Information for Policy Makers 1

Decarbonisation Scenarios leading to the EU Energy Roadmap 2050.

SEFEP working paper 2012

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

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

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About SEFEP

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

Summary

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

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

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

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

1. Introduction

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

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

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

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

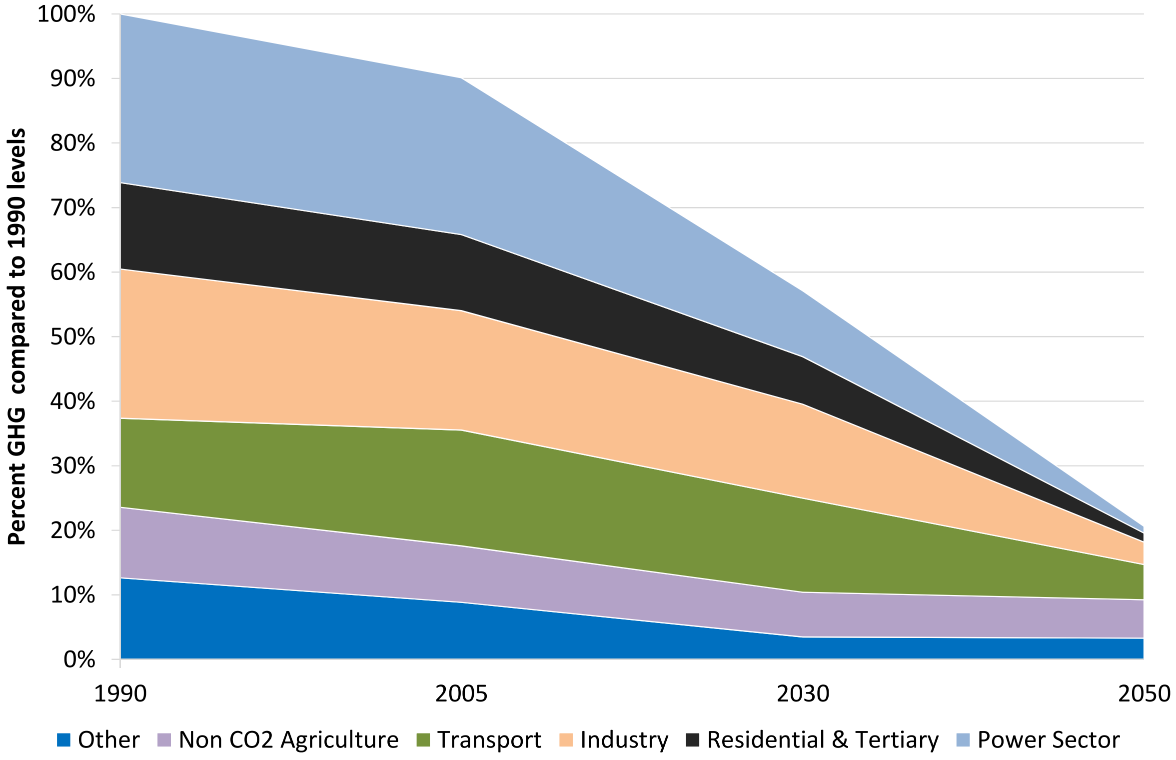
[4] COM (2011): A Roadmap for moving to a competitive low carbon economy in 2050. 112 final.

[5] COM(2011) 885/2.

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

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

Figure 1 EU Roadmap 2050 decarbonisation pathway



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

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

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

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

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

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

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

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[9] COM(2011) 885/2.

2. Shared vision of a decarbonised Europe

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

2.1 Emission trajectories

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

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

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

The CO_2 emission reduction pathways in all of the decarbonisation scenarios illustrated in Figure 2 are similar. However, in comparison to the other pathways the Power Choices scenario exhibits slower CO_2 emission reductions until 2020 followed by relatively deep reductions between 2020 and 2030. The main reason for this is the high relevance of CCS power plant technology in this scenario, which in the study is not assumed to be commercially available until 2025. The ECF Roadmap 2050 decarbonisation scenarios, especially the ECF 40 % and ECF 60 % scenarios also use CCS to a significant extent. Here CCS is assumed to be progressively available from 2020 onwards. Although all

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[10] Hereafter: Greenpeace Adv. Rev.

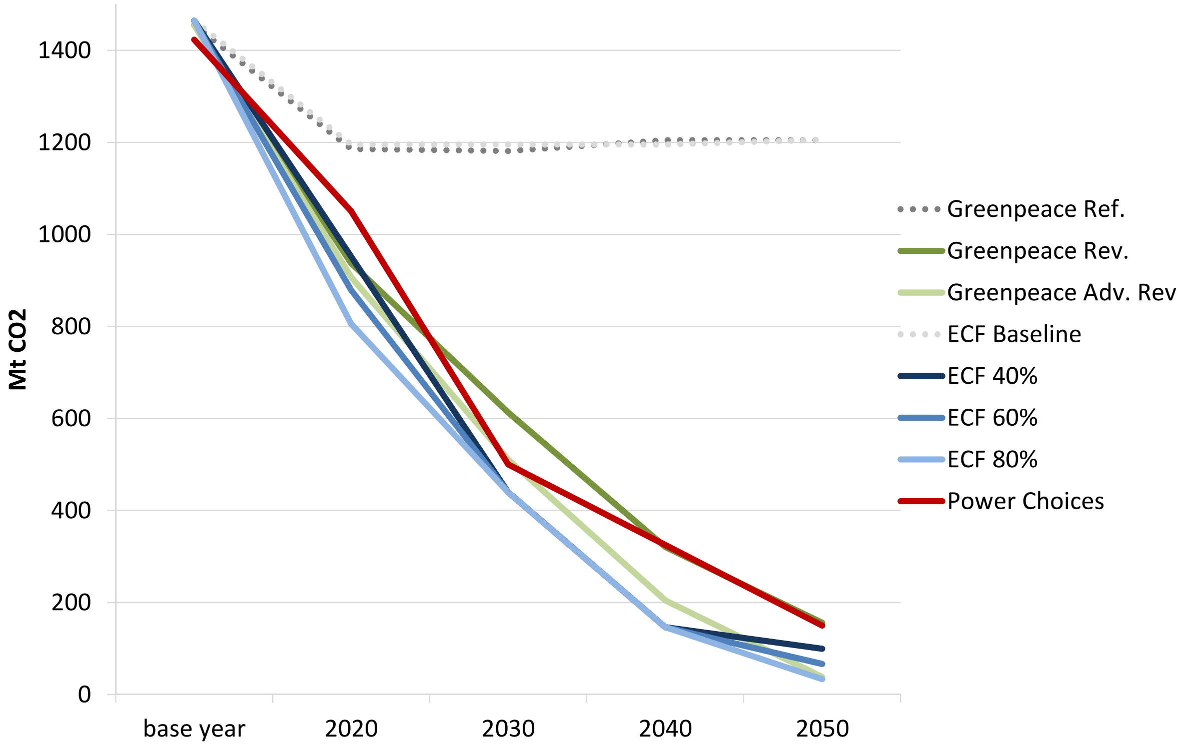
[11] Hereafter: ECF 40%, ECF 60%, ECF 80%.

[12] Hereafter: Greenpeace Rev.

[13] Hereafter: Power Choices

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

Figure 2 CO_2 emission trajectories for reference and decarbonisation scenarios



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

Source: Öko-Institut / Wuppertal Institut (2012)

2.2 Electricity consumption

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

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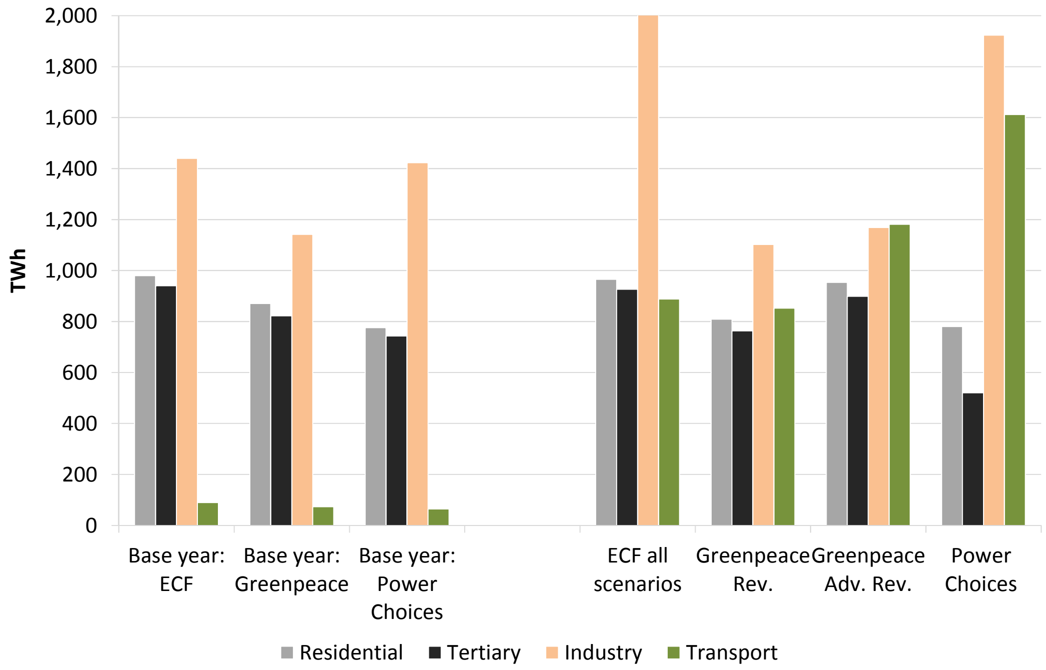
[14] The base year is defined as the year in which values of key variables are provided based on historical values. It provides the base for the first modeled year in each of the scenarios. The base year for the Eurelectric (i.e. Power Choices) and ECF Roadmap 2050 studies is 2005, whilst the Greenpeace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

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

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



Source: Öko-Institut / Wuppertal Institut (2012)

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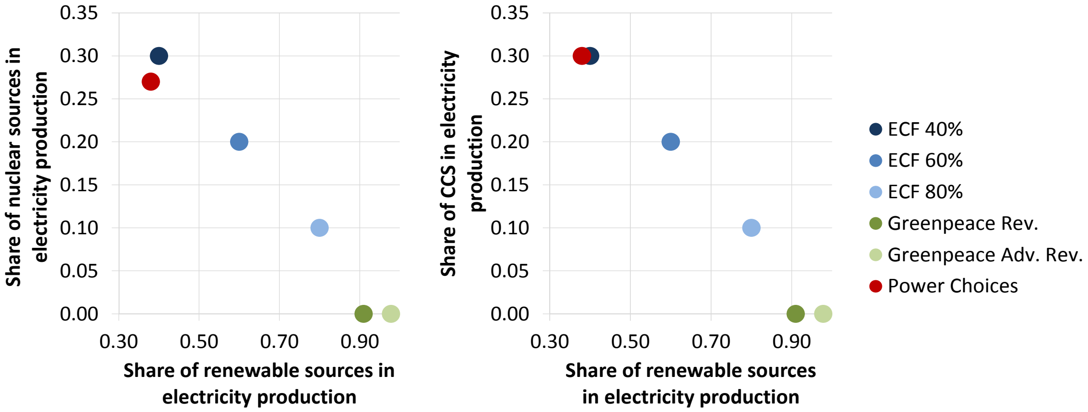
[15] It is important to acknowledge the opposing factors on future electricity demand of energy efficiency improvement in end user appliances on the one hand and the electrification of industrial processes and transportation on the other hand. Reference scenarios are provided in sufficient detail for the Greenpeace and ECF Roadmap 2050 studies and indicate that a strategy to decarbonise the energy system could lead to similar overall electricity demand in 2050 compared to a business-as-usual pathway due to these opposing factors cancelling each other out.

2.3 Sources of electricity production

In line with the overall goal of all the studies' policy scenarios, electricity generation in Europe in 2050 is based entirely or almost entirely on zero or low CO_2 emitting sources. However, the actual mixture of these zero or low CO_2 emitting sources is very different for the decarbonisation scenarios. Given that nuclear power is phased out and CCS is not seen as a viable or desirable technology in both the Greenpeace Rev. and Greenpeace Adv. Rev. scenarios; the electricity supply is based on 91 % and 98 % renewable energy sources in 2050 respectively and this includes electricity imports (Figure 4). The rest is supplied by natural gas power plants. In contrast, the Power Choices scenario and the ECF 40 % scenario from the ECF Roadmap 2050 study rely to a significant extent on nuclear power, which will account for 30 % and 27 % respectively of electricity generation in 2050 (Figure 4). CCS coal and natural gas power plants are also used to a significant extent in the Power Choices scenario and the ECF 40 % scenario from the ECF Roadmap 2050 study, providing 30 % of electricity supply in 2050 in both decarbonisation scenarios.

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



Source: Öko-Institut / Wuppertal Institut (2012)

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

3. Comparison of decarbonisation scenarios

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

3.1 Methodology

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

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

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

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

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

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

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

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

3.2 Results

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

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

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

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

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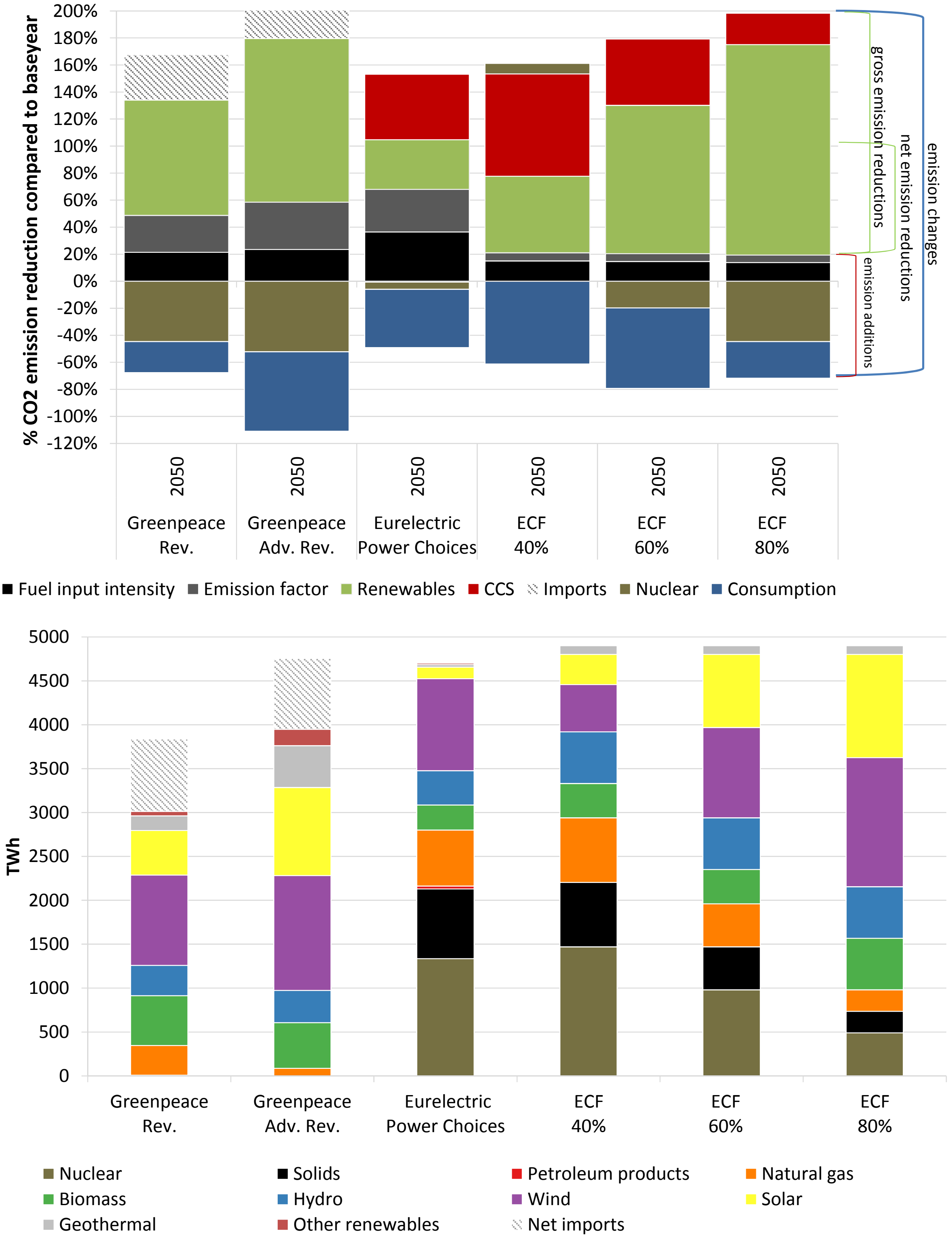
[23] The positive part of each column in Figure 5 (top) represents the gross emission reductions achieved by the causal factors. The positive part of each column is longer than the actual emission reductions achieved because additional emissions triggered by factors depicted in the negative part of each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

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

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



Source: Öko-Institut / Wuppertal Institut (2012)

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

Table 1 Decomposition results of CO_2 emission reduction in 2050 for the decarbonisation scenarios.

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

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

Source: Öko-Institut / Wuppertal Institut (2012)

The results of the decomposition analysis are illustrated further in Table 1, which outlines the absolute reduction in CO_2 emissions between the base year and 2050 attributed to each causal factor measured in million tonnes of CO_2. The CO_2 emission reduction is either negative and thus characterised by additional emissions (i.e. red shading) or is positive and characterised by emission reductions (i.e. green shading). It is important to acknowledge that the emission changes in one scenario are not directly comparable with another scenario as this would require the results to be normalised to account for differences in the base year. However, the trends that emerge from the scenarios decomposition analysis are clear.

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

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

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

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

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

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

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

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

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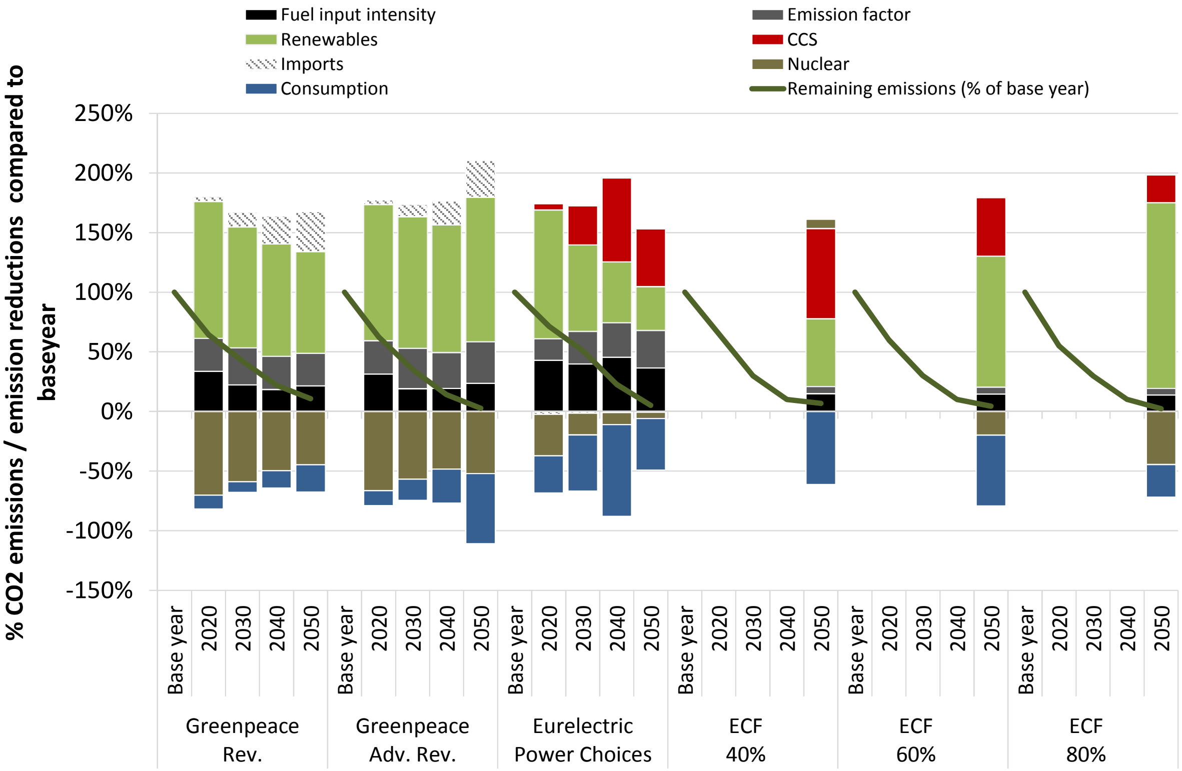
lines. The models used in the other two studies are not explicit power system models and do not have a comparable level of spatial and temporal resolution.

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

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



Source: Öko-Institut / Wuppertal Institut (2012)

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

4. Cost assumptions of the scenarios

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

4.1 Fossil fuel prices

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

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

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

Source: Öko-Institut / Wuppertal Institut (2012)

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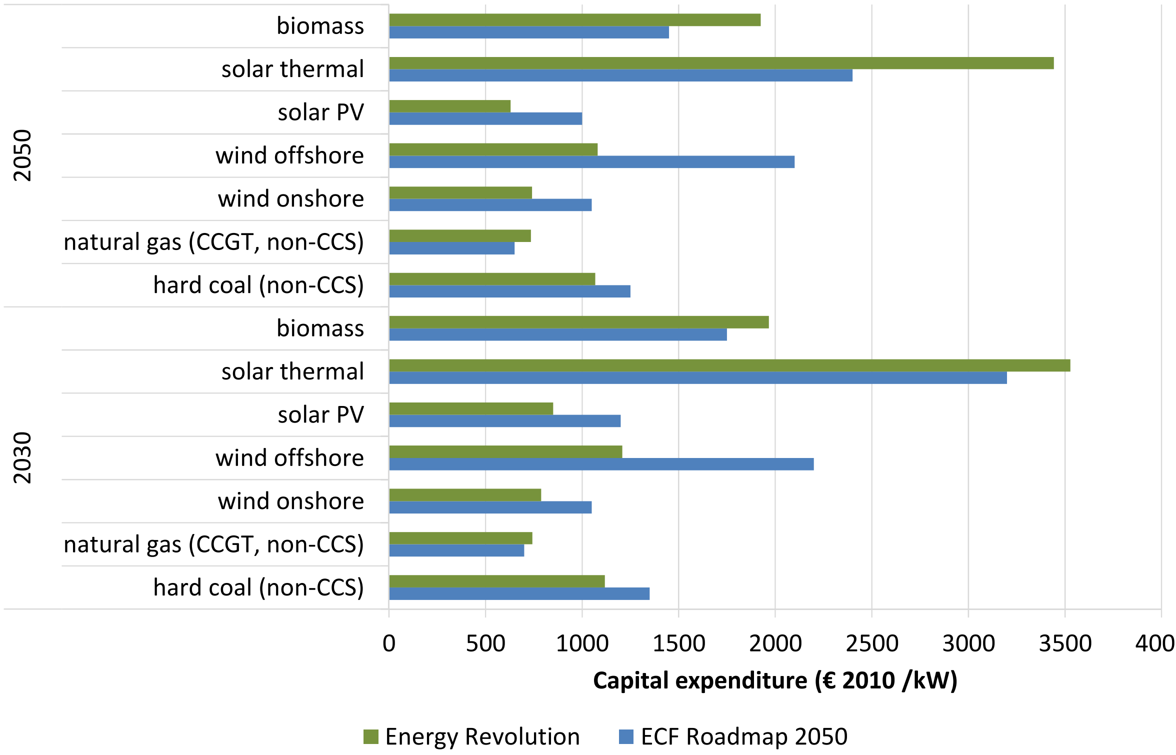
[28] This is also explicitly the case for all the ECF Roadmap 2050 policy scenarios. The ECF Roadmap 2050 scenarios have been developed by explicitly prescribing varying shares of renewables, nuclear and CCS technologies to be reached by 2050. In the Power Choices scenario no such technology-specific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

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

4.2 Capital expenditure

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

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



Source: Öko-Institut / Wuppertal Institut (2012)

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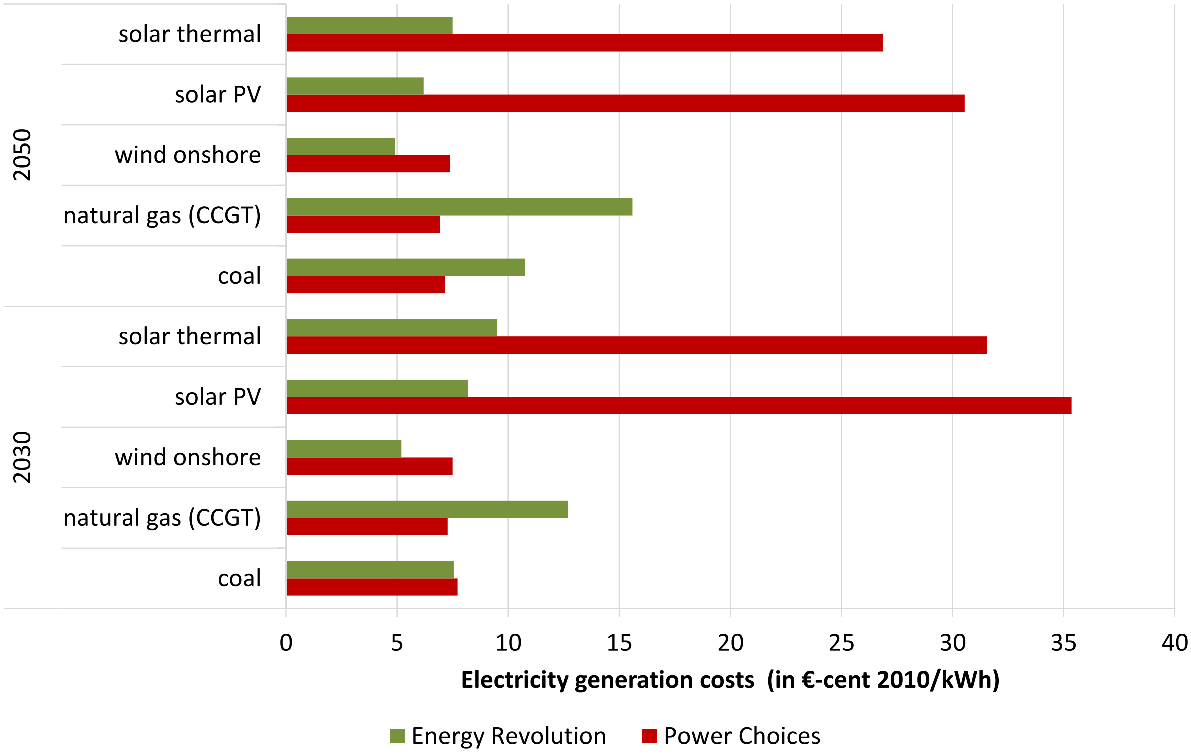
[30] No figures for capital expenditure are provided by the Power Choices study.

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

4.3 Electricity generation costs

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

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



Source: Öko-Institut / Wuppertal Institut (2012)

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

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

4.4 Cost assumptions on nuclear power

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

4.5 Explanation of the difference in cost assumptions

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

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

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

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

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

5. Window of opportunity for political action

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

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

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

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

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

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

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

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

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

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

Source: Öko-Institut / Wuppertal Institut (2012)

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

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

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

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

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

Source: Öko-Institut / Wuppertal Institut (2012)

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

6. Conclusion

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

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

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

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

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

4. **Uncertainty regarding the future role of nuclear and CCS**

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

5. **The issue of energy policy timing is crucial in changing the energy system**

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

6. **Need for greater transparency in energy scenarios**

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

7. References

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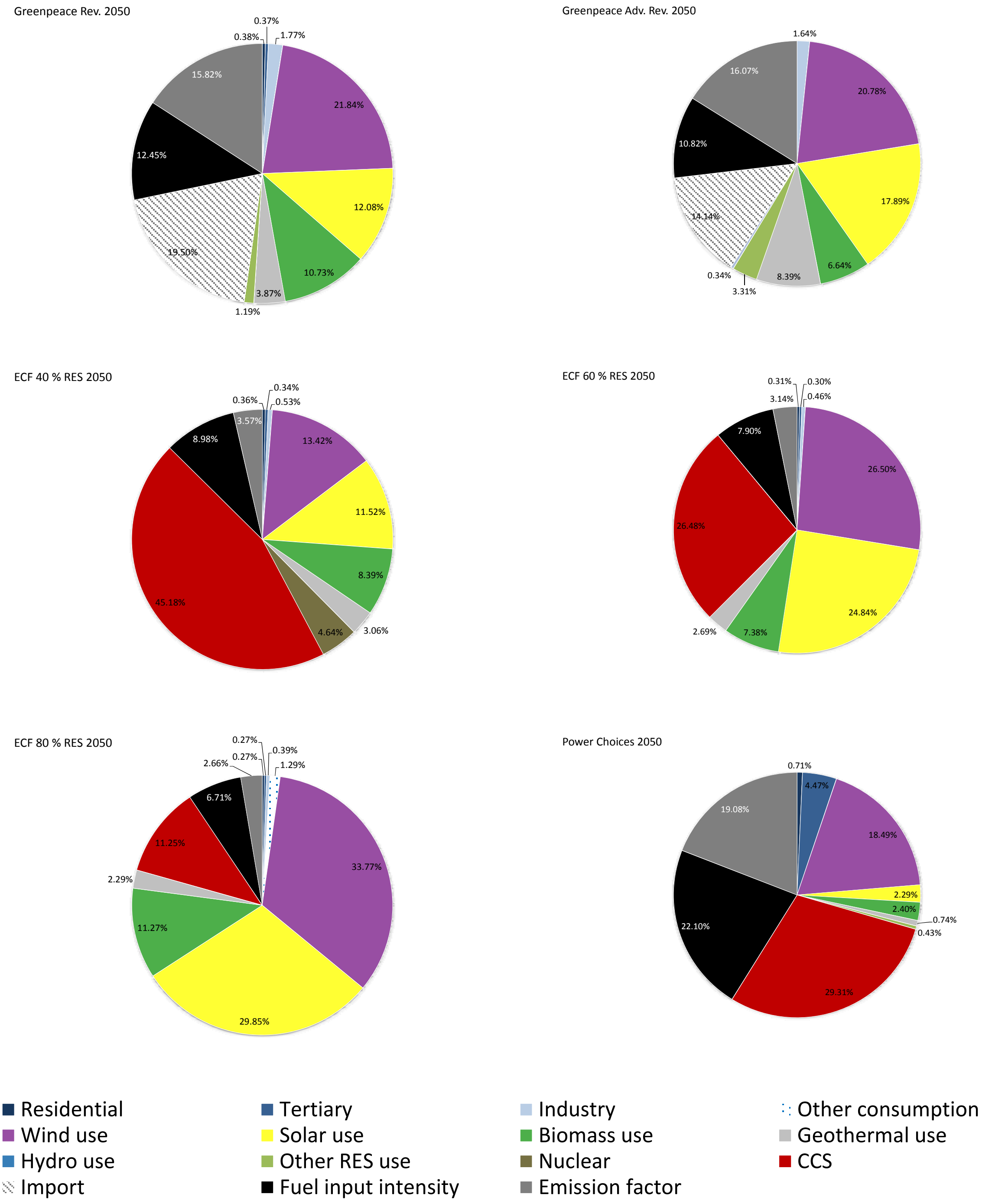
International Energy Agency (2011): *World Energy Outlook 2011*. Paris.

8. Annex

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

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



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

Source: Öko-Institut, Wuppertal Institut (2012)

8.2 Climate Policies in the EU

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

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

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

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

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

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

8.3 Energy models used in the studies considered

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

Table 5 Models used in the studies considered

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

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

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

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

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

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

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

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

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

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

8.4 Suggested standard for data reporting

Common roster of data and information

Metadata on the studies and modelling exercises

General information about study

Study title

Date published (month/year)

Source (URL, if available on internet)

Developed by

Institute(s)

Lead author(s)

Commissioning body/bodies

Context in which study was commissioned/prepared

Consideration of entire energy system (yes/no, only electricity)

Countries included in analysis (EU-27 or different scope?)

Scenarios

Reference scenario (yes/no)

Number of alternative scenarios

Scenario analysed here

Base year

Modelling approach

General modelling approach (if applicable)

Modelling approach for electricty sector

Important (external) model drivers

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

	base year	2010	2015	2020	2025	2030	2035	2040	2045	2050
Key targets, restrictions and assumptions										
Key targets (e.g. CO$_2$ emission reduction target)										
Key restrictions										
Construction of new nuclear power plants										
Construction of CCS power plants										
Assumptions about renewable energy potential										
Biomass share in whole energy system										
Biomass potential available to EU										
Assumptions about CCS storage capacity										

Electricity consumption

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

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

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

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

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

Electricity supply data (in TWh)

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

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

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

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

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

Hydrogen

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

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

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

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

Infrastructure data

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

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

Information about power transmission network(s)

Information about power distribution network(s)

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

Assumptions and results of technologies' cost modelling

Description of cost modelling approach

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

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

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

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

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

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

Biomass - biogas										
Biomass - solid										
Solar PV										
Hydrogen										

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

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

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

Other key information

Interrelationship between electricity and other energy sectors ______________________

Policy measures assumed or deemed necessary ______________________

Reflections on uncertainties and robustness of results ______________________

	base year	2010	2015	2020	2025	2030	2035	2040	2045	2050
Electricity sector CO_2 emissions										
Total (in Mt of CO_2)										
Index (base year = 100)										

Index (1990 = 100)

	base year	2010	2015	2020	2025	2030	2035	2040	2045	2050
Electricity sector CO_2 sequestration (in Mt of CO_2)										
Annual sequestration										
Cumulative sequestration										