The Potential Evolution of the European Energy System to 2020 and 2050

Arno Behrens, Caroline Coulie and Jonas Teusch

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Abstract

This paper assesses the impact of decarbonisation of the energy sector on employment in Europe. Setting the stage for such an assessment, the paper provides an analysis of possible pathways to decarbonise Europe's energy system, taking into account EU greenhouse gas emissions reduction targets for 2020 and 2050. It pays particular attention to various low-carbon technologies that could be deployed in different regions of the EU. It concludes that efficiency and renewables play a major role in any decarbonisation scenario and that the power sector is the main enabler for the transition to a low-carbon economy in Europe, despite rising electricity demand. The extent of the decline in the share of fossil fuels will largely depend on the existence of carbon capture and storage (CCS), which remains a major source of uncertainty.

Research for this paper was conducted as part of the NEUJOBS project, financed by the European Commission's 7th Framework Programme. Its objective is to analyse likely future developments in the European labour market(s), in view of major transitions that will impact employment and European societies in general. This paper was originally published on the NEUJOBS website (www.neujobs.eu) as Deliverable 11.1, dated September 2013.

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°C	Degrees Celsius
2DS	2°C Scenario of IEA Energy Technology Perspectives 2012
a	Annum
bbl	Barrel
boe	Barrel of oil equivalent
CCS	Carbon capture and storage
CHP	Combined heat and power
CO2	Carbon dioxide
CSP	Concentrated solar power
D	Deliverable
DG	Directorate-General
ECF	European Climate Foundation
EJ	Exajoules
ENTSO-E	European Network of Transmission System Operators for Electricity
ETP	Energy Technology Perspectives
ETS	Emissions Trading Scheme
EU	European Union
EUR	Euros
GDP	Gross domestic product
GEA	Global Energy Assessment
GHG	Greenhouse gas(es)
GIC	Gross inland consumption
GW	Gigawatt
HVDC	High voltage direct current
IEA	International Energy Agency
IIASA	International Institute for Applied Systems Analysis
km	Kilometer
kW	Kilowatt
LCOE	Levelised costs of electricity
m	Million
Mbtu	Million British thermal units
Mtoe	Million tonnes of oil equivalent
NEUJOBS	Employment 2025: How will multiple transitions affect the European labour market
NGO	Non-governmental organisation
NREAP	National Renewable Energy Action Plan
OECD	Organisation for Economic Co-operation and Development
p.a.	Per annum
PJ	Peta-Joules
ppm	Parts per million
PV	Photovoltaic
RES	Renewable energy sources
SEFEP	Smart Energy for Europe Platform
SET	Socio-ecological transition
t	Tonne
tCO2e	Tonnes of carbon dioxide equivalent
TFC	Total final consumption
TPED	Total primary energy demand
TPES	Total primary energy supply
TWh	Terawatt per hour
TYNDP	Ten-Year Network Development Plan
UNFCCC	United Nations Framework Convention on Climate Change
USD	United States dollar
USSR	Union of Soviet Socialist Republics
WEM	World Energy Model
WEO	World Energy Outlook
WP	Work Package

The Potential Evolution of the European Energy System until 2020 and 2050

Arno Behrens, Caroline Coulie and Jonas Teusch*

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1. Introduction

This paper reviews various decarbonisation scenarios for the energy sector and thus serves as a background document for assessing the impacts of a transition away from fossil fuels towards low-carbon energy technologies on employment in Europe. A broad range of scenarios is taken into account – from international institutions, European research projects, NGOs and the private sector – all of which depict a decarbonisation of the energy sector in line with limiting global warming to two degrees Celsius above pre-industrial levels. However, since it is far from certain that these ambitious scenarios will materialise by 2020 and 2050, the paper additionally presents a scenario with lowered policy ambitions. This allows for a comparison of the decarbonisation scenarios with a baseline scenario, and thus for an analysis of how much the energy sector will need to change in the context of the socio-ecological transition (SET). The conclusions of this paper, originally published as a contribution to the NEUJOBS project (Deliverable 11.1), are taken further in another report, where the actual impacts of decarbonisation scenarios on employment are analysed in the context of the energy sector (to be published as NEUJOBS Deliverable 11.2).[1]

1.1 Energy in the context of the socio-ecological transition

One of the explicit objectives of NEUJOBS is "to analyse future possible developments of the European labour market(s) under the main assumption that European societies are now facing or preparing to face four main transitions that will have a major impact on employment" (NEUJOBS, 2013). This paper is concerned with only one kind of such transition: the socio-ecological transition (SET). As defined in Work Package 1 (NEUJOBS D1.1), a socio-ecological transition "is a transition between two different societal energy regimes (sources and dominant conversion technologies of energy)" (Fischer-Kowalski et al., 2012).

Sieferle et al. (2006) describe two grand socio-economic regime changes in human history. The first was the Neolithic Revolution some 4,500-10,500 years ago (Diamond and Bellwood, 2003) that transformed hunter-gatherers into agrarian societies. The second was the Industrial Revolution, which led to the transition of agrarian societies to industrial societies with a strong dependence on fossil fuels. While in many parts of the world this transition is ongoing *into* fossil fuels, the European Union is dedicated to substantial greenhouse gas emissions reductions in the long term, and therefore also to a new transition *away* from fossil fuels. This paper is thus concerned with a SET "away from fossil fuels, towards solar and other low carbon energy sources" (Fischer-Kowalski et al., 2012), which will be required if

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* Arno Behrens is a Research Fellow, Caroline Coulie is a Research Assistant and Jonas Teusch was a Researcher at CEPS.

[1] For information on the NEUJOBS project, for which CEPS acts as Coordinator, see www.neujobs.org.

the EU is to meet its long-term objective to reduce greenhouse gas emissions by at least 80% compared with 1990 levels by 2050.

The energy system is at the heart of the SET away from fossil fuels. However, the current EU energy mix is still dominated by fossil fuels, with more than three quarters of EU energy consumption being based on oil, gas and coal (European Commission, 2013). It is thus evident that the new transition will require substantial technological and political efforts in the EU in order for its energy sector to radically change in favour of low-carbon technologies.

Not all parts of the energy system will be decarbonised to a similar extent, however. Large differences exist between sectors. Whereas many scenarios exist under which power generation can be largely carbon free by 2050, greenhouse gas (GHG) emissions in industry may still be significant for beyond this date. Transport currently relies almost exclusively on oil and other fossil fuels, while carbon-free generation capacity in the power sector already exists (renewables and nuclear). The energy transition(s) are also likely to differ considerably across European regions, *inter alia* because the potential for renewables varies but also because of differences in GDP per capita which affect ability and willingness to pay.

It is clear that the energy transition will have an impact on the EU labour market. While the number of "green jobs" will expand associated with a growing number of jobs in low-carbon technologies, some other sectors, such as the oil and refining industries, will see decreasing employment. The net effect of these two developments is of relevance to assessing the employment impact of the decarbonisation in the energy sector.

1.2 Decarbonisation and the next socio-ecological transition

Assessing the impacts of the decarbonisation of the energy sector on employment in Europe is the core objective of WP11, and will be done in D11.2. However, before such an assessment can be made, it is important to set the stage with an analysis of how the transition can actually be achieved. This deliverable (D11.1) is thus intended to give an overview of potential decarbonisation pathways for 2020 and 2050. The report is based on a review of various GHG emissions reduction scenarios. Apart from the baseline scenario, it takes into account only scenarios that actually reflect a new transition required to avoid dangerous climate change (i.e. to keep temperature increases to below two degrees Celsius above pre-industrial levels).

Within this context, it is important to note that the scenarios do not and cannot depict a socio-ecological transition per se, but rather one (albeit crucial) aspect of such a transition: the decarbonisation of the energy sector. As noted in NEUJOBS D1.1, a SET is much broader than that and includes not only changes in the source of energy and energy technologies, but also many other societal changes, such as the economy as a whole, demographics, settlement patterns, social relations and even changes on the individual level. In addition, there are intended and unintended changes to the environment that need to be taken into account when describing a SET. NEUJOBS D1.1 therefore concludes that "the challenge of a new socio-ecological transition for Europe may not just consist in greening the energy system and further improving efficiency, but be more fundamental in requiring substantial biophysical de-growth. Depending on how it is organized this may still be compatible with comfortable and rich lives, but adaptation to this requires institutional, cultural and economic changes" (Fischer-Kowalski et al., 2012).

The scenarios described in this paper do not depict such a full SET. They neither provide feedback loops between energy consumption and societal change nor show the inter-linkages between energy and material consumption. Or to put it in a nutshell: the scenarios lack complexity. However, they are still useful for analysing the potential impact of the new SET away from fossil fuels on the energy sector. And while there will be many causes and effects of a SET other than purely energy related ones, the decarbonisation of the energy sector will be a crucial component of it – in terms of energy efficiency, in terms of new and renewable energy sources and technologies, but also in terms of demand responses and changes. This warrants the approach taken in this paper and in WP11 as a whole of looking at different decarbonisation options – within the context of a SET - and t a later stage of analysing what these options could imply for the labour market.

Decarbonisation in this paper is thus not considered to be a proxy for a more complex SET. It is understood as a key response strategy to current environmental and social challenges – albeit one of several such strategies – and therefore also as a key component of a SET.

1.3 Scenario selection

This report draws on studies commissioned or conducted by a wide range of institutions, including international institutions, European research projects, NGOs and the private sector. More concretely, the scenarios selected were published by the International Energy Agency (IEA), the European Commission, two research projects funded by the European Commission (AMPERE and SECURE), the International Institute for Applied Systems Analysis (IIASA), NGOs including Greenpeace and the European Climate Foundation (ECF), as well as Eurelectric representing the European electricity industry.

Although this selection is arguably somewhat arbitrary, the selected scenarios reflect a broad range of options for the decarbonisation of the energy sector and thus of the energy component of a SET. In addition, the selection followed criteria based on the extent of emissions reductions, geographical coverage, policy relevance and time horizon covered.

The scope of this paper is to compare different decarbonisation pathways. Therefore, only those studies that include decarbonisation scenarios are considered (with the exception of one baseline scenario, which serves as a contrast to the decarbonisation scenarios). This excludes, for example, the *International Energy Outlook 2013* published by the US Energy Information Administration (EIA), which does not reflect GHG emissions constraints in line with a SET as described above.

In order to provide for optimal linkage with D11.2, for each scenario the paper reports developments in total energy consumption and electricity consumption, as well as on the composition of the two. Preference is thus given to studies that provide a detailed breakdown of the share of various energy sources in the energy mix. Specific attention is paid to any information regarding low-carbon technologies that could be deployed in different regions of the EU (wind, biomass, hydro, solar, geothermal, hydrogen, etc.). While the studies and scenarios are compared appraising their quality, *inter alia* by analysing consistency between scenarios, the study does not seek to rank the likelihood of different scenarios but to establish a plausible range of pathways. It is also beyond the scope of this paper to explain and analyse the model structure and assumptions in detail, though brief overviews are given where information is available. This information includes key assumptions regarding economic and population growth, oil prices, carbon prices and energy demand developments.

As the focus of NEUJOBS is on the EU, it is essential that the studies cover the EU27[2] or at least include information about the region that allows conclusions to be drawn for the EU

[2] The Republic of Croatia officially became the 28th Member State of the EU on 1 July 2013. It is generally not yet included in the scenarios published before that date.

(e.g. eastern and western Europe, OECD Europe). Wherever possible, interregional differences within Europe will be reported.

Due to the considerable impact of the financial and economic crisis on energy demand and the large number of recent policy changes in the EU, only up-to-date studies reflecting current policies (e.g. the 2009 climate and energy package) are taken into account in the analysis. This makes sense in particular for the 2020 perspective, but also beyond due to knock-on effects, which can be expected even in the absence of ambitious climate policy measures in the long term.

In order to allow for a reasonably concise comparison of a large range of scenarios, the study will only compare in detail the visions of the energy system at two specific points in time, 2020 and 2050. Important interim developments may, however, be discussed qualitatively. Studies that provide data for both years are preferred. However, publications that only provide data for one of the time points or somewhat different years are included if they fulfil most of the other criteria described in this section (e.g. IEA, 2012a). Within the context of the timeframe, it is also important to note that this differs slightly from the time horizons of the NEUJOBS project in general. While NEUJOBS focuses on the years 2025 and 2050, it was considered necessary to change this focus slightly to 2020 and 2050 because these two years constitute milestones of current EU energy and climate change policies. 2020 is the target year of the energy and climate change package adopted in 2009 and most studies thus focus on this year. This approach has also been adopted for this Work Package.

The usual disclaimer regarding scenario analyses applies. Scenarios are not forecasts of the future, but rather present a range of possible developments. These visions of the future energy system are highly dependent on a number of assumptions being made about an uncertain future. However, in the context of WP11 of the NEUJOBS project, they are helpful in identifying potential future developments in the energy sector, which can then be taken forward to the next task of WP11 (D11.2) where the employment aspects will be analysed.

2. Baseline scenario

Before analysing decarbonisation scenarios, this section depicts a future resulting from no further action to reduce GHG emissions beyond what is in place today. It provides a contrasting perspective for better assessing the extent of the changes required in the energy sector in the context of decarbonisation. For reasons of simplicity, only one such scenario is presented below, which is based on the "Current Policies Scenario" of the IEA's *World Energy Outlook 2012* (WEO 2012). The explicit objective of this scenario is to "provide a baseline that shows how energy markets would evolve if underlying trends in energy demand and supply are not changed" (IEA, 2012a: 35).

The WEO 2012 is based on the World Energy Model (WEM), which has been designed to analyse global energy prospects, CO_2 emissions from fuel combustion, effects of policy actions and technological changes, and investment in the energy sector. The WEO 2012 is based on 2010 data (the model's dataset covers the period from 1971 to 2010, occasionally with preliminary data for 2011) and provides regional and sectoral energy projections to 2035.

Four different scenarios were calculated for the WEO 2012, including the Current Policies Scenario, the New Policies Scenario, the 450 Scenario (see below) and the Efficiency World Scenario, which focuses on energy efficiency. Since the results of WEO 2012 do not extend beyond 2035, the results presented below will focus on 2020 and 2035.

All scenarios of the WEO 2012 are based on non-policy assumptions, including economic growth, population growth, energy prices, CO_2 prices and technology. For the EU, the following assumptions for the Current Policies Scenario apply (all prices are in 2011 US dollars and their equivalent in euros):[3]

- *Economic growth:* 1.7% p.a. (2010-2020) and 1.8% p.a. (2010-2035).
- *Population growth:* 0.2% p.a. (2010-2020) and 0.1% p.a. (2010-2035).
- *Energy prices:* The Current Policies Scenario shows the strongest increase in energy demand, which also translates into higher energy prices. In order to balance supply with increasing demand, the oil price increases from $108 (€78) per barrel in 2011 to $128 (€92) in 2020 and $145 (104) per barrel in 2035. Pushed by demand, European import prices for gas also increase from $10 (€7) per MBtu in 2011 to $12 (€9) in 2020 and $14 (€10) in 2035. On the one hand, gas price increases are moderated by a move towards hub-based pricing, on the other hand, more gas will need to be imported from more distant sources, raising transport costs and thus import prices. Coal import prices in the OECD first decrease from $123 (€88) per tonne in 2011 to $115 (€83) in 2020, and then return to today's levels at $125 (€90) per tonne in 2035 as demand picks up.
- *CO_2 price:* The price of CO_2 under the EU Emissions Trading Scheme (EU ETS) is assumed to rise from $19 (€14) per tonne in 2011 to $30 (€22) in 2020 and $45 (€32) per tonne in 2035.
- *Technology*: In general, the IEA expects no breakthrough technologies to be deployed before 2035. It does, however, expect further cost reductions of commercial technologies resulting from learning and deployment. Similarly, exploration and production techniques are expected to improve, leading to lower unit production costs on the supply side. Key uncertainties include carbon capture and storage (CCS), solar power, advanced biofuels, advanced vehicle technologies and nuclear power.

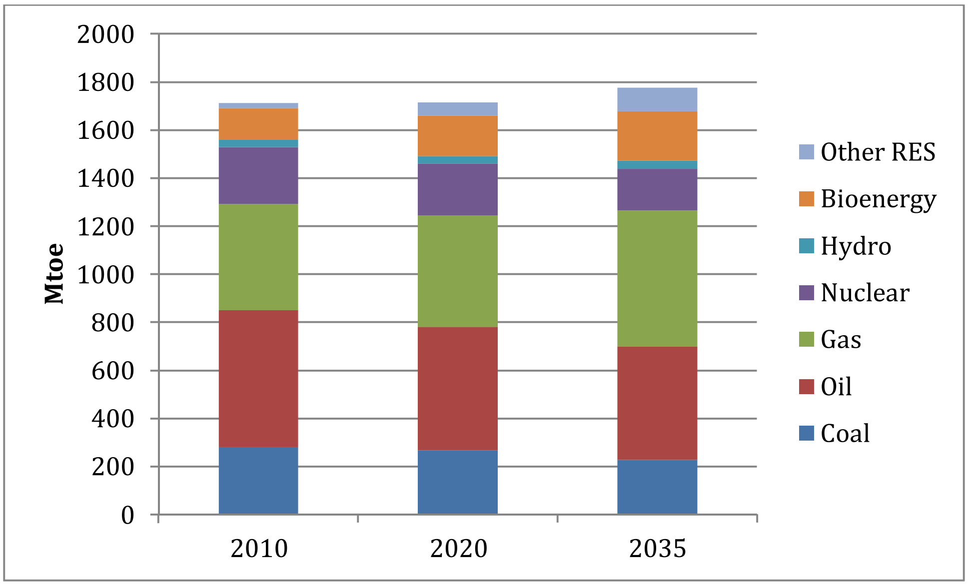
The Current Policies Scenario relies on the outcomes of policies and measures that had been enacted or adopted by mid-2012. In other words, unlike the other three WEO 2012 scenarios, it does not take into consideration any future policy action towards climate change.

In the Current Policies Scenario, global energy demand grows at the fastest rate of all WEO 2012 scenarios (1.5% per year between 2010 and 2035). For the EU, the contrast with other scenarios is even more pronounced, since the Current Policies Scenario is the only one in which energy demand increases. As shown in Figure 1, total primary energy demand (TPED) in the EU is projected to remain constant between 2010 and 2020 at around 1,715 Mtoe and to increase to 1,775 Mtoe by 2035 (an increase of 3.6% between 2010 and 2035). Several general trends can be observed.

First, the share of fossil fuels remains high throughout the period 2010-35. While fossil fuels constitute 75% of TPED in 2010, they still contribute 71% in 2035. However, there is a shift in the composition of fossil fuels away from oil and coal towards natural gas. In fact, while the share of coal in TPED only decreases slightly, gas replaces oil as the largest source of energy by 2035, contributing some 32% to TPED.

[3] The exchange rate is based on the annual average US dollar/euro exchange rate of 2011, as reported by Eurostat (€1 = US$1.3920).

Figure 1. Total primary energy demand of the EU27 in the WEO 2012 Current Policies Scenario



Source: IEA, 2012a.

A second observation shows that although low-carbon energy sources can make up for the (marginal) decline of fossil fuels and even contribute to an absolute increase in TPED, they are not able to gain a major foothold in the EU energy mix by 2035. Their share thus increases only marginally from 25% in 2010 to 27% in 2020 and 29% in 2035. Within the group of low-carbon energy sources, there is a shift away from nuclear energy mainly to bioenergy and other renewables, including wind and solar PV.

These observations are also summarised in Table 1, which clearly indicates the "winners" and "losers" in the Current Policies Scenario in terms of their contribution to energy demand in the EU.

Table 1. Percentage change in total primary energy demand in the EU for different energy sources in the WEO 2012 Current Policies Scenario

	2010-2020	2010-2035
Coal	-1%	-4%
Oil	-3%	-7%
Gas	1%	6%
Nuclear	-2%	-4%
Hydro	0%	0%
Bioenergy	2%	4%
Other RES	2%	4%

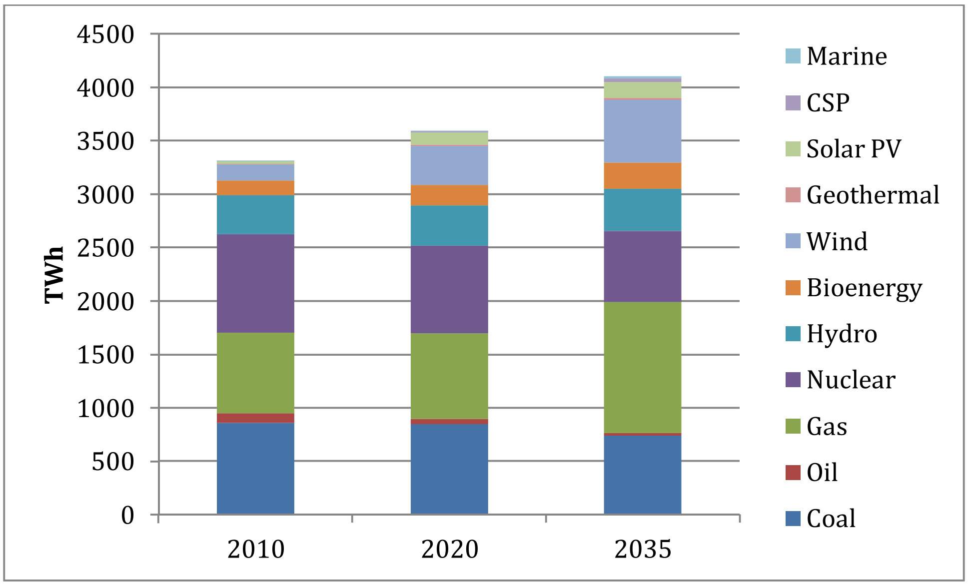
Source: IEA, 2012a.

As shown in Figure 2, trends for TPED translate accordingly into electrical capacity and electricity generation. Electrical capacity is projected to increase from 910 GW in 2010 to 1,083 GW in 2020 (+19%) and to 1,250 GW in 2035 (+37% compared to 2010). Gas will remain the most important energy source until 2035, doubling its capacity between 2010 and 2035. Coal electrical capacity, on the other hand, will be almost halved. In terms of renewables, wind power capacity is projected to double between 2010 and 2020 and to triple between 2010 and 2035. Wind will thus have already overtaken hydro power in terms of installed capacity by 2020. Solar PV capacity will also increase strongly, although mostly between

2010 and 2020 (+247%) and much less afterwards (+330% from 2010 until 2035). Wind, hydro and solar PV cover almost all renewable electrical capacity, which will increase from 32% of total installed capacity in 2010 to 44% in 2020 and 49% in 2035. The share of nuclear capacity, on the other hand, is projected to decline from 15% in 2010 to 11% in 2020 and 8% in 2035.

Electricity generation is expected to increase more in the Current Policies Scenario than in any other WEO 2012 scenario, rising from 3,310 TWh in 2010 to 3,588 TWh in 2020 (+8%) and 4106 TWh in 2035 (+24% between 2010 and 2035). Within the electricity mix, the share of fossil fuels remains more or less constant (changing from 52% in 2010 to 47% in 2020 and 49% in 2035), but the composition of fossil fuels shifts considerably towards gas, which becomes by far the largest contributor to EU electricity generation by 2035. Although the share of nuclear power decreases considerably between 2010 and 2035, it remains the largest low-carbon electricity generator. Renewables, on the other hand, gain substantially in electricity generation, up from 21% in 2010 to 30% in 2020 and 35% in 2035. Similar to 2010, the most important renewable energy source (RES) technologies in 2035 will be wind, hydro and bioenergy, although the role of solar PV becomes increasingly prominent. Other RES technologies, like geothermal, marine or concentrated solar power (CSP), will remain marginal.

Figure 2. EU27 electricity generation in the WEO 2012 Current Policies Scenario



Source: IEA, 2012a.

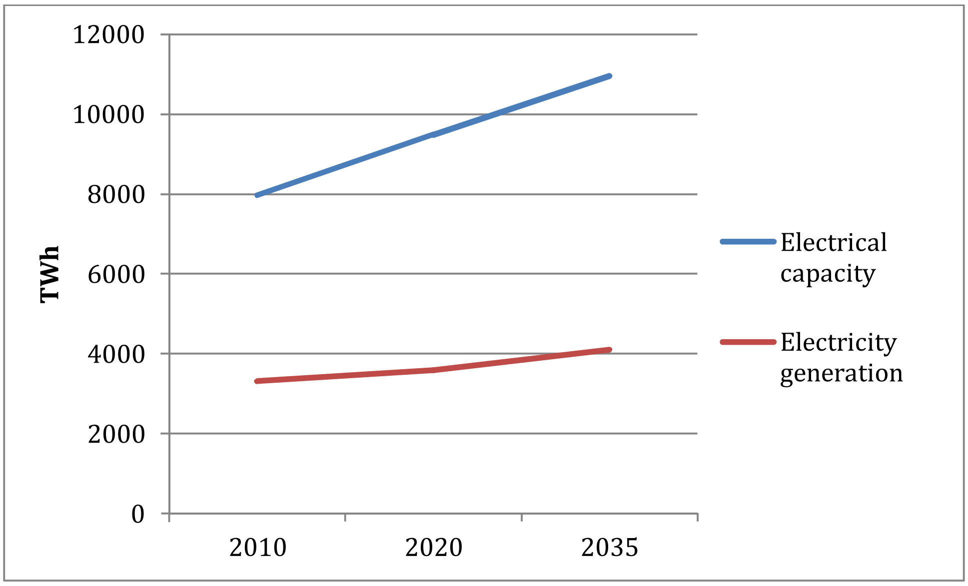
Similar to overall energy demand, gas appears to be the technology with the most potential in this scenario, while nuclear energy, coal and oil are projected to become less important.

The rising share of (variable) renewables also leads to a significantly stronger increase in electrical capacity compared to projected electricity generation. As shown in Figure 3, the ratio[4] of the former to the latter increases from 2.4:1 in 2010 to 2.6:1 in 2020 and 2.7:1 in 2035, indicating that more installed capacity will be needed to generate the same amount of electricity. And indeed, growth rates of installed capacity outpace those of electricity

[4] The ratio expresses installed electrical capacity in relation to projected generated electricity output. It is calculated by converting installed capacity into a theoretical generation maximum, which would be reached if all installed capacity produced electricity at full capacity for every single hour of the year (i.e. 8,760 hours per year), in other words, if the capacity factors for all installed capacity were 100%.

demand, with electrical capacity increasing by 19% between 2010 and 2020 and by 37% between 2010 and 2035 (starting at 910 GW in 2010).

Figure 3. Comparison of theoretical generation potential with actual electricity output in the WEO 2012 Current Policies Scenario



Source: Own calculation based on IEA (2012a).

Note: Electrical capacity is calculated by assuming that installed capacity would function at full capacity all around the year (i.e. with a capacity factor of 100%), while electricity generation reflects the projected electricity output taking into account different capacity factors for different technologies.

In terms of sectoral consumption, the relative share of industry, transport and buildings is not projected to change much, although there is a tendency for increased energy consumption in buildings, mainly at the expense of transport. Similarly stable is the composition of energy sources contributing to each sector's energy demand. Notable exceptions are other renewables in buildings (i.e. excluding bioenergy), biofuels in transport and bioenergy in industry, which on average grow annually by 6.3%, 3.2% and 2.2%, respectively, between 2010 and 2035. However, these growth rates still relate to very low absolute numbers and do not lead to a breakthrough of these technologies in their respective sectors.

Insufficient fuel-switching in primary energy demand and electricity generation, as well as increased consumption by final energy demand sectors, exclude the possibility of a socio-ecological transition under the current trends. Continuing on this track would lead to an increase in temperature of 5.3 degrees Celsius, well above the 2 degrees Celsius international target.

3. Decarbonisation scenarios

This section reviews various decarbonisation scenarios, include those presented by the IEA, the European Commission, two projects funded under the 7th Framework Programme of the European Commission, the International Institute for Applied Systems Analysis (IIASA), Greenpeace, the European Climate Foundation (ECF), and Eurelectric. Each subsection starts with a brief explanation of the modelling approach and the underlying assumptions (except for the *World Energy Outlook*, which was already introduced in the previous chapter) before presenting key results about the development of the energy mix (generally) to 2020 and 2050, both for the EU as a whole and on a regional scale where data is available. Where possible, developments on a sectoral basis are also explained (i.e. consumption patterns in industry, transport and buildings).

3.1 International Energy Agency

3.1.1 World Energy Outlook 2012

The results presented in this section will focus only on the 450 Scenario of the WEO 2012, as this scenario is considered the closest to the new socio-ecological transition as described above. In fact, the 450 Scenario sets out a pathway consistent with a 50% chance of limiting global warming to two degrees Celsius compared to pre-industrial levels. This requires limiting the concentration of GHG in the atmosphere to 450 parts per million of CO_2 equivalent (450 ppm CO2e), hence the name of the scenario.

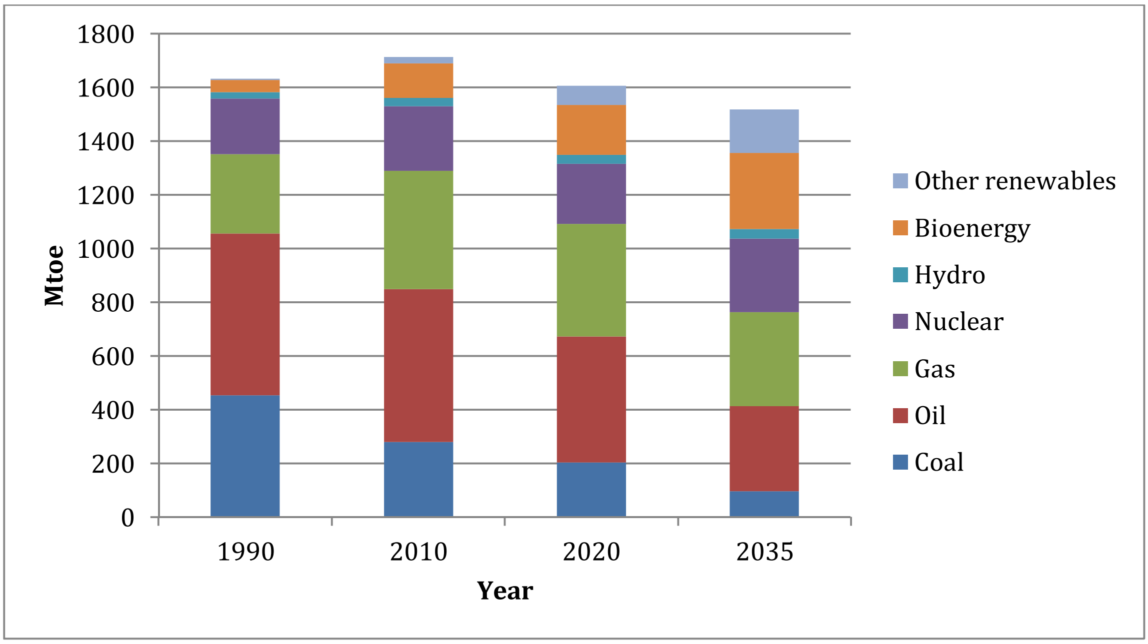
In contrast to the other scenarios, the 450 Scenario is not a projection based on past trends under consideration of known policy actions. Instead, it reflects an energy pathway consistent with the two degrees Celsius target, in view of key non-policy assumptions listed in the previous section. For the 450 Scenario developing in the EU, economic growth, population growth and technology assumptions are the same as for the Current Policies Scenario. Energy and CO_2 prices, however, are expected to evolve differently (reported in 2011 US dollars and their equivalent in euros):[5]

- *Energy prices:* The oil price is expected to increase from $108 (€78) in 2011 to $113 (€81) per barrel in 2020. Due to decreasing oil demand, the price would drop to some $100 (€72) in 2035. European import prices for natural gas are not expected to increase substantially, although the tendency towards more hub-based pricing is offset by rising transport costs of increasing amounts of gas imported from ever more distant sources. As a result, prices will increase from $10 (€7) per MBtu in 2011 to $11 (€8) in 2020, then decrease back to $10 (€7) per MBtu by 2035. As regards the price for coal, climate policies will sharply reduce demand, thus reducing OECD steam coal import prices from $123 (€88) per tonne in 2011 to $98 (€70) in 2020 and further to $70 (€50) by 2035.
- *CO_2 price:* Tight climate policies would push the EU carbon price to $45 (€32) per tonne in 2020. This scenario assumes CO_2 prices to be established in all OECD countries and that prices would converge at $120 (€86) per tonne by 2035.

The results of the 450 Scenario show both a decreasing demand for energy in the EU and a shift in the composition of demand from fossil fuels to renewables and nuclear. Figure 4 shows that TPED in the EU decreases by 6% between 2010 and 2020, and by 11% between 2010 and 2035. In addition, the share of low carbon energy sources will be increased from 25% in 2010 to 32% in 2020 and 50% in 2035. These figures include both renewable and nuclear energy. Renewables alone will increase from 11% in 2010 to 18% in 2020 and 32% in 2035. However, this also means that fossil fuels are projected to remain the main source of energy, constituting 75% of the energy mix in 2010, 68% in 2020 and just over 50% in 2035.

[5] The exchange rate is based on the annual average US dollar/euro exchange rate of 2011, as reported by Eurostat (€1 = $1.3920).

Figure 4. Development of EU total primary energy demand in the WEO 2012 450 Scenario



Source: IEA, 2012a.

Table 2, which is based on the data of Figure 4, shows that the key "winning technologies" in the EU will be "other renewables" (mainly wind and solar power) and bioenergy, which are expected to increase by 218% and 43% between 2010 and 2020, and by 641% and 117% between 2010 and 2035, respectively. Hydro and nuclear power are not expected to increase dramatically. Key "losing technologies" will be all fossil-based energy sources, with coal and oil leading the way.

Table 2. Percentage change in total primary energy demand in the EU for different energy sources in the WEO 2012 450 Scenario

Year	2010-2020	2010-2035
Coal	-27%	-65%
Oil	-17%	-44%
Gas	-5.0%	-21%
Nuclear	-6%	+14%
Hydro	+7%	+19%
Bioenergy	+43%	+117%
Other renewables	+218%	+641%

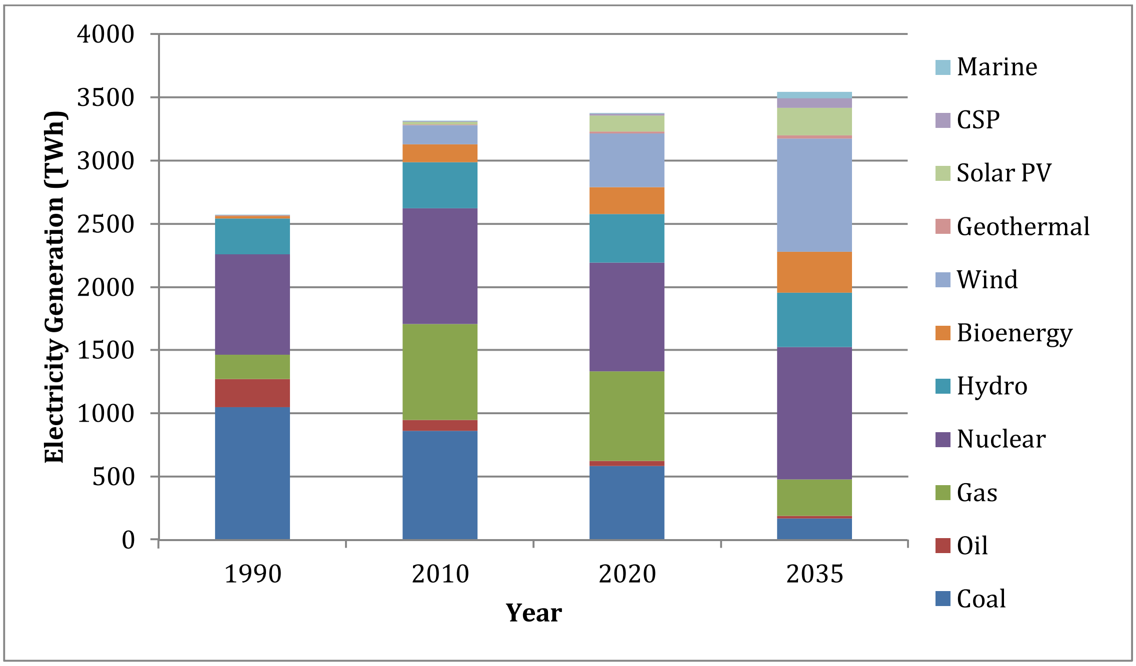
Source: IEA, 2012a.

In contrast to the decreasing primary energy demand, the electricity sector is expected to expand significantly in the 450 Scenario. Electrical capacity is projected to increase from 910 GW in 2010 to 1,116 GW in 2020 (+23%) and then to 1,349 GW in 2035 (+48% compared to 2010). In this scenario, wind power will contribute more than a quarter of total installed capacity in 2035, followed by gas with about a fifth. The rest is almost equally shared between solar PV, hydro and nuclear. Other sources (mainly coal and bioenergy) play a marginal role.

The shift away from fossil fuels is also mirrored in electricity generation. Figure 5 shows that electricity generation in the EU is projected to increase by 2% by 2020 and by 7% by 2035, starting from 3,310 TWh in 2010. The share of low-carbon technologies in total electricity generation (i.e. renewables and nuclear power) is projected to increase from 48% in 2010 to 61% in 2020 and to over 86% in 2035. Renewables alone will increase their share from 21% in 2010 to 35% in 2020 and 57% in 2035. Although nuclear will be the largest source of electricity in 2035, most of this increase is due to the expansion of wind-based power generation, which increases from 149 TWh in 2010 to 426 TWh in 2020 and 896 TWh in 2035 (a six-fold increase between 2010 and 2035). Similarly, biomass and solar PV will contribute to the increasing share of renewables, although at a much lower level than wind.

The share of fossil fuels will decrease to 13% in 2035. Coal, still with the largest share in electricity generation in 2010, will also be marginalised by 2035.

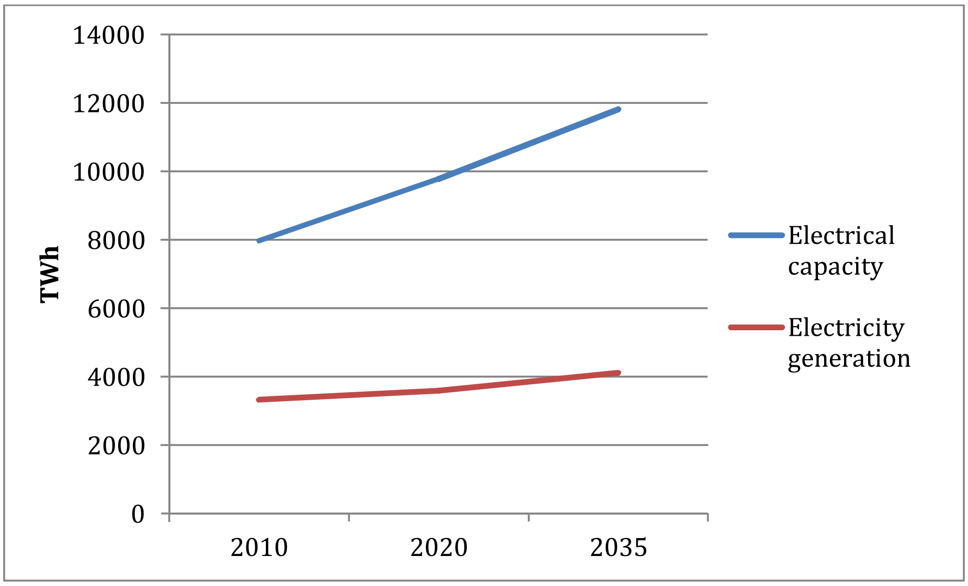
Figure 5. Electricity generation in the EU27 as projected in the WEO 2012 450 Scenario



Source: IEA, 2012a.

Given the large role of variable renewables in this scenario and the lower capacity factors of variable renewables, installed capacity will need to increase much faster than the increase in electricity demand. In fact, electric capacity is projected to increase by 23% between 2009 and 2020 and by 48% between 2009 and 2035. This development can be seen in Figure 6, which also shows that the ratio of installed capacity (or theoretical generation potential) to actual projected electricity generation increases from 2.4:1 in 2010 to 2.7:1 in 2020 to 2.9:1 in 2035, meaning that by 2035 each unit of electricity generated will need to be backed-up by almost three units of equivalent installed capacity.

Figure 6. Comparison of theoretical generation potential with actual electricity output in the WEO 2012 450 Scenario



Source: Own calculation based on IEA (2012a).

Note: Electrical capacity is calculated by assuming that installed capacity would function at full capacity all around the year (i.e. with a capacity factor of 100%), while electricity generation reflects the projected electricity output taking into account different capacity factors for different technologies.

The sectoral analysis reveals that absolute total final consumption (TFC) of industry and buildings will be more or less constant over the period under consideration (2010-2035). Only in transport is final energy consumption projected to decrease significantly, from 319 Mtoe in 2010 to 285 Mtoe in 2020 and 224 Mtoe in 2035, an overall decrease of almost 30%. This decrease is mostly due to increased fuel economy of vehicles. While the consumption of biofuels, electricity and other fuels is expected to increase (albeit at low levels), oil consumption will be halved between 2010 and 2035. However, oil will continue to dominate the transport sector, with two thirds of final energy consumption coming from that source in 2035 (down from 93% in 2010).

The amount of heat consumed is not expected to change in either industry or buildings. WEO 2012 makes no indications about a shift in heat sources.

In the 450 Scenario, the EU nearly halves its CO_2 emissions from 2.5 Gt in 2011 to 1.8 Gt in 2035. A large part (45%) of this abatement is due to electricity savings and energy efficiency. Also important is the substitution of fossil-fuel power plants without CCS with increasing amounts of renewables in the power sector, especially with wind (followed by bioenergy and hydro). Finally, road transport makes a significant contribution to emissions abatement, mainly due to more efficient vehicles, biofuels and plug-in vehicles.

3.1.2 *Energy Technology Perspectives 2012*

Another flagship publication by the IEA with forecasts of technological developments in the energy sector is *Energy Technology Perspectives*, which are published biannually and most recently in 2012 (ETP 2012). In contrast to the WEO 2012, ETP 2012 is primarily based on the ETP model, which combines backcasting and forecasting techniques in order to "identify the most economical way for society to reach a desired outcome" (IEA, 2012b). The ETP model is describes as a "bottom up, technology rich model, containing more than a 1000 technology options" (IEA, 2012b), which integrates from four soft-linked models: energy conversion, industry, transport and buildings. ETP 2012 is based on 2009 data and provides regional and sectoral energy projections to 2075.

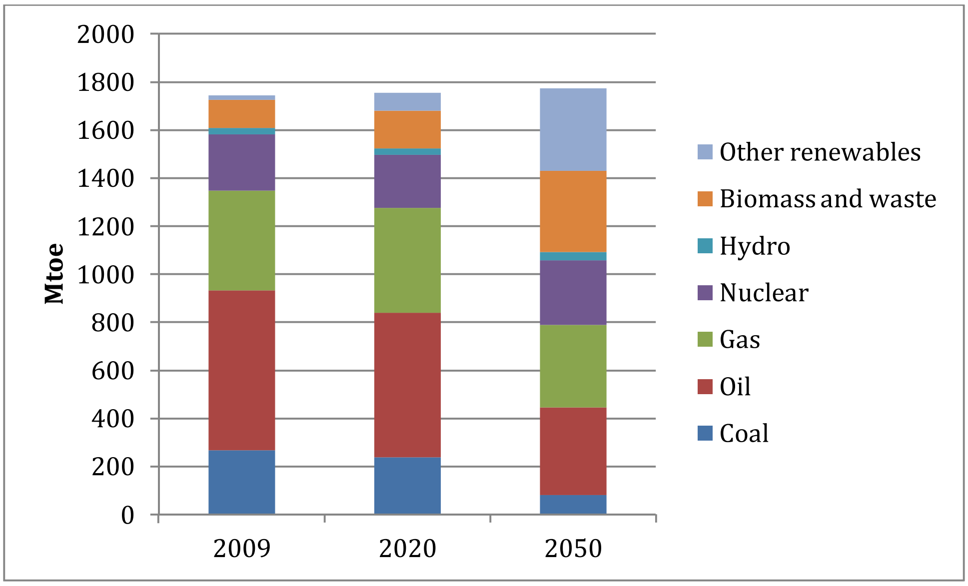
Three different scenarios were calculated for ETP 2012, a 6°C Scenario, a 4°C Scenario and a 2°C Scenario (2DS). In view of the required decarbonisation efforts associated with the new socio-ecological transition as described above, only the 2DS will be reviewed in this section. The 2DS is more ambitious than the 450 Scenario of WEO 2012, describing a pathway consistent with an 80% chance of limiting global warming to two degrees Celsius compared to pre-industrial levels (as opposed to a 50% chance in the 450 Scenario).

As with the WEO and other models, demand for energy in the ETP scenarios is driven by economic and population growth, which in turn have an impact on energy prices. EU GDP growth is expected to decline from 2.0% annually between 2009 and 2020 to 1.8% annually between 2009 and 2050. The number of EU citizens will increase only slightly from 500 million in 2010 to 511 million in 2020 and 512 million in 2050. While assumptions of economic and population growth are equal over all three scenarios, fossil fuel prices (henceforth quoted in 2010 US dollars and their equivalent in euros)[6] are also determined by the level of ambition of climate policies. In the 2DS, the oil price is expected to increase from $78 (€56) per barrel in 2010 to $97 (€73) in 2020. After 2035, the oil price falls to some $87 (€66) in 2050. Due to the large-scale shift away from coal, the OECD steam coal import price is expected to decrease significantly in the long term, from $99 (€75) per tonne in 2010 to $93 (€70) in 2020 and $60 (€45) in 2050. European gas import prices will follow an inverted U-curve between 2010 and 2050, starting at $7 (€5) per Mbtu in 2010, rising to $10 (€8) in 2020 and falling back to $8 (€6) in 2050.

Based on these assumptions, the ETP 2012 projects European total primary energy supply (TPES) to increase only marginally (by 2%) over the period 2009-2050. However, as shown in Figure 7, there will be a considerable shift in energy sources away from fossil fuels towards renewables. Fossil fuels still contribute some 77% to the EU TPES in 2009, but their share is reduced to 73% by 2020 and more drastically to 45% by 2050. Nuclear energy will not be able to increase its role in the energy mix by a large amount, and it is mainly renewables in the form of biomass/waste and "other renewables" (i.e. mostly wind and solar) that will be responsible for greening the energy mix.

[6] The exchange rate is based on the annual average US dollar/euro exchange rate of 2010, as reported by Eurostat (€1 = $1.3257).

Figure 7. Development of EU total primary energy supply in the ETP 2012 2°C Scenario



Source: Own calculations based on IEA (2012b).

Table 3 shows the key "winning" and "losing" technologies. While coal and gas are losing shares, "other renewables", including wind and solar energy, will substantially increase their share in the EU energy mix, followed by biomass/waste.

Table 3. Percentage change in total primary energy supply in the EU for different energy sources in the ETP 2012 2°C Scenario

Year	2009-2020	2009-2050
Coal	-10.7%	-69.6%
Oil	-9.7%	-45.0%
Gas	+5.3%	-17.8%
Nuclear	-6.2%	+15.7%
Hydro	-3.4%	+19.0%
Biomass and waste	+36.5%	+192.9%
Other renewables	+274.4%	+1639.5%

Source: IEA, 2012b.

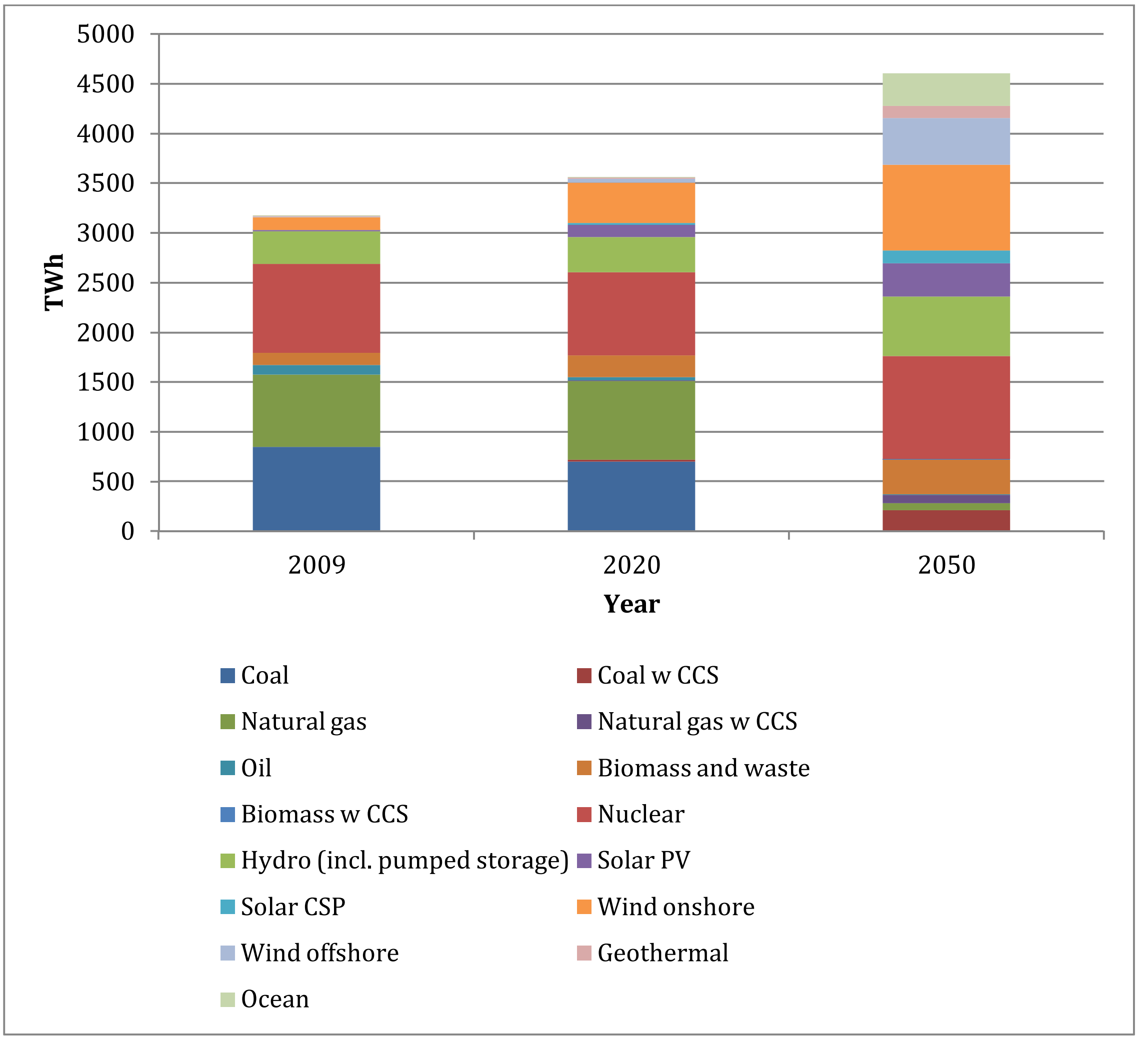
The 2DS of ETP 2012 projects reductions of CO_2 emissions from power generation in the order of 90% between 2009 and 2050. This is considered possible despite the ongoing electrification of the energy system and the related increases in electrical capacity and gross electricity generation. Reductions in CO_2 emissions are first and foremost achieved by increasing the share of renewable energy sources, but also by an increasingly widespread application of CCS in the electricity sector.

Total installed electrical capacity is projected to increase by 29% between 2009 and 2020 and to almost double between 2010 and 2050. Electrical capacity increases particularly quickly after 2020 (see Figure 9) due to the increasing installation of renewables based power plants. While in 2009 natural gas, coal, hydro and nuclear still accounted for 79% of electrical capacity, their share decreases to 31% by 2050. In fact, installed capacity of wind alone will be slightly larger than that of all the four "old" technologies taken together, followed by solar PV as the second largest renewables-based electrical capacity. Wind and solar PV together will contribute more than 50% of installed capacity.

Electricity generation will expand at much the lower levels of 12% between 2009 and 2020, and 45% between 2009 and 2050 (see Figure 8). The share of renewables in electricity generation is projected to increase from 19% in 2009 to 33% in 2020 and 69% in 2050. Key technologies by 2050 will be onshore wind, hydro, offshore wind, biomass, solar PV and ocean (in that order), which together will amount to 81% of all renewable technologies deployed in electricity generation.

CCS is only expected to be applied on a large scale after 2020. In fact, it is assumed that coal-based electricity will be almost completely CO_2 neutral by 2050 due to CCS technology, while only slightly more than half of gas-based electricity generation will be equipped with CCS technology. While in total CCS will only contribute less than 1% of electricity generation by 2020, its share will increase to 6.5% in 2050.

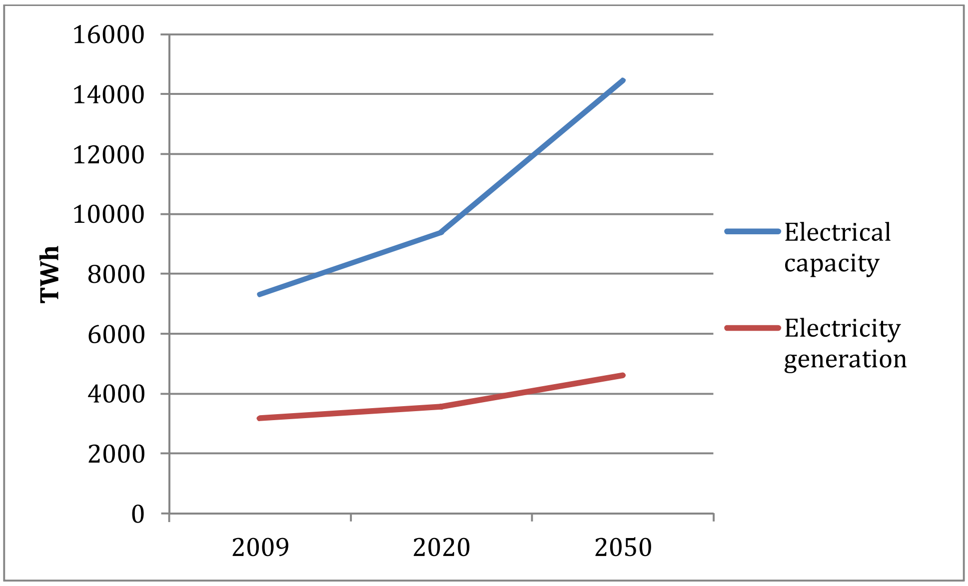
Figure 8. Gross electricity generation in the EU27 as projected in the ETP 2012 2°C Scenario



Source: IEA, 2012b.

Similar to other scenarios above, increasing power generation from renewable energy sources will be accompanied by even greater increases in related generation capacity in order to deal with lower capacity factors of variable renewables, like wind and solar PV, compared to conventional electricity sources. Figure 9 shows that the ratio of installed capacity to electricity generation increases significantly from 2.3:1 in 2009 to 2.6:1 in 2020 and 3.1:1 by 2050.

Figure 9. Comparison of theoretical generation potential with actual electricity output in ETP 2012 2°C Scenario



Source: Own calculations based on IEA (2012b).

Note: Electrical capacity in the graph is calculated by assuming that installed capacity would function at full capacity all around the year (i.e. with a capacity factor of 100%), while electricity generation reflects the projected electricity output taking into account different capacity factors for different technologies.

Electricity will play an increasing role in transport, in particular in passenger road transport and as of the mid-2020s. However, ETP 2012 also projects a larger role for biofuels, mostly in road and air passenger transport, but also in road and water freight transport. The role of hydrogen is expected to be marginal in road transport.

3.2 European Commission roadmaps

Europe 2020 is the EU's ten-year growth strategy. It was proposed by the European Commission in 2010 and follows the Lisbon Strategy for the period 2000-2010. Europe 2020 aims at achieving "smart, sustainable, inclusive growth" and includes concrete targets to be achieved by 2020, *inter alia* in the area of energy and climate change. The latter include a reduction of GHG emissions by a minimum of 20% compared to 1990, an increase in the share of renewables in the energy mix to 20%, as well as an increase in energy efficiency by 20% compared to projections.

One of the seven flagship initiatives under Europe 2020 aims to support the shift towards a resource-efficient, low-carbon economy to achieve sustainable growth. The flagship initiative for a resource-efficient Europe provides a long-term framework for actions in many policy areas, supporting policy agendas for climate change, energy, transport, industry, raw materials, agriculture, fisheries, biodiversity and regional development.

Several strategic documents and policy proposals have been tabled by the European Commission within the context of the resource-efficient Europe flagship initiative. Three of these are of particular relevance for this paper and will be summarised below. They include the *Roadmap for moving to a competitive low carbon economy in 2050*, the *Roadmap to a Single*

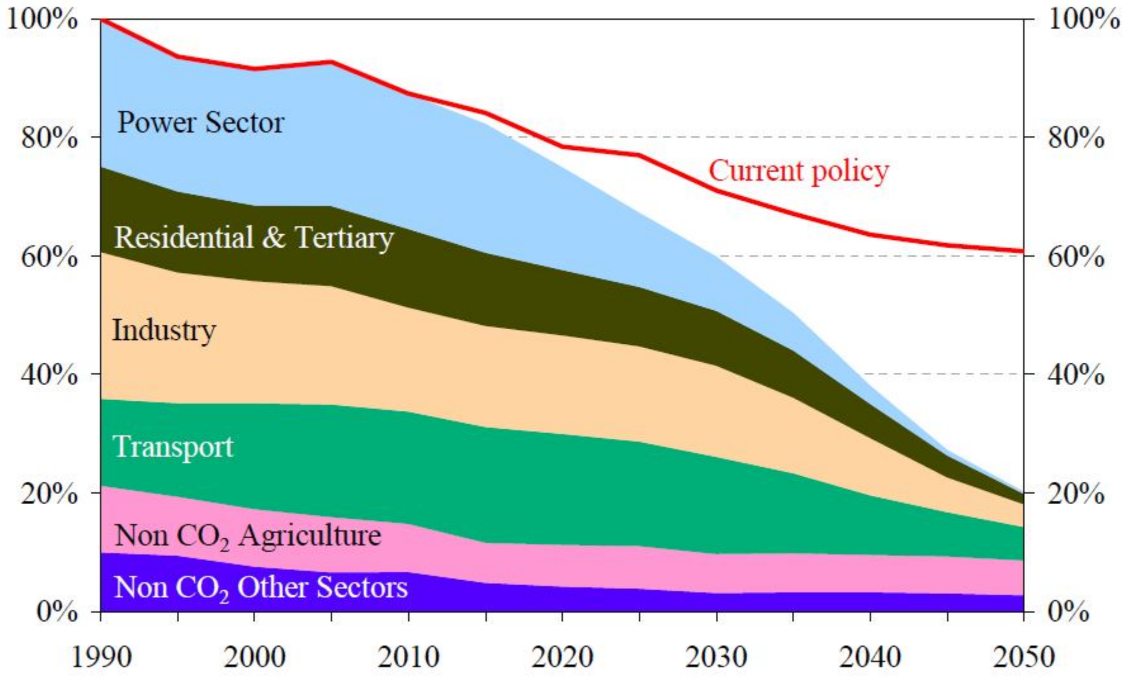
Transport Area – Towards a competitive and resource efficient transport system and, most importantly for this paper, the *Energy Roadmap 2050*. Emphasis will be placed on the latter since it provides the most in-depth assessment of the energy sector and also incorporates the other roadmaps in a consistent manner (i.e. modelling for the three papers was done jointly and with the same dataset in principle).

3.2.1 Roadmap for moving to a competitive low carbon economy in 2050

EU climate change policy continues to be rooted in the 2007/8 Energy and Climate Change Package, which set legally binding targets to reduce GHG emissions by 20% (compared to 1990) and to increase the share of renewable in total energy to 20%. The EU is on track to achieve both targets.

In contrast to these binding short-term targets, the *Roadmap for moving to a competitive low carbon economy in 2050* published by DG Climate Action in March 2011 (nine months before the *Energy Roadmap*) proposes a long-term target for 2050. Delivering on the objective of the European Council to reduce GHG emissions by 80-95% by 2050 (compared to 1990), the *Roadmap* foresees *domestic* EU GHG emissions cuts of 80% below 1990 levels by 2050. In order to reach mitigation levels of up to 95%, the remaining GHG emissions reductions should be offset partly or entirely by the purchase of reduction units outside the EU.

Figure 10. Decarbonisation trajectory by sector, 1990-2050 (1990=100%)



Source: European Commission, 2011a.

Figure 10 shows the evolution of EU GHG emissions by sector towards an overall 80% domestic reduction by 2050. On the one hand, it shows that total domestic emissions would decrease within a cost-effective pathway by 40% by 2030 and 60% by 2040. In fact, these are also the interim targets for GHG emissions reductions proposed by the Commission. On the other hand, the graph shows that all sectors of the economy will need to contribute significantly to emissions abatement. The analysis of the Commission also included pathways for key sectors in different scenarios, assuming different rates of technological innovation and different fossil fuel prices. The results of this analysis are presented in Table 4.

Both Figure 10 and Table 4 show that the power sector will need to take the lead by almost completely mitigating GHG emissions (mainly CO_2) by 2050. This is consistent with the current policy mix, which pushes renewables onto the market by mandates. The 20% renewables target – most likely to be achieved – translates into a renewable share in the power sector of roughly 35%, meaning that the power sector is to be reorganised around the requirements of (intermittent) renewables, even if renewables support is likely to weaken after 2020. This includes smart grids, storage technologies, grid reinforcement, fossil back-up and flexible capacity as well as demand-side measures, etc.

Table 4. Sectoral EU GHG emissions reductions

GHG reductions compared to 1990	2005	2030	2050
Total	-7%	-40 to -44%	-79 to -82%
Sectors			
Power (CO_2)	-7%	-54 to -68%	-93 to -99%
Industry (CO_2)	-20%	-34 to -40%	-83 to -87%
Transport (incl. CO_2 aviation, excl. maritime)	+30%	+20 to -9%	-54 to -67%
Residential and services (CO_2)	-12%	-37 to -53%	-88 to -91%
Agriculture (non-CO_2)	-20%	-36 to -37%	-42 to -49%
Other non-CO_2 emissions	-30%	-72 to -73%	-70 to -78%

Source: European Commission, 2011a.

The residential and services sector will need to decarbonise by up to 91% by 2050 compared to 1990, mainly based on reductions in required heating from improved insulation and greater use of electricity and renewables for building heating, as well as more energy efficient appliances. Industry decarbonisation efforts are boosted after 2030 with the increasing application of CCS to reach some 87% by 2050. Given its high dependence on fossil fuels, the transport sector will not be required to decarbonise to a similar extent although GHG emissions will still need to be reduced by 67% by 2050. This is mainly achieved through fuel efficiency (which is the key driver until 2025), cleaner energy use through new fuels and propulsion systems, and "getting prices right" in the context of a properly functioning competitive market resulting in an economically efficient use of transport resources.

3.2.2 2011 White Paper on Transport

Economic growth, progressive European integration and improved quality of transport itself have led to a substantial increase in transport volumes in recent decades. These positive developments have gradually made apparent the negative side effects of mass transport in Europe, including congestion, air and noise pollution, increasing oil import dependency, injuries and deaths, as well as substantial amounts of GHG emissions. Today the transport sector accounts for about a quarter of EU GHG emissions and therefore has an important part to play in the EU's efforts to move towards a low-carbon economy.

In 2011 the European Commission published a White Paper entitled *Roadmap to a Single Transport Area – Towards a competitive and resource efficient transport system*. This White Paper concludes that in order for the EU to reach its short- and long-term mitigation objectives, "a reduction of at least 60% of GHGs by 2050 with respect to 1990 is required from the transport sector" (which translates into a roughly 70% reduction based on the 2008 level). In order to achieve this reduction objective, the Commission proposes several technology deployment targets, including:

- "halve the use of 'conventionally fuelled' cars in urban transport by 2030";
- "phase them out in cities by 2050"; and
- "achieve essentially CO2-free city logistics in major urban centres by 2030" (European Commission, 2011b: 9).

The Commission (2011b) stresses that the decarbonisation of the transport sector depends initially on technology development towards clean and efficient vehicles based on conventional internal combustion engines. Only when new technologies have become cost-effective will the market allow the deployment of low-carbon vehicles. New and improved technologies and fuels would contribute to substantial energy intensity improvements, which are projected to reach some 70% in EU transport. According to European Commission projections, the energy intensity of passenger transport would decrease by about 65% between 2005 and 2050, mostly due to the enforcement of CO_2 standards,[7] but also due to other measures like eco-driving and fuel efficiency labelling. For freight transport, energy intensity would reduce by around 50% due to intensive policies with the objective of managing demand and encouraging modal shift, provided this is feasible.

The decarbonisation scenarios of the *Energy Roadmap 2050* (see below) take into account the policy measures detailed in the transport White Paper.

3.2.3 Energy Roadmap 2050

In the EU's *Energy Roadmap 2050* (European Commission, 2011c), the Commission presents five decarbonisation scenarios, playing through five different combinations of the four pure decarbonisation options (energy efficiency, RES, nuclear and CCS). All of them detail potential developments of the EU energy mix to 2050 that would allow for a decrease in domestic EU GHG emissions of at least 80% compared to 1990. While the five decarbonisation scenarios are modelled based on specific political priorities reflecting different societal preferences, their common emissions constraint allows for a straightforward comparison of the pathways.

- *High Energy Efficiency scenario:* As a result of the political objective of achieving very high savings in primary energy consumption, substantive energy efficiency policies are assumed to be in place that would not only almost achieve the 20% energy efficiency target for 2020, but would lead to further significant reductions of primary energy demand all the way to 2050.

- *Diversified Supply scenario:* Decarbonisation is achieved by means of carbon prices and carbon values (i.e. an undefined proxy for policy measures that bring about emission reductions), which are applied to all sectors (ETS and non-ETS). The scenario assumes societal support (member states, investors, citizens) for nuclear energy (except for declared 'nuclear sceptics' such as Belgium and Germany), CCS, as well as for RES facilitation policies.

- *High RES scenario:* The political ambition behind this scenario is to achieve a very high share of RES (almost 100% of final consumption in power generation). Technologies deployed include wind (both on- and offshore), solar PV, as well as CSP and storage, increased uptake of heat pumps, etc. An important enabling development is market

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[7] In its Impact Assessment, the EU Commission (2011b: 76) supports the view that CO_2 standards "*correspond to de facto energy efficient standards*" since currently the transport sector depends almost entirely on fossil fuels. However, this may not be the case as other technologies (for example, electricity and hydrogen) increase their market penetration. Beyond 2020, other kinds of standards such as energy efficiency standards, may gain prominence as a transport policy tool.

integration (to increase the efficiency of deployed renewables), which in turn depends on more transmission infrastructure.

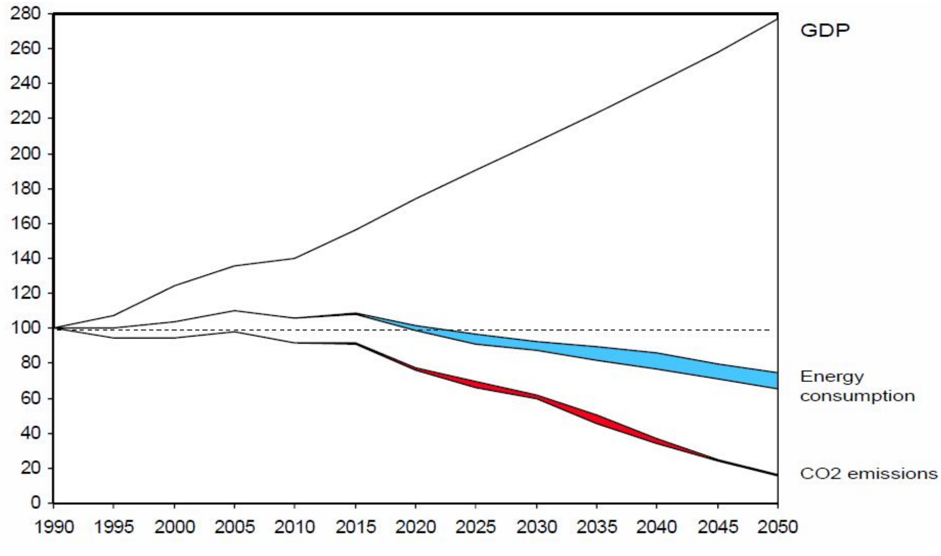
- *Delayed CCS scenario:* The lack of public acceptance of CCS prevents the timely construction of storage sites and transport. As a consequence, large-scale CCS deployment only starts after 2040. In this scenario, however, nuclear is considered a viable option, except for the 'nuclear sceptical countries' (see above).
- *Low nuclear scenario:* Except for those nuclear plants already under construction in Finland and Slovakia, this scenario foresees no further new builds and after 2030 there are no more new decisions on lifetime extensions, even if they were economically attractive. By contrast, CCS technology is deemed commercially and politically viable and serves as a major substitute for nuclear.

The Commission presents detailed data on all scenarios, but only aggregated for the EU27 as a whole. Macroeconomic and demographic assumptions are the same across all decarbonisation scenarios:

- Population grows from 499 million in 2010 to 514 million in 2020, peaking in the 2030s at 520 million before decreasing to 515 million by 2050.
- Average annual economic growth is 2.2% until 2020, 1.7% from 2020 until 2030, and 1.5% from 2030 until 2050.
- The oil price (in constant 2008 US dollars per boe) is assumed to remain quite constant at between \$79 and \$85 until the early 2030s, when if falls to \$79. By 2050 it is assumed to decline to \$70. Price developments are driven by the assumption on global climate action made in the Commission's decarbonisation scenarios.

Carbon prices vary by decarbonisation scenario. In 2020, estimates (all in 2008 euros per tCO2) range from €15-25, 2030 carbon prices fall to a range of €25-63, by 2040 they rise to €87-190, and in 2050 carbon prices reach €234-310.

Figure 11. Development of GDP, primary energy consumption and energy-related CO_2 emissions



Source: European Commission, 2011c.

All scenarios substantively reduce energy-related CO_2 emissions by 2050 (by 83-84%, see Figure 11). By 2020, CO_2 emissions are already estimated to be 22-24% lower. The decarbonisation trajectories resemble those of the Low Carbon Roadmap (see above). Primary energy consumption and CO_2 emissions decrease across all scenarios from 2015. In fact, gross inland consumption of energy decreases by around 4% by 2020 (compared to 2010) and by 30-40% by 2050, depending on the scenario. The continued growth of GDP implies that the decarbonisation scenarios provide an example of absolute decoupling.

Table 5 shows the range of shares that each energy source contributes to the energy mix (expressed in gross inland consumption) in the five different decarbonisation scenarios. The table shows that fuel shares are not expected to differ substantially across the scenarios in 2020. Differences are larger by 2050, depending on technology deployment, which provides evidence for the great uncertainty of the pathway the socio-ecological transition could take in the long run.

Table 5. Energy source as a percentage of gross inland consumption

	1990	*2010*	*2020*	*2050*
Solids	27	16	13-14	2-10
Oil	38	36	34-35	14-16
Natural gas	18	25	22-23	19-26
Nuclear	12	13	13-14	3-18
Renewables	5	9	16-17	41-60

Source: European Commission, 2011c.

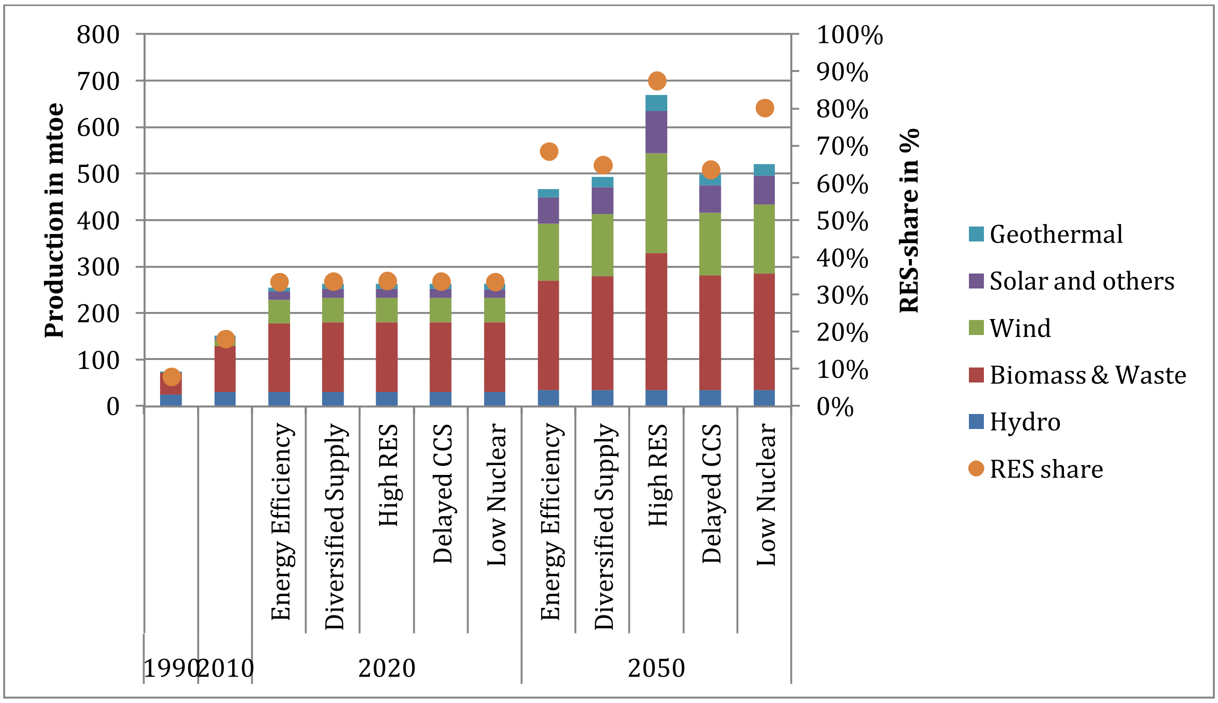
Table 5 shows that the long-run contribution of renewables varies across scenarios. Given the 20-20-20 targets, the prospects for renewables are quite clear up to the 2020s, where they will roughly approach 20% of gross inland energy consumption. In 2050, the share of renewables will vary significantly across scenarios (between 41% and 60%). The 2050 spread for nuclear power is almost as large, at 15 percentage points (between a 3% and 18% share in energy consumption). Generally, the variation is explained by the competition between different low-carbon technologies (renewables, nuclear, fossil fuel-fired with CCS).

Figure 12 allows assessing the role the various RES technologies play in the five decarbonisation scenarios. Looking at domestic production figures makes sense for renewables, as the share of imports is very small (not exceeding 2% of gross EU consumption even in 2050).

Hydro remains fairly constant across the scenarios, contributing 4-5% of total EU27 energy production across all decarbonisation scenarios. The share of biomass and waste, in contrast, is expected to increase significantly across all scenarios, from some 12% in 2010 to 19-20% in 2020 and further to 32-39% in 2050, depending on the scenario. A similar story can be told for wind. Amounting to a mere 2% in 2010, it increases to 7% by 2020 and accounts for 17-23% of total energy production in 2050. Solar, still irrelevant in 2010, has a 2-3% share in 2020, and contributes 7-12% in 2050. Geothermal makes only a minor contribution across all scenarios (a maximum of 4% in 2050).

Figure 12 also shows that the RES share of total domestic energy production will increase significantly across all scenarios. Amounting to 18% in 2010, it increases to 33-34% by 2020 and represents 64-88% in 2050.

Figure 12. Domestic energy production by renewable energy technology across European Commission decarbonisation scenarios



Source: Own graphical representation based on European Commission (2011c).

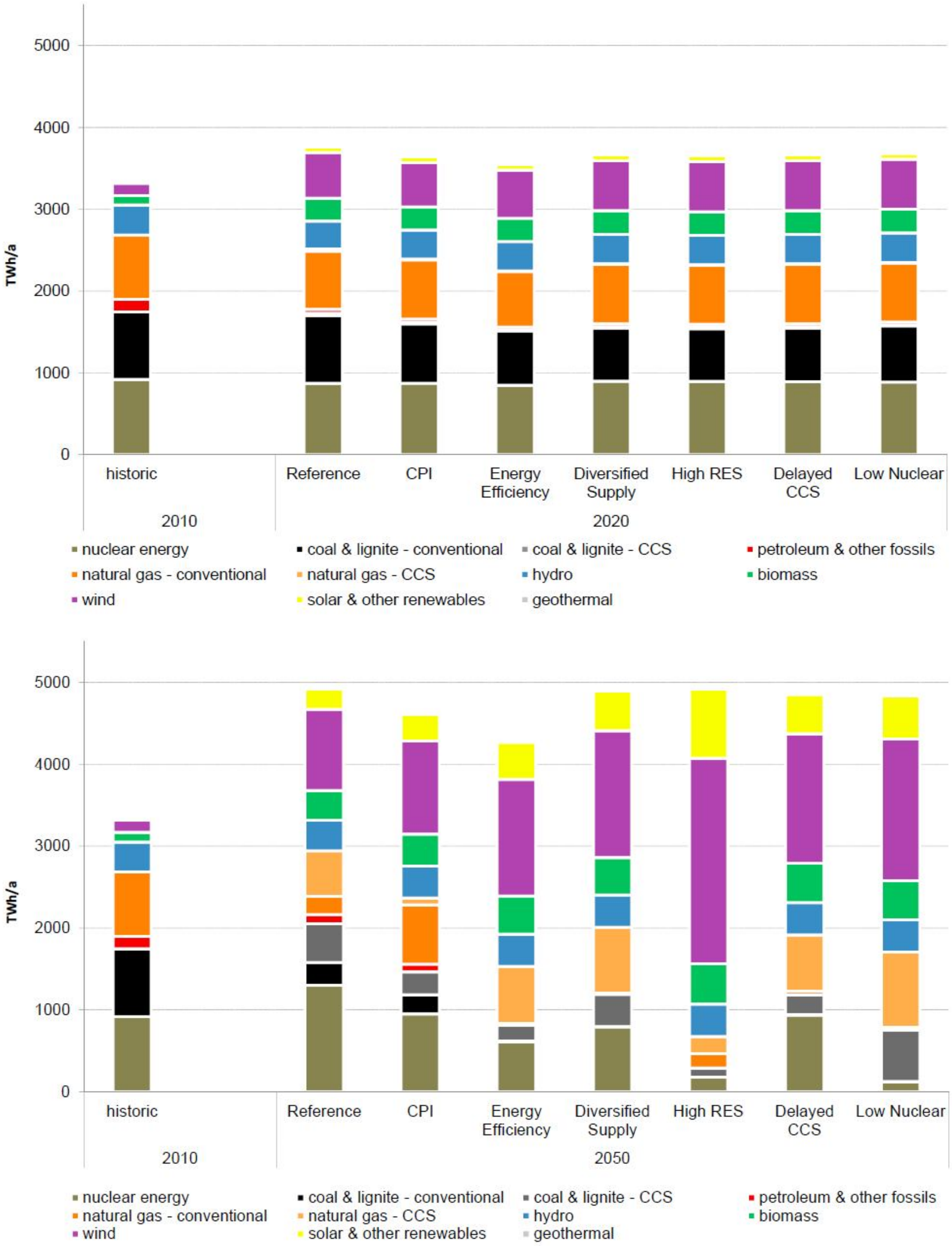
Turning towards the power sector, it has been noted before that this sector will play a crucial role in achieving the EU's GHG emissions reduction targets by 2050. This is also true because the power sector is generally assumed to be key to the decarbonisation of other sectors (e.g. transport).

The increasing importance of the power sector is reflected in the strong growth in electrical capacity. While short-term increases are fairly similar in all scenarios and limited to 23-25% between 2010 and 2020, installed capacity is projected to double by 2050 (ranging from +79% in the High Energy Efficiency scenario to +170% in the High RES scenario). The composition of installed capacity changes from mainly gas and coal-fired, nuclear and hydro, which in 2010 constitute 78% of installed capacity, to much larger shares of wind and solar, which by 2050 could contribute some 60-70% (the latter in the High RES scenario). In fact, wind power capacity is projected to increase from 10% of total capacity in 2010 to 24% in 2020 and some 37-44% in 2050. Similarly, solar capacities could increase from 2% in 2010 to 5% in 2020 and some 22-27% in 2050. Gas-fired thermal plants will also remain important with a projected share of 8-15% in 2050 (down from 27% in 2010).

Figure 13 shows the extent to which various energy sources contribute to gross electricity generation in the EU27 depending on the *Roadmap* scenario and the time horizon under consideration. Although installed capacity increases significantly, the figures for 2020 (upper panel) show that no major differences in total generation are expected across the scenarios in the short term. Nuclear energy, natural gas, coal and wind make up the bulk of electricity generation with more or less similar shares, while hydro and biomass play an inferior role. Other sources are irrelevant in this time perspective.

The situation changes, however, when extending the timeframe to 2050 (lower panel), which expresses a large amount of uncertainty both regarding total electricity generation and the shares of various energy sources. The largest uncertainty regards the extent to which wind contributes to the future generation mix. In the High RES scenario, its share in the EU's power mix in 2050 is almost twice as large as in the other decarbonisation scenarios. Generally, however, wind is expected to become the major source of power generation in all scenarios. A significant share of power will also be generated by nuclear, natural gas, solar and geothermal in most decarbonisation scenarios, but the precise contribution varies widely across scenarios. Only the contribution of hydro power and biomass is fairly constant across all the scenarios.

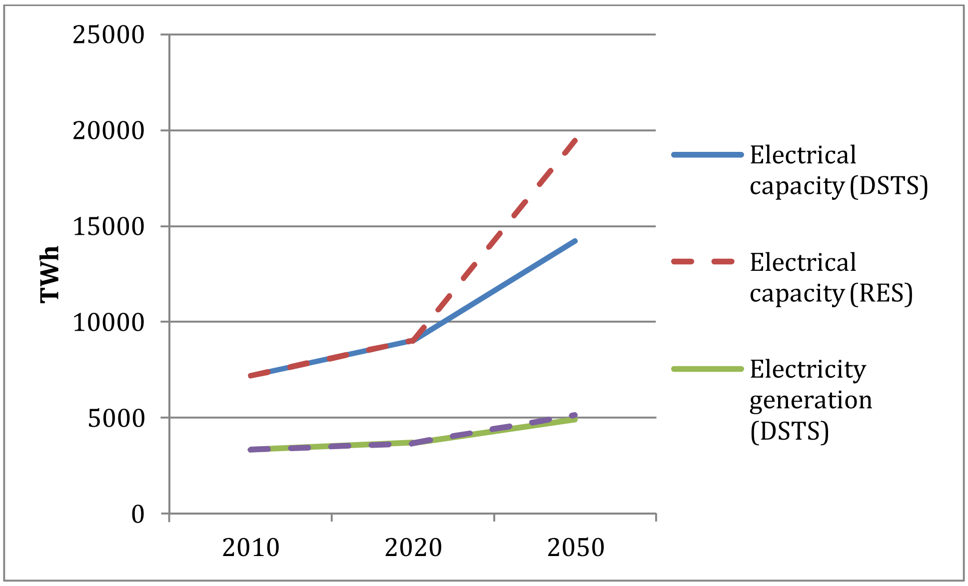
Figure 13. Gross electricity generation in the EU27 by source in 2010 and according to EU Energy Roadmap scenarios in 2020 (top) and 2050 (bottom)



Source: SEFEP, 2012c (based on data from DG Energy).

As regards the ratio of installed capacity to electricity generation, the scenario analysis reveals how a rising share of renewables in power generation (mainly based on the variable sources wind and solar) necessitates ever-larger capacity additions. Figure 14 compares two of the *Energy Roadmap*'s scenarios and shows that electrical capacity increases much faster in the High Renewables scenario than it does in the Diversified Supply Technologies scenario, while electricity generation develops in a similar way. In fact, the capacity-to-generation ratio increases from 2.2:1 in 2010 to 2.5:1 in 2020 (in both scenarios) and reaches 2.9:1 by 2050 in the Diversified Supply Technology scenario and 3.8:1 in the High Renewables scenario. This means that in the latter scenario, each unit of electricity produced is backed-up by almost four units of equivalent generation capacity.

Figure 14. Comparison of theoretical generation potential and actual electricity output in the Diversified Supply Technology scenario and the High Renewables scenario of the Energy Roadmap 2050



Source: Own calculations based on European Commission (2011c).

Note: DSTS = Diversified Supply Technologies scenario, RES = High Renewables scenario. Electrical capacity in the graph is calculated by assuming that installed capacity would function at full capacity all around the year (i.e. with a capacity factor of 100%), while electricity generation reflects the projected electricity output taking into account different capacity factors for different technologies.

The *Energy Roadmap 2050* gives a wide range of options about how the energy sector may decarbonise in the long term. It shows that the almost complete decarbonisation of the energy sector is possible with various (already existing) technologies, but highlights the uncertainties related to long-term forecasts. This becomes especially evident when assessing the role various energy technologies might play in the future. While projections for 2020 are still rather homogenous, they differ widely when looking at 2050, highlighting the uncertainties associated with decarbonisation pathways and more generally with socio-ecological transitions.

3.3 EU research projects

This section presents the results of two projects funded by the European Commission under its 7th Framework Programme for Research (FP7). These two projects not only provide useful insights regarding the future of the energy sector in Europe, but also show how FP7-funded research projects can complement each other by delivering results that are also useful for other projects.

3.3.1 AMPERE[8]

The AMPERE project is dedicated to the "Assessment of Climate Change Mitigation Pathways and Evaluation of the Robustness of Mitigation Cost Estimates". The project is funded by the European Commission (FP7) and will be finalised in early 2014.

AMPERE aims for a broad exploration of mitigation pathways and associated mitigation costs under real-world limitations while offering insights into the differences across models and the relation to historical trends. Uncertainties about the costs of mitigation originate from the entire causal chain, ranging from economic activity and technologies to the response of the carbon cycle and climate system to GHG emissions. AMPERE uses a sizable ensemble of state-of-the-art energy-economy and integrated assessment models to analyse mitigation pathways and associated mitigation costs in a series of multi-model inter-comparisons.

This section gives a brief overview of climate change mitigation scenarios for the EU27, which were used to assess the role of path dependence for EU decarbonisation pathways. The models include PRIMES, TIMES, Green-X and GAINS as energy system models (Green_X focusing only on renewables and GAINS focusing only on non-CO_2 emissions), GEM-E3 and WorldScan as computable general equilibrium models, and NEMESIS as a macro-econometric model. All models make projections to 2050 except for Green-X and NEMESIS, which are limited to 2030.

The assessment of path dependence was based on eight scenarios: (1) a reference scenario which includes all adopted and firmly decided climate and energy policies in EU member states; (2) a basic decarbonisation scenario which can be seen as the least-cost pathway for the EU with perfect foresight (i.e. no delays in mitigation action) and full availability of technologies and decarbonisation options; (3) a series of decarbonisation scenarios under technological limitations, e.g. nuclear phase-out, failure of CCS to become commercially available, delay in transport electrification; and (4) a series of decarbonisation scenarios under myopic anticipations, i.e. with delayed climate action to 2030. All decarbonisation scenarios comply with the EU objective to reduce domestic GHG emissions by 80% by 2050 (compared to 1990) and cumulative emissions are consistent with the international target of limiting climate change to two degrees Celsius. In comparison, the reference scenario only achieves emissions reductions of about 40% by 2050.

Baseline projections with regard to population and GDP are calibrated in all models on figures provided by the European Commission in order to ensure consistency and comparability of results. Moreover, the reference scenario in AMPERE relies to a large extent on the same assumptions as the reference scenario of the European Commission's *Energy Roadmap 2050* (see above).

The results reported here are those of the basic decarbonisation scenario (i.e. the least-cost pathway with full availability of technologies and perfect foresight, see above). Technology options available in that scenario include renewables in power generation and final energy demand, CCS applied to power generation and industrial processes from 2020 onwards, strong energy efficiency measures, and electrification of the transport sector mainly through

[8] Due to the fact that the AMPERE project was still ongoing at the time of writing, this paper and some results were not completely finalised, this section focuses largely on qualitative results. We thank Pantelis Capros of the E3M-Lab of the National Technical University of Athens and Nils Petermann of the Potsdam Institute for Climate Impact Research (PIK) for their help and support in drafting this section.

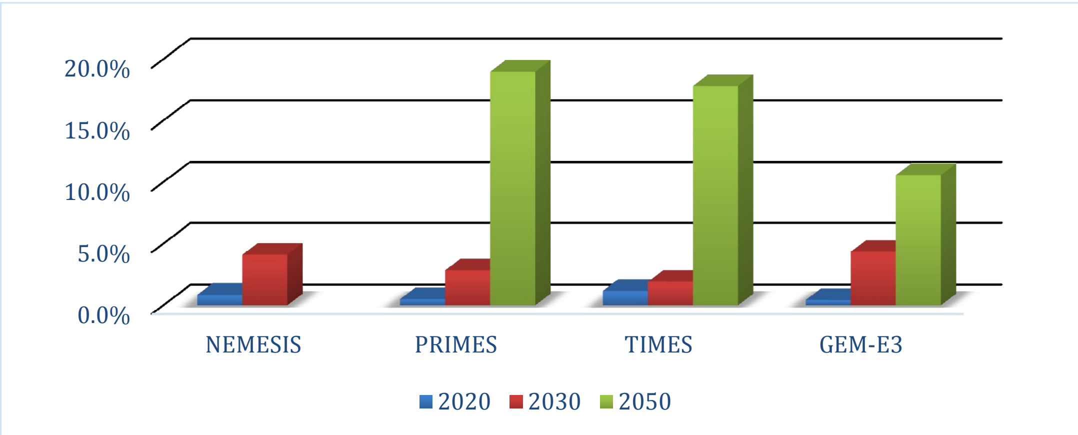
the development of battery recharging infrastructure. Technical and economic progress relies on the assumption of accelerated learning curves.

The main conclusion of the assessment is that the 80% (domestic) CO_2 emissions reduction target by 2050, as well as almost linear reduction of GHG emissions in the time period to 2050, can both be achieved with currently known technologies. Renewables and efficiency play a major role among these, while nuclear and CCS contribute less to emissions reductions. Energy demand (in primary energy terms) that is strongly decoupled from GDP growth is shown by all models in the AMPERE study, this is already the case in the reference scenario and to a much larger extent in the decarbonisation scenarios.

Primary energy consumption is generally projected to be lower in the decarbonisation scenario than in the reference scenario (by all models except TIMES). The largest differences are projected by PRIMES, with a difference of -9% in 2030 and -28% in 2050. The reduction in consumption is not due to reduced activity, but results from a mix of energy efficiency measures and technological changes (e.g. more efficient buildings, electric appliances and heating systems, electrification of stationary and mobile energy uses) as well as from efficient technologies such as plug-in hybrid and electric vehicles or heat pumps combined with fuel switching for power generation (AMPERE, 2013: 25-26).

The share of low and zero carbon energy sources (i.e. biomass, RES and nuclear) within total primary energy consumption is projected to increase in the decarbonisation scenario. The modelling results of PRIMES and TIMES project similar RES penetration patterns, with the share of renewables growing from 9% in 2010 to 22% in 2030 and 42% in 2050.

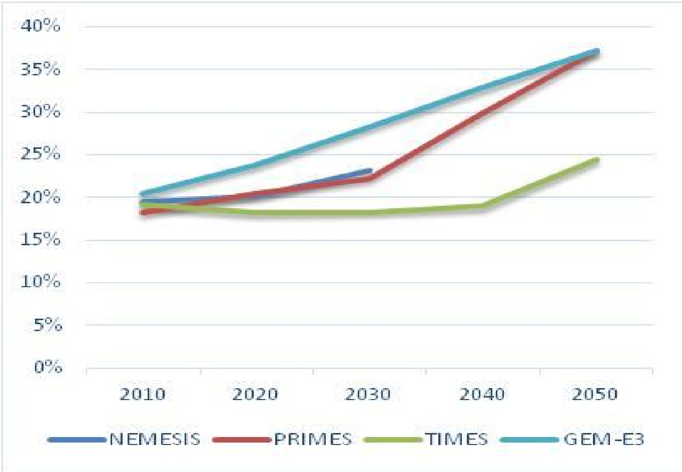
Figure 15. Incremental RES development in the basic decarbonisation scenario compared with the reference scenario



Source: AMPERE, 2013.

Projections of the share of nuclear differ across the models, mainly due to divergent costs and acceptability assumptions in the various models: nuclear development according to PRIMES is lower than in TIMES and consequently, the projected share of gas is higher in PRIMES than in TIMES. In PRIMES, as well as in GEM-E3 and NEMESIS, the share of gas declines modestly until 2030 and then stabilises at around 23% for the next two decades. In TIMES, the decline gets steeper, from 20% in 2030 to 9.4% in 2050. The results of the first group of models can be explained in the short-to-medium term by the substitution of coal for gas in power generation and oil for gas in final energy uses. In the long term, the larger role of gas can be explained by the increasing application of CCS in power generation and industrial processes and the role of gas in supporting balancing of intermittent renewables in the power sector. Despite the deployment of CCS technologies, coal is projected to decline steadily in all models, mostly because of the high RES penetration. Given its substitution with electricity in transport, the predominance of oil in the primary energy mix is set to decrease. This decline is lower in TIMES than in the other models due to lower transport electrification projections in that model.

Figure 16. Share of electricity in final energy demand in the basic decarbonisation scenario



Source: AMPERE, 2013.

As shown in Figure 16, the share of electricity in final energy demand increases in all models compared to the reference scenario. It is indeed "cost-efficient to substitute fossil fuels by electricity in final demand sectors which are more inflexible than power generation in performing decarbonisation" (AMPERE, 2013: 32). Decarbonising the power sector is crucial to reach the EU's long-term decarbonisation objective and already represents a cost-effective option in all models by 2030.

All models in AMPERE show CO_2 emissions from power generation to be reduced, by an average of 98% between 2010 and 2050 the models. Such decarbonisation levels not only allow the reduction of emissions in the power sector itself, but also the substitution of fossil fuels with electricity in other sectors with limited other options to reduce emissions (e.g. mobility, heat uses and industrial processing). Decarbonisation in the power sector is mainly achieved through larger shares of renewables and a massive deployment of CCS, particularly after 2030.

Renewables are projected to account for more than 50% of the power generation mix by 2030 (in PRIMES, GEM-E3 and NEMESIS) and over 60% by 2050 (in PRIMES and GEM-E3). Wind increases the fastest, accounting for 27-28% of the electricity production in 2030 (in PRIMES, GEM-E3 and NEMESIS) and some 34% in 2050. It is followed by solar energy, which grows from under 0.5% in 2010 to 3-6% in 2030 (depending on the model) and exceeds 10% in 2050 in PRIMES and GEM-E3. Biomass and waste develop rapidly to 2030 (from 4% in 2010 to 7.5% in 2030 on average across the models) and then slow down (7.8% in 2050) due to a lack in sufficient feedstock potential. Hydroelectricity, on the contrary, has a declining share amid other growing RES, as its remaining potential is limited due to its already high stage of development in the EU and limited available resources.

The share of fossil fuels in the power generation mix declines substantially, with oil-based power generation almost disappearing in the long term. Coal consumption also declines substantially compared to today's levels, both in the medium and in the long term, despite the development of CCS. In fact, while the application of CCS in coal and gas-fired power plants is still very low in 2030, CCS is projected to reach a share of 20-21% of power generation by 2050, according to PRIMES, TIMES and GEM-E3 modelling results. Against declining shares of oil and coal, gas becomes the most important fossil fuel in power generation, although its share in total power generation decreases as well. The share of natural gas in power generation decreases from 25% in 2010 to 18% in 2030 and 13% in 2050 (average across models). Gas remains important mainly for its ability to balance the load and to serve as a reserve, thus supporting the integration of (variable) renewables into the grid. In the long term, a substantial proportion of gas installations will be equipped with CCS.

The transport sector benefits from the decarbonisation of the power sector mainly after 2030, when electrification of transport will intensify. However, electrification of transport will not push total electricity consumption above levels in the reference scenario due to savings in other sectors and, in particular, increasing electricity savings from efficient appliances. Biofuels are mainly used where electrification is not practical, i.e. trucks, planes and ships.

3.3.2 SECURE

The SECURE project (Security of Energy Considering its Uncertainty, Risk and Economic implications) analysed the risks associated with the supply of various energy sources in the EU in order to come up with concrete policy proposals for their mitigation. It was funded by the European Commission under the 7th Framework Programme and was concluded in 2010. A key conclusion of the project was that security of supply and climate change cannot be considered separately and that there are clear synergies between strong climate action and energy security policies (Behrens et al., 2011).

Within the framework of the SECURE project, a family of scenarios was developed between 2008 and 2010 using the POLES model in order to illustrate the interactions between climate change policies and energy security issues to the year 2050. The first is the Baseline Case, which serves as a hypothetical benchmark projecting a counterfactual development in the absence of climate policy, both at the EU and international levels. A second scenario, the Muddling Through (MT) scenario, describes the consequences of uncoordinated, low-profile climate polices. The Muddling Through & Europe Plus (MT E+) scenario represents the same setting but with some leadership from Europe. Next, the Europe Alone (EA) scenario represents a case where only the EU commits to strong targets that are broadly in line with limiting global warming to two degrees Celsius above pre-industrial levels.[9] Finally, the Global Regime (GR) scenario explores a new world energy system under a strong international climate change agreement consistent with the two degrees target (SECURE, 2010).

This subsection will focus on the results of the Europe Alone (EA) and Global Regime (GR) scenarios, which represent the most ambitious EU and international responses to climate change. In both cases, the population of the EU27 is assumed to decrease from 496 million in 2010 to 487 million in 2050. Also, EU economic growth is assumed to be equal in the two scenarios, with an annual average of just above 1.4% between 2010 and 2050.

3.3.2.1 *Europe Alone*

Most scenarios analysed in this paper "were conducted under the hypothesis that the whole world is acting on climate change which leads to lower demand for fossil fuel prices and subsequently lower prices" (European Commission, 2011a). Such an assumption is based on the fact that the EU in 2010 was responsible for 12% of all global energy-related CO_2

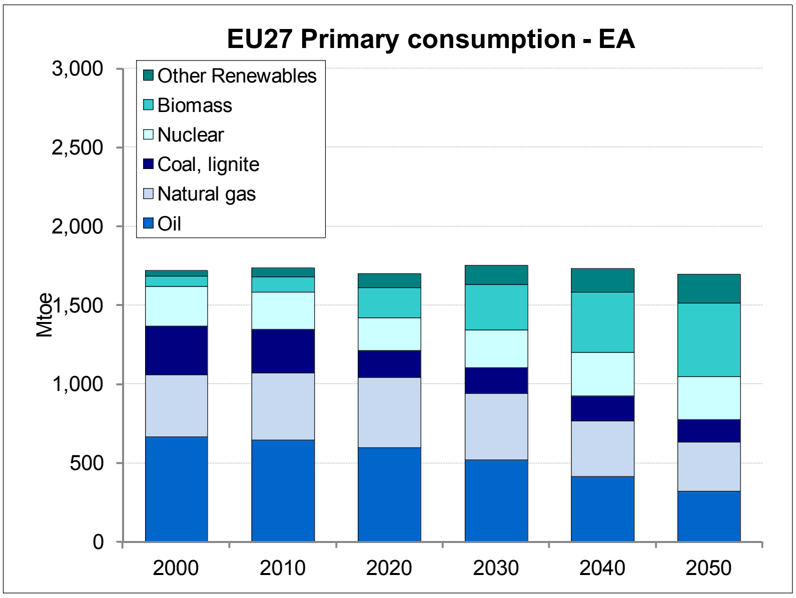
[9] Of course the EU is not in a position to limit climate change all by itself, but in the EA scenario the EU shows leadership in the hope that other industrialised and emerging economies will eventually follow suit.

emissions (IEA, 2012a), with the share continuing to decrease in the future. It is thus clear that unilateral GHG emissions reductions by the EU will not be able to reduce global warming, let alone limit it to two degrees Celsius above pre-industrial levels. Energy and climate change scenarios therefore normally do not take into account a world where Europe is the sole actor on climate policies while the rest continues on a "business as usual" trajectory. This can also be argued from a SET point of view. As argued in WP1 of NEUJOBS (D1.1), a SET may happen out of choice or – more likely – it will be driven by global changes. If the SET is driven by changes in the natural and social sphere of the world, then the European response will also be embedded in the global context. This in turn reduces the likelihood for unilateral action further.

However, since NEUJOBS also looks at a scenario where the EU acts in a "tough", uncooperative world, it is worthwhile mentioning a hypothetical situation where the EU embarks on a decarbonisation pathway in the absence of global action. In the Europe Alone scenario, it is assumed that an internationally binding agreement on climate change will not be reached. Yet, the EU does not abandon its energy and climate change ambitions. European member states not only stick to the 20-20-20 targets by 2020 as agreed in the 2008 Energy and Climate Change Package, but they decide to go further, cutting their domestic GHG emissions by 60% by 2050 compared to 1990. Despite these positive developments, global CO_2 emissions are projected to increase to 57% above 1990 levels (or 11% above 2010 levels), equivalent to a temperature increase of between three and four degrees Celsius.

A key driver for decarbonisation in the EU is an ever increasing EU carbon price, which reaches €180 per tCO2 in 2050. In the rest of the world, a shadow carbon price of €30 per tCO2 in 2050 is not high enough to induce substantial changes in the global energy system. At the same time, the international oil price is projected to move towards $74 (€38)[10] per barrel in 2020 and increases to $117 (€60) per barrel in 2050.

Figure 17. Development of the EU27 energy mix in the SECURE Europe Alone scenario



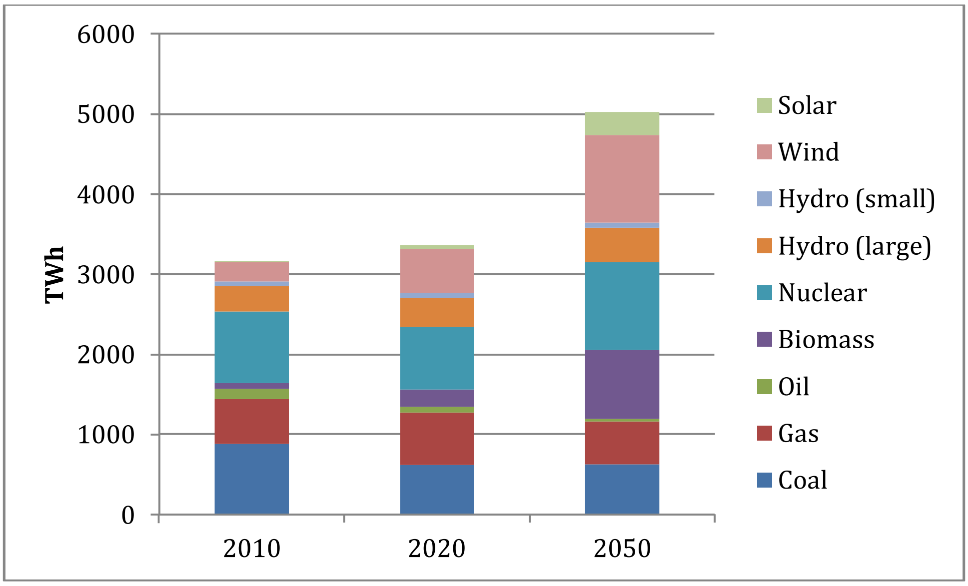
Source: SECURE, 2010.

[10] Expressed in 2005 US dollars. The exchange rate is based on the annual average US dollar/euro exchange rate of 2005, as reported by Eurostat (€1 = $1.9558).

Figure 17 shows that total EU primary consumption of energy in this scenario remains almost unchanged between 2010 and 2050 at around 1,700 Mtoe. However, the composition of energy consumption changes substantially. While in 2010 some 78% of the energy mix was still based on fossil fuels, this share decreases to 71% in 2020 and to 46% in 2050. This shift is mainly based on a strong reduction in the use of oil, coal and, to a lesser extent, gas. The share of nuclear power is projected to increase slightly. Regarding renewables, biomass is projected to overtake oil as the largest source of energy in the EU after 2040, contributing some 28% to total energy consumption by 2050.[11] Other renewables will also gain importance, though they will remain limited to 11% by 2050. In total, renewables will make a contribution of 17% by 2020 and 38% by 2050.

In contrast to energy consumption, electrical capacity and consequently electricity generation within the EU27 are expected to increase substantially. Electrical capacity will increase from 907 GW in 2010 to 1,053 GW in 2020 and 1,489 GW in 2050, representing a 16% increase between 2010 and 2020 and a 64% increase between 2010 and 2050 (see also Figure 20). The share of thermal capacity is projected to decrease from 52% in 2010 to 43% in 2020 and 29% in 2050. While coal and gas decrease in importance in terms of thermal capacity, biomass becomes more important, reaching some 10% of total capacity in 2050. As regards renewables, wind and large hydro make up the lion's share of renewable generation capacity in 2010 (31% of total capacity). While hydro expands only slowly until 2050, wind power capacities more than triple to reach 30% of total capacity by 2050. Large hydro and solar contribute another 14% each to total electrical capacity in 2050.

Figure 18. Development of the EU27 electricity mix in the SECURE Europe Alone scenario



Source: SECURE, 2010.

As a result of expanding capacities, electricity generation within the EU27 is projected to increase from 3,279 TWh in 2010 to 3,499 TWh in 2020 (+7%) and to 5,219 TWh in 2050 (+60%). As shown in Figure 18, this increase is largely based on a strong increase in wind power and biomass. Wind power will more than double between 2010 and 2020 and will reach 1,092 TWh by 2050, or 21% of total EU electricity generation. The growth rates of

[11] In fact, the high reliance on biomass in this scenario raises doubts as to whether such quantities can be produced in a sustainable way.

biomass will be even higher over the entire period. All in all, renewables are expected to reach a share of 35% in electricity generation by 2020 and 52% in 2050.

Further decarbonisation of the power sector is achieved by the increasing use of CCS in coal and gas powered plants, which starts in 2020 at very low levels but reaches almost 70% and 40% in coal and gas, respectively. Similarly, nuclear will continue to contribute substantially to electricity generation. All low-carbon technologies together will thus contribute a share of 59% in 2020 and 86% in 2050.

Like in other scenarios, installed capacity increases faster than generation due to the increasing penetration of variable renewable energy sources. The capacity-to-generation ratio increases from 2.4:1 in 2010 to 2.6:1 in 2020. However, this is the only scenario in this analysis where the ratio decreases after 2020 to reach 2.5:1 in 2050.

From a sectoral perspective, final consumption is expected to decrease in all three sectors – industry, residential and transport. Furthermore, electricity and biomass are expected to play an increasing role in all sectors. However, it is worth noting that electricity will only contribute 22% to final energy consumption in the transport sector by 2050 in this scenario.

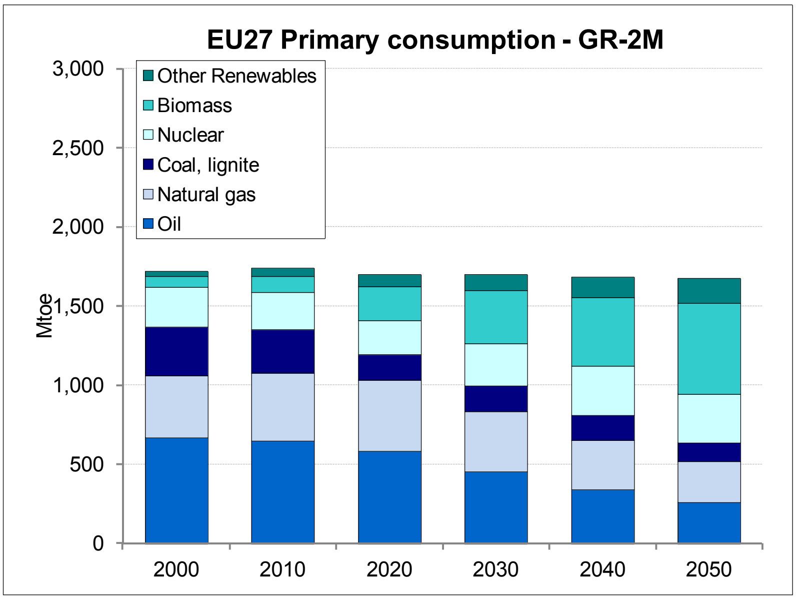
3.3.2.2 Global Regime

The Global Regime scenario assumes a binding international agreement aimed at reducing global GHG emissions by 50% by 2050 compared to 1990 levels, in line with the two degrees target. The commitment of major energy consuming countries – China, the US and India – to cut GHG emissions gives a further incentive to the EU to pursue its climate policy objectives of reducing its GHG emissions by almost 80% by 2050 compared to 1990. Decarbonisation in this scenario is driven by considerably higher carbon prices than in the Europe Alone scenario, reaching €392 per tCO2 in Annex I countries and €257 per tCO2 in non-Annex I countries by 2050. Reduced demand for oil (products) reduces the international oil price to some $70 (€36)[12] per barrel in 2020 and to $71 (€36) per barrel in 2050.

Similar to the Europe Alone scenario, gross inland consumption of energy remains more or less constant in this scenario (see Figure 19), with only marginal decreases projected from 2010 to 2020 (-2%) and to 2050 (-4%). However, the penetration of renewables is slightly more pronounced given the tightened emissions constraints in the Global Regime scenario. While in 2010 renewables contributed only 9% to the energy mix, this share increases to 17% in 2020 and to 44% in 2050. Biomass will be the single largest source by 2050, contributing some 34% alone. In addition, nuclear power is expected to remain important, contributing an additional 18% of low-carbon energy to the energy mix in 2020.

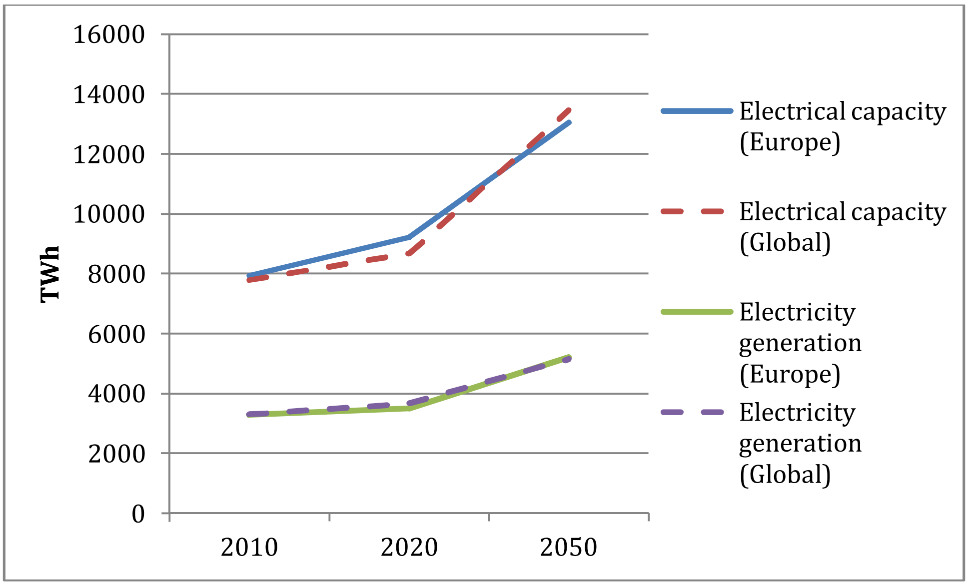
[12] Expressed in 2005 US dollars. The exchange rate is based on the annual average US dollar/euro exchange rate of 2005, as reported by Eurostat (€1 = $1.9558).

Figure 19. Development of the EU27 energy mix in the SECURE Global Regime



Source: SECURE, 2010.

Figure 20. Comparison of theoretical generation potential with actual electricity output in the two SECURE scenarios (Europe Alone and Global Regime)



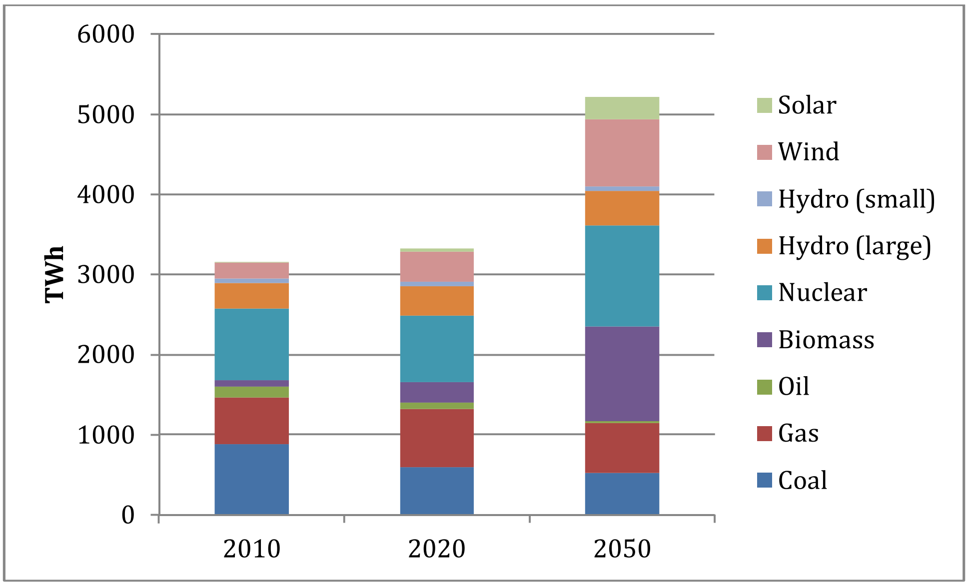
Source: Own calculations based on SECURE (2010).

Note: Europe = Europe Alone scenario; Global = Global Regime scenario. Electrical capacity in the graph is calculated by assuming that installed capacity would function at full capacity all around the year (i.e. with a capacity factor of 100%), while electricity generation reflects the projected electricity output taking into account different capacity factors for different technologies.

Turning to the power sector, electrical capacity is projected to increase stronger than in the Europe Alone scenario, but only after 2020 (see Figure 20). In figures, this means that installed capacity will increase from 888 GW in 2010 to 991 GW in 2020 (+12%) and to 1,535 GW by 2050 (+73% from 2010 levels). The role of thermal generation capacity is slightly more pronounced than in the previous scenario, decreasing from 54% in 2010 to 47% in 2020 and 31% in 2050. Coal-based generation capacity is almost halved between 2010 and 2050, while gas experiences only slight reductions. Biomass becomes much more important, reaching some 11% of total capacity. Wind expands significantly from 11% of total capacity in 2010 to 18% in 2020 and 23% in 2050, although this is less pronounced than in the Europe Alone scenario. Large hydro, solar and nuclear will be equally important in 2050, with a 12-14% share in total installed capacity each.

Electricity generation is projected to increase by 6% between 2010 and 2020, and by 64% by 2050 (see Figure 21). Similar to the previous scenario, biomass is projected to become one of the key sources of electricity. However, in this scenario nuclear power plays a more pronounced role by 2050. The share of renewables will increase to 32% in 2020 and to 52% in 2050. Other low-carbon power sources include nuclear (with 24% in 2020 and 23% in 2050) and CCS. CCS is deployed much faster after 2020 in the Global Regime scenario than in the Europe Alone scenario, and levels off by 2040. In 2050, 90% of coal-based and 65% of gas-based power will be CCS-equipped. This means that in total some 60% of electricity generated in 2020 will be low carbon, and this share will increase to 92% by 2050.

Figure 21. Development of the EU27 electricity mix in the SECURE Global Regime scenario



Source: SECURE project.

With installed capacity increasing much faster than electricity generation (see Figure 20), the capacity to generation ratio increases in the Global Regime scenario remains constant between 2010 and 2020 at 2.4:1 and increases by 2050 to 2.6:1.

The sectoral analysis reveals results that are comparable to the Europe Alone scenario, also as regards electrification of the transport sector.

The Global Regime scenario is clearly the SECURE scenario that projects a future development of the global and EU energy system that comes closest to a socio-ecological transition away from fossil fuels. Although some open questions remain as to the feasibility of increasing the share of biomass and CCS to the elevated levels projected in this scenario, it does give an impression of what the EU energy system could look like under strong climate constraints.

3.4 Greenpeace Energy [R]evolution 2012

Unlike earlier editions, the environmental NGO's Energy [R]evolution study only contains one decarbonisation scenario. The scenario analysis aims to show that it is feasible to achieve emission reductions in the upper range of 80-95% by 2050 (compared to 1990) by relying on renewables and "smarter use" of energy.

Energy data input comes from the IEA's WEO 2011, as do the classifications of the world regions in the global version of the report (Greenpeace, GEWC and EREC, 2012a). As regards Europe, the report contains data for OECD Europe[13] and eastern Europe/Eurasia reported below.[14] The global report is complemented by an EU edition (Greenpeace, GEWC and EREC, 2012b), which provides data for the EU27 and is the main source of information presented here. It provides detailed data for all timescales and sectors of interest. While the study presents a case study on Germany, generally data are only reported for the EU27 as a whole.

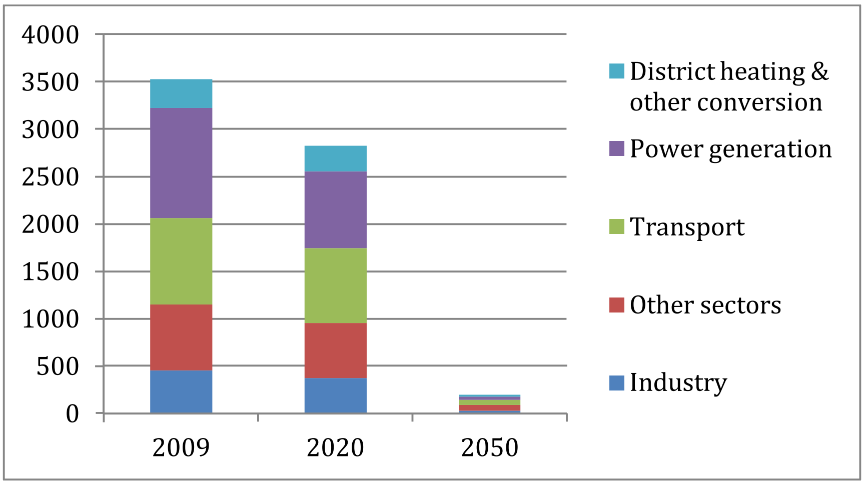
3.4.1 Results for the EU27

The key assumptions of the EU edition of the Greenpeace Energy [R]evolution are:

- population grows modestly from 499 million in 2009 to 511 million in 2020, and then remains relatively constant to reach 512 million in 2050;
- economic growth is estimated at 1.6% per year between 2009 and 2050;
- the oil price rises from €65 per barrel to €93 in 2015 and to €126 per barrel by 2030, and is then assumed to remain constant until 2050 (prices in 2010 euros); and
- the carbon price ranges from €11 in 2015 to €19 by 2020 and €57 in 2050 (prices in 2010 euros per tCO_2).

The Energy [R]evolution scenario estimates a steep decline in EU CO_2 emissions[15] from 2009 (13% less than 1990) to 2020 (-30%) and further to 2050 (-95%).

Figure 22. Sectoral distribution of CO_2 emissions in the Greenpeace Energy [R]evolution scenario (million tonnes of CO_2)



Source: Greenpeace, 2012b.

[13] Austria, Belgium, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Luxembourg, the Netherlands, Norway, Poland, Portugal, Slovak Republic, Spain, Sweden, Switzerland, Turkey, United Kingdom.

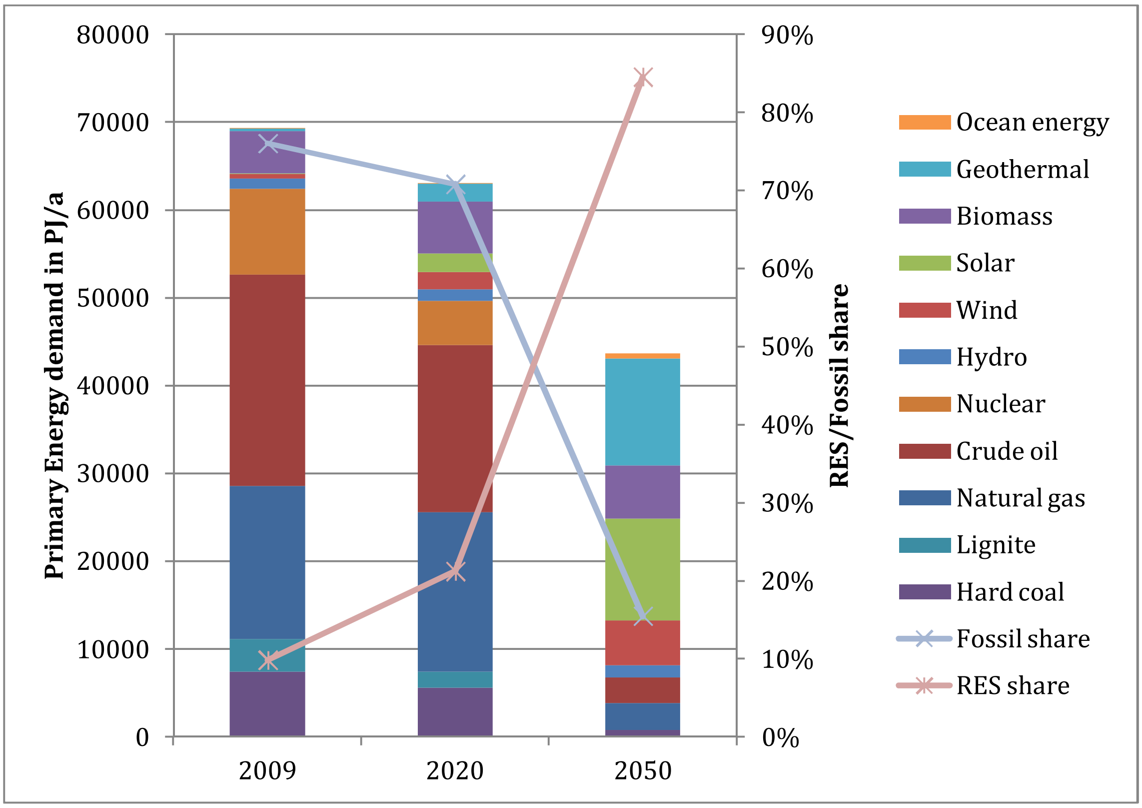
[14] Albania, Armenia, Azerbaijan, Belarus, Bosnia-Herzegovina, Bulgaria, Croatia, Serbia and Montenegro, Macedonia (FYROM), Georgia, Kazakhstan, Kyrgyzstan, Latvia, Lithuania, Moldova, Romania, Russia, Slovenia, Tajikistan, Turkmenistan, Ukraine, Uzbekistan, Cyprus, Malta.

[15] The Energy [R]evolution scenario is an energy scenario, therefore only energy-related CO2 emissions are calculated.

Figure 22 demonstrates that the Energy [R]evolution scenario will require the almost complete decarbonisation of all economic sectors, with only minor variations. The power sector will need to lead the way by reducing emissions by 30% by 2020 and by 96% by 2050 compared to 2009 levels.[16] The transport sector will not need to decarbonise as much in the short term (only 13% by 2020), but by 2050 CO_2 emissions will need to decrease by 94%. Similar efforts are expected of the industry sector – a 17% reduction by 2020 and 93% by 2050. District heating and other conversion will need to decarbonise by 12% by 2020 and 92% by 2050, while other sectors will require decarbonisation efforts of 17% by 2020 and 89% by 2050.

The Energy [R]evolution scenario estimates that primary energy demand in the EU27 will decrease in the long term (Figure 23). The share of renewables in the primary energy demand will rise from some 10% in 2009 to 21% in 2020. By 2050, 85% will come from renewables and the remaining 15% from fossil fuels (nuclear power is phased out in this scenario). Noteworthy is the high share of geothermal, which in 2050 will be the single most important source of energy, followed by solar and biomass.

Figure 23. EU27 primary energy demand in the Greenpeace Energy [R]evolution scenario



Source: Greenpeace, 2012b.

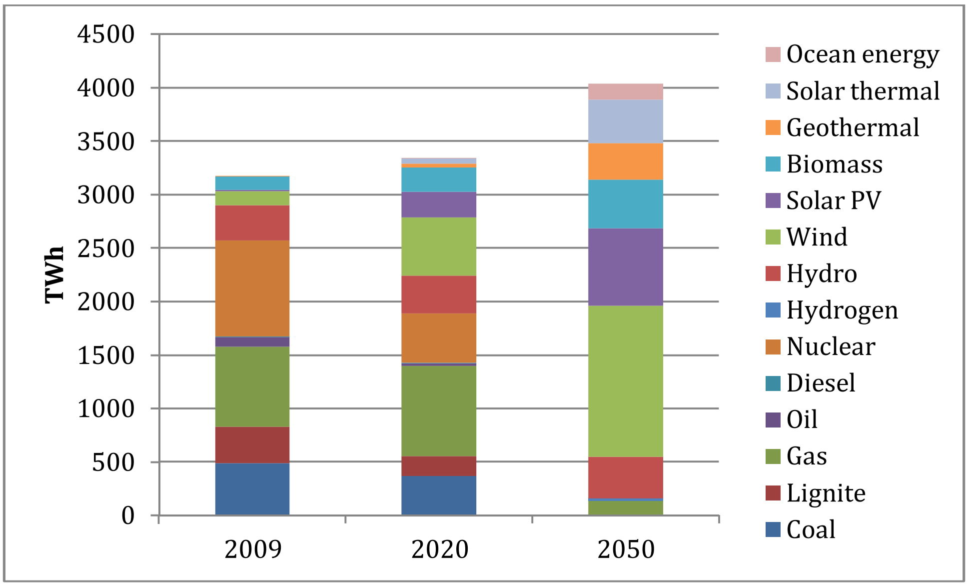
While annual total *final* energy demand (energy use only) will remain relatively constant between 2009 and 2020 at around 44,000 PJ (1,051 Mtoe), it is assumed to eventually decline to some 30,000 PJ (717 Mtoe) by 2050 – corresponding to a one-third reduction of final energy use. Some sectors are expected to decrease their energy use more than others. Transport is expected to decrease its energy demand by 45% between 2009 and 2050, almost all of which is assumed to take place after 2020. In addition, the transport sector is expected to undergo a

[16] As Greenpeace (2012b) does not provide data on 1990 emission levels disaggregated to the sector level, it was not possible to calculate the sectoral emissions reduction compared to 1990.

significant fuel shift as 50% of 2050 final energy demand will be from electric vehicles and 30% from hydrogen-powered vehicles (the role of biofuels being limited to 8%). Industry's contribution is more modest, as 2050 final energy use is "only" 17% below 2009 levels. The energy demand of other sectors is assumed to start decreasing after 2020 by a total of 25% (2009-2050).

The decarbonisation objective is achieved through an assumed massive uptake in renewables. The share of renewables in meeting final energy demand increases from 11.5% (2009) to 23.3% (2020) and to 90% in 2050.

Figure 24. EU27 electricity generation in the Greenpeace Energy [R]evolution scenario



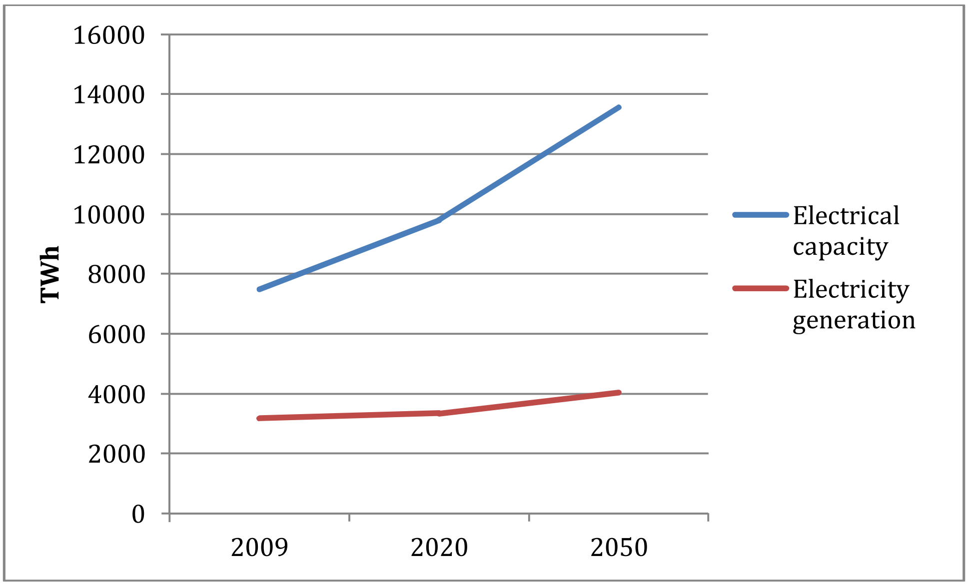
Source: Greenpeace, 2012b.

This development is mirrored in the composition of electrical capacity and electricity generation. Electric capacity increases by 31% between 2009 and 2020 and by 81% between 2009 and 2050 (starting from 854 GW in 2009). Fossil fuels are almost completely phased out, as is nuclear power. This also means that CCS technology becomes obsolete and it is therefore not part of this scenario. Wind and solar PV will have the largest share in installed capacity, with wind increasing from 4% in 2009 to 22% in 2020 and 32% in 2050, and solar PV increasing from 2% in 2009 to 19% in 2020 and 37% in 2050. Wind and solar PV will thus cover almost 70% of installed capacity, while hydro contributes another 11% in 2050.

The picture for electricity generation is similar. Total generation activities increase from 3,175 TWh in 2009 to 3,344 TWh in 2020 (+5%) and 4,040 TWh in 2050 (+27%). However, due to the fact that coal, lignite, oil and diesel (and nuclear) are completely phased out, some 96% of electricity generation will be based on renewables in 2050. As shown in Figure 24, the key technologies will be wind (onshore and offshore to a similar extent) followed by solar PV and, to a lesser extent, biomass, solar thermal, hydro and geothermal. The role of ocean energy and natural gas will be very limited.

Figure 25 puts installed capacity in relation to electricity generation and shows that the ratio between the two increases from 2.4:1 in 2009 to 2.9:1 in 2020 and to 3.4:1 in 2050.

Figure 25. Comparison of theoretical generation potential with actual electricity output in the Greenpeace Energy [R]evolution scenario



Source: Own calculations based on Greenpeace (2012b).

Note: Electrical capacity in the graph is calculated by assuming that installed capacity would function at full capacity all around the year (i.e. with a capacity factor of 100%), while electricity generation reflects the projected electricity output taking into account different capacity factors for different technologies.

3.4.2 *Regional differences*

As Greenpeace (2012a) provides data on both OECD Europe and eastern Europe, it also allows for an overview of the east-west divide.

Key underlying assumptions of the analysis include the following:

- Population
    - OECD Europe: 555 million (2009), 579 million (2020), 600 million (2050).
    - Eastern Europe/Eurasia: 339 million (2009), 341 million (2020), 324 million (2050).
- Economic growth (average annual growth rates, 2009-2050)
    - 1.6% in OECD Europe.
    - 3.0% in eastern Europe/Eurasia.
- Assumptions on oil and carbon prices are the same as in Greenpeace (2012b) reported above, but note that the study only assumes carbon price in non-Annex B countries of the United Nations Framework Convention on Climate Change (UNFCCC) as of 2030.

Total CO_2 emissions of OECD Europe decrease from 97% (of 1990 levels) in 2009 to 72% in 2020 and 5% in 2050. In eastern Europe, emissions savings were achieved earlier due to the collapse of the heavy industry after the dissolution of the USSR. As a result, total CO_2 emissions had already decreased to 62% (of 1990 levels) by 2009 and are projected to decrease further to 51% by 2020 and 6% in 2050.

Per capita CO_2 emissions in OECD Europe, which amounted to 6.8 tonnes in 2009, are assumed to decline to 4.9 tonnes by 2020 and 0.3 tonnes by 2050. Eastern Europe/Eurasia is estimated to maintain somewhat higher per capita emissions (2009: 7.3 tonnes; 2020: 6.0 tonnes; 2050: 0.7 tonnes).

Energy demand is expected to decrease in OECD Europe after 2020 to 69% of 2009 demand by 2050. The decline is most accentuated in the transport sector (with 2050 demand only 41%

of that of 2009). Energy demand in industry is, in contrast, assumed to remain relatively high (at 91% of 2009 demand). Developments are different in eastern Europe/Eurasia, where energy demand only falls to 90% of 2009 levels by 2050 and is roughly the same across the energy sectors.

In both world regions, decarbonisation is driven by the uptake in renewables, which are assumed to be able to meet 91% of OECD Europe's 2050 final energy demand and 89% of eastern Europe's demand.

3.5 European Climate Foundation roadmaps

The European Climate Foundation (ECF) published two decarbonisation studies: *Roadmap 2050 – A practical guide to a prosperous, low-carbon Europe* (ECF, 2010) and a follow up study, *Power Perspectives 2030* (ECF, 2011). Generally, the ECF roadmaps provide information on a number of issues of interest to this study. However, data for 2020 is not always available for sectors other than the power sector and figures are usually only reported in aggregated form, thus not allowing for a comparison between regions.

One objective of the *Energy Roadmap 2050* study is to explore the technical and economic feasibility of an 80% reduction of GHG emissions between 1990 to 2050 without putting the security of energy supply or the competitiveness of the EU at risk. The study assumes that this requires at least a 95% reduction of GHG emissions in the power sector, and consequently pays special attention to this sector. *Power Perspectives 2030* then takes a closer look at the interim steps that would need to be taken in the power sector. Both studies cover the EU27 as well as Norway and Switzerland, and usually only report aggregated data (i.e. no data on individual countries are available). They also make the same technology assumptions. Based on the 450 Scenario of IEA WEO 2009, both studies assume an oil price of $87 per barrel in 2015 which increases to $115 by 2030 and remains flat thereafter until 2050 (quoted in 2010 US dollars). The assumed carbon price for the EU ranges from $50 (2020) to $110 from 2030 onwards.[17] What follows is a brief overview of the original *Roadmap 2050* study, before going into the more detailed *Power Perspectives 2030* study to describe the power sector in 2020.

3.5.1 ECF Energy Roadmap 2050

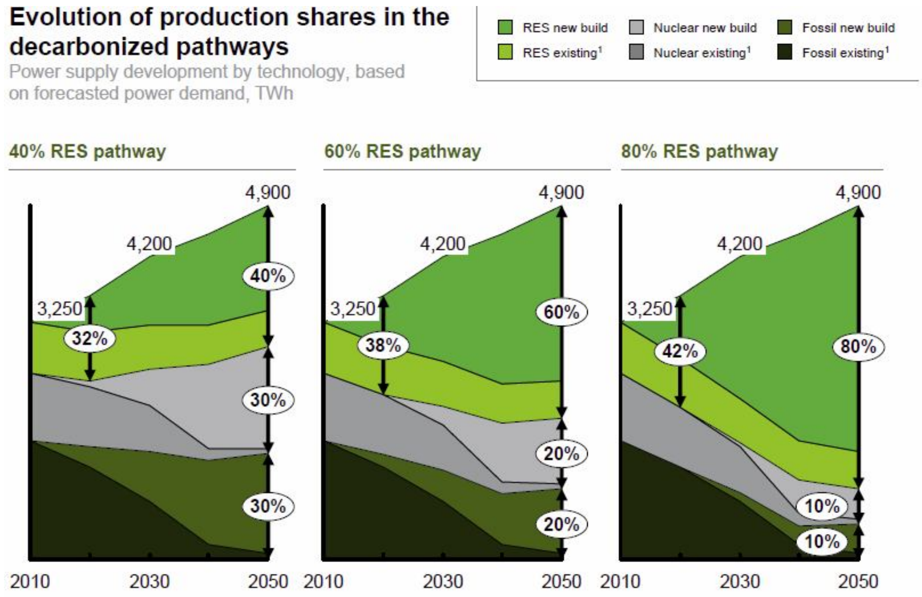
The key result of the *Energy Roadmap 2050* is that an 80% reduction of GHG emissions by 2050 (compared to 1990 levels) is possible with current commercially available technologies (or technologies in the late development stage). However, a decarbonisation of the European economy to such an extent requires a radical transformation of the energy system, with the power sector becoming almost completely decarbonised by 2050. Other elements of the GHG emissions reduction strategy include higher energy efficiency rates (improvements of up to 2% per year), a fuel shift from oil and gas to power and biomass in the building and transport sectors, as well as other emission abatement efforts, such as CCS in industry and afforestation. According to the study, the 2050 targets will only be achievable if the transition starts within the next five years (i.e. by 2015) and if investments are redirected "into new sectors such as low-carbon energy generation, smart grids, electric vehicles and heat pumps" (ECF, 2010: 9).

Focusing on the almost complete decarbonisation of the power sector, the *Energy Roadmap 2050* provides three main decarbonisation pathways for the power sector, differentiated by

[17] Other major economies are assumed to have carbon prices as well. For other major economies (i.e. China, Russia, Brazil, South Africa and the Middle East) a carbon price of $65 is assumed (2030-2050).

the share of renewables in the power mix by 2050: 40% RES, 60% RES, and 80% RES. In all three pathways, the remaining share is equally divided between CCS and nuclear (see Figure 26). An additional pathway exploring the feasibility of 100% renewables is also included.

Figure 26. Decarbonisation pathways for power



Source: ECF, 2010.

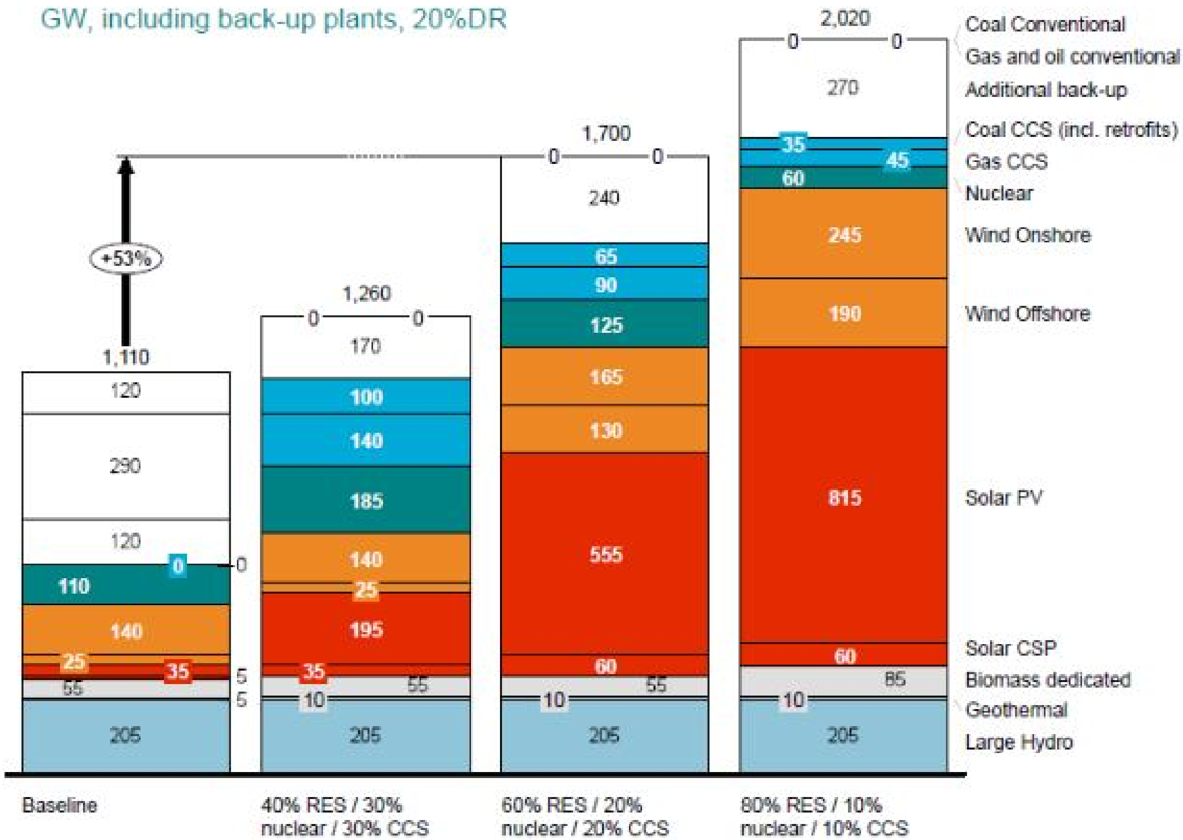
Only one decarbonisation pathway is discussed for the other sectors. The *Roadmap 2050* concludes that power, road transport and buildings will need to be nearly fully decarbonised to reach the target of 80% decarbonisation by 2050. This breaks down into the following decarbonisation rates (by 2050, compared to 1990):

- Power: -95 to -100%
- Road transport: -95% (-75% from fuel shift to electric vehicles, biofuels and fuel cells)
- Air and sea transport: -50% (-20% from biofuels)
- Industry: -40%(-35% through efficiency measures and CCS, -5% from heat pumps)
- Buildings: -95% (-45% through efficiency measures, -50% from heat pumps)
- Waste: -100%
- Agriculture: -20%
- Forestry: -0.25 $GtCO_2e$ through carbon sinks

Decarbonisation of the power sector will need to take place in the face of increasing demand, up from 3,250 TWh per year in 2010 to 4,900 TWh per year in 2050. This represents an increase of 29% by 2030 and 51% by 2050. Although efficiency measures will reduce power demand in the building and industry sectors, demand will increase due to substantial fuel-shift in transport, building and industry. By 2050, power will be supplied by a variety of sources, including hydro, coal and gas with CCS, nuclear, wind (onshore and offshore), solar PV and CSP, biomass and geothermal. In the 80% RES pathway, wind will supply 30% of power (15% onshore, 15% offshore), followed by solar PV (19%), biomass and hydro (12% each). In the 60% RES pathway, all of these technologies have similar shares in power production of 10-12% each.

All decarbonisation pathways require significant investments in (back-up) generating capacity. Figure 27 shows that capacities increase with the share of variable renewable energy sources. While only 1,260 GW of installed capacity are required by 2050 in the 40% RES scenario, this number increases to 2,020 GW in the 80% RES scenario. In scenarios with lower shares of renewables, various technologies contribute similar shares to installed capacities (including CCS). The importance of solar PV and wind increases as renewables become more important in the scenario, with both of these technologies together reaching a share of 62% of installed capacity by 2050 in the 80% RES scenario. In this scenario, CCS only plays a marginal role in the long term.

Figure 27. Resulting capacity mix in 2050 across baseline and pathways in the ECF Energy Roadmap 2050



Source: ECF, 2010.

Increasing capacities, *inter alia* needed to back-up variable renewables sources such as solar PV and wind, lead to significant increases in the capacity-to-generation ratio. While in the 40% RES scenario the theoretical generation potential and projected electricity generation in 2050 stand at a ratio of 2.3:1, this ratio increases to 3:1 in the 60% RES scenario and to 3.6:1 in the 80% scenario. This means that every unit of electricity produced will require four times the equivalent installed capacity to ensure stable supply throughout the year.

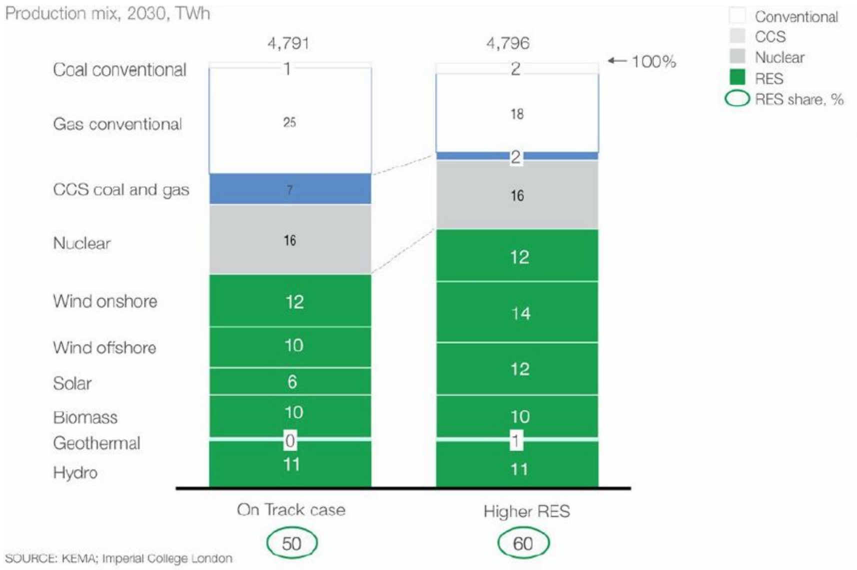
Another interesting aspect of the ECF *Energy Roadmap 2050* is the regional analysis of where renewables capacities may be installed by 2050. In the 80% RES scenario, solar capacities are mainly projected to be installed in the Iberian peninsula, central Europe, France, Italy and Malta, and Benelux and Germany. These five regions/countries will account for almost 80% of installed solar capacity. In terms of wind power, almost 50% of capacities will be found in the UK and Ireland, and Benelux and Germany. Additional capacities will mainly be found in the Nordic countries, France and the Iberian peninsula.

3.5.2 *ECF Power Perspectives 2030*

The aim of the *Power Perspectives 2030* is to give an indication of what needs to be done in the European power sector by 2030 in order to stay "on track" for the decarbonisation targets identified in the *Energy Roadmap 2050*.

Power Perspectives 2030 only reports one main decarbonisation scenario, the so-called "on track" case. It assumes the existing National Renewable Energy Action Plans (NREAPs) and ENTSO-E's pilot Ten-Year Network Development Plan (TYNDP) are fully implemented. A sensitivity analysis is also conducted to see what would happen if only 50% of the grid expansion plans are successful. Just as is foreseen by the legally binding NREAPs, ECF assumes a 35% share of renewables in power generation in 2020. Emissions are reduced by 34% compared to 1990.

Figure 28. RES share in Europe's electricity generation mix in 2030 (in TWh)



Source: ECF, 2011.

By 2020, 35% of power production will be renewables-based, 25% nuclear and 40% fossil. By 2030, the share of renewables will increase to 50% in the "on track" case, with sources being distributed fairly equally across onshore wind, offshore wind, biomass and hydro (with a 10-12% share each in electricity generation). The contribution of geothermal in the electricity mix is hardly relevant, amounting to only 1% even in the more optimistic "Higher RES" case (see Figure 28). The other half of power generation will still come from fossil fuels (mainly unabated natural gas, i.e. without CCS) and nuclear energy.

3.6 IIASA Global Energy Assessment

The International Institute for Applied Systems' (IIASA) Global Energy Assessment (GEA) analysed 60 possible transformation pathways that would help simultaneously achieving the following objectives:

- Affordable energy services to all people on Earth.
- Universal energy access for all (solid fuels and electricity).
- Increasing energy security.
- Reducing GHG emissions in line with the two degrees target.
- Reducing air pollution and related impacts on human health.
- Reducing adverse effects and risks associated with some energy systems.

These 60 transformation pathways were summarised into three illustrative "GEA pathways" for the years 2030 and 2050: (1) GEA-Efficiency pathways, focusing on demand side R&D and solutions to foster energy efficiency and thus to limit energy demand; (2) GEA-Supply pathways, focusing on the rapid scale-up of supply-side options; and (3) GEA-Mix pathways, which are intermediate and describe a diversity of energy supply and technology portfolios. Since the GEA analyses so many different pathways, each of them with two models (MESSAGE and IMAGE), it is very hard to express general trends. While this may be possible at the global level, this is almost impossible for the EU, more so due to the fact that the EU itself is not a regional category in the assessment (the assessment refers to western Europe[18] and to eastern Europe[19]).

However, without going into too much detail, the GEA Scenario Database reveals that primary energy decreases considerably to 2050 in the GEA-Efficiency pathways, much more so in western than in eastern Europe (which starts from much lower levels). Western European primary energy decreases from more than 60 EJ (1,433 Mtoe) in 2005 to below 50 EJ (1,194 Mtoe) in 2050 (-17%). For eastern Europe, primary energy is projected to decrease from below 15 EJ (358 Mtoe) in 2005 to around 10 EJ (239 Mtoe) in 2050 (-33%). In the GEA-Supply pathways, primary energy increases in both regions, and is again stronger in western Europe (to around 70 EJ (1,672 Mtoe) by 2050, or +17%) than in eastern Europe (to below 20 EJ (478 Mtoe) by 2050, or +33%). Finally, in the GEA-Mix pathways, primary energy is more or less stable between 2005 and 2050 in both regions.

As regards the composition of the energy mix, high decarbonisation levels are achieved by a strong increase in the share of renewables complemented by a complete phasing-out of coal without CCS by 2050. CCS becomes essential, particularly in the high demand pathways (GEA-Supply). Natural gas acts mainly as a "bridging or transition technology" while serving as back-up for variable renewable energy sources. Nuclear energy is regarded as "a choice, not a requirement" (IIASA, 2012), meaning that all of the above GEA goals can also be met in case of a nuclear phase-out.

Table 6. Ranges of renewable energy deployments across GEA pathways by region 2050 (in Mtoe)

Region	Bioenergy	Hydro	Wind	Solar	Geothermal	All RES	All RES as % of total
Eastern Europe	31-67	19-24	17-119	5-146	0-7	69-365	23-85
Western Europe	93-263	136-182	72-721	17-690	2-50	320-1906	34-83

Source: Own calculations based on IIASA (2012).

In terms of renewables in primary energy supply, GEA's pathways give various ranges of deployment for each technology. Table 6 shows that the projected deployment of RES is likely to be higher in western than in eastern Europe. Key technologies will be wind, solar and bioenergy. GEA projects that the share of renewables in the total energy mix could

[18] Andorra, Austria, Belgium, Cyprus, Denmark, Finland, France, Germany, Greece, Greenland, Holy See, Iceland, Ireland, Italy, Liechtenstein, Luxembourg, Malta, Monaco, Netherlands, Norway, Portugal, San Marino, Spain, Sweden, Switzerland, Turkey, United Kingdom.

[19] Albania, Bosnia and Herzegovina, Bulgaria, Croatia, Czech Republic, Estonia, Hungary, Latvia, Lithuania, Macedonia (FYROM), Montenegro, Poland, Romania, Serbia, Slovak Republic, Slovenia.

increase to around 85% by 2050. However, given the large deployment ranges, a conclusion on a realistic share by 2050 is not possible.

GEA notes that western Europe in general has more options for systemic change than eastern Europe. In western Europe, a switch away from fossil fuels, increases in efficiency and diversification of transport technologies are expected to lead to a substantial transition of energy systems. In eastern Europe, on the other hand, geography, fossil resource endowments and resource scarcity are likely to slow the transition, opening the door to natural gas, which may dominate the transport and electricity sectors by 2050.

3.7 Eurelectric Power Choices Reloaded[20]

In addition to international institutions, academia and NGOs, actors in the energy sector also model possible futures for energy (e.g. BP, ExxonMobil, Shell, Eurelectric). However, most of the scenarios do not reflect a strong decarbonisation in line with the two degrees global warming threshold. Contrary to other studies from the energy sector, the *Power Choices Reloaded* scenario of Eurelectric is presented in this paper because it depicts a future of the energy sector that is in line with a SET.

Power Choices Reloaded is the 2013 revision of the *Power Choices* study published by Eurelectric in 2009, which examined how to achieve carbon neutrality of the power sector by 2050 within a whole-economy model.[21] The updated study revisits the original by integrating more recent policy and economic developments[22] as well as technology cost data. It confirms the main conclusions made in 2009. The results reported here are issued from a preliminary version of the study and consequently must be read with caution.

Power Choices Reloaded, which is based on the PRIMES model, proposes a reference scenario, a decarbonisation scenario called Power Choices Reloaded (considered the cost-optimal pathway to decarbonisation), and a series of deviations from that optimal scenario, including a "Lost Decade scenario".[23] The reference scenario is an update of the reference scenario of the European Commission's *Energy Roadmap 2050*, including policies adopted to spring 2012 and assuming the achievement of the 20-20-20 targets. Although the EU 2050 goal of 80-95% emissions reductions by 2050 compared to 1990 is not met, the reference scenario already projects a strong decarbonisation of the power sector (-77% by 2050 compared to 2010) due to the ETS.

The Power Choices Reloaded scenario is consistent with the EU contributions needed to limit global warming to two degrees Celsius (i.e. it complies with 450 ppm scenarios). It achieves a reduction of EU GHG emissions of 28% by 2020 and 80% by 2050 compared to 1990 levels. In this scenario, the power sector is fully decarbonised by 2050 under the assumption that all low-carbon technologies and options for emissions reductions are available and deployed throughout the economy. The focus is on strong energy efficiency (rather than fuel

[20] Since the final version of the Power Choices Reloaded was not yet published at the time of writing this paper, this section is based on a preliminary version kindly provided by Eurelectric. The authors give special thanks to Jesse Scott of Eurelectric for her kind support.

[21] In March 2009, 61 chief executives of electricity companies, representing well over 70% of total EU power generation, signed a Declaration committing to action to achieve carbon neutrality by 2050.

[22] The update mainly concerns technology progress and costs, fuel prices, economic trends, nuclear and CCS and, more generally, policies.

[23] Lost Decade scenario (delayed climate action until 2030), Limited Financing scenario, Barriers to Energy Efficiency scenario, Incompletion of the Internal Energy Market scenario, Carbon Price Driven scenario, and Renewable Energy Target in 2030 scenario.

switching) on the demand side and renewables (together with contributions from nuclear and CCS) on the supply side. The substitution of fossil fuels with electricity is only foreseen in sectors that cannot decarbonise otherwise (e.g. transport and heating). In terms of biomass, only second-generation feedstock and technologies are taken into account.

On top of these technological assumptions, other non-policy assumptions are the following:

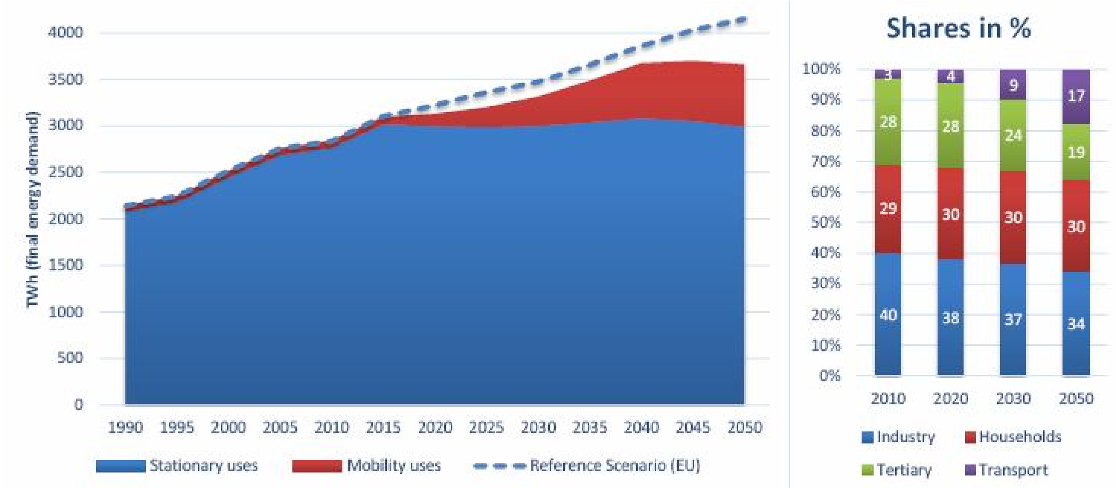
- EU GDP is assumed to grow by an average of 1.4% annually between 2010 and 2050.
- Energy prices are derived from the results of the Prometheus model and range between the Current Policies and New Policies scenario results of the WEO 2012. Oil prices rise to about $118 (€89)[24] per barrel (boe) in 2020 and further to $140 (€106) in 2050 (in 2010 US dollars). Gas prices remain broadly stable, fluctuating at around $80 (€60) per boe between 2020 and 2050, while coal prices increase steadily up to $40 (€30) per boe in 2050.
- The ETS carbon price only applies until 2020. Afterwards there is a uniform carbon price across the whole economy (i.e. ETS and non-ETS sectors), which serves as an incentive for decarbonisation but which differs from an ETS carbon price as it is currently defined or used. The uniform carbon price is introduced for modelling purposes, as Eurelectric does not suggest the abolishment of the ETS.

In the Power Choices Reloaded scenario, final energy demand decreases substantially to 2050, leading to a reduction also in primary energy demand. Eurelectric makes a distinction between stationary and transport uses. For stationary uses (i.e. the industry, residential, tertiary, and agriculture sectors), final energy demand drops by 13% by 2030 and 35% by 2050 compared to the reference scenario. The decrease is largest in the tertiary sector, with a reduction in final energy demand of 43% between 2010 and 2050. This is followed by the residential sector with a 34% decrease, and industry with a 14% decrease over the same period. In the residential sector, heating uses the most energy, although its share in consumption decreases from 65% in 2010 to 50% in 2050. Final energy demand in transport also decreases strongly by 39% from 2010 to 2050. However, the composition of the fuel mix for transport evolves significantly, with the share of oil decreasing from 93% in 2010 to 45% in 2050, and electricity and biofuels reaching shares of 26% and 30% in 2050, respectively.

Rising electricity demand in transport also contributes to a 29% increase in total electricity demand by 2050 compared to 2010. Figure 29 shows that while electricity demand in the stationary demand sectors is projected to level off after 2020, transport is the main cause for increasing electricity demand in the EU27. Within the transport sector, the share of electricity in final energy demand is projected to increase from 1.8% in 2010 to 3.2% in 2020 and 26% in 2050. As a result, total electricity demand of all sectors grows by 29% between 2010 and 2050.

[24] Expressed in 2010 US dollars. The exchange rate is based on the annual average US dollar/euro exchange rate of 2010, as reported by Eurostat (€1 = $1.3257).

Figure 29. Electricity demand by final energy demand sector



Source: Eurelectric, 2013.

For power generation, the key changes in the period 2010-2020 are projected to be the decline of solids (coal and lignite) and of nuclear power, and the significant expansion of wind power. The development of other low-carbon technologies is not projected to accelerate in a major way, with CCS not being available for commercial utilisation at all. The share of renewables in this scenario will be 36% in 2020.

Looking at the power mix in 2050, the decline of conventional fossil fuels (coal, gas-GTCC and conventional oil and gas) is most evident, together with the ongoing expansion of wind power. Regarding the former, most fossil fuel based generation will be equipped with CCS technologies, thus still allowing for a fossil share of 22% in the power mix. CCS mainly kicks in after 2030, but unevenly among EU member states. Countries with fewer low-carbon resources (i.e. limited renewables potential and limited or zero nuclear capacity) invest more in CCS technologies, including Denmark, Germany, Hungary, Italy, Poland and Romania.

The share of renewables is projected to increase to 55% by 2050. Wind will remain the single most important renewable energy source in this scenario, with a share of 31% alone (see Table 7). Other technologies, such as biomass and solar, do not really take off, while hydro even declines due to limited additional potentials.

Table 7. Share of various energy sources in the power generation mix (%)

	2010	2020	2050
Nuclear	27	22	23
Solids	26	20	0
CCS	0	0	19
Gas-Turbine Combined Cycle	18	15	1
Conventional oil and gas	8	7	2
Biomass	3	6	7
Hydro	11	10	8
Wind	5	17	31
Solar	1	3	9
Peak devices	1	0	0

Source: Eurelectric, 2013.

Increasing power generation based on increasing shares of (variable) renewable energy sources will be accompanied by ever-increasing installed capacities. In fact, electrical capacity is projected to increase by 21% between 2010 and 2020 and by 75% between 2010 and 2050. Wind will be the single largest power source in terms of installed capacity already by 2020, while solar will remain marginal in the short term. Intermittent renewables (both wind and solar taken together) will cover a share of almost 60% to 2050. Together with hydro and biomass, renewables will thus make up more than 70% of installed electrical capacity. In the Power Choices Reloaded scenario, the capacity-to-generation ratio does not change much over the period 2010-2050, remaining between 2.6:1 and 2.8:1.

It is also worth mentioning the Lost Decade scenario, which assumes a complete lack of policy action and appropriate investment levels between 2020 (i.e. after the achievement of the 2020 targets) and 2030. However, the EU's long-term decarbonisation target for 2050 is still reached, with the entire decarbonisation action occurring in the two decades between 2030 and 2050. This scenario is the main focus for Eurelectric due to the added cost of delayed technology development, delayed supply chains, stranded assets, and late development of energy efficiency. Although such a scenario would hardly be feasible in real life, it serves to highlight the importance of the decade from 2020 to 2030, as any delay in action would have huge cost consequences (for the power sector and other sectors).

Another key message delivered by the Eurelectric modelling exercise for decarbonising the power sector is that renewables are the preferred option to do so, but should be complemented both by base-load power generation in the form of nuclear and conventional fossil fuels equipped with CCS power plants, as well as balancing and reserve load in order to compensate for variable renewables (mainly wind power). The improvement of grid infrastructure and, more generally, the completion of the internal market are key pre-conditions for these developments.

Finally, the study concludes that energy savings are crucial on the demand side in order for electricity to be used in sectors that have no other options to decarbonise. The less energy demand decreases, the more the power sector has to compensate by decarbonising in order to meet the 80% GHG emissions reduction target. In fact, energy efficiency is projected to contribute some 39% to total emissions reductions in the power sector by 2050 (followed by renewables with 32%, natural gas with 13%, nuclear with 11% and CCS with 6%).

4. Summary and key trends

This section summarises the key findings of the scenario analysis presented above. Due to the large range of different scenarios analysed in this paper, a reasonable range of the possible decarbonisation pathways can be established, both for 2020 and for 2050. It is also possible to point to some technologies and sectors that are generally assumed to be particularly crucial for decarbonisation. At the same time, there are aspects where uncertainty is still high and where views differ considerably, most notably with regard to CCS and nuclear power.

In order to maintain the consistency of individual scenarios, this section does not intend to summarise or merge them into additional "super scenarios", but rather presents various general trends that can be assumed to take place in the EU energy sector as the EU economy becomes increasingly low-carbon.

4.1 The low-carbon economy is possible

The first conclusion from the scenario analysis is that decarbonisation of the EU economy is possible using currently known technologies. Reducing domestic EU GHG emissions by at least 20% by 2020 and 80% by 2050 compared to 1990 is not only considered realistic, but sometimes also less costly than the reference/business-as-usual approach. The European Commission (2011c), for example, projects that average annual energy system costs between 2011 and 2050 will decline compared to the reference case in three out of its five scenarios presented above. The reason is that increases in capital costs and direct energy efficiency costs are projected to be compensated by reduced costs for energy purchases (i.e. a reduction in the external fuel bill). Various models present an optimal pathway, usually assuming availability of all technologies and no delays in mitigation action. Costs increase as the optimal pathway is deviated from with delays both in terms of technology deployment and/or serious mitigation efforts. However, even in the optimal pathway, major GHG emissions reductions set in only after 2020. Though all sectors will need to make considerable efforts to achieve this decarbonisation objective, the importance of an almost complete decarbonisation of the power sector is repeatedly mentioned.

4.2 Decreasing energy demand

Achieving the 80% decarbonisation objective is generally associated with a decrease in energy demand. By **2020**, most scenarios project **decreases in the order of 2-6% compared to 2010** (e.g. European Commission, 2011c; IEA, 2012a; SECURE, 2010). In the long term (i.e. by **2050)**, demand reductions are much higher and may reach up to 38% in the European Commission's energy efficiency scenario (European Commission, 2011c). More generally, however, long-term demand reductions are projected to be **in the range of 20-30%** (AMPERE, 2013; European Commission, 2011c; Greenpeace, 2012b; IIASA, 2012).

Two outliers are IEA (2012b) and the IIASA (2012) GEA-Supply pathway. While IEA (2012b) projects energy demand to stay more or less constant between 2010 and 2050, IIASA (2012) projects an increase of up to 17% in western Europe and 33% in eastern Europe.

It is worthwhile noting that the abovementioned demand reductions will need to be achieved within the context of a growing EU economy,[25] thus requiring an absolute decoupling of economic growth from energy demand. Energy efficiency plays a crucial role in achieving demand reductions and high energy efficiency assumptions lead to higher reductions in energy demand.

4.3 Changing energy mix towards renewables

There is strong emphasis placed by all scenarios on a shift away from fossil fuels towards renewable energy sources. While today's **share of renewables** in energy demand is around 9-11%,[26] this may increase to up to 22-23% by **2020** (AMPERE, 2013; Greenpeace, 2012b). Other scenarios are less ambitious, reporting the projected share to be **13-18%** (European Commission, 2011c; IEA 2012a, 2012b; SECURE, 2010). In **2050**, a realistic projected share of renewables in the energy mix may be **somewhat above 40%** (AMPERE, 2013; European

[25] In some scenarios, EU GDP is estimated to roughly double between 2010 and 2050, while its population is expected to grow only marginally over the same period.

[26] IEA (2012a) reports 11% of renewables in TPED for 2010, while the European Commission (2011c) reports 9% of renewables in gross inland consumption (GIC) for the same year.

Commission, 2011c; IEA, 2012b). However, projections differ widely, ranging from 21-22% (SECURE, 2010; IIASA, 2012) to around 90% (Greenpeace, 2012b; IIASA, 2012).

Although fossil fuels – and especially coal – tend to lose shares in the energy mix, they will still have a role to play in 2050. In 2010, more than three quarters of the energy mix was still based on **fossil fuels** (European Commission, 2011c; IEA, 2012a). This share drops to around **70%** in all scenarios **by 2020**. **By 2050**, most scenarios project a fossil fuel share in the energy mix of **40-50%** (European Commission, 2011c; IEA, 2012b; SECURE, 2010). Fossil fuels will remain particularly important in sectors where they are difficult to replace, for example in transport modes like aviation and maritime freight. The share of fossil fuels in the energy mix also depends on technological assumptions regarding the availability of CCS technology. The latter particularly benefits coal in the long term. Finally, gas is likely to remain important, not least as a back-up for variable renewable energy sources. Gas also benefits from the availability of CCS and thus maintains a higher share when CCS is assumed to be available.

4.4 Electricity demand on the rise

The substitution of fossil fuels with electricity from low-carbon sources presents a cost-efficient strategy particularly in sectors that are less flexible than power generation in reducing GHG emissions. As a result, all decarbonisation scenarios project growing electricity generation, mainly driven by increasing demand in transport and heating/cooling. **Until 2020**, most scenarios project electricity demand to grow by about **5-10%** compared to 2010 (European Commission, 2011c; Greenpeace, 2012b; SECURE, 2010). The increase is less pronounced to 2020 but then gains speed, especially after 2030 when electrification in transport is projected to accelerate. **By 2050**, demand may thus increase by up to 64% in some scenarios (e.g. SECURE, 2010), although lower demand increases in the order of **30-50%** compared to 2010 are more likely (ECF, 2011; Eurelectric, 2013; European Commission, 2011c; Greenpeace, 2012b; IEA, 2012b).

4.5 Power sector takes the lead

The sectoral analysis reveals that the power sector is the main enabler of decarbonisation and that is a prerequisite for the success of other sectors, such as transport and heating. The reason for such a focus on the power sector is that it is currently less expensive (in terms of marginal abatement costs) to reduce emissions in this sector than in others due to the wide range of well developed low-carbon power-generating technologies (compared to technologies available in other sectors).

Many scenarios assume that a decarbonisation of the power sector by 95% and further by 2050 (compared to 1990) will be required to achieve the overall EU decarbonisation objective. These savings will need to be achieved in the face of growing electricity demand, as laid out above. Energy efficiency and the upscaling of renewables are the two key strategies to decarbonise the power sector.

4.6 Energy efficiency is key

Energy efficiency plays a major role in all energy scenarios. For example, ECF (2010) estimates that cost-effective energy efficiency measures could reduce the demand for power by some 220 GW by 2050, equivalent to some 440 medium-sized coal plants, and reduce the cost of transition to a decarbonised power sector by up to 30%. The importance of energy efficiency is also highlighted by Eurelectric (2013), which projects that almost 40% of GHG emissions savings in the power sector will come from energy savings. In fact, energy efficiency is beneficial for two reasons. First, it reduces the overall demand for electricity. Second, and as a result of the first reason, it also reduces the requirement for additional low-carbon electricity generating sources as Europe undergoes the SET away from fossil fuels.

4.7 Focus on wind, biomass, hydro and solar PV

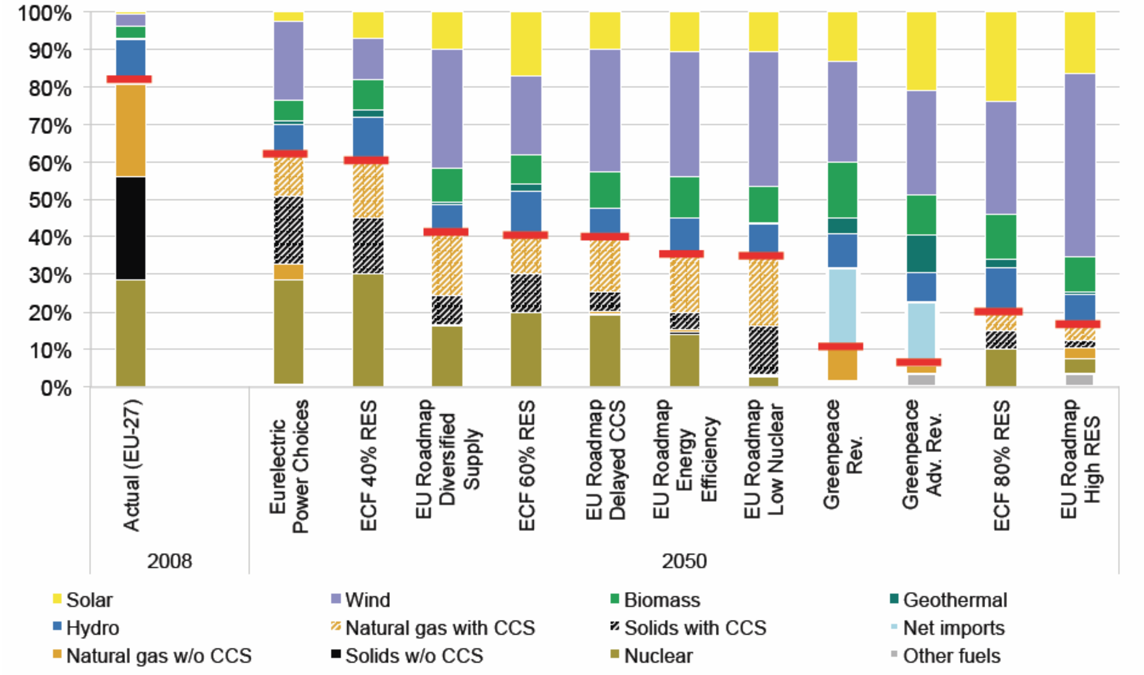
All scenarios project an increasing role for renewables in power generation. While today, some 20% of electricity generated comes from renewable sources (European Commission, 2011c), this share is projected to increase to around **35% by 2020** in most scenarios (European Commission, 2011c; ECF, 2011; IEA, 2012a and 2012b; SECURE, 2010), which is also in line with the binding EU renewable energy target. Such early progress is crucial to avoid the lock-in to carbon-intensive technologies.

Wind and hydro will be the most important renewable energy sources in power generation in 2020. **Wind** may cover some **12-15%** of total power generation in 2020 (Eurelectric, 2013; Greenpeace, 2012b; IEA, 2012a and 2012b; SECURE, 2010) and **hydro** could contribute another **10-12%** (Eurelectric, 2013; Greenpeace, 2012b; IEA, 2012a, 2012b; SECURE, 2010). **Biomass and solar** (mostly PV) make up the bulk of the rest with **6-8% and 3-6%,** respectively. Other technologies are too marginal to be reported here.

By 2050 the share of renewables in power generation is projected to increase further, though the range of projections is very wide (see Figure 30). ECF (2010), for example, published one pathway in which renewables contribute only 40% to electricity generation in the EU27. Greenpeace (2012b), on the other hand, reports a share in its scenario of 96%. The majority of scenarios, however, project a range of **60-85%** (AMPERE, 2013; ECF, 2011; European Commission, 2011c; IIASA, 2012, 2012b; SECURE, 2010).

In most scenarios, **wind** will be the single most important source of power in 2050, contributing some **30-35%** to power generation (AMPERE, 2013; ECF, 2011; Eurelectric, 2013; Greenpeace, 2012b; IEA, 2012b). About half of the power generated by wind will come from offshore wind parks by 2050 (Greenpeace, 2012b; IEA, 2012b). Other power sources are much less important, with **biomass and hydro** contributing similar shares of **8-13% each** to power generation, and **solar** falling behind with some **5-10%**. Major outliers are ECF (2011) and Greenpeace (2012b), which report much higher rates of 19% and 28%, respectively, for solar. Similarly, SECURE (2010) is an outlier in terms of biomass, reporting a share of up to 22% in power generation.

Figure 30. Shares in net electricity generation by source (including imports) in 2050



Source: SEFEP, 2012a.

Other renewable energy sources play no role in most scenarios, with the exception of Greenpeace (2012b) and IEA (2012b), which project a role for ocean-generated electricity in the order of 4% and 7%, respectively, by 2050. Greenpeace (2012b) also sees a role for geothermal power to contribute some 8% to EU power generation by 2050.

In contrast to renewable energy sources, nuclear power is at best assumed to maintain its current share (below 30%), but loses out significantly in most decarbonisation scenarios. The share of fossil fuels in power generation (which consists almost exclusively of gas and coal) is generally expected to decrease significantly, even in scenarios that foresee the commercial viability of CCS (usually only after 2030).

4.8 Uncertainty over nuclear and CCS

Scenarios differ considerably with regard to the importance they attribute to **nuclear** in the future power mix. While Greenpeace advocates a complete phasing-out by 2040, other sources provide scenarios where nuclear is still relevant even in 2050 (ECF, 2010; Eurelectric, 2013; European Commission, 2011c; IEA, 2012a, 2012b; IIASA, 2012). The European Commission (2011c) stresses that nuclear power can play an important role in decarbonisation, especially if the large-scale deployment of CCS were to be delayed. Yet, even in the Commission's scenarios, nuclear power does not exceed an EU-wide share of **19%** in power generation by 2050, and may contribute as little as **3%** depending on the scenario.

As with nuclear power, the studies are divided over the future contribution of **CCS**. However, only Greenpeace (2012b) projects a future completely without it. In all other scenarios CCS plays a role, albeit only after 2030/2040. In the European Commission's (2011c) scenarios, for example, CCS is projected to contribute **7-32%** to power generation. CCS is less important in scenarios with a higher share of renewables, while it increases in importance when nuclear power generation is low. CCS is also interpreted as an insurance policy, allowing for decarbonisation in case there are problems with energy efficiency, renewables and nuclear which mean a greater reliance on fossil fuels than expected.

CCS is not only potentially relevant for the power sector, but could also contribute to abating industry emissions. For example, ECF (2010) argues that in addition to efficiency improvements, CCS is also critical in industry to achieve the decarbonisation target. In fact, their decarbonisation scenarios all depend on the assumption that by 2050, 50% of heavy industry (cement, chemicals, iron and steel, petroleum and gas) use CCS when burning fossil fuels.[27]

4.9 Variability necessitates more generation capacity

The rising share of variable renewables, such as wind and solar PV, will require an increase in installed electric capacity greater than the increase in power output. This necessity is related to lower capacity factors of intermittent renewables, which naturally do not produce electricity when there is no wind or when there is no sun, for example. Additional "back-up" capacity is thus projected in every scenario, which increases with the level of variable renewables. Generally, electrical capacity is projected to increase by about **20-30% by 2020** (Eurelectric, 2013; European Commission, 2011c; Greenpeace, 2012b, IEA, 2012a, 2012b). In the long term (i.e. **by 2050)**, electric capacity will need to increase further by about **80-100%** compared to 2010 (Eurelectric, 2013; European Commission, 2011c; Greenpeace, 2012b, IEA, 2012b). The largest increase is projected in the European Commission's High Renewables scenario, which might require a capacity increases of 170% by 2050 (compared to 2010). Wind and solar PV will play a major role in capacity expansions, reaching about 60% of installed capacity by 2050 (European Commission, 2011c).

As electric capacity expands faster than generated output, the capacity-to-generation ratio[28] increases substantially in most scenarios. Starting in 2010 at around 2.2-2.4:1 in most scenarios (ECF, 2010; European Commission, 2011c; Greenpeace, 2012b; IEA, 2012a, 2012b; SECURE, 2010), it increases to around 2.5-2.7:1 by 2020 (European Commission, 2011c; IEA, 2012a, 2012b; SECURE, 2010) and further to around 3:1 and above (European Commission, 2011c; IEA, 2012b). In some scenarios, the ratio increases to as much as 3.6-3.8:1 (ECF, 2010; European Commission, 2011c), which would mean that each unit of electricity produced may need to be backed-up by nearly four equivalent units of installed capacity to cover for intermittencies.

4.10 More flexibility in the electricity system

Given the increasing reliance on variable renewables such as wind and solar, it is also widely recognised that the electricity system has to become more flexible. There are several resources for flexibility in the electricity system that can be categorised into: (i) generation, (ii) transmission/distribution, (iii) demand-side response and management, and (iv) storage.

i. ECF (2010) identifies "the potential remaining need for highly flexible open-cycle gas turbines" to meet the flexibility challenge. The European Commission (2011a) also mentions biomass and gas-fired flexible generation capacity as back-ups for variable RES.

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[27] Note that costs for CCS in industry are highly uncertain; ECF (2010) assumes €100 per tCO2e.

[28] As indicated before, this ratio puts the installed electrical capacity in relation with the projected generated electricity output. It is calculated by converting installed capacity into a theoretical generation maximum, which would be reached if all installed capacity produced electricity at full capacity for every single hour of the year (i.e. 8,760 hours per year), i.e. if the capacity factor for all installed capacity was 100%.

ii. The European Commission (2011a) states that its decentralisation scenarios, and especially the high renewables case, require a substantial increase in interconnection capacity (e.g. HVDC lines from the North Sea to the centre of Europe). The ECF Roadmaps also heavily depend on transmission expansion.[29] Little attention is paid to the flexibility potential of the distribution system.

iii. Better demand response through smart metering would allow for peak-shaving and is generally deemed to be important for the decarbonisation of the European energy system.

iv. Storage deployment in the form of pumped storage, CSP and hydrogen is a common way for the scenarios to deal with the variability that cannot be handled by the other options. The European Commission (2011a), for instance, refers to increased pumped storage to deal with the variability of RES. Excess electricity is transformed into hydrogen (power to gas or, where this is not technically or economically feasible, stored as hydrogen). The extent to which hydrogen storage is used varies across the different decarbonisation scenarios.

4.11 Fuel switch, electrification and biofuels in transport

Several scenarios show that the European Commission's target of reducing GHG emissions from the transport sector by 60% compared to 1990 levels is feasible. Increasing fuel economy is frequently projected to lead to an overall decrease in energy demand. Hydrocarbons, which currently contribute 97% of the transport sector's fuel mix are likely to continue to play an important role even in 2050. Electricity will play an increasing role in transport, in particular in passenger road transport, but most probably only after 2030 when electrification is projected to accelerate. Biofuels will be part of the solution, especially in transport modes where electrification is less practicable, such as aviation and shipping. However, since transport volumes will increase further, the potential share of biofuels will be limited, albeit increasing (to almost 25% by 2035 in IEA (2012a), much less in ECF (2010). The role of hydrogen is expected to be marginal in road transport.

The strategy for the transport sector is summarised in IEA (2012b) as "avoid/shift/improve", where "avoid" stands for slowing travel growth (e.g. through city planning or demand management), "shift" stands for the shift to less carbon-intensive transport modes, and "improve" stands for the adoption of new technologies and fuels.

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[29] 2020: ECF (2011) concludes that ENTSO-E's transmission expansion plans (42,000km increase from 2010-2020; current total around 300,000km) are sufficient if implemented on time (a 2020 RES curtailment of merely 0.6%). Local exceptions exist, however, for example Ireland, where 31% of wind energy would be curtailed (ibid). However, the new 2012 TYNDP (which was published after ECF (2011)) warns that "one in three planned investments are experiencing delays in implementation due to long permitting processes". ECF's less transmission sensitivity analysis (50% less capacity for every line built) reveals that RES curtailment would be 17% higher.

2050: The transmission capacity requirements to make ECF's 80% renewable scenario possible are considerable. Transfer capacity is expected to increase from 34 GW (base year) to 127-166 (higher value represents no demand response case). Especially striking, given the troublesome history of the existing 1.4 GW interconnector, is the assumption that interconnection capacity between France and Spain will increase to some 45-52 GW. Transmission requirements are lower in the 60% and 40% renewables scenarios.

4.12 Energy efficiency in buildings

The significant potential for demand reduction in the heating sector can mainly be realised through energy efficiency improvements, such as better thermal insulation, more energy efficient equipment, and technology switching (e.g. replacing a fossil fuel-fired boiler with a heat pump for space heating) (IEA, 2012a). The biggest potential is in the residential sector, where heating and cooling account for two thirds of the energy use (European Commission, 2011a). Decarbonisation scenarios project a demand reduction of 32-63% by 2050 (European Commission, 2011c), mainly impacting on gas. However, the effect may not be uniform across member states, as in some gas may remain more cost-effective than electric or other fossil fuels-based heating (European Commission, 2011d).

4.13 Regional differences

The scenario analysis reveals several pronounced differences between western Europe and central and eastern Europe (herein defined as the member states that joined the EU in 2004, 2007 and 2013, with the exception of Cyprus and Malta).

The first result is that eastern Europe achieved much higher rates of decarbonisation than western Europe between 1990 and 2009 (-38% compared to -3%, as reported by Greenpeace (2012b)). This is mainly a result of the collapse of heavy industry in the context of economic transition. Future decarbonisation rates will thus need to be higher in western Europe than in the east if both regions are to reach similar decarbonisation levels by 2050 (compared to 1990).

Second, there is uncertainty about the regional development of energy demand between now and 2050. While Greenpeace (2012b) projects future energy demand to decrease much faster in western Europe (-31%) than in eastern European countries (-10%), IIASA (2012) projects the opposite (-17% and -33%, respectively). In the IIASA GEA-Supply pathways, energy demand may even increase in both regions, much more so in eastern Europe (+17% and +33%, respectively).

Third, projected deployment of renewable energy sources by 2050 is higher in the west than in the east, although the difference is more pronounced in IIASA (2012) than in Greenpeace (2012b) and ECF (2010). Greenpeace (2012b) projects shares of renewables in final energy demand of 91% for OECD Europe and 89% for eastern Europe, while IIASA (2012) projects renewables shares in primary energy demand of 34-83% in western Europe and 23-85% in eastern Europe. ECF (2010), on the other hand, projects that 90% of renewables capacity will be installed in western Europe, with the main hubs being Benelux and Germany, the Iberian peninsula and France. Solar capacities are mainly projected to be installed in the Iberian peninsula, central Europe, France, Italy and Malta, and Benelux and Germany. In terms of wind power, almost 50% of capacities will be found in the UK and Ireland, and Benelux and Germany. Additional capacities will mainly be found in the Nordic countries, France and the Iberian peninsula. In fact, Poland, the Baltics and all EU member states in southeast Europe will only contribute some 13% to installed renewables capacity by 2050 (ECF, 2010).

Finally, CCS may play a larger role in countries with lower renewables potential and is projected by 2050 to feature most prominently in the electricity mix of Poland and Italy, followed by Germany, Romania, Hungary and Denmark (Eurelectric, 2013).

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CENTRE FOR EUROPEAN POLICY STUDIES, Place du Congrès 1, B-1000 Brussels, Belgium
Tel: 32 (0)2 229 39 11 • Fax: 32 (0)2 219 41 51 • www.ceps.eu • VAT: BE 0424.123.986