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Power Sector Decarbonisation: Metastudy

WP 2.3

Existing decarbonisation studies on specific EU Member States

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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

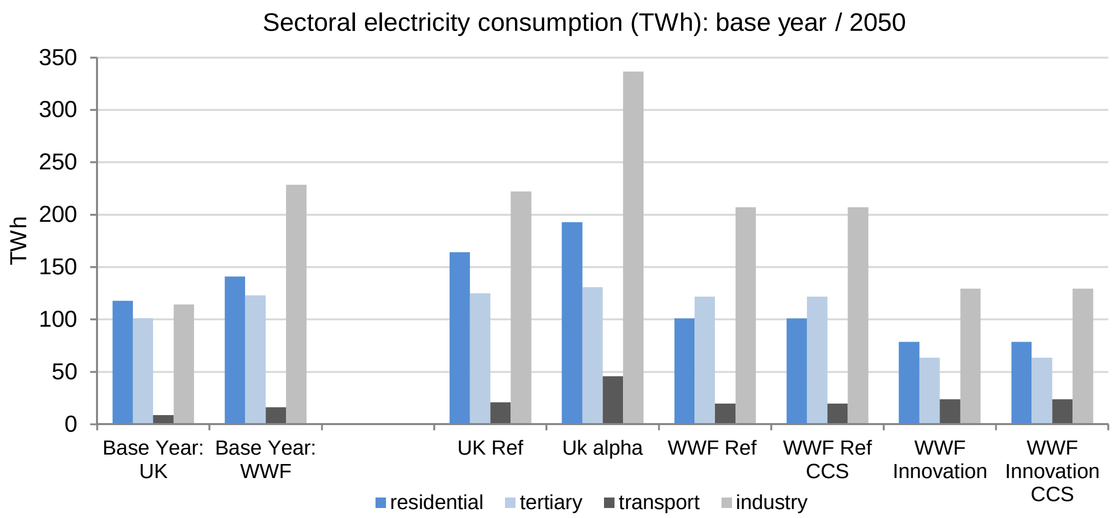
- two scenarios from the 2050 Pathways Analysis
  - o Reference
  - o Pathway Alpha

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.

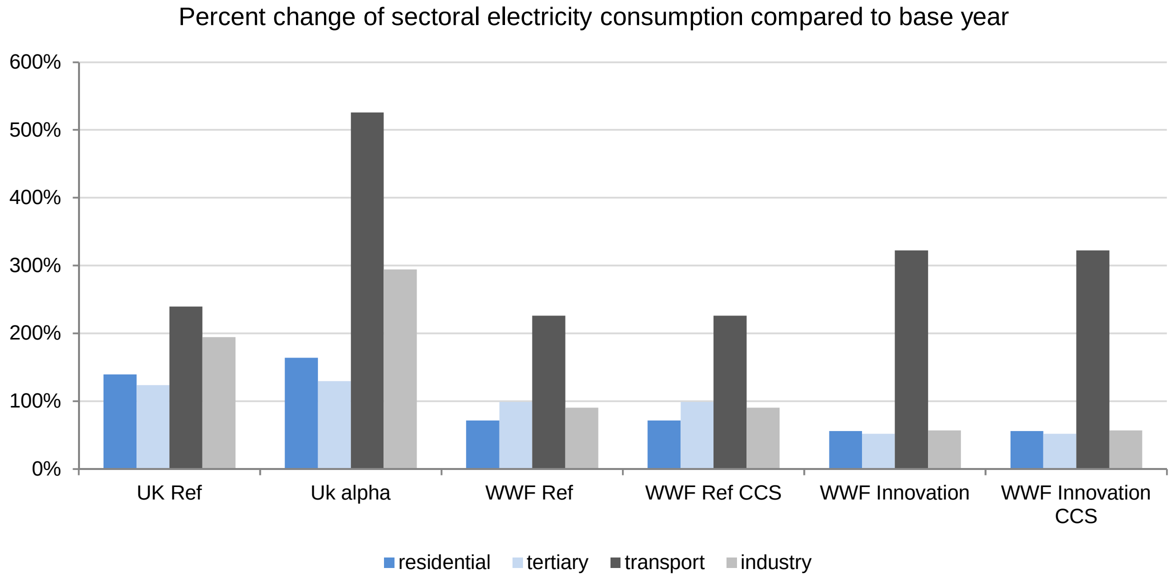
Figure 1 Electricity demand in the base year and in 2050



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

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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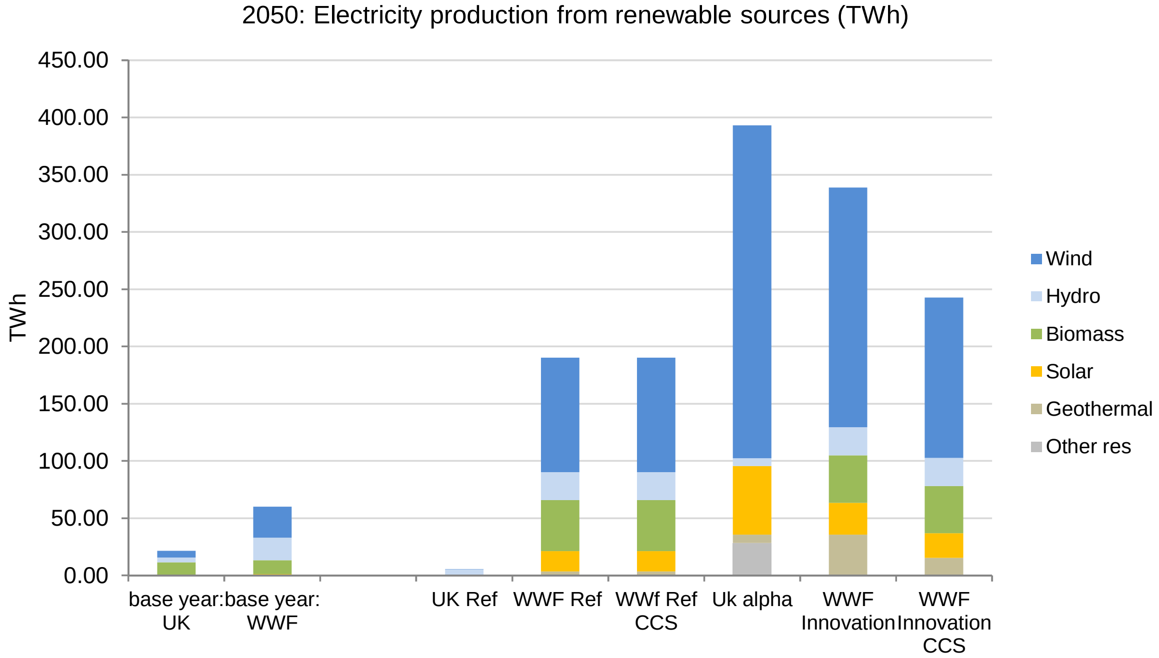
[6] (WWF, 2009a), p. 206
[7] (DECC, 2010), p. 63

Figure 3 Electricity Generation by source in base year and 2050



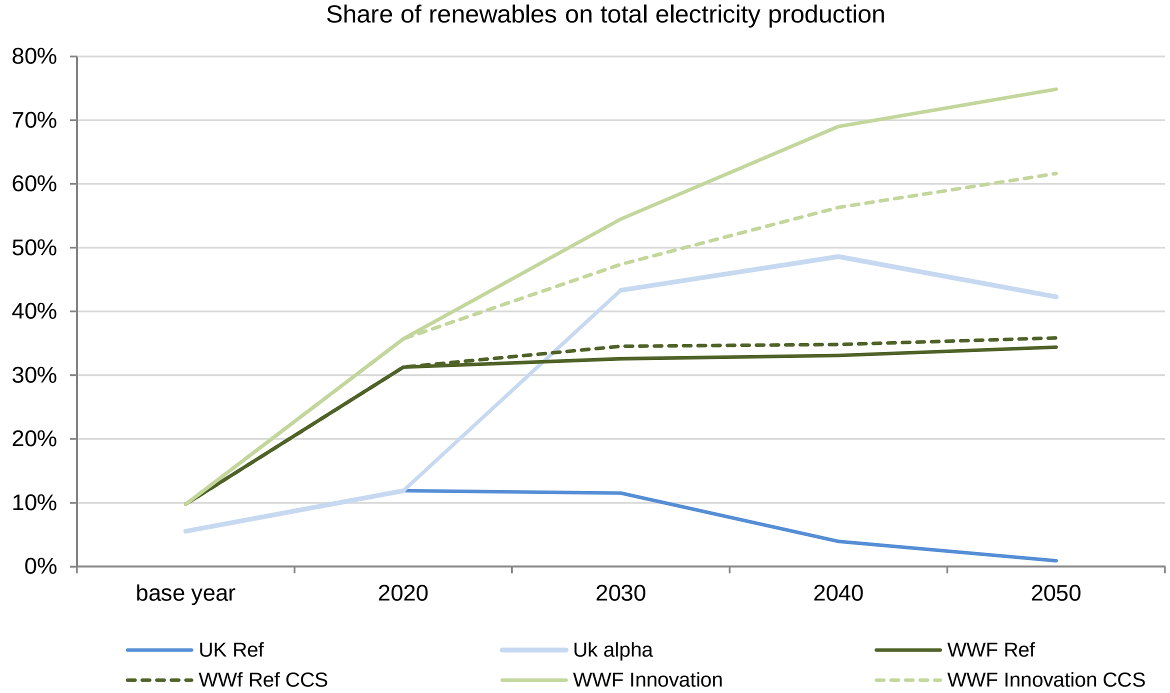
Source: compiled from (WWF, 2009a), (DECC, 2010, 2011)

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

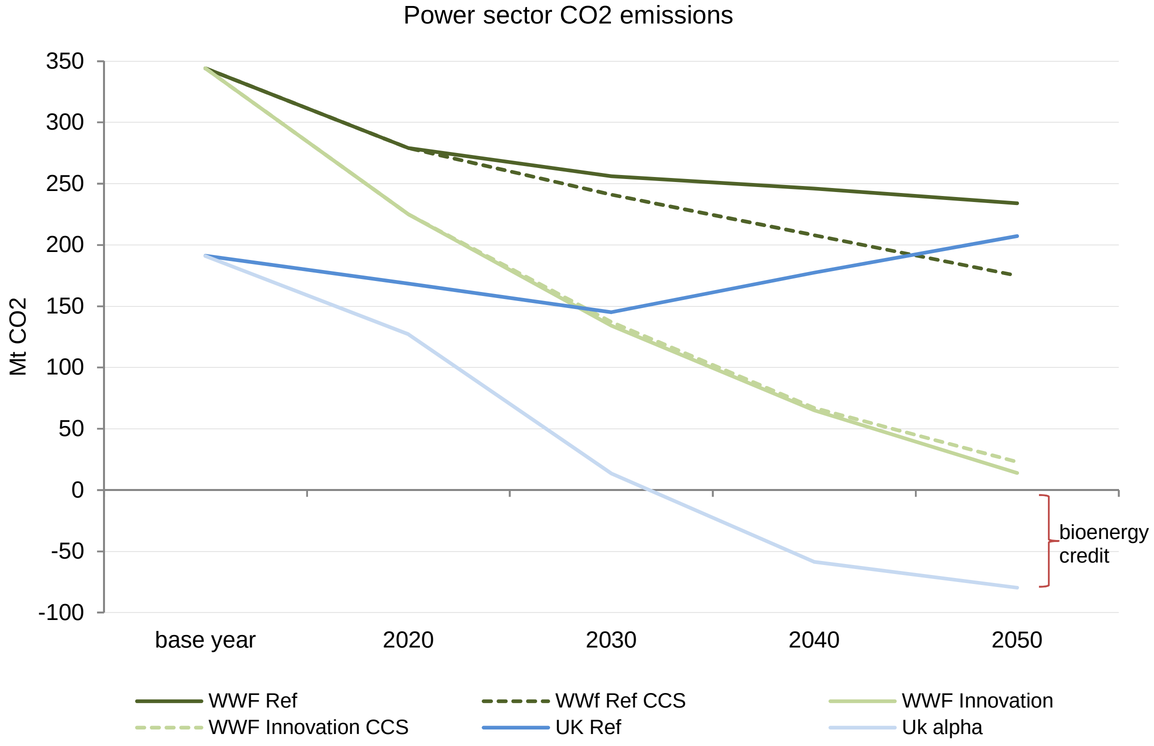


Source: compiled from (WWF, 2009a) and (DECC, 2010) and (DECC, 2011).

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.

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 (%)

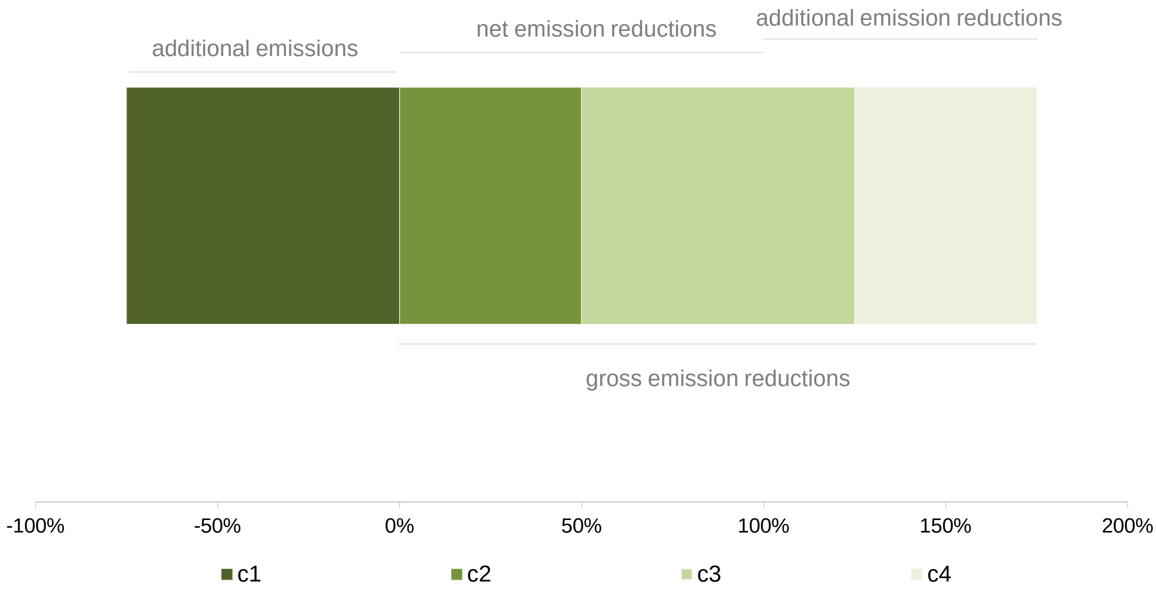
causal factor	Mt	%
c1	75	-75%
c2	-50	50%
c3	-75	75%
c4	-50	50%

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.

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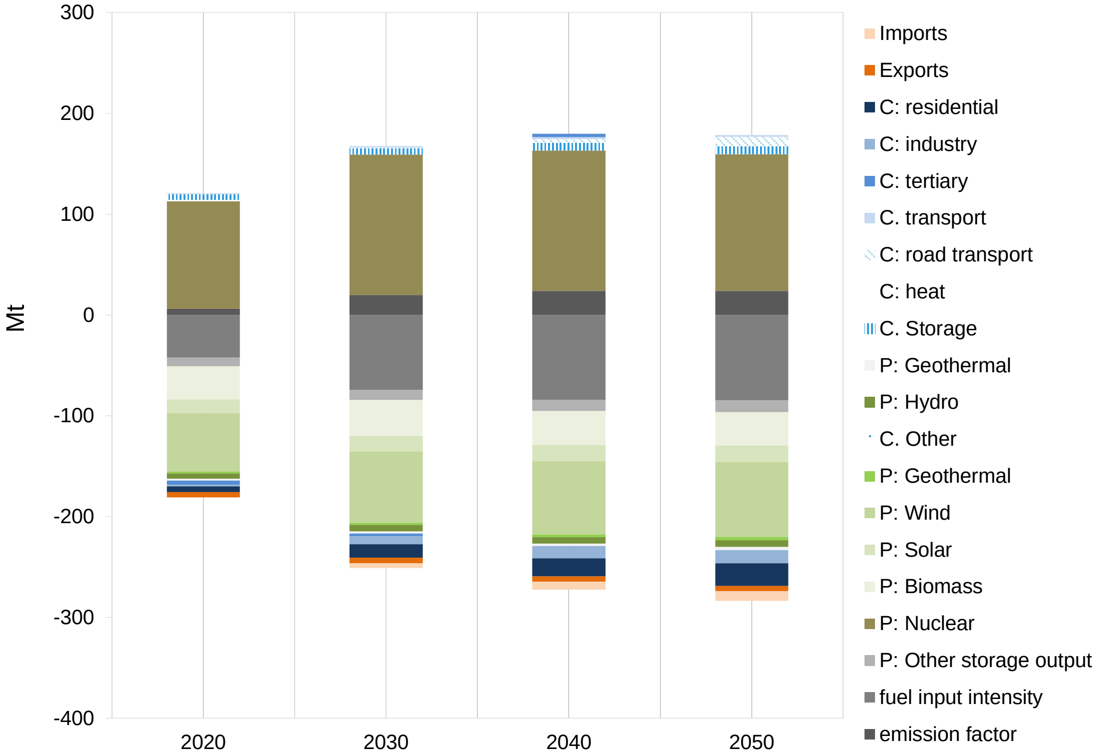
[11] As mentioned in WP 1.2., exports are accounted for on the demand side under the following assumption: exports relate to electricity **consumed** by consumers abroad, while imports are accounted for on the production side as they reflect electricity **produced** abroad.

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.

[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.

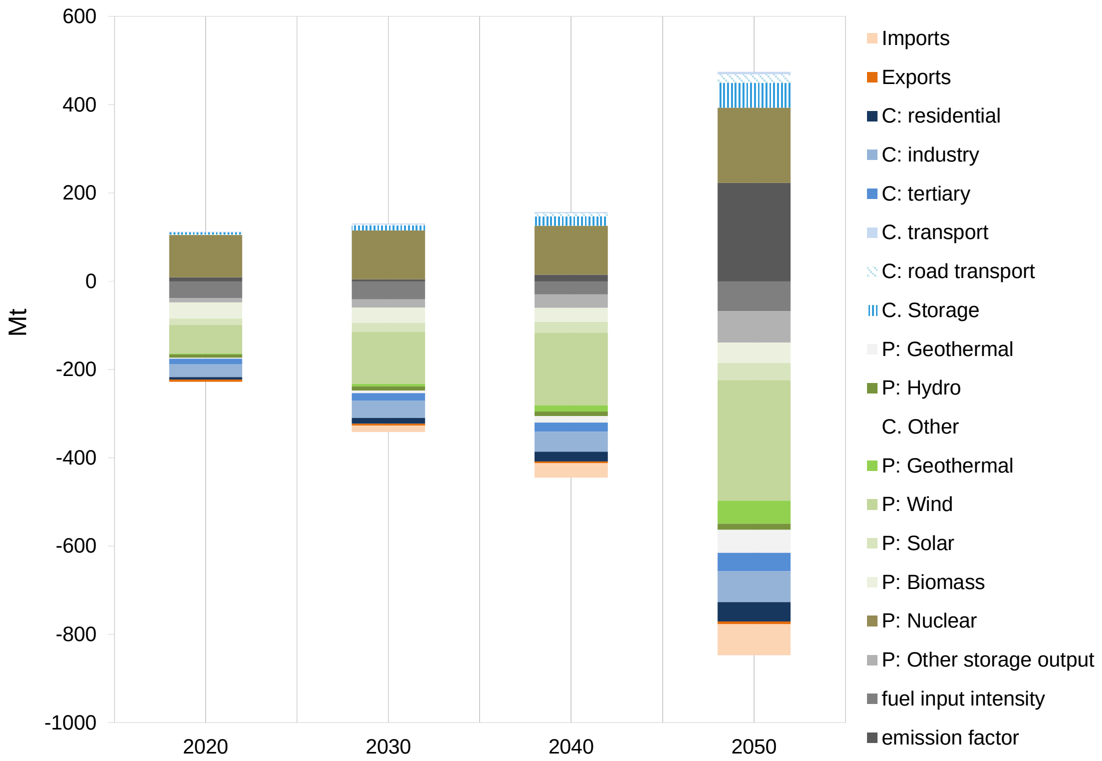
With regards to the production of electricity, it is evident that the increasing share of renewables in electricity production contributes considerably to emission reductions. Figure 8 shows that emission reduction contribution from renewables increases in absolute terms from 125 Mt in 2010 to 424 Mt 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.

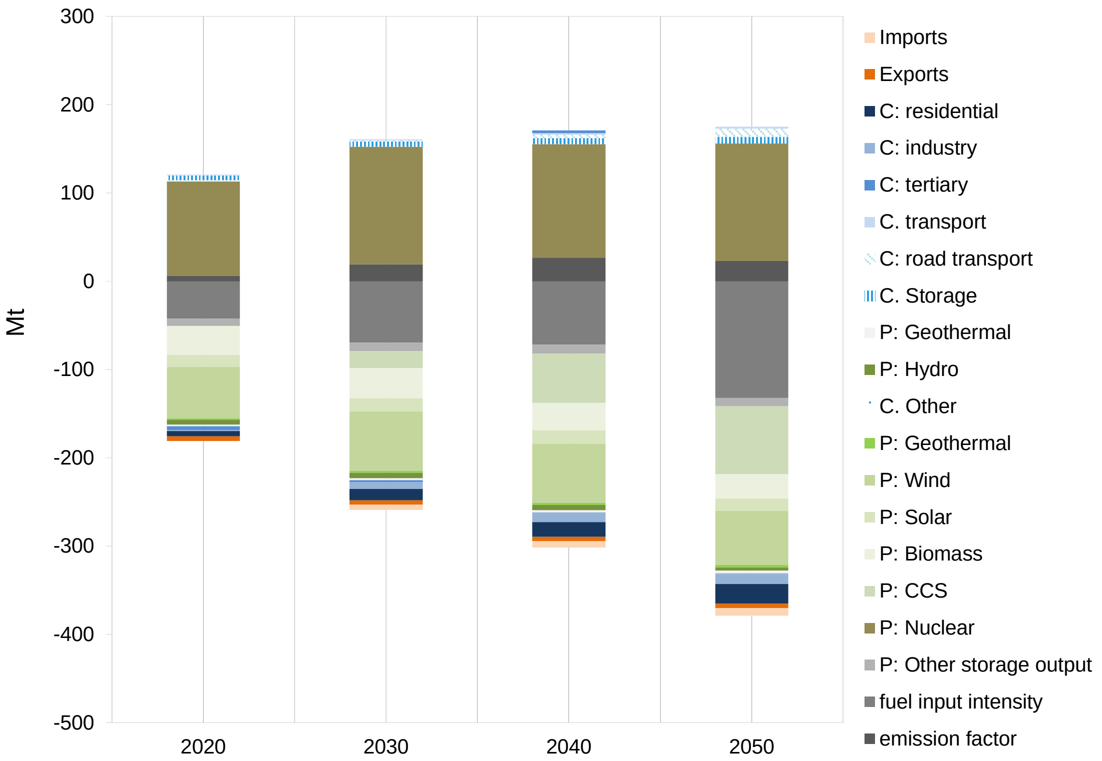
Interestingly the production of electricity by renewable energies contributes steadily to emission reductions (111 Mt in 2010, 109 Mt in 2050). This represents a clear difference from the reference scenario without CCS and demonstrates the effect that the inclusion of CCS technology in the energy mix 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

[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

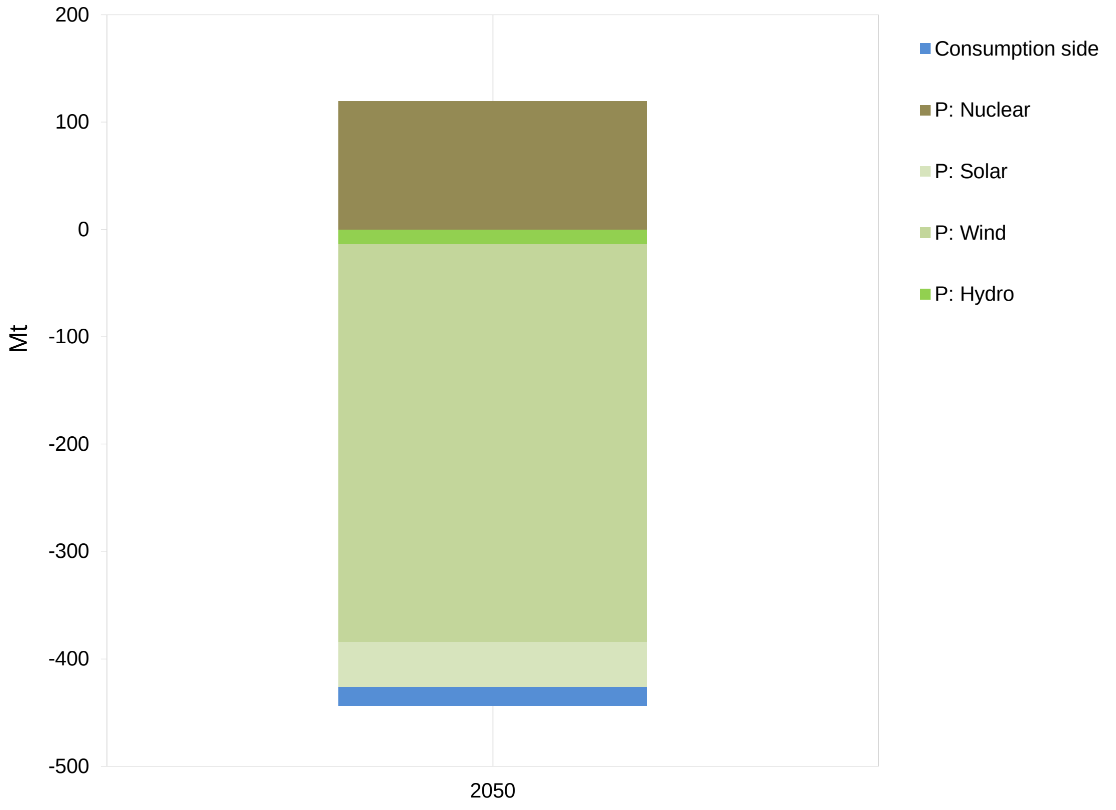
Causal factor	2050
Consumption side	5%
C: Consumption	6%
C. Other	-0.28%
Production Side	95%
P: Renewables	131%
P: Hydro	4%
P:Wind	114%
P: Solar	13%
P: Nuclear	-37%
relative emission reduction compared to base year	100%

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:

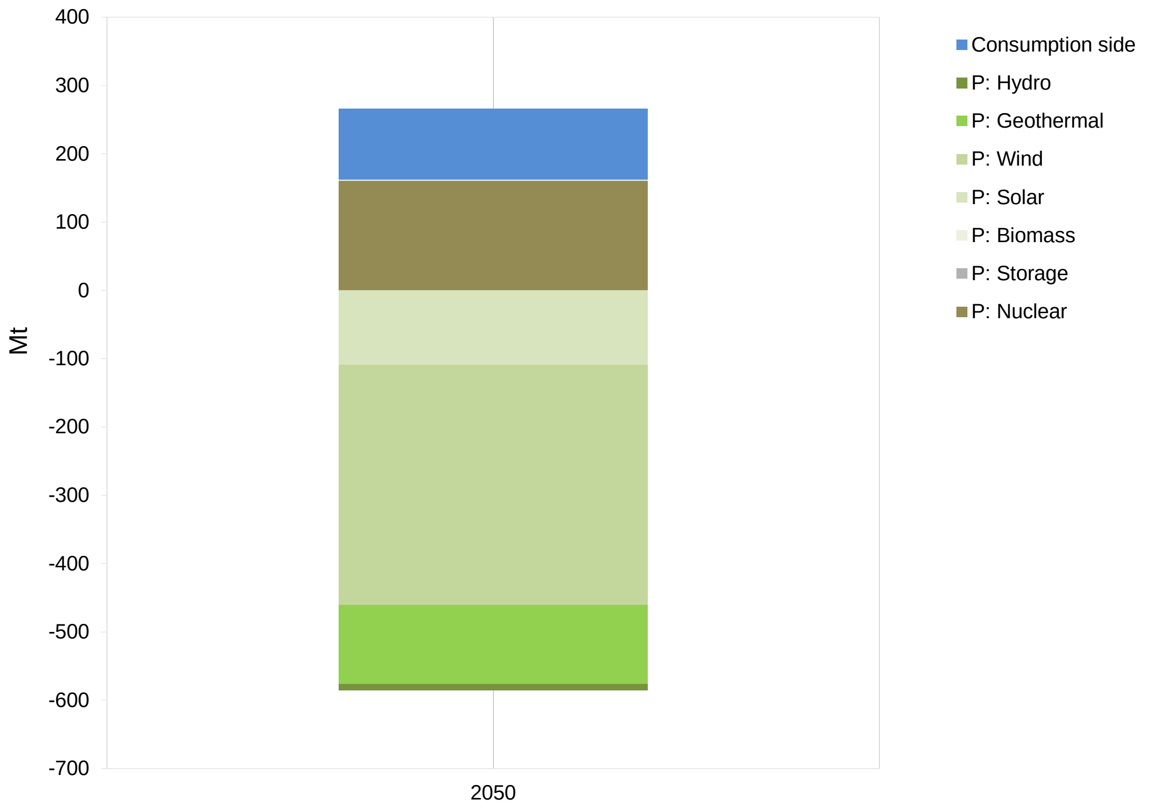
Causal factor	2050
Consumption side	-32%
C: Consumption	-37%
C. Other	-0.3%
Exports	5.3%
Production Side	132%
P: Renewables	180%
P: Hydro	3%
P:Wind	109%
P: Solar	34%
P: Biomass	-0.4%
P: Geothermal	36%
P: Nuclear	-49%
P: Storage	1%
relative emission reduction compared to base year	100%

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

[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

[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

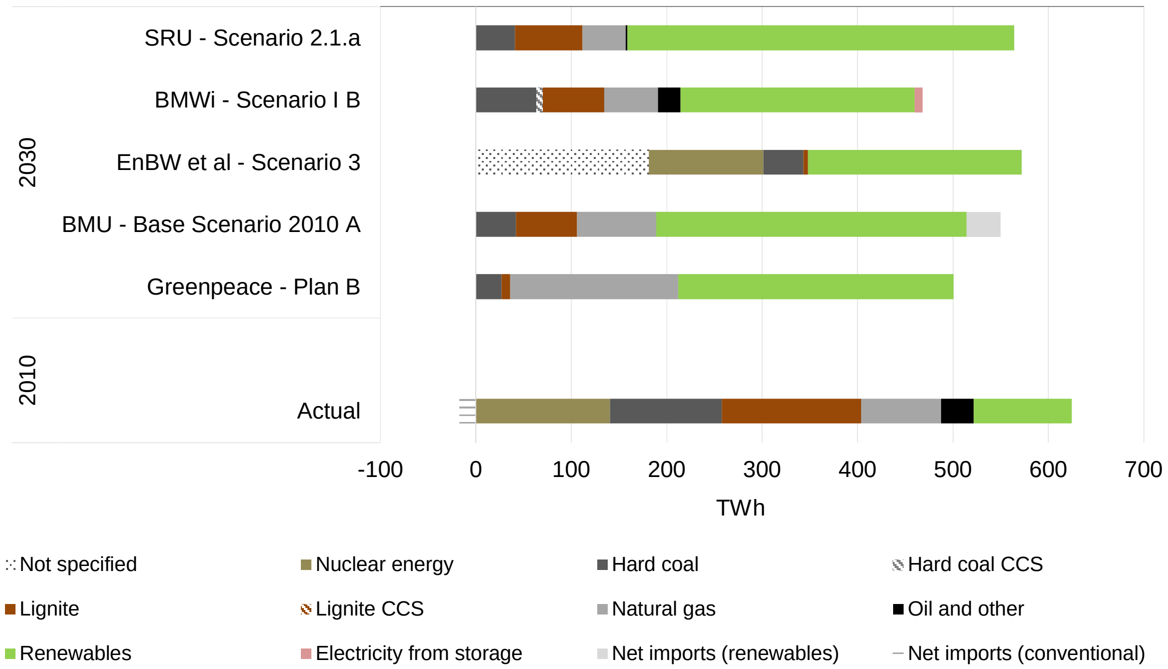
The following two figures show German electricity supply in the various scenarios for the years 2030 and 2050 (compared to actual data from 2010). Mainly due to the assumed improvements in energy efficiency, all scenarios assume that less electricity generation is needed in 2030 compared to today. However,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

[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

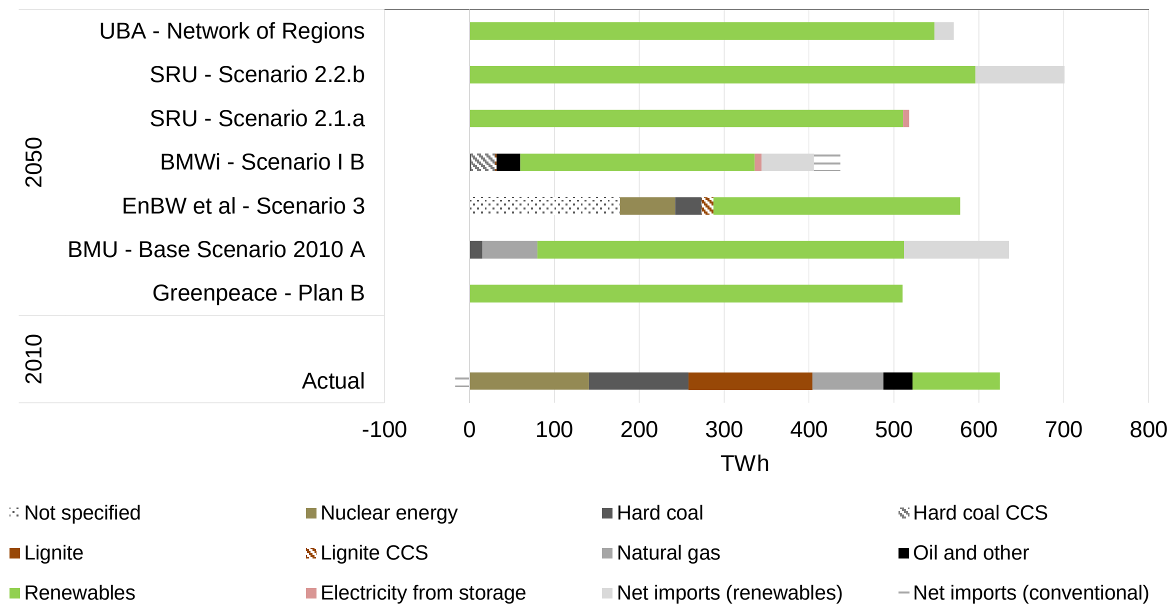


Source Own figure, data based on energy scenario studies quoted and for actual data on (AG Energiebilanzen, 2011)

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.

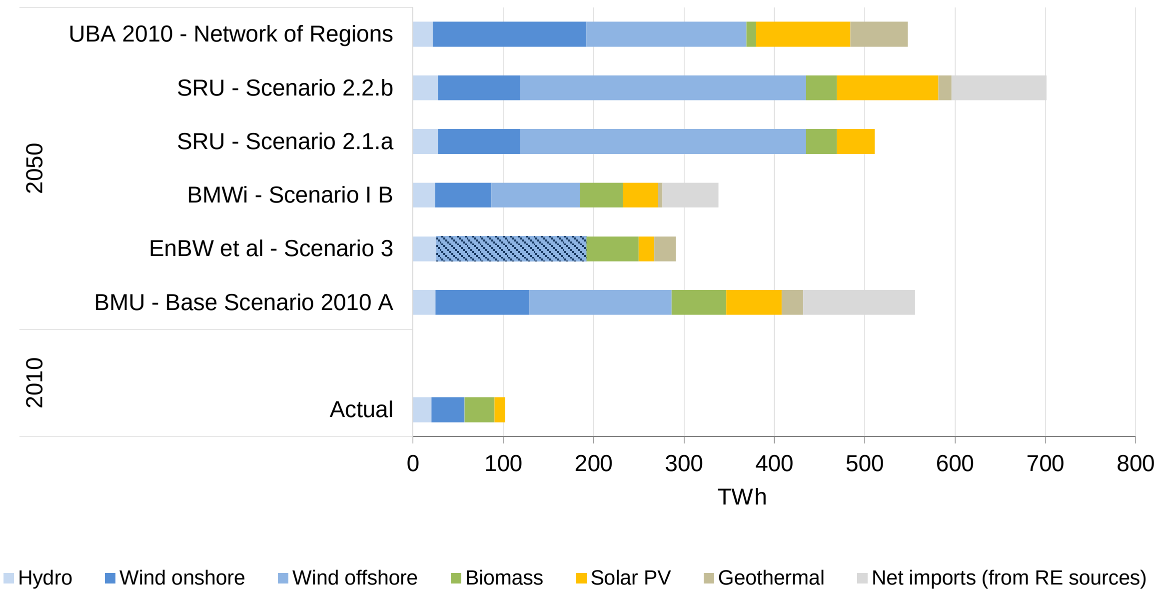
Figure 13 Electricity generation by source (including net electricity imports) in 2010 (actual) and in 2050 in various scenarios



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

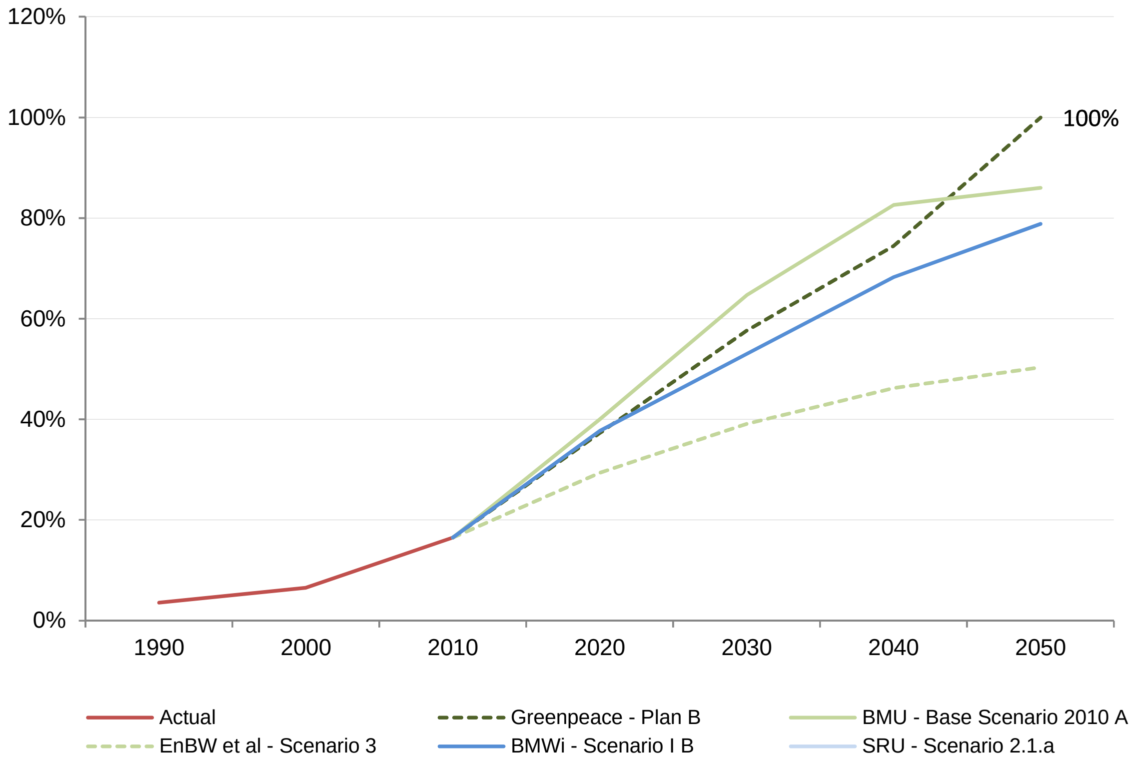


Source: Own figure, data based on energy scenario studies quoted and for actual data on (AG Energiebilanzen, 2011) . Note: (EnBW, e.on Energie, Power, & Europe, 2009) do not provide separate numbers for onshore and offshore wind. To account for this, the corresponding segment is visualized with dashes.

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]

[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

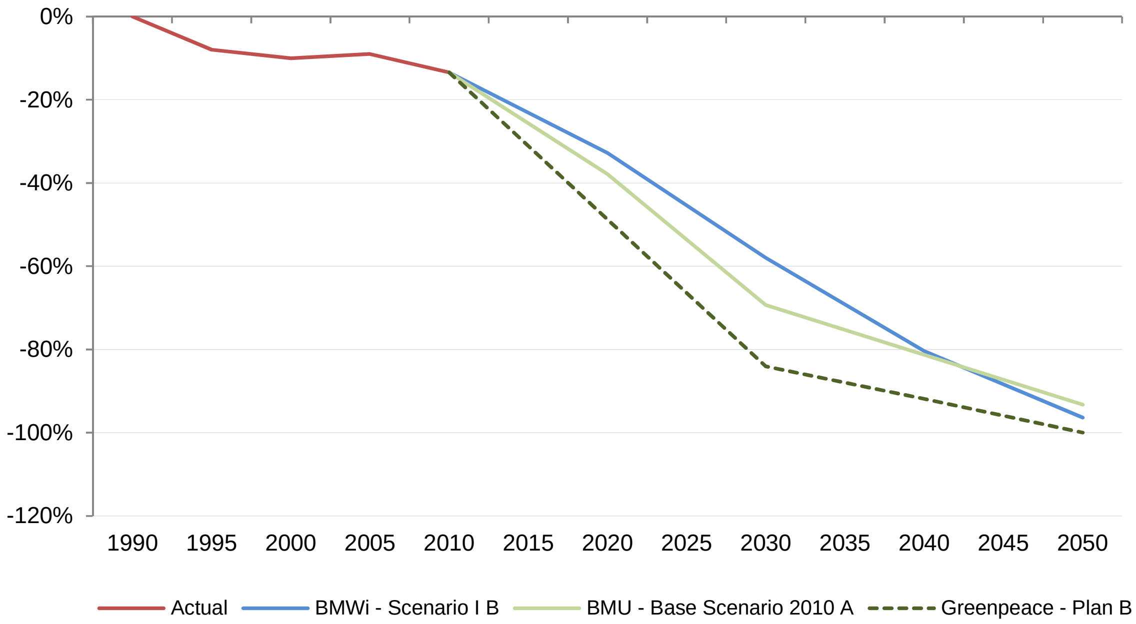


Source: Own figure, data based on energy scenario studies quoted and for actual data from (BMU, 2011)

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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