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TRANSFORMING THE EUROPEAN ENERGY SYSTEM: MEMBER STATES' PROSPECTS WITHIN THE EU FRAMEWORK

BRIGITTE KNOPF[*,§§], BJØRN BAKKEN[†], SAMUEL CARRARA[‡],
AMIT KANUDIA[§], ILKKA KEPPO[¶], TIINA KOLJONEN[||], SILVANA MIMA[**],
EVA SCHMID[*] and DETLEF P. VAN VUUREN[††,‡‡]

[*]*Potsdam Institute for Climate Impact Research (PIK)*
Research Domain Sustainable Solutions
P. O. Box 60 12 03, 14412 Potsdam, Germany

[†]*SINTEF Energy AS, Postboks 4761 Sluppen, 7465 Trondheim, Norway*

[‡]*Fondazione Eni Enrico Mattei (FEEM)*
Euro-Mediterranean Center on Climate Change (CMCC)
Isola di San Giorgio Maggiore, 30124 Venezia, Italy

[§]*KanORS-EMR, SDF L-7B, NSEZ*
Dadri Road Phase II, NOIDA UP 201305, India

[¶]*University College London, UCL Energy Institute*
14 Upper Woburn Place, London, WC1H 0NN, UK

[||]*VTT Technical Research Centre of Finland*
P. O. Box 1000, 02044 VTT, Finland

[**]*PACTE-EDDEN, CNRS, 1221 rue des Résidences*
38400 Saint-Martin-d'Hères, BP 47 - 38040 Grenoble CEDEX 9, France

[††]*PBL Netherlands Environmental Assessment Agency*
P. O. Box 30314, 2500 GH. The Hague, Netherlands

[‡‡]*Utrecht University, Department of Geosciences*
Heidelberglaan 2, 3584 CS Utrecht, Netherlands
[§§]*knopf@pik-potsdam.de*

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The Energy Modeling Forum 28 (EMF28) performed a large-scale model comparison exercise to illustrate different technology pathways for cutting European greenhouse gas emissions by 80% by 2050. Focusing on selected countries (France, Germany, Italy, Sweden, and UK), this paper first analyzes climate and energy policy objectives and debates in the respective countries. It then compares EMF28 model results to the short-term projections of the National Renewable Energy Action Plans (NREAPs) and the long-term transformation pathway given in the European Commission's "Energy Roadmap 2050". It concludes that there is sufficient agreement with the NREAPs and national policies to accept the model results as conceivable scenarios. The scenarios suggest that in the future a variety of different national energy mixes will continue

[§§]Corresponding author.

to reflect the different resource bases and preferences of individual Member States. In order to ensure a cost-efficient transformation, it is important to improve coordination between Member State policies and those at the EU level.

Keywords: European climate and energy policy; National Renewable Action Plans (NREAPs); environmental federalism; mitigation scenarios.

1. Introduction

The European Union (EU) has set an aspirational goal of an 80–95% reduction in greenhouse gas (GHG) emissions by 2050 relative to 1990 levels (European Council, 2009), confirmed by the European Council (2011). This long-term climate mitigation target is underpinned by three mid-term targets specified for the year 2020, known as the 20-20-20 targets[1]: reducing GHG emissions by 20%, increasing the share of renewable energy in final energy consumption to 20% and improving energy efficiency by 20%. Even though the 20-20-20 targets are formulated at the level of the EU as a whole, the actual policies required to achieve them will need to be implemented at Member State level. As part of the Renewable Directive (European Union, 2009), Member States had to report their strategy on the deployment of renewable energies in the official National Renewable Energy Action Plans (NREAPs) (EEA, 2012).

In 2011, the European Commission launched a debate on the long-term climate mitigation strategy by issuing three roadmap documents: on a low carbon economy (European Commission, 2011b), on transport (European Commission, 2011d) and the "Energy Roadmap 2050" on transforming the energy system (European Commission, 2011c). Despite the fact that the European Commission sees the Energy Roadmap 2050 as "the basis for developing a long-term European framework" (European Commission, 2011c), aspects related to energy strategies remain national responsibilities. According to Article 194 of the Treaty on the Functioning of the EU (European Union, 2010) all measures needed to preserve and improve the environment "shall not affect a Member State's right to determine the conditions for exploiting its energy resources, its choice between different energy sources and the general structure of its energy supply". Thus, the domestic energy mix ultimately lies within the sovereignty of Member States. However, individual national preferences and policies play an important role in national strategies that together determine the success of European long-term mitigation strategy.

Recently, several modeling studies (including the EMF28 study, Knopf *et al.*, 2013) analyzed the energy transition within the EU that would be necessary to meet the long-term climate mitigation target. In the Energy Roadmap of the European Commission (European Commission, 2011a,c), different pathways to decarbonize the European energy system, depending on the specific technological setting, have been analyzed by means of a model of the European energy system. Other studies focus solely on Europe as a single entity and less on the interplay between specific national and European strategies.

[1]For more information consult: http://ec.europa.eu/clima/policies/package/index_en.htm.

Some recent examples are the "Power Choices" study by Eurelectric (2009), with a focus on the power sector, and the "Roadmap 2050" by the European Climate Foundation (2011) that investigated a number of pathways with different shares of renewables.

Since these studies analyze the energy system transformation in Europe as an *aggregate* of 27 different energy mixes, they do not dig further into the inter-relationship between national and European strategies. The Energy Roadmap, for example, concludes that several different strategies to reach decarbonization in Europe are possible, but that they all show that "renewables rise substantially, [...] that carbon capture and storage (CCS) has to play a pivotal role in system transformation [...] and that nuclear energy provides an important contribution" (European Commission, 2011c). However, it is not stated whether these conclusions hold equally for all Member States or whether national strategies may deviate substantially from this. From the perspective of the European Commission, Article 194 determines that they do not have a mandate to influence Member States' choice concerning certain technologies. Yet, when it comes to translating these technology pathways into policy measures for implementation, it is of fundamental importance to understand what the European energy transition demands at the level of individual Member States.

This paper makes a first attempt to overcome this gap in research by analyzing the transition within selected Member States and relating it to the European transformation. To our knowledge this is the first attempt to relate the EU Energy Roadmap to model results and policies of individual Member States. Our analysis is based on model scenarios generated in the Energy Model Forum (EMF) 28 model comparison (see Knopf *et al.*, 2013). In this paper, we look in more detail at the country level strategies within these scenarios. In order to keep our analysis manageable, we focus on a limited number of selected countries as case studies for which a critical number of model results are available: France, Germany, Italy, Sweden, and UK. Except for Sweden, these countries constitute the four largest emitters and together account for more than 55% of the European CO_2 emissions.[2] These five Member States cover the spectrum of energy mixes across Europe, ranging from coal-based countries, such as Germany, to those with high shares of hydro energy, such as Sweden. The key questions are:

(1) What are the national policies and roadmaps to achieve the overall European target of 20% emission reduction and 20% renewables by 2020 and 80% emission reduction in the long-term?
(2) Are models able to capture different approaches in national energy mixes? How do the model scenarios compare to the actual short-term political ambitions as expressed in the NREAPs? What do models project for the long-term future development of the energy mix for the Member States?
(3) What are the policy implications that can be drawn from this analysis?

[2] It should be noted that in order to cover the full European perspective it would be of utmost importance to also include the eastern-European countries in this analysis, especially as Poland for example is the sixth largest emitter. Unfortunately, due to the lack of participants in EMF28 from eastern European countries this aspect could not be covered.

Table 1. Models of the EMF28 modeling comparison exercise considered in this analysis.

	Economic coverage	Geographic coverage (number of EU regions)	Inter-temporal solution methodology	International trade
FARM EU [A]	Full economic coverage in CGE	Global (5)	Recursive dynamic	All commodities
POLES [B]	Partial equilibrium model of the energy sector	Global (27)	Recursive dynamic	Fossil fuels
PRIMES [C]	Partial equilibrium model of the energy sector	EU (25)	Perfect foresight in power sector, 10-year foresight in demand sectors	Electricity and gas in Europe
TIMES PanEU [D]	Partial equilibrium model of the energy sector	EU (23)	Inter-temporal optimization with perfect foresight	Electricity, biomass, biofuels
PET [E]	Partial equilibrium model of the energy sector	EU (25)	Inter-temporal optimization with perfect foresight	Electricity, biomass, biofuels
EMELIE-ESY [F]	Partial equilibrium model of the electricity sector	EU (27+2)	Inter-temporal optimization with perfect foresight	Electricity

Notes: [A] (Sands *et al.*, 2013); [B] (Criqui and Mima, 2012); [C] (Capros *et al.*, 2012); [D] (Blesl *et al.*, 2012); [E] (Kanudia and Gargiulo, 2009); [F] (Traber and Kemfert, 2012; Schroeder, 2012). All six models provide results for France, Germany, and UK. Five models provide numbers for Italy and Sweden.

1.1. *Participating models and scenario set-up*

From the 13 models participating in EMF28 and presented in Knopf *et al.* (2013), six provide results on a regional level for Europe, see Table 1. The models differ with respect to their economic and geographical coverage, as well as their inter-temporal solution methodology and options to trade energy carriers. This affects the degree of flexibility as to when and where given mitigation targets will be achieved. All models resort to simplifying assumptions based on economic theory, e.g., perfect markets or symmetric information, and generate normative scenarios that show what needs to be done in a specific scenario setting in order to achieve exogenously set mitigation targets. Therefore, model results can be compared with real developments and political ambitions in the respective Member States as stated, for example, in the NREAPs. The model scenarios also provide long-term transformation pathways that can serve as a basis for policy makers to derive mitigation strategies.

With respect to the sectoral and geographical coverage, there are two global models, one of which covers all sectors of the economy, splitting Europe into five aggregate regions (FARM-EU) while the other only covers the energy sector, but represents each of the individual 27 Member States (POLES). There are three models of the European energy sector designed on a country basis (PRIMES, TIMES-PanEU, PET) and one model that is confined to the electricity sector (EMELIE-ESY). The degree of when- and where-flexibility in the models differs, both due to how the time dimension is treated in the solution methodology and which energy carriers are considered for trade across countries. When-flexibility in myopic models that solve with a recursive dynamic method is much lower than in models that assume perfect foresight over the modeled time horizon. Inter-temporal optimization models with perfect foresight do not assume any burden sharing of CO_2 reduction according to GDP or any similar measure, but implicitly assume an emission trading market (with no transaction costs and perfect information). Except for POLES, electricity is tradable in all models, allowing for full where-flexibility in the power sector.

The starting point for the analyses in this paper is the scenario definition of the Energy Roadmap 2050 (European Commission, 2011c), in particular the "Diversified supply technologies" scenario. We investigate a mitigation scenario with 80% GHG reduction by 2050, referred to as 80% DEF scenario in Knopf *et al.* (2013).[3] All models assume their default technology setting, including the carbon capture and sequestration (CCS) technology. Specific national technology policies and renewable supporting schemes are not represented in the models, with the exception of the consideration of nuclear phase-outs in some countries. The scenario assumes that the EU takes leadership of the global climate policy regime by committing unilaterally to an emissions reduction target of 80%, while the rest of the world continues with moderate targets.

2. National Energy Mixes, Policies and Roadmaps

The status quo in the selected countries (France, Germany, Italy, Sweden, and UK) is reflected in the 2010 energy mix. Primary energy mixes clearly differ among Member States, see Fig. 1. Oil is the only fuel that is used to a similar extent in all Member States because fuel for all modes of transport is predominantly based on oil products. While the transport sector, based on almost 100% oil, is structurally the same across Member States, the most substantial differences can be seen in the power sector, see Fig. 2. Some observations really stand out for the selected Member States: (i) a high proportion of nuclear in France, (ii) substantial use of coal in Germany, (iii) relatively high share of natural gas use in Italy, (iv) an almost 100% use of non-fossil electricity, i.e., hydro, biomass, and nuclear in Sweden, and (v) a fossil based system with a mixture of coal and gas in the UK.

In the following sections, we analyze national policies in the five selected countries. Some Member States have also formulated national roadmaps that present plans and scenarios to achieve climate reduction targets. This can be seen, for example, in Notenboom *et al.* (2012) which gives a very comprehensive overview of roadmaps for the

[3]We concentrate here on the mitigation scenario EU6 and do not consider the reference scenario EU1 with 40% GHG reduction by 2050, as in Knopf *et al.* (2013) it was shown that the strategic differences on technology choices between the two scenarios are not substantial, especially in the electricity sector which is the focus of the analysis in this paper.

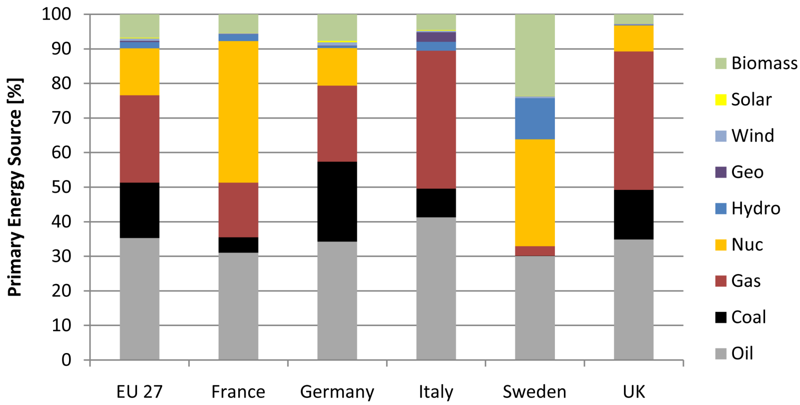

Figure 1. Primary energy mix in EU27 and selected Member States in 2010. Data based on (Eurostat, 2012).

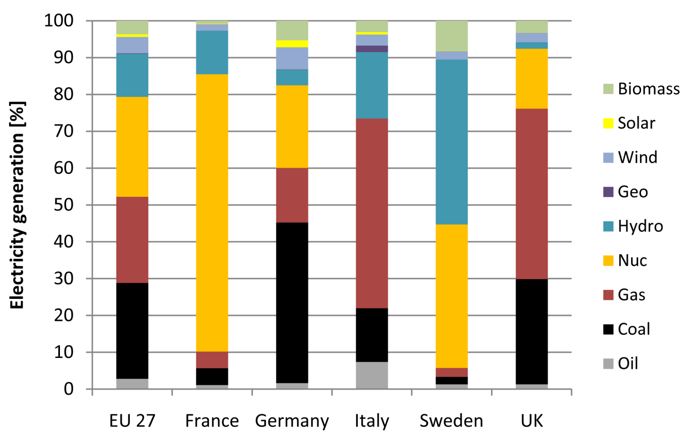

Figure 2. Electricity generation in EU27 and selected Member States in 2010. Data based on Eurostat (2013b).

north-western European countries. In this section, for each of the five countries, we will give a short introduction to the political targets, current debates and preferences on national GHG reduction targets and on attitudes towards low carbon technologies such as renewable energy sources (RES), nuclear, and CCS and relate this to the model scenarios.

2.1. *France*

In France, the energy law of 2005 (Grenelle de l'environnement) laid down targets for (i) GHG emission reductions of 40–45% by 2030 and 75% by 2050, (ii) the share of renewables to be 23% by 2020 in line with the French commitment to the 20-20-20 targets, and (iii) energy efficiency. Recently, a number of studies on energy system transitions up to 2050 have been presented by Government and other organizations (ADEME, 2012; Percebois and Mandil, 2012; Association négaWatt, 2011). None of these can be considered as official scenarios, but they have the merit of testing different assumptions on mid-term and long-term GHG emission reduction. At the end of November 2012, the French Minister for Ecology launched a public debate on the Government's proposals on how to achieve the European 20-20-20 targets and the pledge of the French president to cut nuclear energy from 77% in 2011 to 50% of France's power mix by 2025.

There are differing opinions concerning the future of nuclear energy; currently, nuclear energy is the dominant technology for power generation in France and extending the lifetime of existing plants is seriously considered, because this appears to be the cheapest way to generate low-carbon power. This option, however, is not in line with the electoral commitment of François Hollande to reduce the role of nuclear energy over the coming years. French energy industry leaders do not approve of the move away from nuclear power.

France has a large potential for RES, especially for onshore wind. However, social acceptance is sometimes lacking. In addition, France has relatively large agricultural and forest areas available per capita, which indicates that biomass production could be important in the future, especially for transport. Furthermore, France has a relatively large potential for solar energy production in the south of the country and expects natural gas to provide flexibility in the electricity system. The French Minister for Ecology has announced that the Government has not closed the door on the discussion of exploration for shale gas, but hydraulic fracturing process is prohibited because of environmental concerns. The Government has recently rejected seven applications to develop France's shale deposits. Currently, France exports a large quantity of base-load electricity. More wind and solar power in the surrounding countries will lead to additional production to cover the peak demand in these countries, which will influence France's export potential.

2.2. *Germany*

The German Government has released a set of energy and climate targets for both the mid-term period and the target year of 2050 in its Energy Concept (Federal Government, 2010). The GHG reduction targets of 80–95% by 2050, compared to 1990 level, with interim targets of 40% (2020), 55% (2030), and 70% (2040), are not binding but they declare intentions and serve as a reference point. The Government has no official scenario but a few studies serve as a basis for designing a long-term strategy. The "Leitstudien" (Lead studies) (DLR/IWES/IFNE, 2010, 2012) commissioned for the Federal Ministry for the Environment (BMU) play an important role in renewable deployment. They also served as a basis for the NREAPs and provide orientation for the targeted quantities of installed capacities supported by the feed-in tariff (FIT) scheme for RES. In addition, the "Energy Scenarios for an Energy Concept of the Federal Government" (EWI/GWS/Prognos, 2010) are an important point of reference. The targets for installed RES capacities in the Energy Concept agree with selected numbers from the "Leitstudie" as well as the "Energy Scenarios" — though without explicitly stating so. An official scenario framework for network planning of the electricity grid was recently published. This included an extensive public consultation process (Bundesnetzagentur, 2012).

The German Government decided to phase-out nuclear energy by 2022. This was initially agreed in 2000 and confirmed in 2011 after the Fukushima nuclear accident. While phasing out nuclear energy, Germany intends to substantially increase the deployment of RES. In this respect, it is important to note that in Germany the CO_2 targets are not legally binding, unlike the targets for renewables. Germany has a very ambitious target of reaching a minimum share of 80% renewables in the electricity mix by 2050, as specified in the Renewable Energy Act. Recently, the development has been very dynamic, particularly in the electricity sector. The share of renewables has nearly tripled in the last decade from 8% in 2002 to 23% in 2012 (BDEW, 2013a).

Despite the nuclear phase-out, Germany is still a strong exporter of electricity with net exports in 2012 reaching a peak at more than 20 TWh (BDEW, 2013b). This compares to a domestic consumption of roughly 600 TWh. These exports were mainly to the Netherlands (BDEW, 2013b), displacing the Dutch gas power plants that now face the problem of declining competitiveness in the joint European market. This effect emphasizes that unilateral national activities in the liberalized market will clearly have an effect on neighboring countries, see, for example, Fischer and Geden (2011).

2.3. *Italy*

In March 2013, the Ministry of the Economic Development released the final version of the 2020 National Energy Strategy (Strategia Energetica Nazionale) (Ministero dello Sviluppo Economico, 2012) after a consultation with institutions, trade unions and social partners on the contents of the first draft produced in October 2012. The report indicates that the overall electricity demand will remain roughly constant until 2020 (345–360 TWh against 346 TWh in 2010). Electricity supply is expected to be obtained as follows: 35–40% from gas, 35–38% from RES, 15–16% from coal, 7–10% from imports, 1% from oil, and 2% from other sources. The electricity mix is thus supposed to continue to rely on a mixture of natural gas and RES (c.f. Fig. 2), even though the focus partially transfers from gas to RES.

The new target for the share of RES in electricity production is, at 35–38%, well above that reported in the NREAPs of 26%. The RES share in the gross final energy consumption is also higher: 19–20% (from 10% in 2010) compared to the European 17% NREAP target. This reformulation of the Italian target has also become necessary in the light of the massive deployment of solar PV plants in 2010 and 2011 which was boosted by a very favorable FIT support scheme. An intense, though lower, development also took place in 2012. The installed capacity, which was 38 MW in 2005 and 431 MW in 2008, increased to 12.8 GW in 2011 and reached a level of 16.4 GW at the end of 2012 (APER, 2008; GSE, 2013b), while the target indicated in the NREAP, released in June 2010, was 8 GW by 2020.

Nuclear has been discarded as an option for the future in Italy. The Government had recently planned a re-start of this technology, which was abandoned in the late

1980s after a referendum following the Chernobyl incident; nuclear was planned to contribute 25% of the domestic production in some 20 years. However, after the Fukushima nuclear accident another referendum was held, and because there was a clear public aversion to this option, all plans for new nuclear power plants have been abandoned. As a consequence, nuclear will not be deployed in the country in the short or medium-term.

There is a very different picture for the use of CCS. In Italy, a small pilot plant exists in Brindisi (capturing 8 $ktCO_2$/yr) and a large-scale demonstration plant (1 $MtCO_2$/yr) is being built in Porto Tolle, although it faces some bureaucratic problems. A major application of CCS in the forthcoming decades could therefore be a possibility. It is important to point out that the storage capacity of carbon dioxide in the country has been assessed to be 13.3 $GtCO_2$ (Caliri and Panei, 2012). Considering that the overall annual production of carbon dioxide in 2010 was 404 $MtCO_2$ storage capacity does not represent a constraint for the deployment of CCS.

2.4. *Sweden*

Sweden's long-term vision is to decarbonize the economy by 2050. However, this vision includes sinks and international trade of carbon credits. By adopting existing Swedish nuclear policy, which sets limits to additional new nuclear reactors but allows the replacement of old ones, there is no real obstacle in envisaging Swedish electricity to be 100% fossil-free in the long term. However, the Government's vision that by 2030 Sweden will have a vehicle fleet that is independent of fossil fuels would definitely be a challenge. Another challenge is to decarbonize Swedish energy intensive industries, which needs the adoption of CCS in steel and cement, as well as pulp and paper industries (IEA, 2013; Regeringskansliet, 2009, 2013).

Today Sweden has a diverse energy mix with high shares of non-fossil primary energy (approximately 38% in 2010), generated from hydro, biomass, and nuclear; nearly 100% electricity production comes from non-fossil fuels due to high shares of hydro and nuclear. Bioenergy is the main source of renewable energy supply in Sweden, and is primarily produced and used in pulp and paper industries. Biomass is also used in district heating and for combined heat and power production (co-generation). Over the last decade, wind power has become an increasingly important source; generation reached 6 TWh in 2011, and the increase was 75% over the year 2010. On the other hand, solar is only a limited resource due to Nordic conditions (IEA, 2013).

The Swedish Parliament has adopted a national overall target for renewable energy of one percentage point above the target given in the NREAPs. This means that the proportion of RES in the total final energy consumption is expected to be 50.2% in 2020. In the electricity sector, in the NREAPs the Federal Government estimates that there will be a 62.8% share of renewable energies in by 2020. The share in the heating/cooling sector will be 62%, while in the transport sector it will amount to 12.4%.

The Swedish electricity system is part of the Nord Pool Spot market, which trades within participating countries and Central Europe. Within Nord Pool Spot, Norway, Finland, Denmark, and Sweden are the largest electricity trading partners. The Nord Pool market is characterized by a high share of both hydro and wind, and therefore the net export/import balance depends significantly on the climatic conditions. During cold winters, more electricity is also used for heating, which has an impact on the net export/import balance. Due to a growing share of variable generation in Central Europe, an increasing number of European countries are dependent on the balancing power from the Nordic region. Therefore, more interconnections are expected to be built between the Nordic region, including Sweden, and Central Europe.

Decarbonizing the Swedish industrial sector would require the application of CCS, which would be a challenge as Sweden does not have any suitable storage sites; it would mean that captured CO_2 would have to be transported to the North Sea or to some other storage site. On the other hand, Nordic studies, and recently the International Energy Agency (IEA), have indicated that Sweden has good potential to apply bio-CCS to its pulp and paper industries or co-firing boilers using both biomass and fossil fuels (IEA, 2013; Teir *et al.*, 2010).

2.5. *United Kingdom*

The UK has a legally binding long-term target to reduce GHG emissions by 80% by 2050, established by the Climate Change Act in 2008 (UK Gov, 2008). The transition towards this long-term target is being managed through five-year long carbon budgets, which help to reduce planning uncertainty for prospective investors. The latest of such assessments focused on the period 2023–2027 (Committee on Climate Change (CCC) 2010; HMG, 2011). There are no policies in place that would exclude a specific technology option and a variety of technologies are expected to contribute in the future.

There exists no official UK scenario, but the Government contracts scenario work for advice on current issues (Committee on Climate Change (CCC), 2010; AEA, 2011a,b). This can also be seen in Ekins *et al.* (2013), which compares a number of recent UK MARKAL scenarios, including those of CCC and AEA. Additionally, a number of other studies investigate the transition towards a low carbon or even zero carbon future for the UK, for example WWF (2011) and CAT (2010).

A number of national policy instruments were implemented to reduce emissions and increase the contributions from low carbon options. Renewables for electricity generation are directly supported through the renewables obligation, a green certificate scheme aimed at large facilities, and a FIT scheme for the renewable plants that have a capacity below 5 MW. The proposed electricity market reform would, however, introduce new measures such as "contracts for difference" and "emissions performance standard". The former of these would in time replace the renewables obligation, in addition to supporting other low carbon electricity, such as CCS and nuclear. Additionally, a carbon price floor will be in place from 1st April 2013 onwards. The carbon price floor is essentially a tax on fossil fuels used for electricity generation. It is expected to be £16/tCO2 in 2013, £30/tCO2 in 2020, and £70/tCO2 in 2030 (in

2009 prices). A number of instruments aimed at reductions in other sectors also exist (e.g., Climate Change Levy, Carbon Reduction Commitment, and Renewable Heat Incentive).

In terms of technologies, the UK can support a range of options as it has CCS storage options available, supports the building of new nuclear plants and has good wave and wind resources. For CCS the Department of Energy and Climate Change recently published a roadmap (DECC, 2012), which sets as a goal the "commercial deployment of CCS in the UK in 2020s". The Government also launched the second competition for building a commercial scale CCS facility, after the first competition failed to lead to a successful project. Considerable CCS deployment is projected, with a median value of captured emissions of 120 $MtCO_2$ and a 25% share of electricity from fossil-CCS in 2050. Concerning nuclear, the UK policy supports the building of new nuclear capacity but the realization of the projects depends on the companies finding such investments economically lucrative. There are currently three consortiums with plans to build new nuclear capacity in the UK. Additionally, the Government announced that exploratory hydraulic fracturing for shale gas could resume in the UK, which could eventually lead to a significant increase in the domestic natural gas production. The UK has excellent wind resources and this is incorporated in the projections made in the NREAP, which projects about 15 GW of onshore and 13 GW of offshore capacity for 2020.

3. Model Perspectives for Transforming the Energy Sector

In this section, we come back to the second set of key questions raised in Sec. 1 — are models able to capture the diversity of national energy mixes and different national preferences and policies described in the previous section? How do the model scenarios compare to the actual short-term political ambitions as expressed in the NREAPs? What do models project for the long-term future development of the energy mix for the Member States?

3.1. *Short-term model projections: Comparison with NREAPs*

In the 20-20-20 package, the EU has committed to raising the share of EU energy consumption produced from renewable resources to 20% by 2020 (European Union, 2009). Member States have laid down their plans of how they expect to reach this legally binding target in the NREAPs including interim steps required up to 2020. These deployment plans can therefore be seen as a vision by policy-makers on the deployment of renewables for their respective country. In the following, we compare these short-term and medium-term visions, provided in the NREAPs, with model results.

Based on the NREAPs, the most important contribution of renewable electricity technologies for the year 2020 is expected to be from wind power (41%). The second largest provider is expected to be hydropower (30%). Biomass electricity will contribute 19% and solar electricity 9% (EEA, 2012). EMF28 results in general support this ranking of the importance of technologies, indicating contributions of 35% from

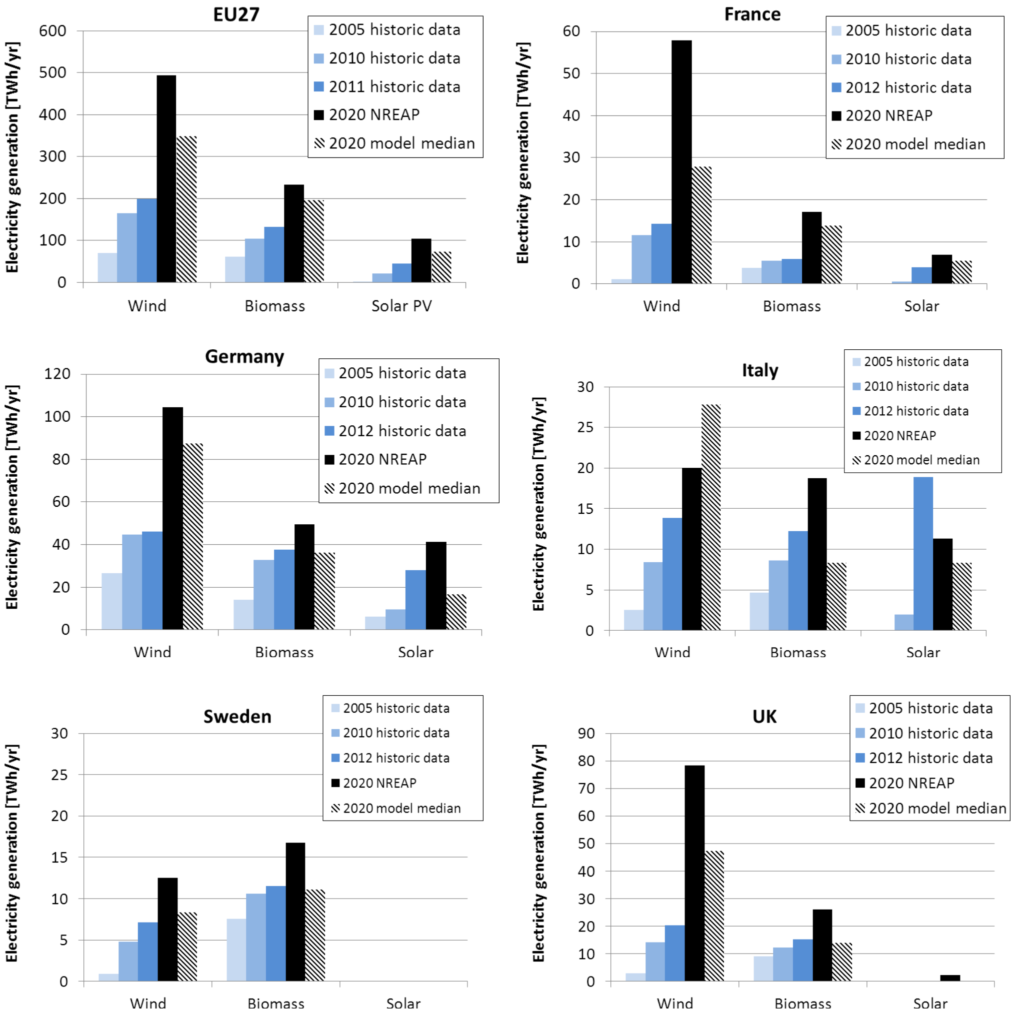

Figure 3. Electricity generation in EU27, France, Germany, Italy, Sweden, and UK for wind (on and offshore), biomass and solar PV. Comparison is made of historic data, NREAP projections for 2020 (EEA, 2012) and EMF28 model scenario results for 2020. For the historic data the following sources are used: EEA (2012) for 2005 and 2010; Eurostat (2013a) for 2012 for wind, and for 2011 for solar and biomass. In addition, the following data is used for 2012: RTE (2012) for solar and biomass for France; BDEW (2013a) for solar for Germany; GSE (2013a) and GSE (2013b) for biomass and solar for Italy; and UK Gov (2013) for UK. Note the different scales.

wind, 38% from hydro, 18% from bioenergy, and 7% from solar in 2020. Figure 3 gives the electricity production for wind, biomass, and solar envisaged by the NREAPs,[4] the median of the models for 2020, and the historic values for 2005, 2010, and 2012 for comparison. This shows that EMF28 models also support the absolute

[4]Hydro is more or less constant over time in the model scenarios and in the NREAP projections and therefore not taken into account in the figure.

level of renewable deployment on a European-wide scale, but indicate that this deployment for 2020 is generally less than envisaged in the NREAPs.

One remarkable discrepancy is seen, however, concerning the deployment of solar PV in Germany and in Italy (see Fig. 3); model results tend to indicate much lower contributions than the NREAPs. It becomes apparent, especially when comparing model results to 2012 numbers, that solar PV deployment in Germany and Italy is already much higher than projected in the models for 2020. What is the reason for this discrepancy between the model results and the NREAPs and why is there such a discrepancy between the models and current deployment levels? The following three reasons can explain this discrepancy.

Firstly, most models concentrate on cost-optimal responses to the policies included in the model. Based on current assumptions on the development of specific investment costs, learning rates, and conversion efficiencies, the models consider solar PV as too costly for it to be deployed on a large-scale level, certainly in Northern Europe. In reality, however, the FIT systems installed in Germany and Italy providing high and secure rates of return on investment, the differences in tax tariffs, and consumer preferences have led to a high deployment of solar PV. The tax difference also exists in other countries, for example in the Netherlands, although there is no FIT. None of these factors are explicitly considered in the models.

The second reason is limitations in the modeling itself, especially related to model calibration. As can be seen for Germany and Italy for example, deployment levels of the model median are below the actual level for 2012. Many models are calibrated to the base year 2005 and may therefore not fully consider the significant progress that has been made both in deployment and cost reductions during recent years, see e.g., Grau *et al.* (2012) and Bazilian *et al.* (2013). Investment costs for solar PV start with levels as high as 4.200 €/kW for PRIMES or 6.300 €/kW for POLES in 2010, while in Germany a decrease from 5.000 €/kW to 2.000 €/kW was experienced between 2006 and 2012 (Diekmann *et al.*, 2012). So it might be that an updated calibration would improve results. For comparison, investment costs for onshore wind are considered to be much lower, with a maximum of 1.600 €/kW in 2010 for the different models.

Thirdly, the discrepancies might arise because the sole objective of the models is to reduce GHG emissions. They do not take into account other reasons for PV deployment that might play a role in the real world and encourage policy makers to support this particular technology. Such support may be driven by a perceived technology potential and a market failure in pushing the technology down the cost curve.[5] It may also arise from consideration of co-benefits (GEA, 2012; Edenhofer *et al.*, 2013c) such as employment effects, local value added, additional environmental benefits and industrial policy (e.g., Machnig, 2011; Lehmann and Gawel, 2013; BMU, 2012b). Many of these aspects are certainly important drivers for PV in Germany. Manufacturers and

[5]It is important to note that most models do not consider learning by doing endogenously, i.e., costs of the given technology do not go down as a function of the cumulative deployment of that technology.

suppliers of solar PV plants had a world market share of 46% in 2011, reaching an export rate of 87% (Wirth, 2012), and the PV sector provides more than one quarter of all employment in the renewable energy sector (BMU, 2012a). This suggests there are multiple objectives implicitly or explicitly considered by national policymakers in the choice of renewable policies apart from GHG mitigation (Edenhofer *et al.*, 2013b; Pahle *et al.*, 2012) and these other objectives are not captured by the models.On the other hand, policy makers should carefully consider whether renewable deployment is the most cost-efficient way of achieving other policy objectives that are associated with renewables, e.g., "more indigenous energy sources, reduced energy import dependence, and jobs and growth" as stated in the EU green paper on the 2030 framework (European Commission, 2013a).

For biomass, a similar but less pronounced discrepancy as for PV can be seen between actual electricity generation for 2012 and model results for 2020, as for Germany, Italy, Sweden, and UK the model median hardly reaches the 2012 level. Here the main reason is probably that in the models the limited available biomass is used in the transport or the heating sector, but only to a limited extent in the electricity sector where many other options are available.

While we have seen that current plans for wind in the NREAPs agree reasonably well with the models, one issue is noteworthy that is specific for offshore wind power. It plays an important role both in the NREAPs and in EMF28 model results and in the three models that include offshore wind, it provides 41.3 GW installed capacity by 2020 (NREAP) and an installed capacity of 22, 37, and 65 GW by 2020 (EMF28). However, so far only about 3 GW have been installed at the EU level in 2010 (UK: 1.340 MW, Denmark: 855 MW), so the discrepancy between political targets and reality is apparent (see also Schmid *et al.* (2013) for an analysis of the German case). EMF28 models consider offshore wind power as a comparatively cost-efficient solution as offshore locations come with high wind speeds that yield high feed-in, while the expensive infrastructure investments in power grid connections are not taken into account in detail in most models. Even though public aversion to onshore wind can play a role in favoring offshore wind (see Toke, 2011), current deployment levels seem too low to reach the 2020 target.

The recent report by the EU Commission on progress in renewable energy (European Commission, 2013b) concludes that although interim targets for 2010 are met, "more efforts will still be needed from the Member States in order to reach the 2020 targets". In the context discussed above, it is interesting to note that in their analysis it is considered likely that only PV deployment will meet the 2020 targets. Offshore wind is expected to considerably lag behind.

3.2. *Model projections for the long-term energy transformation*

While the comparison with the NREAPs focuses on the short-term, we now concentrate on the long-term transformation leading up to 2050. For the five selected

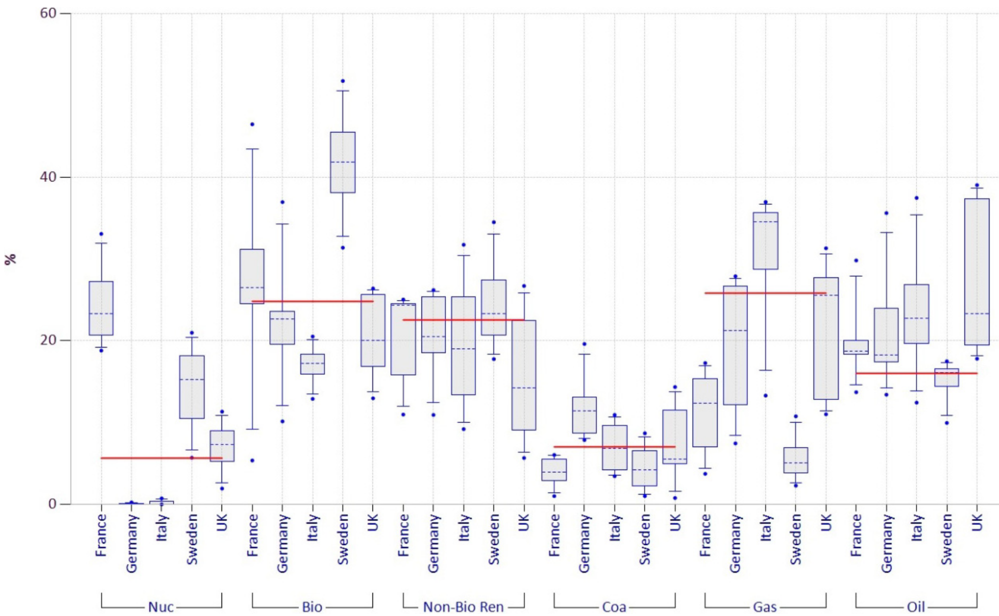

Figure 4. Percentage share of different technologies for primary energy production for the EU27 and the five selected countries in 2050 for the models given in Table 1. The dotted line represents the median, the box contains the 50% interval, the whiskers mark the 90% interval, and the dots mark the extreme values. The horizontal line indicates the numbers from the Energy Roadmap for the EU27.

countries, the primary energy supply in 2050 required for an 80% reduction in GHG is shown in Fig. 4. The share of different technologies in the mix differs considerably between Member States in 2050 and is furthermore very different from the aggregated EU27 energy mix from the Energy Roadmap, that is given for comparison. Common findings are the strong decrease in the share of oil by 2050. This combines with an almost complete phase-out of the use of coal on the one hand, and the strong increase in both bio-energy and non-biomass renewables (NBR) on the other hand. The differences in model scenarios between the Member States become apparent in the electricity mix (Fig. 5) which indicates that shares for fossil fuels with CCS, nuclear, wind, and hydro, vary considerably among Member States.

Some general conclusions can be drawn from these five selected countries. In the model scenarios, countries that currently rely primarily on coal or gas undergo a substantial transformation towards biomass, NBR and CCS (e.g., Germany and the UK). In countries that already apply low carbon technologies such as nuclear (in France) or large-scale hydro (as in Sweden) the trend continues in the scenarios. Italy, as a gas-based country, undergoes a shift to gas-CCS in some models, but in others the electricity mix continues to include a considerable amount of gas without CCS. It seems that there is a substantial deviation between the proportions of individual technologies derived from the model scenarios for the different Member States, and the

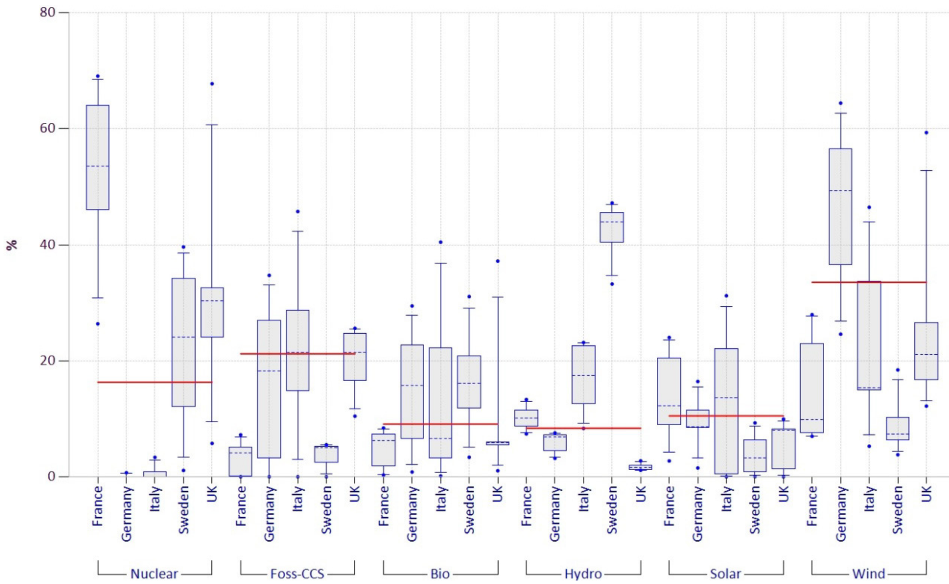

Figure 5. Percentage share of different technologies for electricity production for the EU27 and the five selected countries in 2050 for the models given in Table 1. The dotted line represents the median, the box contains the 50% interval, the whiskers mark the 90% interval, and the dots mark the extreme values. The horizontal line indicates the numbers from the Energy Roadmap for the EU27.

aggregate of those given in the Energy Roadmap for the EU27 (see horizontal bar in Figs. 4 and 5). Despite the fact that technology deployment in each selected country is very different and the reduction of carbon intensity is diverse across countries (see Fig. 6, right), the reduction of energy intensity is of considerable importance across all five countries (see Fig. 6, right).

In the following, we relate the model results in more detail to the national policies of the selected Member States described in Secs. 2.1 to 2.4. Overall, the models capture the national differences quite well.

Comparing the EMF28 scenarios for France with the national policies, it transpires that nuclear energy will clearly continue to play an important role in the future energy mix of France, in line with the view of analysts, energy experts, industry, and politicians. Only the EMELIE-ESY model projects a low (27%) level of nuclear by 2050 due to its capital costs being around 50% higher than those assumed in the Energy Roadmap. CCS plays only a minor role in the model scenarios with a share of fossil CCS in the electricity mix lower than 6% and a maximum captured emissions of 120 $MtCO_2$ in 2050. This development is consistent with current perceptions of CCS in France. Nonetheless, despite considerable CCS potential, the future of CCS technology in France depends on the successful demonstration of pilot projects, public acceptance and, on the appropriate carbon price. All models expect RES to contribute a sizeable proportion of the electricity mix, i.e., 26–70% by 2050.

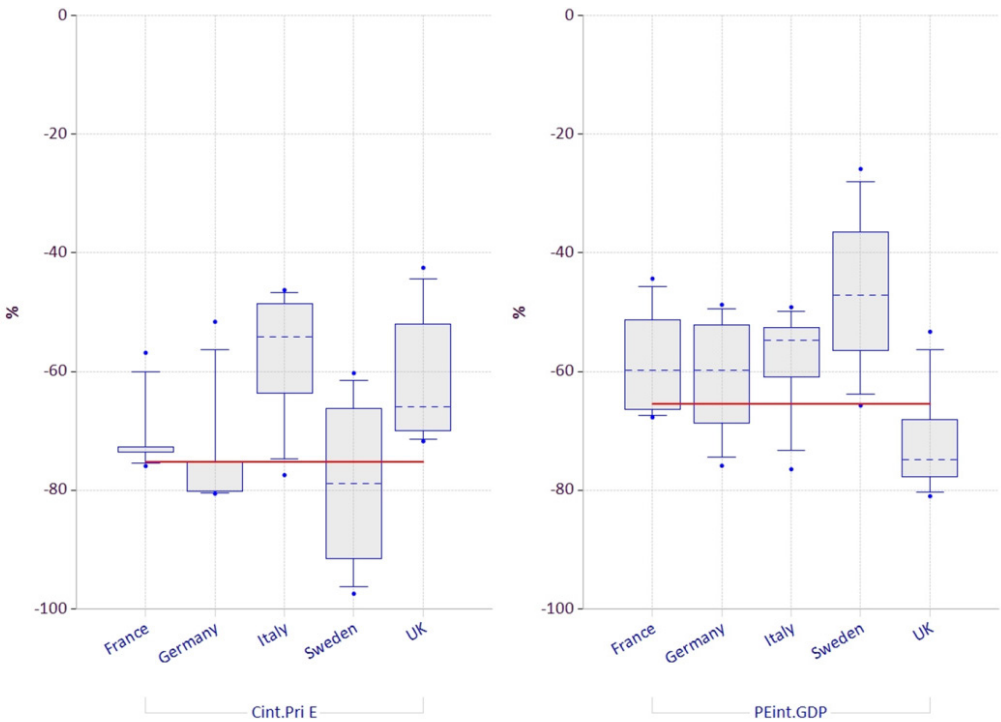

Figure 6. Reduction of carbon intensity (CO_2 per primary energy, left) and energy intensity (primary energy per GDP, right) between 2050 and 2010 for the five selected countries for the models given in Table 1. The dotted line is the median, the box contains the 50% interval, the whiskers mark the 90% interval, and the dots mark the extreme values. The horizontal line indicates the numbers from the Energy Roadmap for the EU27.

In the case of Germany, the nuclear phase-out by 2022 is well covered by the EMF28 scenarios, but they show a much slower development of the share of RES in the electricity sector than envisaged by German law. This is particularly the case for solar PV, see discussion in Sec. 3.1. With its renewable FIT system, Germany has an effective policy instrument to trigger the deployment of renewables that by the end of 2012 made up 21.9% of the electricity mix. However, EMF28 scenarios only indicate a median share of 67% RES by 2050 rather than the envisaged 80%. On the contrary, CCS technology, which plays a prominent role in the EMF28 model results, achieved a share of more than 20% and 230 $MtCO_2$ of captured emissions in 2050. For comparison, the remaining CO_2 emissions are roughly 130 $MtCO_2$ in 2050, so a much larger proportion is projected to be captured than emitted. However, these high levels are currently unlikely to be realized in Germany, as the attempt to implement legislation for CCS failed in 2011. Public opposition and a lack of political will are reasons for this failure (von Hirschhausen *et al.*, 2012). EMF28 results indicate a great importance of gas in the future power system. In Germany, there is an ongoing discussion as to whether gas plants remain profitable in an energy market which has a high share of variable RES. The debate is whether a so-called capacity mechanism for conventional, dispatchable technologies should be implemented (Flinkerbusch and Scheffer, 2012). The future German electricity mix will certainly depend on this strategically important decision.

In Italy, as in Germany, the FIT RES supporting scheme has triggered an enormous deployment of renewables, especially solar PV. The rejection of nuclear in Italy is taken into account in the EMF28 model scenarios (except the model POLES which indicates a very low capacity of 2 GW by 2050). Most EMF28 models apply the CCS option in combination with natural gas, which contributes a considerable share of around 20% in the Italian electricity mix by 2050.

In the EMF28 scenarios, the Swedish electricity mix is largely composed of RES and nuclear although the shares differ between the models (see Fig. 5). The deployment of CCS in the model scenarios is limited. Among renewables, hydropower is the most important component with a model median of more than 50% of the electricity production in 2050. Altogether, the median share of RES electricity production is about 60% in 2020 and 70% in 2050. Sweden already has a large share of carbon-free technologies and, according to the models, still a great potential for CO_2 reduction, so the need for reduction of energy intensity is much smaller than in the other countries (Fig. 6), whereas carbon intensity decreases considerably.

As described in Sec. 2.5, the UK does not exclude any of the main technology options and therefore different future transitions could be considered plausible and few options can be excluded in advance. EMF28 scenarios capture this by showing a quite balanced and diversified mix, with similar shares for gas, coal, renewables, and nuclear deployment. Interestingly, the UK electricity mix appears to be a good proxy for the EU27 energy mix produced by the models. However, the requirement for reducing energy intensity is much higher than the European median (Fig. 6, right).

Overall, we can conclude that there is sufficient agreement between the NREAPs and national policies to accept the model results as conceivable scenarios for the different Member States.

4. Policy Implications

In this section, we deduce some policy implications that can be derived from the modeling results. According to the models, we may continue to see a variety of national energy mixes in the future, reflecting the different resource bases of the Member States. This diversity may remain even under an EU-wide GHG reduction target. The models assume that the challenge and the implicit tension of contributing to the overall European target, given the diversity between Member States' policies and preferences, can be solved in a fully cooperative way among EU Member States. In order to realize this, some implicit assumptions in the models have to be transferred into policy and action. In the following, we therefore relate the model results to three key areas of European cooperation: the grid infrastructure, the internal energy market, and the design of policy instruments.

The model results depend on the assumption that technologies available can be deployed in a cost-efficient manner, under full where- and when-flexibility (see Sec. 1.1). The implicit presumption behind this is that the electricity infrastructure is not a bottleneck and that grid connection is fully available. In this way, cheaper energy sources can be developed in one country and transported to another whenever the model finds it cost-optimal to do so. In reality, the physical infrastructure in many areas of Europe is still a major barrier for transnational exchange and considerable investments are needed. In the latest 10-Year Network Development Plan (TYNDP), the European Network of Transmission System Operators for Electricity (ENTSO-E) identifies the need to invest €104 billion in the refurbishment or construction of roughly 52,300 km of extra high voltage power lines clustered into 100 investment projects across Europe (ENTSO-E, 2012). In addition to the economic challenge involved in realizing these investments, there is also a serious public opposition to new overhead lines in most regions of Europe.

The models also assume a fully functioning internal energy market. The EU is committed to a fully integrated energy market by 2014, but international wholesale electricity markets only exist in some regions of Europe: the NordPool region (Norway, Sweden, Denmark, Finland), Central Western Europe (Austria, Belgium, Germany, France, Netherlands, Switzerland), Central Eastern Europe (with market coupling between Slovenia, Czech Republic, and Hungary), as well as wholesale trading between Spain — Portugal and UK — Ireland. Electricity trade and cross-border flow increased by 7% in the second half of 2012 compared to the same period in 2011 (DG-Energy, 2013). This illustrates the increasing integration of the European electricity markets. Traded volumes in the European wholesale electricity markets have been growing continuously since 2005, with total traded volume in 2012 exceeding 1200 TWh. However, this represents just 43% of European annual electricity consumption, so there is still some way to go before the market is fully integrated.

We can also draw some conclusions for the design of policy instruments. We have seen that the aggregated EU27 energy mix gives only a rough indication of which technologies are important for energy transformation in each individual Member State. The EU Energy Roadmap can therefore only provide limited guidance for the implementation of such transformation pathways at a national level. At the same time, there seem to be a number of technologies that are becoming increasingly important in all Member States. From our model analysis, we can indicate which technologies may actually be promoted based on their expected long-term potential across all countries. These include bio-energy, CCS, and energy efficiency improvements. Although overall NBR increase in all Member States, the picture on the individual NBR technologies varies considerably. This diversity might pose a challenge for the implementation of European policy instruments additional to that of the European emissions trading scheme.

In order to achieve ambitious climate change mitigation in the EU, given such diversity, it is important to improve alignment between EU-level and national Member State policies. This could include a review of the EU emission trading scheme and national renewable subsidy schemes, with the aim of reducing mitigation costs below current levels (Edenhofer *et al.*, 2013a). However, this topic goes beyond the analysis of this study and points towards a new direction of research. When it comes to implementation of the technology pathways and to the design of policy instruments and measures, the different levels of governance between the EU and its Member States have to be considered. This leads to the questions of: (i) the level to which mitigation policies should best be assigned, (ii) how the different levels should interact and (iii) how coordination between different levels can be achieved. Despite national sovereignty over the energy mix laid down in Article 194 and the fact that subsidiarity is the guiding principle of the EU, the idea of polycentric governance (Ostrom, 2010) can provide a new perspective. This perspective takes into account the existence of multiple political actors at different governance levels (i.e., the EU and Member States). In Shobe and Burtraw's (2012) analysis of environmental federalism, for example, they conclude that policies that take advantage of the federal structure of the heterogeneity of costs and preferences at different governance levels can improve climate policy outcomes. Further research in this direction is required in order to facilitate the European energy transition.

5. Conclusion

In this paper, we relate national mitigation scenarios to the long-term European energy transformation. Our analysis is based on the EMF28 multi-model assessment, including six models with different economic coverage and solution methods, and concentrates on five selected Member States (France, Germany, Italy, Sweden, and UK) as case studies. Firstly, we analyzed national climate and energy policy objectives and debates in the respective countries. We then related EMF28 model results to these national perspectives and compared model projections with both the short-term projections of the NREAPs and the long-term transformation pathway given in the European Commission's "Energy Roadmap 2050". Three main conclusions can be drawn from the analysis: (i) the models are by and large able to capture national differences that are compatible with current policies; one noteworthy discrepancy is concerning current deployment of solar PV in some countries; (ii) as national energy mixes will continue to reflect the different resource bases and preferences of individual Member States, the aggregated European pathway provided by the Energy Roadmap gives only limited guidance for policy implementation at the Member State level; (iii) ensuring a cost-efficient transformation of the European energy system is tantamount to increasing the level of cooperation between Member States and the EU level in terms of infrastructure expansion, fostering the internal energy market and the coordination of the design of policy instruments.

The analysis of the national policies and roadmaps that are currently implemented in the five selected countries revealed that they differ considerably in terms of ambition, scope, and preference concerning specific technology choices. Relating the model results to these national policies and to the NREAPs, which provide the short-term visions of the different Member States on the deployment of renewables, shows that the models are indeed able to capture national differences. With some exceptions, for example the deployment of CCS in Germany at high levels that is currently unlikely to be realized, there is generally sufficient agreement with national policies to credit the model results as being conceivable scenarios for the different Member States. However, an important discrepancy concerning solar PV is revealed. The contribution from PV is considerably lower in the models compared to current and projected deployment levels. Despite the fact that the models do not take into account supporting schemes for renewables and therefore underestimate the current development of solar PV, this discrepancy might also indicate that the model objective of reducing GHG emissions might not be the only reason for selecting a particular technology. In reality, there are other factors and assumed co-benefits, such as local employment effects, local value added, additional environmental benefits, and industrial policy which are taken into consideration. Therefore, although the models seem to capture national differences reasonably well, it would be important to acknowledge the existence of multi-objectives in the models. On the other hand, policy makers should carefully consider whether renewable deployment is the most cost-efficient way of achieving the other policy objectives that are associated with renewables.

Many recent studies on the energy transformation in Europe focus on the top–down perspective by considering Europe as an entity and concentrating on the aggregated EU27 energy mix. Our model-based analysis at the national level, however, shows that the strategies for transforming the energy system vary considerably across Member States. National differences in energy mix, for example due to different political preferences or resource availabilities, are likely to continue to play a dominant role in the future through lock-ins and path dependencies for specific technologies. In that sense the EU27 energy mix is not a good indicator of how to achieve the energy transition in individual countries. Our analysis showed that the transformation pathways at the Member State level indeed differ substantially from the aggregated European perspective laid down in the Energy Roadmap of the European Commission.

This discrepancy indicates that the Energy Roadmap provides only limited guidance for implementation of policy measures in Member States. For the design of policy instruments — both at European and national level — it is of pivotal importance to link the European energy transition to those of individual Member States and *vice versa*. Therefore, much more work on national roadmaps and the development of national scenarios is needed. Scenarios at the national level may also help to identify interdependencies where enhanced collaborations between countries may be desirable in terms of costs and for the ultimate goal of reaching the mitigation target. Regional cooperation might be a way to initiate this. The penta-lateral cooperation in Northwest Europe (Belgium, France Germany, Luxemburg, and Netherlands) and cooperation among Nordic countries (Denmark, Finland, Norway, Sweden) are such examples of regional cooperation, but potential for further regional cooperation exits. In this context, the development of grid infrastructure is also important in order to reap the benefits of regional disparity and geographic differences e.g., concerning the renewable resource potential.

Finally, we gave an overview on how to improve coordination and alignment between EU-level and national Member State policies. For the design of policy instruments, the different levels of governance between the EU and its Member States have to be considered. This leads to the questions of: (i) the level of governance to which mitigation policies should best be assigned, (ii) how the different levels should interact and (iii) how coordination between different levels can be achieved. These questions are addressed in the research field of environmental federalism, which deserves more attention in order to reap the benefits of cooperation between Member States and the EU as a whole in the context of a low-carbon energy transition.

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