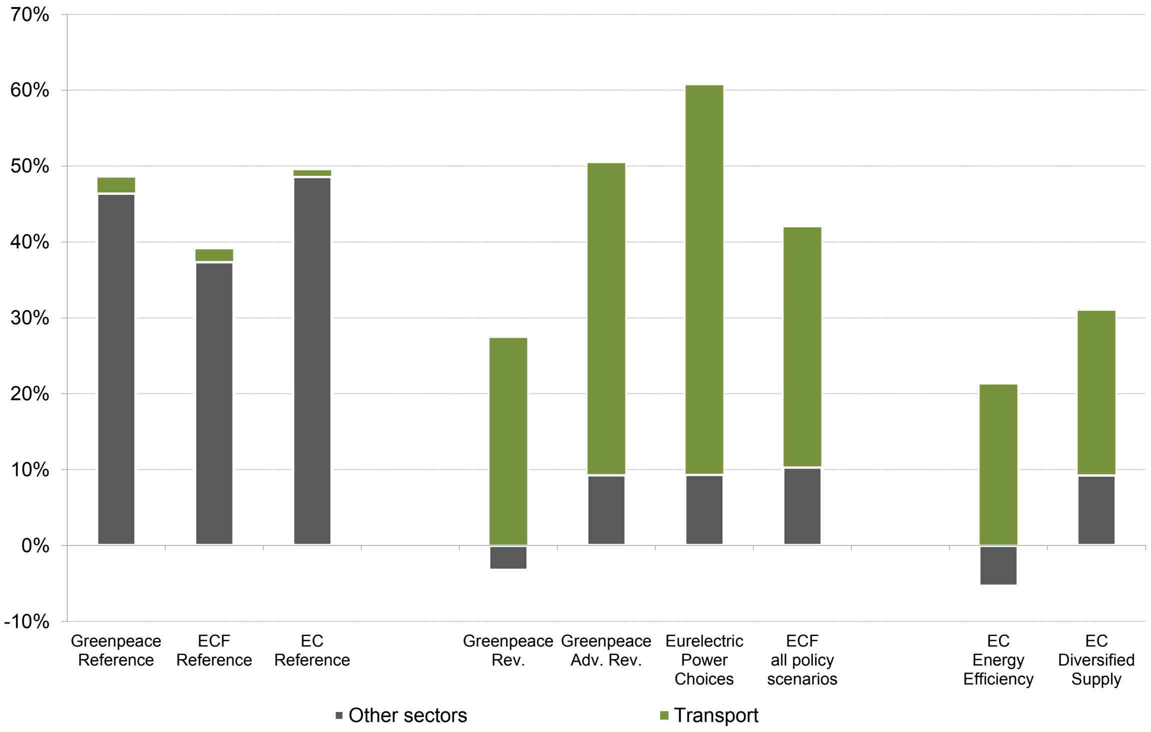
[16] See Sefep (2012) for more details on these other energy scenarios.

mostly due to the widespread introduction of full or hybrid electric cars. Compared to the policy scenarios of other studies, the decarbonisation scenarios of the EU's Energy Roadmap 2050 are a little more conservative regarding the future electricity demand in the transport sector. Interestingly, as evidenced by electricity demand in the reference scenarios, without adequate policy support, none of the studies compared here expect electricity to play a much larger role in the transport sector in 2050 compared to today.

Figure 4 Change in final electricity demand in the EU-27 from 2005/2007 to 2050 in various scenarios, differentiated by the transport sector and the other sectors

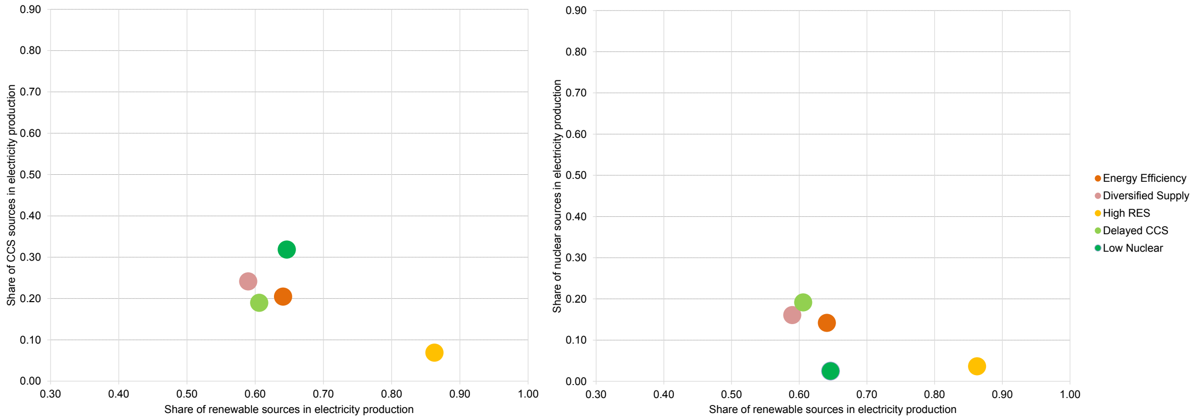


Source: Öko-Institut / Wuppertal Institute (2012) compiled from data in (European Commission 2011) (for the EU's Energy Roadmap 2050 scenarios) and (Greenpeace International & European Renewable Energy Council 2010; eurelectric 2009; European Climate Foundation 2010).

2.3 Sources of electricity production

In line with the overall objective of the decarbonisation 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 for the decarbonisation scenarios. Figure 5 shows that in 2050 renewable technologies dominate the electricity system, holding shares in gross electricity generation of 59 % (Diversified supply) to 86 % (High RES) in the decarbonisation scenarios. However, CCS power generation becomes an important element in the EU's power system, reaching shares of 19 % (Delayed CCS) to 32 % (Low nuclear) in most decarbonisation scenarios. Only in the High RES is CCS of little significance, contributing only 6 % by the middle of the century. The share of nuclear energy in 2050 is lower in all scenarios than today, falling from 27 % in 2010 to 26 % in the Reference and to only 2 % in the High RES and Low nuclear scenarios.

Figure 5 Share of electricity from renewable sources compared to the share of electricity from nuclear energy / CCS electricity generation for the decarbonisation scenarios by 2050



Source: Öko-Institut / Wuppertal Institut (2012), compiled from data kindly provided by DG Energy.

All of the individual factors described in this section (the sources of consumption and production of electricity), despite their different (technical) nature, have one characteristic in common: their level of use/non-use triggers changes in CO_2 emissions over time. The decomposition analysis in Section 3 uses this common denominator as a metric to derive the effect that each of these individual factors has on emission changes in a given decarbonisation scenario.

3. Comparison of decarbonisation scenarios

The overview in the previous section outlined the important similarities and differences with regards to the overall timing of CO_2 emission reductions, technologies deployed and rates of electricity consumption. However, this analysis is unable to attribute emission changes to the specific changes to the electricity system advocated in all of the decarbonisation scenarios. The objective in the following is therefore to quantitatively analyse all of the decarbonisation scenarios based upon decomposition techniques in order to determine how the causal factors drive changes in emissions.

3.1 Methodology

A decomposition analysis requires an equation that describes the influence of several causal factors on the observed changes of a variable of interest (CO_2 emissions). According to the decomposition equation developed for this policy paper[17], the total amount of CO_2 emissions can be determined by

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[17] $$E_t = C_t(1-\pi_t^f)\frac{I_t}{P_t^{fos}}\frac{E_t}{I_t}$$

the electricity consumption in the various sectors[18] which is being supplied, by the electricity production from a mix of different technologies[19] that differ in their need for fossil fuels[20] (old coal plants need more coal than new ones, wind farms need no fossil fuel) which in turn will have different emission factors[21], implying differing CO_2 emissions per energy unit (gas less than coal). An in-depth description of the decomposition equation is provided in the background document accompanying this policy paper entitled *WP 1.2: Comparison Methodologies*. Input data from all of the decarbonisation scenarios were collected and supplemented with transparent gap-filling techniques to ensure that the decomposition equation could be successfully executed.[22] Based upon the Laspeyres decomposition method, the isolated effect of a causal factor on the CO_2 emissions of the power sector in 2050 was calculated by changing the value of a causal factor to its scenario value in 2050 whilst ensuring that the remaining causal factors remain at their base year value. By replicating this calculation for all the causal factors, the outcome of the decomposition analysis is to attribute changes in emissions to changes in the consumption of electricity, the production of electricity from different technologies, the fossil fuel input and the different emission factors associated with the use of different fossil fuels.[23]

3.2 Results

The results of the decomposition analysis in the year 2050 are presented in

Figure 6 along with the respective electricity generation mix of the decarbonisation scenarios in Figure 7. The coloured bars in

Figure **6** for each decarbonisation scenario represent the CO_2 **emission change** from the base year due to different causal factors, which can either positively or negatively contribute to CO_2 emissions. For example, Figure 6 shows that additional CO_2 emissions would result from a phase out or the reduced use of nuclear power as illustrated by the negative dark blue segment while additional deployment of renewable energies (the positive green segment) would result in CO_2 emission reductions. The **net emission reduction** delivered by each decarbonisation scenario (actual emission

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[18] In the decomposition equation this is referred to as 'electricity consumption',C_t , which is defined as the consumption of electricity from various sectors at time step *t*.

[19] In the decomposition equation this is referred to as 'electricity production', $1-\pi_t^f$, which is defined as the share of production from CO_2 emitting electricity generation technologies at time step *t.*

[20] In the decomposition equation this is referred to as 'fuel input intensity', I_t/P_t^{fos}, which is defined as the fossil fuel input per unit of electricity production at time step *t*.

[21] In the decomposition equation this is referred to as 'emission factor', which is defined as the CO_2 emissions per unit of fossil fuel input at time step *t*, E_t/I_t.

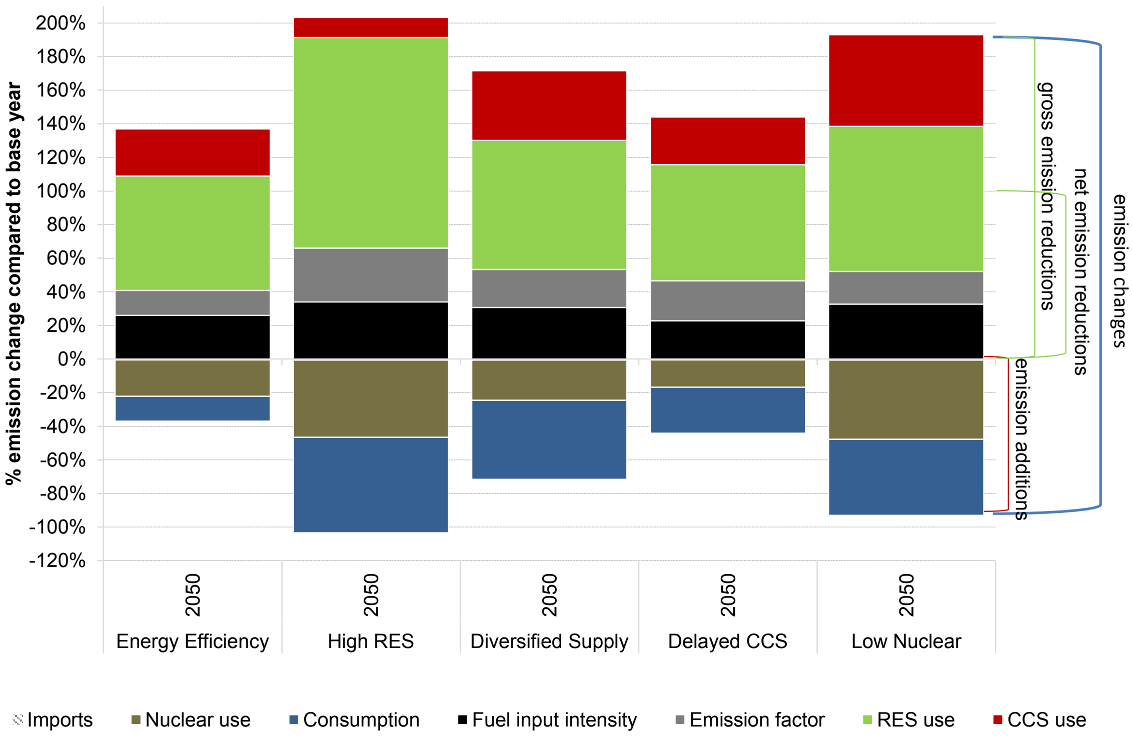
[22] See *WP 3.1. Quantitative Analysis of scenarios from the EU Energy Roadmap 2050* (hereafter WP 3.1.).

[23] The extent to which we can attribute the observed changes in the variable of interest to the explanatory factors depends upon the size of the residual from the decomposition. The residual occurs due to the 'mixed effect' of explanatory factors interacting with one another to contribute to the observed change in the variable of interest. The residual has been distributed to the causal factor proportional to their contribution to overall CO_2 emission changes. See also WP 1.2.

reductions) is determined by subtracting the **additional emissions** (negative segments) from the **gross emission reductions** (positive segments).[24]

The coloured bars in Figure 6 for each decarbonisation scenario represents the absolute contribution of an electricity generating technology, which is measured in TWh, in supplying electricity. For example, the absolute contribution of wind energy in supplying the total electricity of a decarbonisation scenario in the year 2050 is illustrated by the purple segment. It is important to acknowledge that the total electricity demand varies between the decarbonisation scenarios due to the different assumptions with regard to electricity consumption, which were previously discussed in Section 2.

Figure 6 Overview of the contribution of different causal factors to emission changes in 2050 compared to the base year



Note: The decomposition analysis was accomplished based on gross electricity production values. Thus, on the demand side, electricity consumption for conversion, line losses and consumption from refineries and other uses is included in the aggregate consumption depicted in the figure

Source: Öko-Institut / Wuppertal Institute (2012) results from the decomposition analysis

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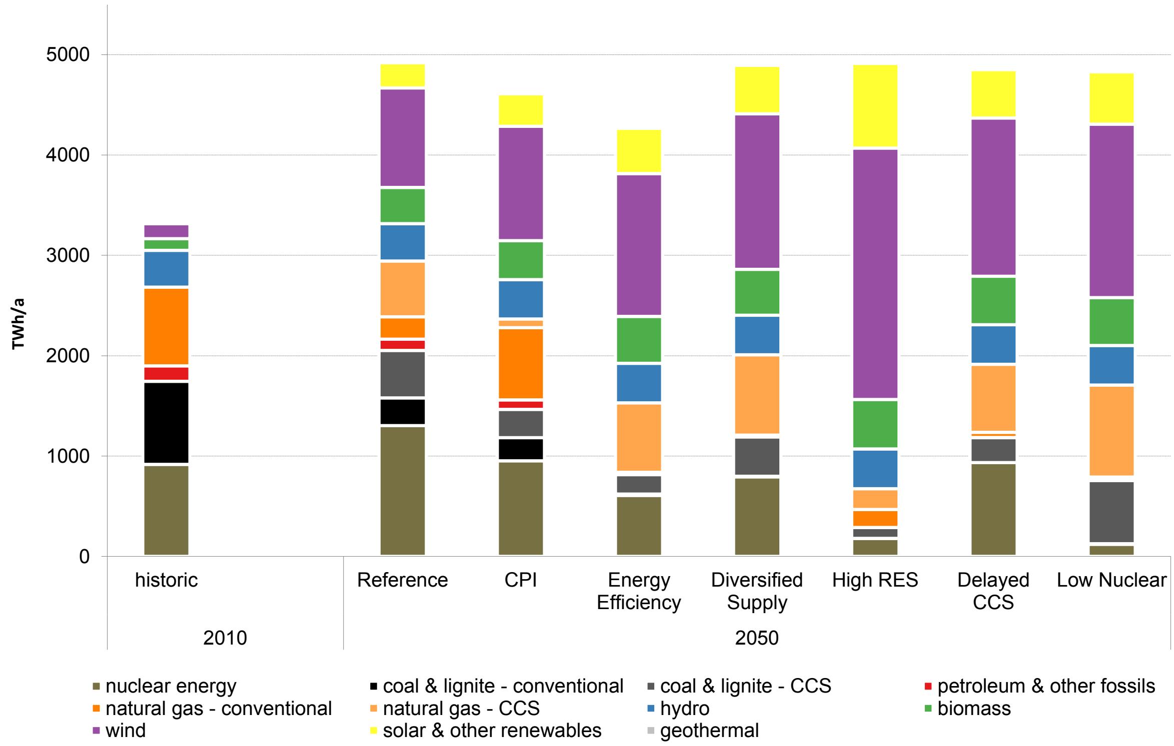
[24] The positive part of each column in **Figure 6** represents the gross emission reductions achieved by the causal factors. The positive part of each column is longer than the actual emission reductions achieved because additional emissions triggered by factors depicted in the negative part of each column need to be compensated for in order to reach the emission goal of each scenario which is equal to the net emission reductions achieved.

Figure 7 The electricity generation mix in 2010 and within the different scenarios in 2050



Source: Compiled from data kindly provided by DG Energy.

Figure 6 demonstrates the relationship between changes in emission levels (compared to the base year) and changes in the electricity generation mix that are associated with the different decarbonisation scenarios by the year 2050. For example, the rapid deployment of renewable energy technology envisaged in the High RES scenario represents 86 % of the electricity generation mix and is responsible for 125 % (60 % of the gross emission reductions by causal factors)[25] of emission changes by 2050. The emergence of CCS technology will also play an important role in emission reductions by the year 2050, especially in the Low nuclear scenario whereby CCS technology will eventually represent 32 % of the electricity generating mix and contribute to an emission change of -

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[25] The value in the bracket represents the share of that causal factor’s emission reduction on the gross emission reductions achieved by the causal factors. These shares are illustrated in the Annex for each scenario. Hereafter all brackets following text on emission changes will refer to the share of that causal factor’s contribution on gross emission reduction achieved by the causal factors.

55 % (28 % of the gross emission reduction by causal factors) by 2050. In contrast, the decline of nuclear energy to 3 % of the electricity generating mix by 2050 in the Low nuclear scenario will result in additional emissions of 47 % that will need to be offset by additional emission reductions (i.e. deployment of renewables, CCS). Additional emissions may also be generated via increased levels of electricity consumption by 2050; however the stringent efficiency measures applied in the Energy efficiency scenario considerably limit additional emissions from electricity consumption and this is reflected in Figure 7 as the absolute level of electricity production in the Energy efficiency scenario (4,281 TWh) is considerably lower in 2050 relative to the other decarbonisation scenarios.

Table 1 Decomposition results of CO_2 emission reduction in 2050 for the decarbonisation scenarios.

	Energy Efficiency	High RES	Diversified Supply	Delayed CCS	Low Nuclear
	Million tonnes of CO2				
C: Residential	74.0	-54.3	-88.7	-66.8	-83.3
C: Tertiary	74.1	58.2	20.1	130.6	31.1
C: Industry	7.9	-13.2	-29.3	-19.7	-21.6
C. Transport	-181.7	-224.0	-231.2	-177.1	-228.5
Renewable use	901.9	1622.4	1021.6	913.5	1144.6
P: Hydro	-1.4	-28.4	-29.1	-23.3	-26.7
P: Wind	560.4	1090.7	670.8	594.4	757.9
P: Solar	190.0	382.7	223.8	194.0	243.3
P: Biomass	151.0	167.7	153.8	144.5	165.4
P: Geothermal	1.9	9.6	2.3	4.0	4.6
P: Other	0.0	0.0	0.0	0.0	0.0
P: Nuclear	-287.1	-594.9	-319.2	-214.9	-625.7
P: Hydrogen	0.0	0.0	0.0	0.0	0.0
Imports	-6.2	-7.7	-7.8	-6.7	-7.7
CCS use	369.9	155.2	551.1	373.6	723.0
Fuel input intensity	343.7	439.7	408.1	301.8	433.0
Emission factor	196.3	415.0	299.9	314.1	257.8

Note: Negative values reflect emission additions, while positive values reflect emission reductions.

Source: Öko-Institut / Wuppertal Institute (2012), results from decomposition analysis.

The results of the decomposition analysis are illustrated further in Table 1, which outlines the absolute reduction in CO_2 emissions between the base year and 2050 attributed to each causal factor measured in million tonnes of CO_2. The CO_2 emission reduction is either negative and thus characterised by additional emissions (red shading) or is positive and characterised by emission reductions (green shading).

All of the decarbonisation scenarios analysed in this policy paper assume that electricity consumption will increase considerably for road transport and heat applications by 2050. This is due to the envisaged growth in new electric appliances (electric mobility, heat pumps), reducing CO_2 emissions by switching from other fuels to low carbon electricity. For example, the electrification of road transport is assumed in all of the decarbonisation scenarios, whereby 80 % of private passenger transport activity in 2050 will involve the use of plug-in hybrid or pure electric vehicles.[26] This trend is

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[26] SEC (2011) 1565.

dependent however upon political action, which will be necessary to facilitate the commercialisation of new appliances such as electric vehicles, which are currently too expensive for a widespread diffusion. For example, political action may consist of public investments in infrastructural developments (charging points) and tax subsidies to lower the capital costs associated with purchasing electrical vehicles. As a consequence of the increase in electricity consumption for both road transport and other new appliances used for heating in 2050, additional CO_2 emissions will be generated within the electricity system.[27] It is therefore essential that political action should be taken in parallel to transform the energy system so that low carbon technology is primarily used to generate electricity. It is important to acknowledge that in all decarbonisation scenarios, including even the Energy efficiency scenario, improvements in the efficiency of traditional applications in the residential, tertiary, industry and transport sectors will not entirely offset the increase in electricity consumption from the new appliances by 2050 as well as additional electricity consumption caused by GDP growth in any of the decarbonisation scenarios, given the base year's electricity mix.

The decomposition analysis demonstrates that an increase in the share of electricity generated from renewable technology will result in considerable emission reductions by 2050. All of the decarbonisation scenarios envisage that wind energy will account for the largest share of electricity generation from renewables in 2050. There is also a general consensus among the decarbonisation scenarios that an increase in solar and biomass energy will greatly contribute to emission reductions in 2050. The increasing deployment of renewables in all of the decarbonisation scenarios assumes that the capital expenditure cost of these technologies will reduce over time (see Section 4); however political action in the form of market deployment policies as well as public investment in the research and development of renewable technologies will be necessary for these cost reductions to materialise. Policy makers also need to address the existing barriers to the deployment of renewables (planning permission, capital costs) that considerably increase lead times. Access to capital and the fast-tracking of planning applications for renewables will be essential for realising the High RES scenario, which assumes that the total RES capacity would need to increase to over 1,900 GW by 2050 (this is more than eight times the current RES capacity).[28] Infrastructural investments in transmission grids and storage technology will also be necessary in the longer term to overcome issues concerning both the distribution of electricity and the intermittency of supply.

There is agreement amongst the decarbonisation scenarios that CO_2 emissions will be reduced by 2050 as a consequence of an increase in the average conversion efficiency of the remaining fossil fuel plants (an improvement in the fuel input intensity) and due to the fossil fuel input becoming cleaner (an improvement in the emission factor by fuel switch from coal to gas). All of the decarbonisation scenarios expect the average conversion efficiency of fossil fuel plants and the cleanliness of the fossil fuel input to improve by 2050. In particular, the Energy efficiency scenario is characterised by

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[27] Given that the decomposition analysis only calculates the 'isolated effect' of a causal factor, the emissions reduction from an increase in consumption is negative (i.e. additional emissions) as the energy mix remains the same as in the base year. The residual of the decomposition accounts for 'mixed effects' such as an increase in electricity consumption and an increase in the share of renewables in the energy mix and is distributed proportionally to each causal factor, so that the mixed effects are accounted for.

[28] SEC (2011) 1565.

the lowest rate of primary energy consumption of all of the decarbonisation scenarios with a reduction of 16 % in 2030 and 38 % in 2050 compared to 2005 and reflects the effect of stringent energy efficiency policies such as ‘an obligation that existing energy generation installations are upgraded to the BAT every time their permit needs to be updated’.[29] The increasing efficiency of fossil fuel consumption and the switch from coal to gas envisaged in these decarbonisation scenarios may be further encouraged by reducing the subsidies associated with fossil fuel use and by setting CO_2 taxes to increase the cost of fossil fuel use.

The impact of nuclear energy use on emission change in all of the decarbonisation scenarios contributes to additional emissions by 2050. The political response of Member States such as Italy (i.e. abandoning substantial nuclear plans) and Germany (i.e. revision of nuclear policy) to the recent nuclear accident in Fukushima has been incorporated into the decarbonisation scenarios under consideration in this policy paper with lower expectations for the rate of nuclear penetration by 2050. For example, the share of nuclear use in the electricity generation mix declines to 2 % by 2050 in the Low nuclear scenario due to the underlying assumption that there is no new investment in nuclear capacity (except for plants currently under construction) and that investments into the extension of lifetimes of existing plants can only occur until 2030. Even under the most ambitious scenario for the penetration of nuclear energy (the share of nuclear energy in the electricity mix is 18 % by 2050 in the Delayed CCS scenario) the causal factor nevertheless contributes to additional emissions. This partly reflects the fact that the share of nuclear energy declines in all scenarios compared to the base year.[30]

All of the decarbonisation scenarios depend upon the emergence of CCS technology, albeit to varying extents, in order to reach the necessary level of emission reductions by 2050. It is assumed within the modelling exercise that the capital expenditure of CCS technology will be considerably reduced until 2030 and thereafter (see Section 4) enabling the abatement technology to be highly utilised in the Low nuclear scenario. The use of CCS technology is only constrained by barriers relating to the potential for CO_2 storage and transport, which are reflected in the lower contribution of CCS technology to emission changes in 2050 (18 % of gross emission reductions) in the Delayed CCS scenario. In order to realise all of the decarbonisation scenarios, significant investment in CCS technology will be required to ensure the widespread penetration of this abatement measure, which obtains the support of the general public with regard to the financing and construction of dedicated CO_2 transport grids.[31]

In order to provide policy makers with further insights into the importance of the timing of political action between 2020 and 2050 to reduce CO_2 emissions;

Figure 6 is extended in Figure 8 to show how the different causal factors contribute to CO_2 emission change at various time horizon intervals (i.e. 2020, 2030, 2040 and 2050) always compared to the

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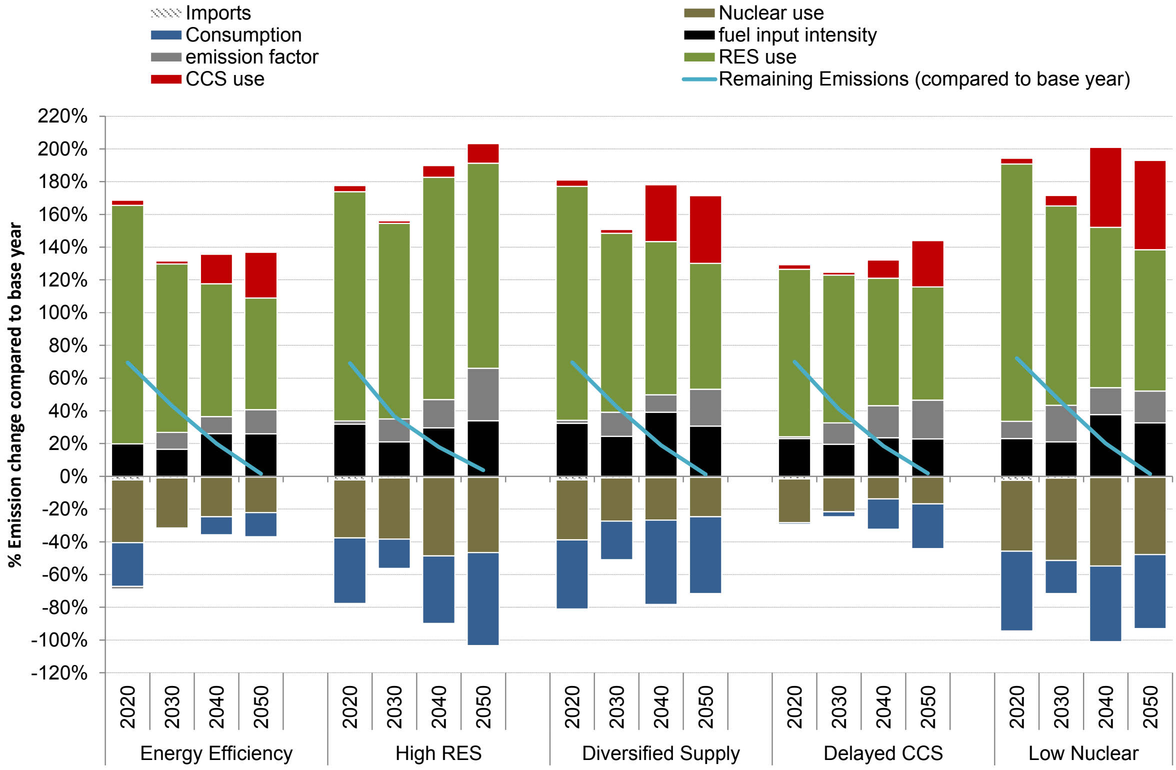
[29] SEC (2011) 1565.

[30] The residual produced by the decomposition analysis is higher in the delayed CCS scenario than in the others. This may be due to the gap filling assumptions that needed to be accomplished and which add uncertainty to the analysis. These assumptions are documented in WP 3.1

[31] SEC (2011) 1565.

base year. The emissions relative to the base year are illustrated in Figure 8 by the blue line for each decarbonisation scenario, which demonstrates that in all scenarios the gross emission reductions offset the additional emissions so that the power sector is nearly fully decarbonised by 2050.

Figure 8 Overview of the contribution to emission change from the base year of different causal factors in the decarbonisation scenarios between 2020 and 2050



Note: The decomposition analysis was accomplished based on gross electricity production values. Thus, on the demand side, electricity consumption for conversion, line losses and consumption from refineries and other uses is included in the aggregate consumption depicted in the figure.

Source: Öko-Institut / Wuppertal Institute (2012)

Although all of the scenarios achieve an almost fully decarbonised power sector in Europe by 2050, the combinations of causal factors differ between the decarbonisation scenarios, which influence the overall timing of CO_2 emission reductions. For example, the High RES scenario – as its name suggests – depends primarily upon the deployment of renewable energy to reduce CO_2 emissions maintaining a high contribution to CO_2 emission change (i.e. in excess of 100 %) throughout the 2020 to 2050 period. In contrast, the relative contribution of renewable energies to total emission reductions in all the remaining decarbonisation scenario declines throughout the 2020 to 2050 time frame and is progressively substituted by the emergence of either CCS technology (i.e. illustrated by the red bars in Figure 8) or improvements in energy efficiency. For example, the Energy efficiency scenario is characterised by both an increase in the efficiency rate of fossil fuel combustion and a decrease in electricity consumption throughout the 2020 to 2050 time horizon. The decline of nuclear energy use results in additional CO_2 emissions because it would need to be replaced by alternative sources of electricity production that may – under specific circumstances – be more CO_2

intensive. However, as Figure 8 demonstrates, the deployment of renewable energies alone in all scenarios is more than sufficient to offset additional emissions associated with a decrease in the use of nuclear energy.

4. Cost assumptions of the scenarios

All of the decarbonisation scenarios considered in this policy paper are characterised by a similar level of ambition, yet it is evident that the combination of abatement measures to deliver these CO_2 emission reductions vary. The cost assumptions of various power generation technologies are an important driving factor influencing the structure of electricity supply in all of the decarbonisation scenarios.[29] The aim of this section is to provide a transparent comparison of the various assumptions (fossil fuel price, technology costs) applied in these decarbonisation scenarios regarding the cost development of the various power generating technologies until 2050.

4.1 Fossil fuel costs

As in most energy models, cost assumptions are a crucial element in determining model results in the partial market equilibrium model (PRIMES) used. For the EU's Energy Roadmap 2050 modelling two different sets of assumptions have been made about the development of the market prices of fossil fuels. In the decarbonisation scenarios lower prices have been assumed than in the reference scenarios, based on the assumption that countries outside the European Union will also follow ambitious climate mitigation pathways and will thus reduce demand for fossil fuels, lowering world market prices as a consequence. Table 2 shows both the price assumptions in the two reference scenarios and the price assumptions in the five decarbonisation scenarios between 2015 and 2050 and contrast these with the respective assumptions in two other European energy scenario studies released within the past two years.

Table 2 Fossil fuel import prices (in €$_{2005}$) in the EU's Energy Roadmap 2050 scenarios compared to respective prices in other scenario studies

		Crude oil import price (€2005/barrel)	Natural gas import price (€2005/GJ)	Hard coal import price (€2005/tonne)
ECF Roadmap 2050	2015	55	6	57
	2030	73	9	69
	2050	73	9	69
Energy Revolution	2015	92	12	96
	2030	124	16	118
	2050	124	22	143
EU Energy Roadmap (baseline)	2015	74	8	111
	2030	98	12	147
	2050	118	15	151
EU Energy Roadmap (decarbonisation scenarios)	2015	71	7	98
	2030	73	9	116
	2050	65	7	93

Source: Öko-Institut / Wuppertal Institute (2012), compiled from (European Commission 2011d) and (European Commission 2011c)

In the EU's Energy Roadmap decarbonisation scenarios, it is assumed that the world market price of crude oil will remain relatively stable until 2030; after which the price is expected to steadily decrease steadily until 2050.[32] A similar development is assumed for natural gas, while the price for hard coal is expected to rise a bit between 2010 and 2030, before also dropping off until 2050. In summary it can be concluded that the fossil fuel price assumptions in the decarbonisation scenarios are at the lower end of current price scenarios. Higher price assumptions for natural gas and for hard coal would worsen the economics of CCS.

4.2 Technology costs

While the EU's Energy Roadmap 2050 does not provide specific electricity generation costs per technology, capital expenditure per unit of capacity is given for several technologies. Figure 9 shows a comparison of how capital expenditure changes over time for several renewable energy technologies in the EU's Energy Roadmap 2050 and in two other European energy scenarios.[33] For wind and especially solar PV relatively modest future cost reductions are assumed in the EU's Energy Roadmap 2050. For solar thermal on the other hand, costs are assumed to drop off considerably until 2050.[34] Interestingly, the EU's Energy Roadmap 2050 scenarios assume a steady decrease in the capital expenditure for new nuclear power plants, decreasing from around 4,380 $€_{2010}$/kW in 2010 to around 3,600 $€_{2010}$/kW in 2050. Considerable cost reductions over time, especially in the assumed early deployment phase between 2015 and 2030 are also assumed for power plants equipped with CCS. For example a coal CCS power plant (pulverised coal, supercritical) using the oxyfuel process reduces its capital expenditure from 3,480 $€_{2010}$/kW assumed for today to around 2,000 $€_{2010}$/kW by 2040. Compared to expectations from some other stakeholders and experts the EU's Energy Roadmap assumes only modest future cost reductions for the most important renewable energy technologies. This in combination with rather optimistic assumptions regarding the future cost reduction potential (and technological viability) of CCS technologies seems to lead to a relative disadvantage of renewable energy technologies in the electricity system in the PRIMES modelling.[35]

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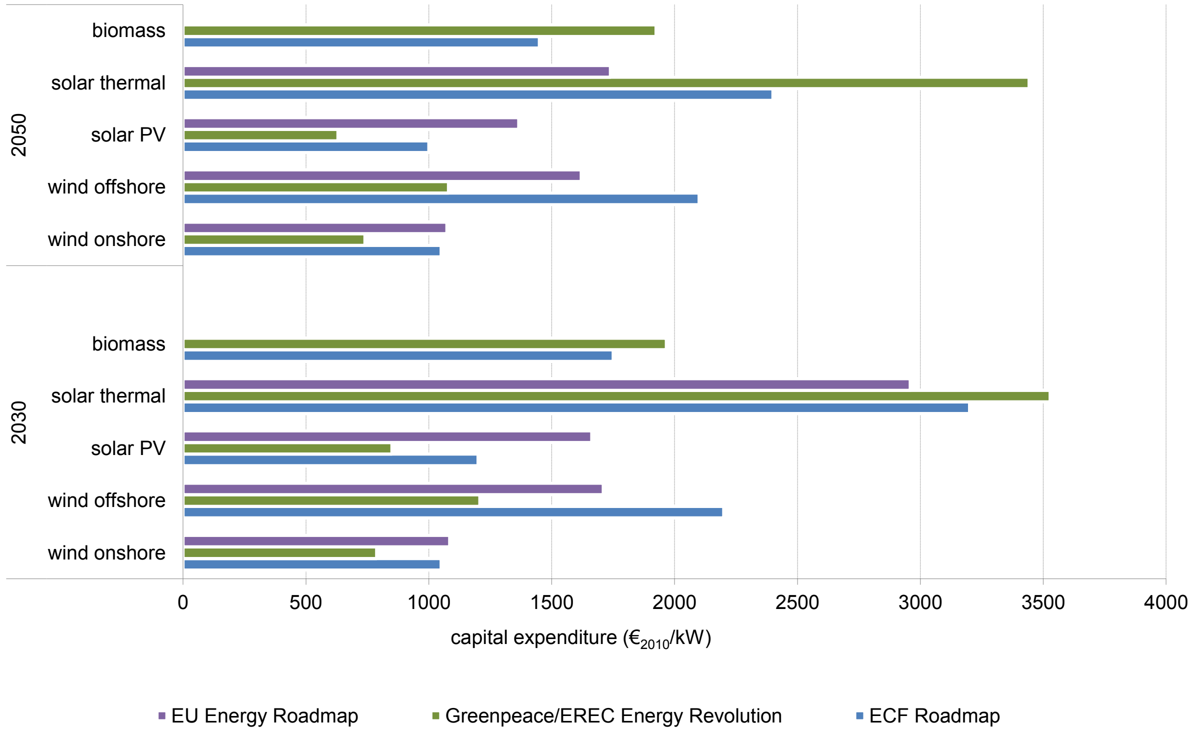
[32] While crude oil is of little direct importance to the electricity system, its price development heavily influences the prices of natural gas and coal.

[33] See the first policy paper within this project for more information about the cost assumptions in other European energy scenario studies.

[34] No information about the capital expenditure of biomass power plants is found in the EU's Energy Roadmap publications.

[35] It would be highly welcome in future EU energy modelling work if sensitivity analysis were to be performed and published on the effects of different fuel and technology cost assumptions on the energy system and specifically the average electricity price in various scenarios.

Figure 9 Comparison of assumptions on capital expenditure for several renewable energy technologies in several scenario studies (in €$_{2010}$/kW)



Source: Öko-Institut / Wuppertal Institute (2012), compiled from (European Commission 2011d)

5. Window of opportunity for political action

The window of opportunity for political action to prevent runaway climate change is rapidly closing as high-carbon energy generation facilities continue to be built around the world, resulting in an emissions ‘lock in’ effect that reduces the likelihood of limiting global temperature rise to a maximum of 2°C (likely requiring stabilization of atmospheric levels of greenhouse gases at no more than 450 ppm of CO_2 equivalent). According to (International Energy Agency 2011) a continuation of current trends in energy generation will result in 90 % of the available ‘carbon budget’ until 2035 being used up by 2015 already.[36] Political action at both the international and national level is therefore urgently required to incentivise low-carbon investments in order to decarbonise the world’s energy generation. The purpose of this section is to provide further guidance on the timing of this political action from the European perspective by identifying the windows of opportunities for implementing important abatement measures that can be divided into the following categories:

- Existing abatement measures (i.e. renewable energies, fuel switching etc.)
- Key innovations (i.e. CCS technology, electric mobility etc.)

The outcome of the decomposition analysis outlined in Section 3 is re-organised in Table 3 to incorporate the above distinction between the evolutionary development of existing measures and the key innovations that require breakthroughs in technology to deliver the CO_2 emission reductions envisaged in the decarbonisation scenarios. Furthermore, the contribution of the causal factors to overall CO_2 emission changes is presented in relative terms to enable a better comparison between the decarbonisation scenarios and to complement Figure 6 and Figure 8.

The dark green shaded row in Table 3 illustrates that the deployment of renewable energy plays a central role throughout the 2020 to 2050 period in all of the decarbonisation scenarios; however there is a greater level of consensus on the short-term contribution to CO_2 emission reductions than in the longer term. The contribution of renewable energy to CO_2 emission changes in 2020 narrowly ranges from 140 % to 157 % relative to the base year for four of the decarbonisation scenarios (i.e. Energy efficiency, High RES, Diversified supply and Low nuclear) and reflects the renewable energy target set within the EU Climate Package. The contribution of renewable energy to CO_2 emission changes in 2020 is considerably lower in the Delayed CCS scenario (i.e. 102 % relative to the base year) and this is mostly due to the higher share of electricity generated in 2020 by nuclear energy according to this scenario. It is important that policy makers are aware of the potential for delays in the lead times that are associated with the deployment of renewable technologies and to legislate accordingly in order to ensure that this policy target is achieved by 2020.

Although renewable energy continues to plays an important role in reducing emissions until 2050, it is evident from Table 3 that in the medium to long term clear differences emerge amongst the decarbonisation scenarios with regards to both the implementation of CCS technology and the phase down of nuclear energy use. As a consequence, the contribution of renewable energy to CO_2

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[36] IEA (2011): World Energy Outlook 2011.

emission changes in 2050 declines in all of the decarbonisation scenarios compared to 2020, however the extent of this decline varies depending upon the use of alternative abatement options.

In all of the decarbonisation scenarios it is expected that improving the efficiency of fossil fuel plants and switching to cleaner fuel inputs (i.e. from coal to gas) will result in CO_2 emission reductions consistently throughout the 2020 to 2050 time period for all decarbonisation scenarios (Table 3). In order to encourage these improvements, political action will be required that progressively increases the cost of carbon until the year 2050, for which there exist a range of policy instruments (i.e. environmental taxes, emissions trading). Furthermore, the dark red shaded row in Table 3 demonstrates that the majority of the decomposition scenarios expect the role of nuclear power to decline by 2050, which will result in additional emissions that will need to be offset by introducing policies aimed at encouraging the rapid deployment of alternative sources of low carbon electricity generation (see column *RES use*) and improvements in energy efficiency.

Table 3 The contribution of existing abatement measures to CO_2 emission change compared to the base year of each scenario between 2020 and 2050.

		Resid. Cons.	Tertiary Cons.	Industry Cons.	Transport Cons.	RES Use	Nuclear Use	CCS Use	Emission Factor	Fuel Intensity
Energy efficiency	2020	-9%	-9%	-3%	-7%	146%	-38%	3%	-2%	20%
High RES		-14%	-15%	-4%	-6%	140%	-35%	4%	2%	32%
Diversified supply		-15%	-16%	-4%	-6%	143%	-37%	4%	2%	32%
Delayed CCS		-9%	16%	-2%	-4%	102%	-27%	3%	1%	23%
Low nuclear		-16%	-19%	-5%	-7%	157%	-43%	4%	11%	23%
Energy efficiency	2030	3%	3%	0%	-11%	103%	-31%	2%	10%	17%
High RES		-7%	-3%	0%	-11%	120%	-37%	2%	14%	21%
Diversified supply		-8%	-3%	-1%	-12%	109%	-26%	2%	15%	24%
Delayed CCS		-6%	12%	-1%	-9%	90%	-21%	2%	13%	20%
Low nuclear		-8%	-1%	-1%	-12%	122%	-50%	6%	22%	21%
Energy efficiency	2040	5%	5%	0%	-16%	81%	-24%	18%	10%	26%
High RES		-7%	1%	-2%	-19%	136%	-48%	7%	17%	30%
Diversified supply		-10%	-2%	-3%	-21%	94%	-26%	35%	11%	39%
Delayed CCS		-6%	11%	-3%	-13%	78%	-13%	11%	19%	24%
Low nuclear		-9%	0%	-2%	-19%	98%	-54%	49%	16%	38%
Energy efficiency	2050	6%	6%	1%	-14%	68%	-22%	28%	15%	26%
High RES		-4%	4%	-1%	-17%	125%	-46%	12%	32%	34%
Diversified supply		-7%	2%	-2%	-17%	77%	-24%	41%	23%	31%
Delayed CCS		-5%	10%	-1%	-13%	69%	-16%	28%	24%	23%
Low nuclear		-6%	2%	-2%	-17%	86%	-47%	55%	19%	33%

Note: This table has been turned around compared to Table 1: Scenarios are listed in the rows, while causal factors are listed in the columns. This is done in view of the time dimension that adds additional information to the table.

Positive values reflect emission reductions, negative values correspond to emission additions. A detailed breakdown on shares of causal factors on gross CO_2 emission reductions in each scenario can be found in the Annex.

Source: Öko-Institut / Wuppertal Institute (2012), results from decomposition analysis.

The commercialisation of CCS technology in the medium term is expected to contribute in several decarbonisation scenarios considerably to CO_2 emission reductions towards the end of the 2020 to 2050 time horizon. For example, the deployment of CCS technology will account for 55 % of emission changes (28 % of gross CO_2 emission reductions) in 2050 according to the Low nuclear scenario. A potential vulnerability to the realisation of these decarbonisation scenarios is the potential reliance on a single technology which is not yet in a commercial state. The assumption that CCS technology will become financially viable in the medium term depends to a large extent upon the level of investment in research and development that is provided to deliver the technological breakthroughs that are necessary. Therefore, decarbonisation scenarios dependent upon CCS technology for emission reductions rely upon the development of an abatement technology that is highly uncertain.

It is evident from Table 3 that the rising electricity demand over time for new appliances such as electric vehicles and heat pumps presents policy makers with even more urgency to successfully decarbonise the power sector by 2050 to prevent electric vehicles from contributing to CO_2 emissions in the future. Given the dependency of these new appliances on a low carbon electricity grid, political action is urgently required now to ensure that these key innovations can be increasingly utilised from 2020 onwards to reduce CO_2 emissions.

6. Conclusion

This paper identifies robust energy system strategies followed within the different Energy Roadmap 2050 scenarios. For these strategies political action is urgently required in order to deliver the 'shared vision' that the European Commission is aiming for with its decarbonisation scenarios. Given that the window of opportunity for political action to prevent the 'lock in' of carbon intensive technologies in the power sector is time-limited, it is essential that political action is taken within the next decade to implement the 'key innovations' for CO_2 emission reductions that were identified in the decomposition analysis and discussed in Section 5. Further political debate will be necessary to decide upon the more controversial elements of decarbonisation (i.e. the deployment of nuclear power and CCS technology in the energy mix) and this policy paper challenges the robustness of decarbonisation scenarios that are highly dependent on assumptions associated with high levels of uncertainty (i.e. commercialisation date of CCS).

The following three robust energy system strategies have been identified by the analysis of the Energy Roadmap 2050 scenarios[37]:

- **Efficiency improvements critical**
  The decomposition analysis has shown that efficiency measures aimed at reducing the growth of electricity demand compared to a reference development are absolutely crucial to achieve the decarbonisation of the power system as envisioned in the policy scenarios. Efficiency improvements not only allow limiting electricity demand growth but also enable significant amounts of electricity to be used in the heating and especially the transport sector, thus "exporting" CO_2 emission reductions to these sectors – given supply side technologies in the power sector are decarbonised in parallel.

- **Renewables are most important supply side mitigation option, while the role of nuclear power will be limited**
  In all of the decarbonisation scenarios technologies using renewable energy sources are by far the most important supply-side mitigation option in the electricity system. The role of nuclear energy on the other hand will decrease in all of the decarbonisation scenarios.

- **Fluctuating electricity sources to capture major share in power generation within the next four decades**
  Of all renewable energy sources wind is by far the most important one for the decarbonisation of the electricity system. Robust growth in wind power is expected already in the near-term as the technology, especially onshore wind, is relatively mature and among the most economically attractive low carbon electricity generation options. By 2050 wind onshore and offshore is responsible for more than 30 % of electricity generation in all of the decarbonisation scenarios and even for around 50 % in the High RES scenario. This also

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[37] These findings are largely in line with the respective findings of a previous analysis of other European energy scenarios conducted within this project (see SEFEP 2012). The main area of disagreement is in regard to nuclear power, as a few (pre-Fukushima) scenarios envision a more important role for this technology than the EU's Energy Roadmap 2050 scenarios

means that a large share of future electricity generation in Europe will be from fluctuating renewable energy sources (especially wind and solar PV). Policymakers should be aware of this and should prepare strategies early on for the electricity system to be able to deal with such a high share of fluctuating electricity supply.

In many of the decarbonisation scenarios **CCS technologies** also play an important role in reducing CO_2 emissions in the power sector. However, the High RES scenario indicates that the role of CCS may be limited when a high deployment of renewable technologies as well as their system integration will be successful. Even in the other scenarios, CCS is not expected to be deployed to any significant extent before 2030. This assumption about the relatively late relevance of CCS reflects current uncertainties about its technological viability and its economics, including infrastructure and CO_2 storage capacity. The high growth rate for CCS plants after 2030 and the assumed falling technology costs critically require both of these core CCS technology challenges to be solved by then, i.e. a significant technological maturity and sufficient public acceptance will be necessary.

Apart from the analysis of scenario results, the work within this project on the Energy Roadmap 2050 and on previous scenario studies has made it clear that the scenario studies themselves could be improved to further add to their relevance for energy policy making. Especially the following two issues should be addressed:

- **Need for greater transparency in scenario results**
  A few key assumptions, for example on specific generation costs and technological attributes (like the efficiencies of the various types of power plants and the capture rate assumed for CCS plants) as well as some key modelling results (like the amount of electricity generated in PV and CSP plants individually or in natural gas CCS and coal CCS plants) have not been made public and their availability would considerably help to analyse and better understand the reasons and implications of the differences in the seven Roadmap scenarios.

- **Sensitivity analyses could help explore effects of different technology price assumptions on electricity mix**
  It would prove useful if sensitivity analyses regarding crucial parameters were systematically applied to decarbonisation scenarios (for example capital cost assumptions). Such analyses would enable the exploration of capital cost corridors in which one or the other technology becomes economically viable.

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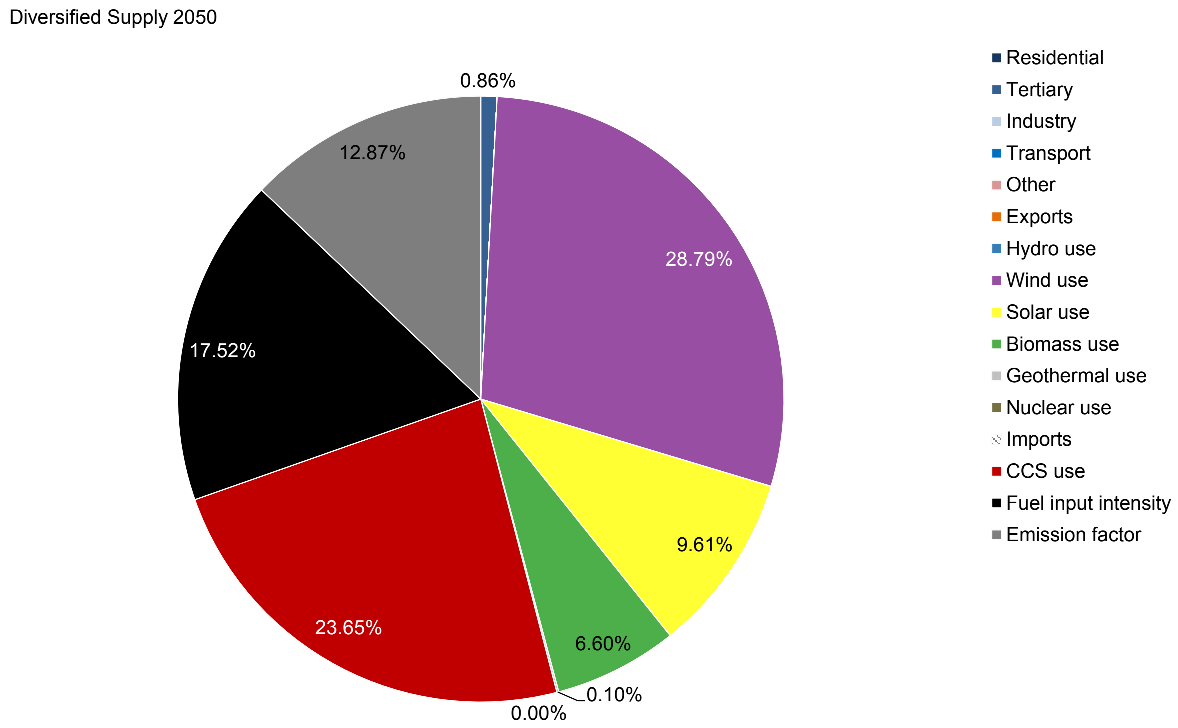
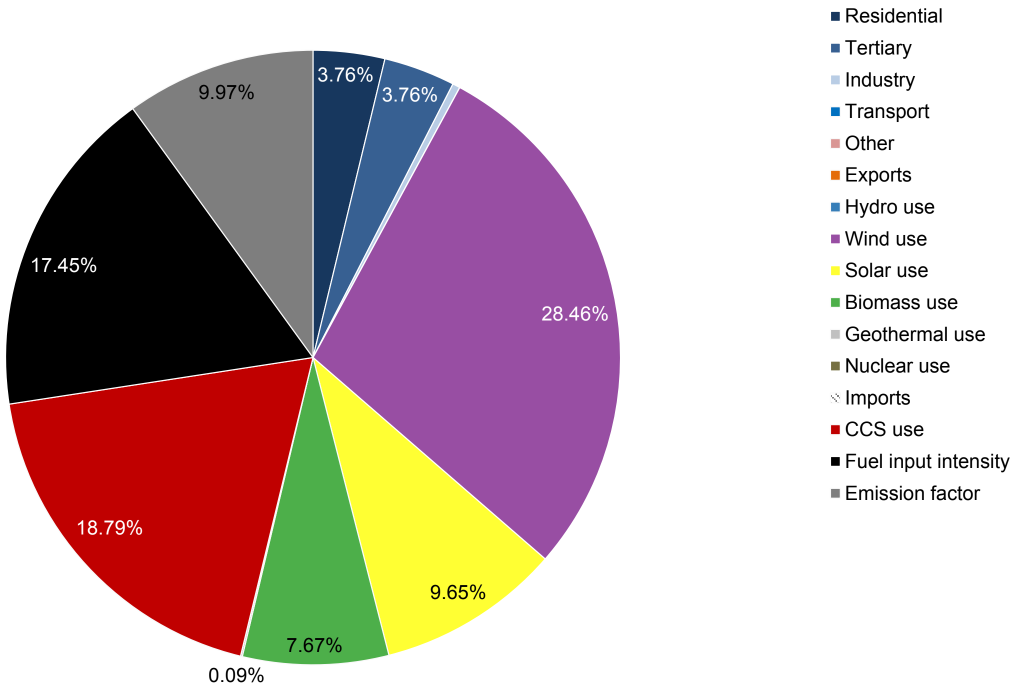
8. Annex

8.1 Shares of causal factors on gross CO_2 emission reductions in each scenario

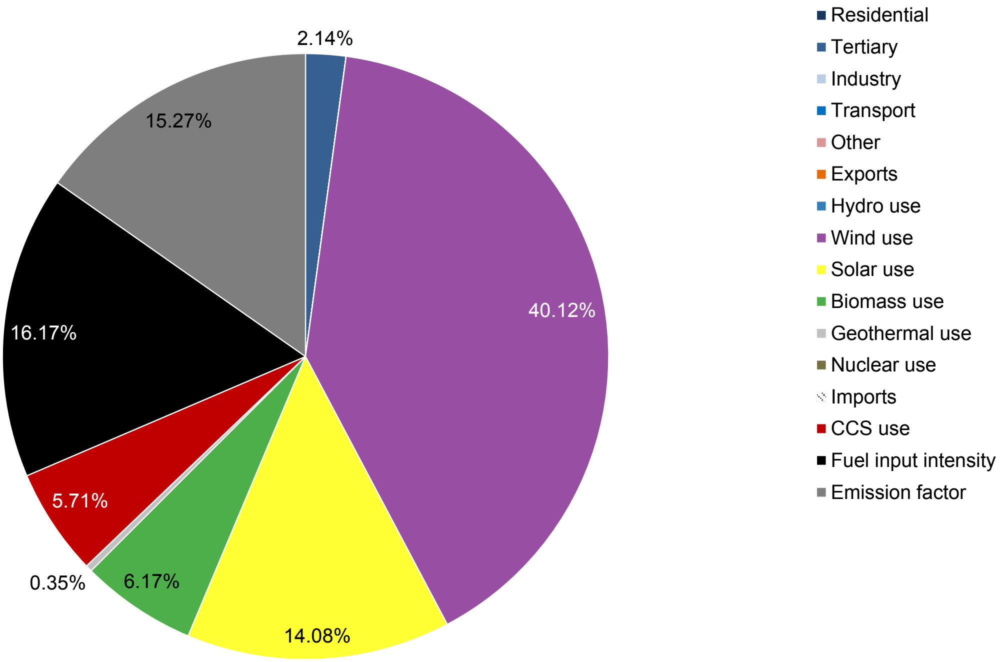
Figure 10 Shares of causal factors on gross CO_2 emission reduction in each scenario in 2050.

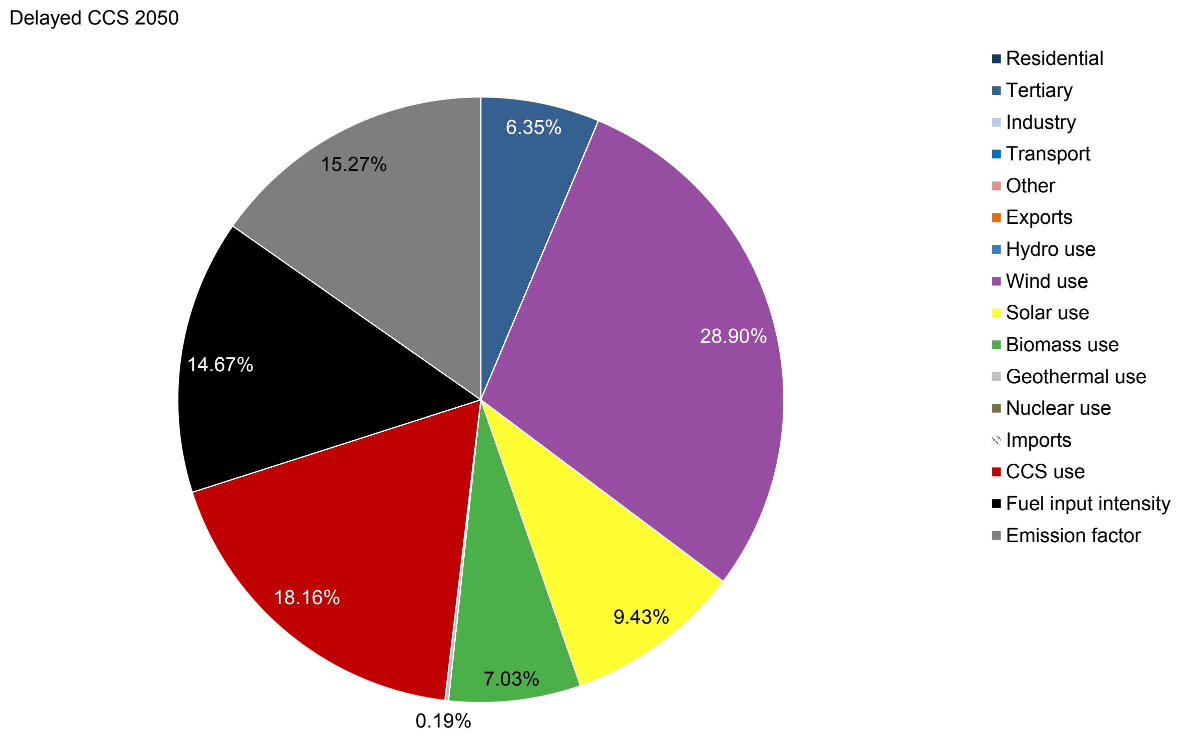


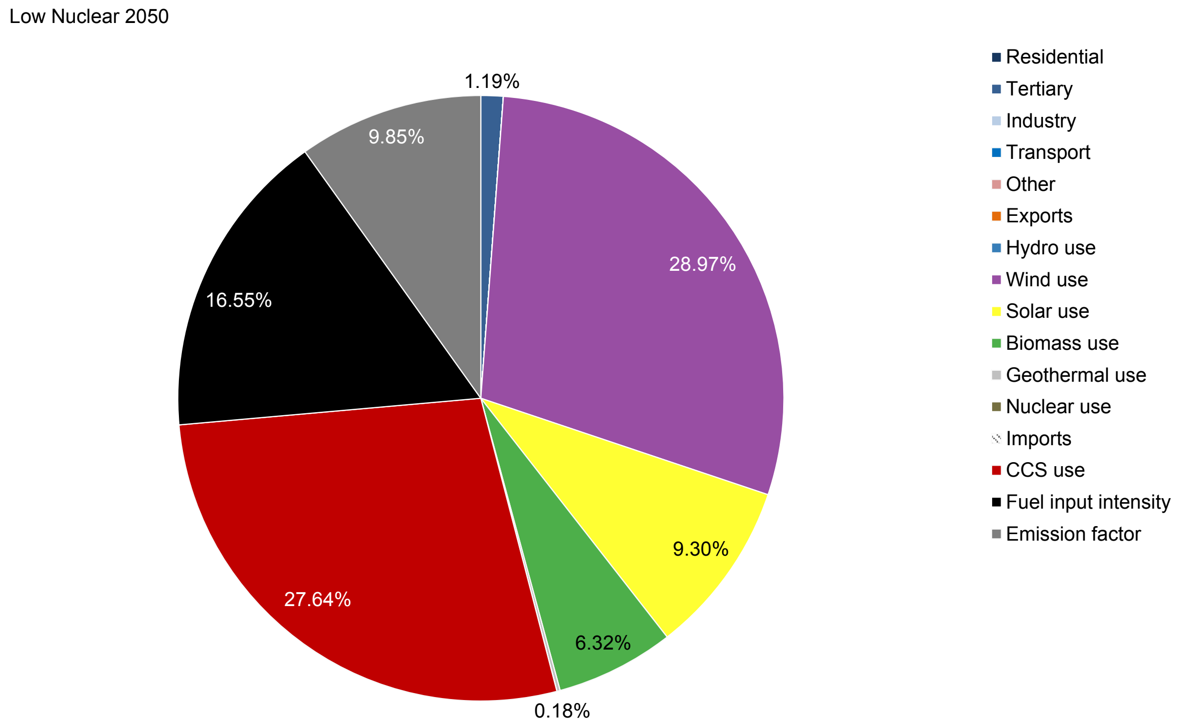
Energy Efficiency 2050



High RES 2050







Source: Öko-Institut / Wuppertal Institute (2010), results of decomposition analysis.

Climate Policies in the EU

In December 2008, the European Union (EU) adopted a comprehensive energy and climate package to further enhance the international reputation of the EU as a leader on climate policy. The objective of the energy and climate package is to reduce greenhouse gases (GHGs) by at least 20 % by 2020 relative to 1990 emission levels, increase the share of renewable energy in meeting the EU's final energy demand to 20 % and to reduce energy consumption by 20 % compared to projected trends.

An essential policy instrument to achieve these climate policy objectives is the Emissions Trading System (ETS), which was introduced in 2005 (Directive 2003/87/EC) and regulates over 11 000 installations that are responsible for almost half of the GHG emissions emitted in the EU. The ETS is based upon the principle of cap and trade, which can be briefly summarized as follows:

- A cap or limit on the total amount of particular GHG emissions that can be emitted is set for all factories, power plants or other installations participating in the EU ETS;
- Emission Unit Allowances (EUAs), which are equivalent to the emissions limit set under the cap, are distributed to the installations participating in the ETS;
- Installations are then required to surrender at the end of each year one EUA for each tonne of GHG which they have emitted;
- The ability to trade allowances enables installations that do not have enough allowances to cover their emission level for a compliance period by purchasing allowances on the market. In contrast, installations with a surplus of allowances can sell these on the market.
- These transactions creates a price per tonne of GHG that provides the financial incentive for installations to either reduce their level of emissions to sell their allowance surplus on the market or to buy allowances if this is more cost effective than reducing their own emissions.

The third trading phase of the EU ETS will commence in 2013 with the introduction of an EU wide cap on emissions, which will reduce at an annual rate of 1.74 % to ensure that the EU achieves a -21 % reduction in the ETS sector relative to 2005 emission levels (Directive 2009/29/EC). Emissions from sectors not covered by the ETS (i.e. buildings, transport and agriculture) are subject to the Effort Sharing Decision (406/2009/EC), which obliges the Member States to ensure that collectively non-ETS emissions are reduced by -10 % below 2005 levels by 2020. If the policies are fully implemented in both directives, it is envisaged that the EU objective of an economy wide reduction of -20 % below 1990 emission levels will be achieved by 2020.

National binding targets have been set for each Member State to ensure that the average renewable share across the EU reaches 20 % by 2020 (Directive 2009/28/EC). Given that the starting point, the renewable energy potential and the energy mix varies for each Member State, the EU target of 20 % was translated to individual targets that ranged from a renewables share of 10 % in Malta to 49 % in Sweden. If these national binding targets are achieved then the EU objective of increasing the share of renewable energy in meeting the EU's final energy demand to 20 % will also be achieved by 2020. To ensure that the energy efficiency objective is also achieved by 2020 the European Commission recently proposed new legislation (COM (2011) 370 Final) to obligate Member States to establish energy saving schemes.

8.2 Suggested standard for data reporting

Common roster of data and information

Metadata on the studies and modelling exercises

General information about study
Study title
Date published (month/year)
Source (URL, if available on internet)
Developed by
Institute(s)
Lead author(s)
Commissioning body/bodies
Context in which study was commissioned/prepared
Consideration of entire energy system (yes/no, only electricity)
Countries included in analysis (EU-27 or different scope?)

Scenarios
Reference scenario (yes/no)
Number of alternative scenarios
Scenario analysed here
Base year

Modelling approach
General modelling approach (if applicable)
Modelling approach for electricty sector
Important (external) model drivers

	base year	2010	2015	2020	2025	2030	2035	2040	2045	2050
Key socioeconomic assumptions										
Population (in million)										
Population (index, base year = 100)										
real GDP (in billion €$_{2008}$)										
real GDP (index, base year = 100)										

	base year	2010	2015	2020	2025	2030	2035	2040	2045	2050
Key targets, restrictions and assumptions										
Key targets (e.g. CO$_2$ emission reduction target)										
Key restrictions										
Construction of new nuclear power plants										
Construction of CCS power plants										
Assumptions about renewable energy potential										
Biomass share in whole energy system										
Biomass potential available to EU										
Assumptions about CCS storage capacity										

Electricity consumption

	base year	2010	2015	2020	2025	2030	2035	2040	2045	2050
Total electricity consumption (in TWh) EU-27										
Electricity consumption per country (in TWh) area under study										

	base year	2010	2015	2020	2025	2030	2035	2040	2045	2050
Electricity consumption per sector (in TWh)										
Residential										
Tertiary										
Industry										
Transport										

	base year	2010	2015	2020	2025	2030	2035	2040	2045	2050
Share of electricity consumption per sector										
Residential										
Tertiary										
Industry										
Transport										

	base year	2010	2015	2020	2025	2030	2035	2040	2045	2050
Electricity consumption from traditional appliances (in TWh)										
Residential										
Tertiary										
Industry										
Transport										
Electricity consumption from "new" appliances (in TWh)										
Road transport										
Heat market										
Electricity input for storage (in TWh)										
Pumped storage										
Compressed air storage										
Hydrogen production										
Battery storage										
Other types of storage										

	base year	2010	2015	2020	2025	2030	2035	2040	2045	2050
Electricity consumption from power generation (in TWh)										
Consumption for conversion										
Line losses										

Electricity supply data (in TWh)

	base year	2010	2015	2020	2025	2030	2035	2040	2045	2050
Net electricity generation per source (in TWh)										
Nuclear										

Fossil (CO2 emitting) energy sources										
Hard coal										
of which CCS										
Lignite										
of which CCS										
Natural gas										
of which CCS										
Oil										
Waste (non-biogenic)										
Renewable energy sources										
Hydro										
Wind										
of which onshore										
of which offshore										
Biomass										
of which from biogas										
of which from solid (including biogenic waste)										
Solar										
of which PV										
of which solar thermal										
Geothermal										
Ocean energy and other renewables										
Hydrogen (storage output)										
Synthetic natural gas (storage output)										
Output from other storage technology										

	base year	**2010**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Gross electricity generation per source (in TWh)										
Nuclear										
Fossil (CO2 emitting) energy sources										
Hard coal										
of which CCS										
Lignite										
of which CCS										
Natural gas										
of which CCS										
Oil										
Waste (non-biogenic)										
Renewable energy sources										
Hydro										
Wind										
of which onshore										
of which offshore										
Biomass										
of which from biogas										
of which from solid (including biogenic waste)										
Solar										
of which PV										
of which solar thermal										
Geothermal										
Ocean energy and other renewables										
Hydrogen (storage output)										
Synthetic natural gas (storage output)										
Output from other storage technology										
Power plants' own consumption of electricity										

	base year	**2010**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Net electricity generation from storage plants (in TWh)										

	base year	**2010**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Primary energy use for electricity generation by source (in PJ)										
Uranium										
Fossil fuel sources										
Hard coal										
Lignite										
Natural gas										
Oil										
Waste (non-biogenic)										
Renewable energy sources										
Biomass (including biogenic waste)										
Hydro										
Solar										
Wind										
Geothermal										
Ocean energy and other renewables										

Hydrogen

	base year	**2010**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Net electricity generation per country (in TWh)										
Austria										
Belgium										
Bulgaria										
Cyprus										
Czech Republic										
Denmark										
Estonia										
Finland										
France										
Germany										
Greece										
Hungary										
Ireland										
Italy										
Latvia										

Lithuania										
Luxemburg										
Malta										
Netherlands										
Poland										
Portugal										
Romania										
Slovakia										
Slovenia										
Spain										
Sweden										
United Kingdom										

	base year	2010	2015	2020	2025	2030	2035	2040	2045	2050
Export and import of electricity from outside Europe										
Export of electricity (in TWh)										
of which from renewable sources										
Import of electricity (in TWh)										
of which from renewable sources										
Net import of electricity (in TWh)										
of which from renewable sources										
Share of net imports in electricity consumption (in %)										

	base year	2010	2015	2020	2025	2030	2035	2040	2045	2050
Electricity generation from CHP and from decentralized sources										
Electricity generation from CHP (in TWh)										
of which small-scale CHP										
Share of CHP generation in electricity consumption (in %)										

Infrastructure data

	base year	2010	2015	2020	2025	2030	2035	2040	2045	2050
Power plant capacity (in GW)										
Nuclear										
Fossil energy sources										
Hard coal										
of which CCS										
Lignite										
of which CCS										
Natural gas										
of which CCS										
Oil										
Waste (non-biogenic)										
Renewable energy sources										
Hydro										
Wind										
of which onshore										
of which offshore										
Biomass										
of which biogas										
of which solid (including biogenic waste)										
Solar										
of which PV										
of which solar thermal										
Geothermal										
Ocean energy and other renewables										

	base year	2010	2015	2020	2025	2030	2035	2040	2045	2050
Storage capacity (in GW)										
Pumped storage plant										
Compressed air storage plant										
Hydrogen production plant										
Battery storage										
Other types of storage										

Information about power transmission network(s) ____________________

Information about power distribution network(s) ____________________

Information about system services (smart grids, DSM, etc.) ____________________

Assumptions and results of technologies' cost modelling

Description of cost modelling approach ____________________

Assumed learning curve (in % per doubling of capacity)	base year	2010	2015	2020	2025	2030	2035	2040	2045	2050
Nuclear										
Hard coal - without CCS										
Hard coal - with CCS										
Lignite - without CCS										
Lignite - with CCS										
Natural gas - without CCS										
Natural gas - with CCS										
Renewable technologies										
Hydro - general										
Hydro - small scale										
Hydro - large scale										
Wind - general										
Wind - onshore										
Wind - offshore										
Biomass - general										
Biomass - biogas										

Biomass - solid										
Solar PV										
Solar Thermal - general										
Solar Thermal - without storage										
Solar Thermal - with storage										
Geothermal										
Ocean energy										
Tidal energy										
Wave energy										
Hydrogen										

	base year	**2010**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Power plants' investment costs ($€_{2008}$ per kW)										
Nuclear										
Hard coal - without CCS										
Hard coal - with CCS										
Lignite - without CCS										
Lignite - with CCS										
Natural gas - without CCS										
Natural gas - with CCS										
Renewable technologies										
Hydro - general										
Hydro - small scale										
Hydro - large scale										
Wind - general										
Wind - onshore										
Wind - offshore										
Biomass - general										
Biomass - biogas										
Biomass - solid										
Solar PV										
Solar Thermal - general										
Solar Thermal - without storage										
Solar Thermal - with storage										
Geothermal										
Ocean energy										
Tidal energy										
Wave energy										
Hydrogen										

	base year	**2010**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Specific electricity generation costs (in €-$cent_{2008}$/kWh)										
Nuclear										
Hard coal - without CCS										
Hard coal - with CCS										
Lignite - without CCS										
Lignite - with CCS										
Natural gas - without CCS										
Natural gas - with CCS										
Renewable technologies										
Hydro - general										
Hydro - small scale										
Hydro - large scale										
Wind - general										
Wind - onshore										
Wind - offshore										
Biomass - general										
Biomass - biogas										
Biomass - solid										
Solar PV										
Solar Thermal - general										
Solar Thermal - without storage										
Solar Thermal - with storage										
Geothermal										
Ocean energy										
Tidal energy										
Wave energy										
Hydrogen										

	base year	**2010**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Assumed conversion efficiency of new plants (in %)										
Nuclear										
Hard coal - without CCS										
Hard coal - with CCS										
Lignite - without CCS										
Lignite - with CCS										
Natural gas - without CCS										
Natural gas - with CCS										
(Relevant) renewable technologies										
Biomass - biogas										
Biomass - solid										
Solar PV										
Hydrogen										

	base year	**2010**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Assumed average conversion efficiency of plants in stock (in %)										
Nuclear										
Hard coal - without CCS										
Hard coal - with CCS										
Lignite - without CCS										
Lignite - with CCS										
Natural gas - without CCS										
Natural gas - with CCS										
(Relevant) renewable technologies										

Biomass - biogas										
Biomass - solid										
Solar PV										
Hydrogen										

	base year	**2010**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Average full load hours of plants in stock (in hours/a)										
Nuclear										
Hard coal - without CCS										
Hard coal - with CCS										
Lignite - without CCS										
Lignite - with CCS										
Natural gas - without CCS										
Natural gas - with CCS										
Renewable technologies										
Hydro - general										
Hydro - small scale										
Hydro - large scale										
Wind - general										
Wind - onshore										
Wind - offshore										
Biomass - general										
Biomass - biogas										
Biomass - solid										
Solar PV										
Solar Thermal - general										
Solar Thermal - without storage										
Solar Thermal - with storage										
Geothermal										
Ocean energy										
Tidal energy										
Wave energy										
Hydrogen										

	base year	**2010**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
World market prices for energy sources (in €$_{2008}$/GJ)										
Oil										
Natural gas										
Hard coal										
Uranium										

	base year	**2010**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
CO2 price in (European) ETS (in €$_{2008}$/tCO2)										

Other key information

Interrelationship between electricity and other energy sectors ____________________

Policy measures assumed or deemed necessary ____________________

Reflections on uncertainties and robustness of results ____________________

	base year	**2010**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Electricity sector CO_2 emissions										
Total (in Mt of CO_2)										
Index (base year = 100)										

Index (1990 = 100)

	base year	**2010**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Electricity sector CO_2 sequestration (in Mt of CO_2)										
Annual sequestration										
Cumulative sequestration										

Power Sector Decarbonisation: Metastudy

WP 4
Promising future meta-research on decarbonisation studies

Berlin, Wuppertal 29.2.2012

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Content

List of Tables

1 Introduction

The EU's Roadmap for moving to a competitive low carbon economy in 2050 (European Commission 2011a) is based upon economic modeling and scenario analysis, which considers how the EU can become a low carbon economy assuming continued global population growth, increasing global GDP and by varying trends in terms of international climate action, energy and technological development. This roadmap recommends that the EU should reduce GHG emissions by 80 % below 1990 levels by 2050 and that this target is technically feasible and financially viable using proven technologies if strong incentives (i.e. carbon pricing) exist.

As a separate document the Commission has recently published the Energy Roadmap 2050 (European Commission 2011b), which builds upon the previous modelling work by analysing in more detail several post-2020 scenarios that aim to decarbonise the energy sector of the EU. Although these post-2020 scenarios represent a 'shared vision' on the level of emission reductions by 2050, the abatement options implemented in these post-2020 scenarios vary considerably, influencing both the timing and cost effectiveness of climate policy action.

The SEFEP funded project entitled *Power Sector Decarbonisation: Metastudy* aims at analysing and comparing various relevant decarbonisation scenarios. These decarbonsiation scenarios include pre Energy Roadmap 2050 scenarios (Greenpeace International & European Renewable Energy Council 2010; eurelectric 2009; European Climate Foundation 2010), decarbonisation studies on Member State level (WWF 2010; Statistics Sweden 2011; SRU 2011) and the scenarios from the Energy Roadmap 2050 itself (European Commission 2011b).

While all of these scenarios provide insights into the design of the energy sector in the future (e.g. evolution of electricity demand and supply) they do not assess quantitatively the role that each of the causal factors (e.g. exploitation of wind energy, electrification of road transport) plays in delivering emission reductions (or additions). The additional value of the project is the completion of a decomposition analysis to determine emission reductions (or increases) by causal factors in the power sector and in parallel to investigate crucial assumptions that underlie modeling exercises and how these assumptions may influence the results.

One of the aims of the project is to inform policy makers on the timing of political action ('windows of opportunity') necessary to realise these decarbonisation scenarios. Furthermore, the project aims to identify 'robust corridors' whereby the majority of the scenarios share a similar vision for the European power sector (e.g. high share of renewables) in terms of the factors leading to emission reductions. Two policy papers have been prepared in order to provide this information on the European level and it has been found that the shared vision includes the following robust energy system strategies:

- Efficiency improvements are critical.
  The decomposition analysis has shown that efficiency measures aimed at reducing the growth of electricity demand compared to a reference development are absolutely

crucial to achieve the decarbonisation of the power system as envisioned in the decarbonisation scenarios.

- Renewables are most important supply side mitigation option, while the role of nuclear power will be limited.
  In all of the decarbonisation scenarios technologies using renewable energy sources are by far the most important supply-side mitigation option in the electricity system. The role of nuclear energy on the other hand will decrease in nearly all of the decarbonisation scenarios.

- Fluctuating electricity sources to capture major share in power generation within the next four decades.
  Of all renewable energy sources wind is by far the most important one for the decarbonisation of the electricity system. Robust growth in wind power is expected already in the near-term as the technology, especially onshore wind, is relatively mature and among the most economically attractive low carbon electricity generation options. In many of the decarbonisation scenarios analysed solar energy, another fluctuating energy source, will also play a significant role in electricity generation towards the middle of the century.

Further the study has found that there is a **need for greater transparency in the documentation of scenario assumptions and results.** Throughout the studies several key assumptions have not been made publicly available while their availability would considerably help further utilization of the scenarios and help to better understand the reasons and implications of the differences between decarbonisation scenarios.

Similar results have been found on Member State level and are summarized in Work Package 2.2

This current paper intends to summarize the lessons learnt while undertaking the analyses described above and provides insights into promising future meta-research in this area. This paper is structured as follows: Chapter 2 provides information on lessons learnt. Chapter 3 identifies those variables that are the most sensitive ones to the power system in view of future decarbonisation. Chapter 4 provides information on additional dimensions with potential to support ambitious decarbonisation strategies while Chapter 5 concludes this paper. The Appendix provides some food for thought and discussion on potential initiatives to improve meta-studies.

2 Lessons learnt about decomposition methodology and preparation of scenario studies

2.1 Lessons learnt with respect to the decomposition analysis

This section focuses on the experiences gained while developing and applying the decomposition analysis that has been documented in Work Package 1.2.

The decomposition analysis has been applied to the analysis of 22 scenarios in the course of this project. These scenarios are summarized in Table 1, which lists for each study considered the scenarios that have been analysed. These scenarios correspond to those scenarios that provided a sufficient amount of data to the decomposition analysis.

Table 1 Overview over the scenarios that were analysed using the decomposition methodology documented in WP 1.2

EU wide studies					Member State studies	
Capros, et. al (2010)	ECF (2010)	Eurelectric (2009)	Greenpeace (2010)	EC (2011)	SRU (2011)	WWF (2010)
Reference 2009	Baseline	Power Choices	Reference	Reference	2.1a	Reference
Baseline 2009	40 % RES	Power Choices	Energy revolution	CPI	2.1b	CCS
	60 % RES		revolution	Energy efficiency		Innovation
	80 % RES			High RES		
				Delayed CCS		
				Low nuclear		
				technologies		

Note: The studies' titles are listed in the footnote[1]

2.1.1 Lesson 1: Data availability is key

To apply the decomposition analysis, a specific set of data needs to be available. This set is listed in Table 2. Data market with ++ are necessary to complete the decomposition analysis. Data marked + are ideally available, and the more data of this type is available the more detailed the decomposition analysis. Within the project an effort has been made to retrieve data by contacting authors and applying gap-filling approaches if deemed sensible. In several cases, as demonstrated by Table 1, data availability was not sufficient to allow for gap-filling, and in turn, these scenarios were not decomposed. In view of the different modeling approaches adopted in the different studies, gap-filling procedures had to be tailor-made in order to account for the information available from the given study. As no one-size-

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[1] Capros, P. et al., 2010. EU energy trends to 2030. Update 2009, Brussels.
Eurelectric. 2009. Power Choices. Pathways to carbon-neutral electricity in Europe by 2050. Brussels.
European Climate Foundation. 2010. Roadmap 2050 - A practical guide to a prosperous, low-carbon Europe. Technical analysis.
European Commission. 2011. Energy Roadmap 2050. Impact Assessment. Part 2/2. SEC(2011) 1565. .
Greenpeace International, European Renewable Energy Council, 2010. energy revolution - a sustainable world energy outlook.
WWF, 2009. Blueprint Germany. A strategy for a climate safe 2050. Berlin, Basel

fits-all gap-filling procedure could be employed, gap-filling proved a time-critical factor on the analysis, thus data availability is key to a successful and complete analysis.

Table 2 Data required for the decomposition analysis.

Total electricity consumption (TWh)	
Traditional appliances	++
Residential	+
Tertiary	+
Industry	+
Transport	+
New appliances	+
Transport	+
Heat market	+
Power input from storage	+
Pumped storage	+
Compressed air storage	+
Hydrogen production	+
Battery storage	+
Other types of storage	+
Other consumption (lines losses etc)	+
Net electricity exchange	
Imports	+
Exports	+

++ = mandatory
+ = ideally included

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

Source: Öko-Institut / Wuppertal Institute (2012)

2.1.2 Lesson 2: Decomposition analysis results require careful explanation to highlight their value added

All studies considered in the course of this project deal with future projections on how either the European economy or the economy of EU Member States (or in some cases only their power sector) can be decarbonized. All of them provide descriptions of how the future power sector may be characterised on the demand and supply side. The supply side is always described by the technologies used to generate electricity and their share in electricity production. Such information is already valuable in itself.

These shares allow for quantifying the total emissions produced at a given point in time, e.g. in 2050. They do, however, not allow for the quantification of the contribution of a specific factor (e.g. utilization of wind power) to emission reductions that have been achieved compared to a starting year (emissions in the base year minus emissions in the observed year).

The decomposition analysis allows for such a computation and enables the calculation of emission reductions by causal factors that may exhibit very different technical characteristics. What they have in common however is that their use or non-use triggers emissions and the decomposition analysis provides a metric to quantify these emissions.

Providing these emission reduction quantifications in turn can help to gain a feeling on the magnitudes involved and the timing needed, considering a system that is characterized by considerable lead-times and uncertainties (e.g. in regard to CCS deployment).

It has proven as a challenge within this project to communicate the difference between the quantification of emission reductions and the quantification of shares in electricity production. In the future it may prove useful to develop a set of definitions and figures that provide a clear distinction between the two approaches (charaterisation of a future power sector vs. quantification of emission reductions by causal factor of future power sector).

2.1.3 Lesson 3: Mixed effects could be accounted for in an advanced way

Application of the decomposition analysis has shown that the methodology chosen is sufficiently applicable to the given scenarios. The residuals seem sufficiently small and the Laspeyres method has been extended to distribute the residuals proportionally to the causal factors (see WP 1.2. for documentation).

The residuals that occur when applying a Laspeyres decomposition analysis describe the existence of mixed effects that cannot be explained by this type of analysis itself. A mixed effect could for example be the parallel development of increasing electricity demand in the transport sector through growing electrification (which would trigger additional emissions viewed alone), and a parallel decarbonisation of electricity supply (which could offset the additional emissions through growing transport electrification).

Currently, the residual that occurs because the mixed effects cannot be accounted for is distributed proportionally to all causal factors considered in the analysis.

Future research on extending the decomposition analysis to detect types of mixed effects and to extend the analysis to include these as additional causal factors could help to refine the understanding of the power sector and the interdependencies of causal factors in view of their contribution to emission reductions.

2.1.4 Lesson 4: Energy efficiency improvements could be taken into account more explicitly

Currently the decomposition analysis takes energy efficiency implicitly into account, namely on the demand side. However, changes in final energy demand are currently used as a proxy for efficiency improvements, even though changes in final energy demand actually reflect not only changes in energy efficiency but also changes in the level of energy services (e.g. more or less household appliances in use). Introducing a causal factor that explicitly describes energy efficiency would help to refine the decomposition analysis and would enable to explicitly highlight the role that energy efficiency improvements play in decarbonizing the power sector. However, for this approach the scenario studies analysed would need to provide detailed information on changes in the level of energy services.[2]

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[2] Indicators for service levels in the respective sectors could be (on a relatively aggregated level): “person kilometres” and “ton kilometres” in the transport sector, “industrial value added” in the industrial and commercial sectors and “disposable income” in the household sector.

2.2 Lessons learnt with respect to future scenario studies

The energy system insights gained through the analysis and comparison of various European energy scenarios within this project are an indication of the general usefulness of such energy scenarios. For example, the energy scenarios analysed strongly indicate that the EU's long-term mitigation targets can only be reached if significant energy efficiency improvements are realised and renewable energy technologies are deployed rapidly. Such findings can help policymakers grasp and evaluate the need and urgency of energy policy measures. Such approaches can also guide them to see necessary direction the energy system would need to take in view of the information provided by the scenarios.

However, the analysis of available EU and Member State energy scenario studies within this project has also shown that in regard to advancing energy policy decisions, none of the studies take advantage of the *full* potential that approach of scenario development offers. Therefore some general areas for improvement in energy models and their application are suggested in this section.

2.2.1 Lesson 1: Lack of data transparency provides a barrier to in-depth analysis

The documentation standard across the scenario studies considered in the course of the metastudy varied. Several studies provided a very well documented set of data throughout tables and appendices, e.g. (Greenpeace International & European Renewable Energy Council 2010; WWF 2009; European Commission 2011b), others did not report data in a very detailed manner or data was documented throughout text, in several figures and smaller tables, for example (Gode et al. 2010; European Climate Foundation 2010).

The documentation standard applied to each of the study naturally focuses on the scope of the study itself. However, considering the broader context within which the studies are embedded – a current and European-wide discussion on strategies towards decarbonisation – it would provide value added to take a further step in documentation and provide access to all data required to accomplish a given study. Such "open-source" availability of data would enable the further utilization of data for decarbonisation analyses beyond the original scope of a study.

For example the set of data reported in (European Commission 2011c) and kindly provided by DG Energy is very detailed and contains much information that is often not documented. A few key assumptions, for example on specific generation costs and technological attributes (like the efficiencies of the various types of power plants and the capture rate assumed for CCS plants) as well as some key modeling results (like the amount of electricity generated in PV and CSP plants individually or in natural gas CCS and coal CCS plants) have not been made public and their availability would considerably help to analyse and better understand the reasons and implications of the differences in the seven Roadmap scenarios.

If the transparency of decarbonisation scenario studies regarding data reporting increased and conformed to a European-wide standard this would add value for further utilisation of the data by the European Commission and others. A blank data roster sheet is provided in the annex, which suggests how data and accompanying assumptions could be reported in a standardised way.

Provision of more data as well as detailed explanations about the method/model(s) used would increase the usefulness of scenario studies for policymaking by enabling a better understanding of the respective scenarios and the reasons for various pathways that differ across scenarios.

2.2.2 Lesson 2: Conducting more sensitivity analysis would highlight relevance of key uncertainties

Many of the scenario studies analysed develop more than one scenario or describe scenario variants to highlight key uncertainties regarding, inter alia, the availability or level of social acceptance of certain low carbon technologies (for example the “Low nuclear” scenario in the EU’s Energy Roadmap 2050 or the “CCS Delay” scenario variant in the Eurelectric study). These additional scenarios provide valuable information about the magnitude of changes that can be expected if some key (but highly uncertain) assumption were to turn out differently than expected in another scenario. Such analysis helps policymakers understand the relative importance of certain mitigation options and can show which other technologies one may have to rely on to a greater extent in the future if a certain mitigation technology will not be available or shall not be used.

However, noticeably absent as a subject of such sensitivity analysis in the scenario studies analysed are technology cost developments. This is striking because the evolution of future technology costs is known to be highly uncertain[3] and the relative costs of various mitigation technologies are in most energy models a key determinant in deciding about technology deployment.[4] In general a combination of high uncertainty and high relevance indicates a useful area for sensitivity analysis. Such analysis that uses a range of technology costs would tell policymakers how sensitive the deployment of certain technologies is in regard to the cost assumptions. Among other uses, such sensitivity analysis could tell policymakers by how much the costs of certain mitigation technologies (e.g. CCS or PV) would have to decrease in the future to enable those technologies to obtain a significant share in the electricity generation mix. This is of special importance to policymakers as policy measures like RD&D support and (niche-) market deployment can induce cost reductions and can thus help achieve a competitive cost level.

2.2.3 **Lesson 3: Increasing sectorial detail and capturing interdependencies between sectors crucial to fully reflect energy system dynamics**

This project as well as some of the scenario studies analysed within the project focus on the electricity sector. This can be justified by pointing to the high relevance of this sector in any decarbonised future energy system. However, as all scenario studies show, over time there will be an increasing interdependency between the electricity sector on the one hand and the heat and transport sectors on the other hand. Looking at all sectors within one coherent

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[3] The comparison of cost assumptions in the various scenario studies has shown the high level of uncertainty or disagreement between energy experts about the future development of energy technology costs.

[4] This is especially true in decarbonisation pathways, in which capital costs (especially for renewable energy technologies, but also for nuclear energy and CCS) become relatively more important than fuel costs compared to today’s energy system.

model that captures these interdependencies would thus provide significant additional insights. Even those scenario studies that include the heating and transport sectors do this in a much more aggregated way compared to the electricity sector (e.g. the EU's Energy Roadmap 2050), although both transport and heating may well be the more challenging sectors to decarbonise. A stronger focus on those two sectors as well as on their interdependencies with the electricity sector would therefore be beneficial. Models would be needed that are able to capture the main interdependencies.[5]

2.2.4 Lesson 4: Providing "transition knowledge" helps policymakers to implement the required changes

All scenario studies provide numerical results in 10-year or even 5-year steps and all studies also highlight (usually in separate chapters) key policy measures regarded to be essential in reaching the mitigation pathways they describe. However, the development of the energy system and the policy measures proposed are largely discussed separately. This indicates that today's modelling tools are limited in their ability to "translate" specific policy changes into resulting changes in the energy system.[6] As knowledge about the specific effects of policy measures on the energy system is of great interest to policymakers, efforts to expand models in this regard are important. This could also lead to policy roadmaps, which describe specific policy measures needed over the course of time.

Furthermore, apart from policymakers other actors are only briefly addressed in the scenario studies analysed. However, the significant changes to the energy system required within the next four decades will not be achieved without the support of many societal groups like industry associations, unions, consumers and NGOs. Each of these groups may be supportive or dismissive of changes to the energy system. A stronger focus on society and its dynamics, its groups and their respective interests could help to highlight possible barriers and synergies to system changes. Based on this information policymakers could better address measures to overcome the barriers identified and to exploit the potential synergies.

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[5] For example both sectors could contribute to solving the problems associated with a growing supply of electricity generation from fluctuating sources. Car batteries could potentially be used as storage devices within the electricity system at times when cars are not used and heat pumps could preferably be generating heat in times of high generation from wind and solar power plants, while reducing operation during times when electricity generation from these sources are low (and overall demand high).

[6] Measures directly aiming at economic parameters like changes in energy taxes or the implementation of emission trading are exceptions, as such measures and their likely effects can usually be portrayed in energy models.

3 Scenario analysis insights: Most sensitive variables for the electricity sector

The current project analysed 22 decarbonisation scenarios in detail (see Table 1) using a two-step approach:

1. A general comparison of main features of the scenarios was accomplished which included variables such as CO_2 emission development over time, cost assumptions, development of sectoral electricity demand and the electricity mix until 2050.

2. Separately, a decomposition analysis focused on 22 scenarios and quantified emission reductions/additions by several important causal factors. These causal factors include the demand and the supply side of electricity and thus also features analysed within the first comparison. The decomposition did not include costs as causal factors.

During the analytical process the importance of a few variables to which the electricity sector is sensitive could be detected:

- Scope and location of energy efficiency improvements
  Significant efficiency improvements are vital in order to limit CO_2 emission increases through the increase in electricity consumption resulting from economic growth and electrification of various energy services (especially transportation) to an appropriate level. However, while there is agreement within the scenario studies that faster improvements in energy efficiency are essential to limit future growth in electricity demand, there is no consensus in which sectors such improvements can be reached best and most economically. Enhancements of the decomposition method would be needed to separately account for changes in efficiency (see Section 2.1.4).

- Level of growth of electricity demand in the transport sector
  There is a shared understanding that electricity demand will increase in the transport sector which will be pivotal in helping the transport sector reduce its CO_2 emissions. In all of the scenarios electricity will play a much larger role in transportation by 2050, while the share of electricity used in public transportation (which mostly uses electricity already today) is also expected to increase in most scenarios. The power sector is highly sensitive to this variable as in order for electric mobility to deliver CO_2 emission reductions in all aspects, not only does transport need to be electrified, but the electricity generation mix needs to change at the same time. Otherwise CO_2 emissions reduced by avoiding emissions from fuel combustion in cars would re-enter the system via the electricity supply mix.

- Pace and extent of the increase of the share of renewables in electricity generation, considering costs and system integration issues
  The majority of scenarios analysed assume that the aggregate of renewable energy technologies combined will be the most important mitigation option in electricity supply. The scenarios also agree that of all renewable sources, wind (onshore and offshore) will be the single most important one. While no technological breakthroughs are required to realise these visions, continued innovation and cost reductions are essential for some of the renewable technologies, especially for solar PV, offshore wind, solar thermal and (important in some scenarios) geothermal energy. Thus, renewable energy sources are a variable that the power sector reacts sensitive to, as its use/non-use would significantly contribute to the characteristics of the power sector and its emissions. Further, their use/non-use depends highly on capital cost assumptions (see next bullet point).

- Technology cost assumptions
  Most of the modeling exercises behind scenario critically depend on the assumptions made about several cost factors, such as fuel cost and capital cost. While fuel cost are an important factor to scenarios that rely on the use of fossil fuels, the importance of fuel costs decline in scenarios that are designed to utilise a high share of renewable energies. As the majority of scenarios analysed rely on a high share of renewable energy sources in the future power sector, capital cost play an increasing role, as a system characterized by a high share of renewable energy sources is more capital intensive than today’s system dominated by fossil fuels. Thus capital cost assumptions play a crucial role in determining the results for the power sector. Results of decarbonisation scenarios are likely to be very sensitive to changes in capital cost assumptions. The sensitivity can only be explored by the modeling teams themselves and by systematically applying sensitivity analyses to decarbonisation.

4 Additional dimensions with potential to support ambitious decarbonisation strategies

The scenario analysis within this project and more specifically the decomposition approach employed has focused on the CO_2 emissions of the electricity sector. The rationale behind this focus is the high awareness within the European Union about the considerable risks associated with climate change. Contributing to the internationally agreed long-term target of limiting the global temperature increase to 2 °C over pre-industrial levels requires significant greenhouse gas emission reductions within the EU. Climate change is also high on the policy agenda in many of the larger Member States like Germany, the UK and France. Therefore all energy scenario studies analysed likewise also focus on the need to considerably reduce CO_2 emissions in the energy or electricity sector until the middle of the century.

However, it is worth noting that there are other reasons to considerably change the structure of the electricity system within the next decades. These following reasons could be cited:

- Concerns about energy supply security
- Vulnerability to energy price increases or fluctuations
- Concerns about air quality
- Lack of social acceptance for some technologies used widely today

These issues are addressed to a varying degree in the scenario studies analysed within this project.

Concerns about energy supply security

Most scenario studies at least briefly point to their mitigation scenarios' "co-benefit" of considerably reducing the EU's import dependency. The EU's Energy Roadmap as well as the Power Choices scenario by Eurelectric both provide figures on how the EU's energy import dependency changes over time. As Table 3 shows import dependency would fall from 54% in 2009 to between 35 and 46% until 2050 in the mitigation scenarios of these two studies, while dependency in the reference scenarios would increase compared to today to reach about 60% in 2050.[7]

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[7] Figures in the table apply to the overall energy system. The studies provide no separate import dependency data for the electricity system.

Table 3 Level of import dependency of the EU's energy system in various scenarios in 2050

Scenario study	Scenario	Import dependency 2050
Power Choices (Eurelectric 2009)	Reference	60%
	Power Choices	46%
Energy Roadmap 2050 (EC 2011)	Reference	58%
	CPI	58%
	Energy Efficiency	40%
	Diversified	40%
	High RES	35%
	Delayed CCS	39%
	Low Nuclear	45%

Sources: (eurelectric 2009; European Commission 2011c)

Vulnerability to energy price increases and fluctuations

None of the studies analysed put considerable emphasis on the lower vulnerability to energy price increases and fluctuations that go along with lower fossil fuel use in the climate protection scenarios. However, the ECF's Roadmap 2050 study casually mentions its mitigation scenarios' “[s]ubstantial benefits [that] can be expected in terms of the resilience of the economy to volatility in fossil fuel prices.” Vulnerability to energy price increases and fluctuations will be higher in those scenarios that continue to rely on coal and especially on natural gas in the electricity system using CCS technology. Scenario studies should emphasise that fossil fuel price developments will in reality likely look much different than the rather smoothly changing fossil energy prices assumed within the scenarios.

Concerns about air quality

Interestingly, air quality improvements, another potentially important benefit of some mitigation strategies are also hardly mentioned in the scenario studies analysed. Various studies[8] have shown the considerable human health and material damages caused by burning fossil fuels. Scenario studies could try to quantify the cost savings of air quality improvements resulting from substituting fossil fuels by renewable energy sources, nuclear energy or energy efficiency improvements. The extent of air quality “co-benefits” depends on the type of low carbon technologies used. Notably, natural gas and especially coal or lignite CCS power plants do not lead to improvements in local air pollution levels.[9]

Lack of social acceptance for some technologies used widely today

Mitigation scenarios relying to a large extent on renewable energy technologies have the potential to avoid the problems of social and specifically local resistance to new conventional power plants, especially coal, lignite and nuclear power plants. At the same time renewable plants, especially onshore wind plants and the supporting grid infrastructure may also suffer from a lack of local acceptance.

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[8] See for example (Holland et al. 2005; Bollen et al. 2009; Nemet et al. 2010)

[9] To the contrary, the lower conversion efficiencies of CCS plants would lead to higher air pollution compared to a non-CCS plant of the same type.

Scenarios relying on CCS technology could lead to additional problems, as social acceptance of CCS power plants (including CCS infrastructure and storage sites) is highly uncertain. The scenario studies analysed make different assumptions about the level of social acceptance for CCS. The Greenpeace/EREC study assumes that CCS is not used while some other scenario studies like Eurelectric's Power Choices study do not specifically mention any problems with CCS concerning public acceptance. A stronger focus on societal groups or stakeholder within energy modelling, as mentioned in previously could help scenario developers become more aware of potential challenges for realizing mitigation scenarios for which social acceptance in some countries might be lacking.

5 Conclusions

The extensive analysis performed on a number of European and EU Member State energy scenarios within this project has lead to several insights with relevance for both policymakers and researchers.

Policymakers may utilise the project results to obtain a better understanding of the similarities and differences pathways envisioned by various stakeholders and the European Commission regarding a future low carbon power sector. A number of similarities have been highlighted which indicate – at least from today's point of view – robust elements of a future decarbonisation pathway of Europe's electricity system:

- Considerable demand-side efficiency improvements critical
- Renewables are most important supply side mitigation option
- Fluctuating electricity sources, especially onshore and offshore wind power will capture a major share in power generation within the next four decades

These developments will not materialize in a business-as-usual approach to the extent required for ambitious CO_2 emission reductions, so there is an urgent need for additional policy measures on the European as well as on the Member State level. As the transition towards a decarbonised electricity system will have to be realized within four decades, there is considerable urgency for policy action in a system characterized by long lead times (e.g. in regard to the infrastructure/grid).

At the same time policymakers should be aware of the uncertainties about the future power system pathway, which become apparent through the application of the decomposition analysis. The main elements of uncertainty identified are the following:

- Where (i.e. in which sectors) can electricity demand be reduced to what extent?
- How much electricity will be used in the transport sector in the coming decades?
- What will be the future role of nuclear power and CCS technology, which both depend on the level of public acceptance and (especially in the case of CCS) on cost?

At the same time the project has provided specific suggestions for researchers in the field of energy modelling and energy system analysis. The extensive use of the decomposition approach has lead to insights on how the decomposition methodology can be further advanced and better utilised in the future. Furthermore, the comparison of scenarios and scenario studies has lead to a number of conclusions on how these studies could be improved in the future to better suit the needs of both policymakers and researchers:

- Need for greater transparency in documenting methods, assumptions and results
- Sensitivity analyses should be performed to help explore effects of key uncertainties like technology cost assumptions
- Increasing sectorial detail and capturing interdependencies between sectors in order to fully reflect the dynamics within the energy system
- A stronger focus should be on the transition *process*, i.e. how the power system will evolve from its initial state to its target state and which role various stakeholders will play in this process.

Finally the work within the project has also shown that recent energy scenarios studies have very much focused on the challenge of mitigating climate change. While this focus is certainly understandable, some other potential benefits of a transition towards a sustainable energy system could be stressed more clearly in the future. These “co-benefits” of climate mitigation pathways include reducing concerns about energy supply security and (sudden) energy prices increases and improving air quality.

The scenario method is a very helpful tool for policymakers, especially in times of high uncertainty about future energy system developments. In the future attempts should be made to take advantage of the full toolbox that this method has to offer.

The Appendix provides some food for thought with respect to potential future initiatives for meta-study research based on what has been stated within this paper and what has been found out while conducting this project.

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7 Appendix: Future initiatives to improve meta-studies?

Naturally, meta-studies are studies based on results of studies that have already been accomplished. Given the great impact that transparency of documentation has on the further utilization of results from scenario studies (not only for researchers, but also for the policymakers), the definition of a European-wide minimum standard of model and scenario documentation would provide several advantages to future meta-studies and use of results.

Several initiatives may be useful to pave the road towards such a minimum standard and into the further understanding of modeling exercise. They shall be listed here shortly to provide food for thought and discussion.

The definition of a topology of meta-research (i.e. definition of various meta research tiers and methods for each tier) would enable the definition of several sets of standard documentations, the level of detail of each depending on the type of meta-research question. The more specific the research question the richer the set of data required. This would enable the definition of tiers for documentation, tier one providing the minimal set of documentation necessary to accomplish the least detailed analysis defined in the topology, while the most detailed tier would allow, in principle, for a complete re-calculation of modeling results (given the meta-researches have the tools at hand), and thus provide a first step towards open-source modeling.

Consultations with modellers on documentation requirements could help to explore the domain of discourse and provide useful information towards the generation of a topology of meta-research.

Open source modeling and documentation would arise as a consequence from the previous two activities.

Definition of types of sensitivity analyses on crucial assumptions in decarbonisation scenarios in future modeling exercises. It would prove useful if sensitivity analyses regarding crucial parameters were systematically applied to decarbonisation scenarios (for example capital cost assumptions). Capital cost sensitivity analyses would, for example, enable the exploration of capital cost corridors in which one or the other technology becomes economically viable. The definition of several key parameters to use for sensitivity analyses could be used as guidance for further modeling work.