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DECARBONIZING THE EUROPEAN ELECTRIC POWER SECTOR BY 2050: A TALE OF THREE STUDIES

Erik Delarue, Leonardo Meeus, Ronnie Belmans, William D'haeseleer and Jean-Michel Glachant

EUROPEAN UNIVERSITY INSTITUTE, FLORENCE
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ERIK DELARUE, LEONARDO MEEUS, RONNIE BELMANS, WILLIAM D'HAESELEER AND JEAN-MICHEL GLACHANT

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For further information
Loyola de Palacio Energy Policy Chair
Nicole Ahner (scientific coordinator)
Email contact: Nicole.Ahner@eui.eu
Robert Schuman Centre for Advanced Studies
European University Institute
Via delle Fontanelle, 19
I-50016 San Domenico di Fiesole (FI)
Fax: +39055 4685755
http://www.loyola-de-palacio-chair.eu

Abstract

If Europe is serious about climate change, it has to reduce its overall greenhouse gas emissions by 80% by 2050, thereby effectively going to a (near-) zero carbon energy and thus, electricity system. The European Climate Foundation, Eurelectric, and the International Energy Agency have consequently published a study elaborating on the final goal of this transition. The studies project scenarios of how such a (near-) zero electricity system would look like and provide recommendations on the policies needed to guide the transition. In this paper, we observe that these studies tell a tale with many similarities. In spite of increased energy efficiency, the electricity demand is projected to increase substantially, with up to 50% from today towards 2050, due to shifts from other sectors towards electricity. This demand will be supplied by a minimum of 40% electricity generation by RES, with the remainder being filled up with nuclear and fossils with CCS. The importance of grid reinforcement, expansion, and planning in this context is emphasized in all three studies. While all three studies further recommend relying on the EU ETS for the transition, the European Climate Foundation and the International Energy Agency consider continuing with targets for RES in combination with a more harmonized EU RES support scheme.

Keywords

European Energy Policy; Electric Power Generation; Decarbonization

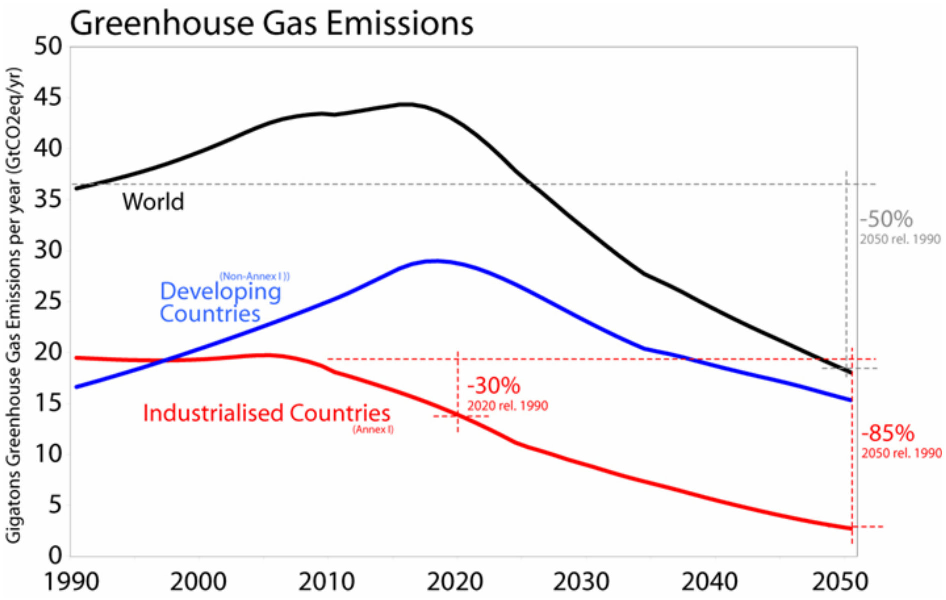
1. Introduction

1.1 Background to the decarbonization of the European electric power sector by 2050

To minimize the impact of global warming, the global atmospheric temperature increase should be limited to 2 – 2.4 °C. This requires greenhouse gas (GHG) atmospheric stabilization levels of 445 – 490 ppm, corresponding to a CO_2 concentration of 350-400 ppm (IPCC, 2007). The current concentration level of CO_2 is about 385 ppm (compared to a level of 280 ppm CO_2 before the industrial revolution), and still rapidly increasing, as current global GHG emissions amount to about 50 Gton per year (IPCC, 2007). To achieve the targeted stabilization level and limit the temperature increase to about 2°C, an immediate drastic reduction in GHG emissions is required: global emissions will have to come down by at least 50% (up to even 85%) in 2050, compared to the level in 2000 (IPCC, 2007).

If the global population will be around 9 billion people by 2050, then the average per capita emission should not exceed about 2.5 ton per year per person. One of the hot potatoes in the current debate is how to distribute the required efforts among the different regions in the world. Historic and current emission levels are very disproportioned, with North America and Europe having the highest per capita emissions: CO_2 emissions (from fuel combustion) were about 18 ton CO_2/y/p in the US and about 8 ton CO_2/y/p in Europe, in 2008 (IEA, 2010b). In terms of GHG emissions, these levels were about 24 ton CO_2-eq/y/p in the US and 10 ton CO_2-eq/y/p in Europe, in 2000 (MacKay, 2009). When calculating cumulative emissions, the discrepancy between the developed and developing regions becomes even more apparent. Thus, given the current disproportionate emission levels and the expected economic growth of developing countries, a general consensus exists that the developed world will have to engage a larger effort than the reported 50%. A reduction in the range of -80% is often proposed (in many reports as scenario benchmark, see further, confirmed at the G8 meeting in 2009 in L'Aquila). Furthermore, given the fact that the whole world will have to contribute to this reduction of emissions, it can be assumed that the targeted 80% of emission reduction in the developed world will have to take place *within* these regions themselves. This envisaged emission reduction towards 2050 is presented in Figure 1.

Figure 1. Greenhouse gas emission pathway towards 2050. Source: (Delbeke, 2009).



The targeted 80% emission reduction implies that the energy sector and definitely the electric power sector will have to become carbon free. The reason is that the limited emissions that can still occur in 2050 (i.e. 20% of what was emitted in 2000), will be emitted in sectors where it is more difficult to reduce GHG emissions, i.e., emissions from agriculture and meat consumption (CH_4 and N_2O), emissions in specific transport sectors (air, maritime, freight – although bio fuels and/or hydrogen might play a role on a longer term) and several non-CO_2 emissions from industry (ECF, 2010; Jones and Glachant, 2010).

1.2 Tale of three studies

The paper will focus on the European electric power sector. We analyze the following three studies and scenarios:

- The Power Choices scenario, from the Power Choices report by Eurelectric (2010).
- The three decarbonized pathways from the Roadmap 2050 report by the European Climate Foundation, ECF (2010).
- The BLUE Map scenario, from the Energy Technology Perspectives (ETP) of the International Energy Agency, IEA (2010a).

These studies have in common that they project scenarios in which Europe moves towards a near carbon free electricity system[1]:

- The Power Choices scenario features a 75% reduction in 2050 compared to 1990 levels for the EU's overall CO_2 emissions. This overall reduction implies a near carbon free electricity system. The remaining emissions in the power sector in 2050 are projected to be 25 kg/MWh.
- The Roadmap 2050 features an overall 80% reduction of GHG across the EU-27 below 1990 levels by 2050. This results in a decarbonized power sector, with power sector emissions reported to decrease by 96% compared to 1990, resulting in about 10 kg/MWh in 2050.

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[1] The electric power sector's current CO_2 emission intensity (2007) amounts to about 400 kg/MWh (Eurelectric, 2009).

- The BLUE Map scenario of the ETP features a global halving of CO_2 emissions, with OECD Europe needing to reduce CO_2 emissions by 75%, in 2050, compared to the 2007 level. The electric power sector is projected to be almost decarbonized, with the emission intensity in 2050 reported as 15 kg/MWh.

To facilitate the readability of the paper, we will refer to the scenarios under consideration by basically referring to the organizations that released the studies, i.e., Eurelectric for the Power Choices scenario, the ECF for the Roadmap 2050 decarbonized pathways, and the IEA-ETP for the BLUE Map scenario.

The studies are also comparable in their geographic scope:

- Eurelectric presents numbers for the EU 27.
- The ECF presents numbers for the EU 27, but some figures include Norway and Switzerland.
- The IEA-ETP has a global focus, but does present separate numbers for OECD Europe, being 19 EU Member States, and Iceland, Norway, Switzerland and Turkey.

The paper starts by comparing the (near-) zero carbon electricity systems that are projected in these studies in terms of demand, supply, balancing of demand and supply, and costs (Section 2). Our work then focuses on the policy recommendations given in the studies to guide the transition towards a decarbonized European power sector (Section 3). The paper finally concludes with pointing out the main similarities and differences that result from this comparison.

2. The electric power system in 2050

This section first focuses on the demand for electricity in the above mentioned scenarios. Second, an overview of the trends in the system's generation portfolio is presented. Third, the matching generation and demand is considered. Fourth, the projected additional costs of such a transition are discussed.

2.1 Demand for electricity

2.1.1 Introducing the options

The demand for electricity is determined by several factors, being population, wealth, the degree of electrification and energy efficiency on the demand side. Assuming the trends in population and welfare as given, only the last two parameters are left to influence the electricity demand.

First, the degree of electrification plays an important role because the electricity sector is a sector where decarbonization is feasible, both technically and institutionally. The options in the other energy sectors, i.e., transport and heating and cooling are much more limited. In transport, CO_2 emissions can be reduced by more stringent norms on cars, but when using an internal combustion engine running on fossil fuels, the potential further increase in energy efficiency is limited by the laws of thermodynamics, and a significant amount of emissions remains. To move to a low or even zero carbon transport system, basically three options exist: bio fuels, hydrogen and electric vehicles. Bio fuels might play a role, but there are concerns related to sustainable production and security of supply (when these bio fuels would be imported) and conflicts with food and feed production. Hydrogen is an energy carrier just like electricity. It can be produced from electricity, or directly from fossil fuels (which would have to be equipped with Carbon Capture and Storage (CCS) in a zero carbon framework). Hydrogen has a very high energy density per unit mass (but quite low per unit volume), and can be converted to kinetic energy in a combustion engine or to electricity by means of a fuel cell. However, the transition towards a full hydrogen economy seems currently still very uncertain. Hence, given these considerations, electricity has to play a role in transport. A similar story applies for the heating and cooling sector. The available options are using solar heat or biomass, applying district heating (fueled on biomass or fossil fuels with CCS) or make use of heat pumps and air-conditioning. The options of solar heat, biomass and district heating should be employed whenever economically and technically feasible. However, heat pumps will play a role and hence, a shift towards electricity will occur. To conclude, a shift from both the transport and the heating and cooling sector towards electricity is a typical outcome of the projection scenarios with stringent carbon constraints on the overall energy sector (ECF, 2010; Eurelectric, 2010; IEA, 2010a).

The second factor that has an impact is the energy efficiency on the demand side. Increasing energy efficiency is often identified as *the* priority in climate action. Current electric devices (lighting, fridges, motors, etc) leave room for improvement. Energy efficiency improvements in other sectors, e.g., insulating houses so as to minimize heating requirements for heat pumps (or making heat pumps more efficient themselves), or enhancing the efficiency of electric vehicles can further have an effect on the demand for electricity.

2.1.2 Scenario comparison

Improved energy efficiency in low-carbon scenarios results in an electricity demand that is about 10 to 20% lower compared to the baseline cases (net of any demand shift) (ECF, 2010; Eurelectric, 2010). However, due to the demand shifts from transport and heating and cooling towards electricity, demand amounts to values comparable to the baseline cases (in the IEA-ETP, demand in the baseline remains higher). The following values for the European electricity demand in 2050 are reported in the three scenarios under comparison:

- Eurelectric: 4776 TWh
- ECF: 4600 TWh (4900 TWh when including Norway and Switzerland)
- IEA-ETP: 4306 TWh[2]

The demand for electricity in the EU 27 in 2007 amounted to 3136 TWh (Eurelectric, 2009); so a significant increase in the use of electricity is projected in all three studies, with up to as high as 50%, mainly as a consequence of an increase in overall energy use and an increasing degree of electrification.

2.2 Electricity generation

A European zero carbon power system in 2050 will most likely consist of a mix of Renewable Energy Sources (RES), nuclear and fossils with Carbon Capture and Storage (CCS). In what follows we introduce the options and then compare which ones are taken in the scenarios of the three studies.

2.2.1 Introducing the options

The crucial parameter related to RES is the potential, both technically and economically (what is available and at what cost). The current economically most attractive technologies are hydro, wind and certain forms of biomass. Solar PV, concentrated solar power (CSP) and wave/tidal are currently too expensive to make them competitive with classic generation any time soon, while conventional geothermal is very location-specific. Enhanced geothermal is attributed a very high potential, but many uncertainties (also related to cost) remain. In Europe’s current RES generation portfolio, hydro has the largest share (Eurelectric, 2009). The potential for the deployment of additional large-scale hydro is, however, limited in Europe, although some potential in south-eastern Europe and for small-

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[2] The value from the ETP (IEA, 2010a) on p308 is reported here, which differs from the considerably lower value reported on p313, i.e., 3636 TWh.

scale installations remains. Wind is projected to enjoy the largest growth in the period up to 2050, and to constitute the largest share of RES in 2050. Both on- and offshore wind is expected to be developed further and to benefit from reducing costs (already on the short term). Biomass currently is widely used, but the further potential is uncertain, given the possibly limited availability, concerns related to sustainable production and security of supply and conflicts with food and feed production. At present, PV faces costs as high as 200 up to 400 €/MWh (IEA/NEA, 2010), dependent on the location, i.e., level of irradiation. However, costs are expected to come down rather fast. Once cost competitive, a wide-spread potential across Europe is available. As CSP requires direct sunlight, the potential is limited to Southern Europe, although being substantial. Wave/tidal and enhanced geothermal are still in an immature state and the actual potential and costs remain uncertain.

Concerning nuclear, the development will be mainly determined by political and public acceptance. After a long period of nuclear submissiveness, new reactors are currently being built in Finland, Bulgaria, Slovakia and France, with a combined capacity of 5888 MW (European Nuclear Society, 2010; Sioshansi, 2009). Some other member states have also expressed their intentions to start with the development of nuclear, or to expand the existing capacity with additional units. Whether a so-called nuclear renaissance actually will occur, remains to be seen. It might already turn out challenging to keep the current amount of nuclear generated electricity stable, as many units are approaching the end of their economic lifetime (Sioshansi, 2009). The cost of new nuclear is very uncertain and wide ranges and regional differences are reported (IEA/NEA, 2010).

The theory of CCS is clear: keep using fossil fuels and capture and store the released CO_2 underground. Given the world wide massive reserves of easily available coal, CCS seems indispensible in a low carbon future (as this coal *will* be used, certainly on a global scale). However, the technology is currently still in a developing state and has to be demonstrated to be feasible on a large scale at acceptable cost. Apart from high investment costs, a high CO_2 price or regulations will be required to trigger actual use of the CCS part, as a significant share of the power is needed to drive the CCS part[3], thereby lowering the plant's net efficiency and flexibility.

2.2.2 Scenario comparison

Table 1 below presents the electricity generation[4], by fuel, as [%] of the total generation for the scenarios considered. The projected shares for 2010 are also included (Eurelectric, 2010). The ECF basically postulates three decarbonized scenarios for the EU's power system (ECF, 2010), with RES ranging from 40% up to as high as 80%, with the remainder being equally divided between nuclear and fossils with CCS.

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[3] Energy is required to separate the CO_2 from the flue gases in post combustion, to create H_2 in an IGCC, or to create pure O_2 for the combustion in an oxyfuel installation.

[4] It should be stressed that these values are for electricity generation, i.e., energy [MWh]. Figures for installed capacity [GW] are presented further in the paper.

Table 1. Comparison of relative electricity generation by technology.

	2010	2050				
		Eurelectric	ECF			IEA-ETP
			40% RES	60% RES	80% RES	
	[%]	[%]	[%]	[%]	[%]	[%]
Hydro	10.3%	7.5%	12.0%	12.0%	12.0%	17.1%
Wind onshore	4.8%	11.6%	9.0%	11.0%	15.0%	14.2%
Wind offshore	0.5%	8.7%	2.0%	10.0%	15.0%	7.9%
Biomass	3.5%	6.9%	8.0%	8.0%	12.0%	7.1%
Biomass + CCS	0.0%		0.0%	0.0%	0.0%	0.4%
Solar PV	0.5%	4.3%	4.0%	12.0%	19.0%	3.9%
Solar CSP			3.0%	5.0%	5.0%	2.2%
Geothermal	0.2%	1.4%	2.0%	2.0%	2.0%	1.7%
Tidal	0.0%		0.0%	0.0%	0.0%	0.7%
Other	0.0%		0.0%	0.0%	0.0%	0.0%
Tot RES	19.8%	40.4%	40.0%	60.0%	80.0%	55.2%
Nuclear	28.5%	28.4%	30.0%	20.0%	10.0%	29.3%
Coal + CCS	0.0%	16.9%	10.0%	7.0%	3.0%	11.0%
Coal + CCS retrofit	0.0%		5.0%	3.0%	2.0%	0.0%
Other solids	25.5%		0.0%	0.0%	0.0%	0.0%
Gas	24.3%	13.6%	0.0%	0.0%	0.0%	1.5%
Gas + CCS	0.0%		15.0%	10.0%	5.0%	3.0%
Oil	2.0%	0.7%	0.0%	0.0%	0.0%	0.0%
Tot	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

Note: Recall that geographic regions differ slightly: Eurelectric is EU 27, ECF is EU 27 + Norway and Switzerland, IEA-ETP is OECD Europe.

When focusing on the share of renewables, the following observations emerge. The minimum share of renewables is 40%, resulting from the Eurelectric scenario, and postulated in the 40% RES scenario of the ECF. Between both, there is a difference between hydro and offshore wind, likely due to the fact that the numbers of the ECF include Norway and Switzerland, both having significant hydro resources. The amount of renewables proposed in the IEA-ETP scenario is higher, about 55%, with especially a high number for hydro. This is again partly due to the geographic region considered (OECD Europe for example includes Norway, Switzerland and Turkey). When comparing IEA-ETP and the 60% RES scenario of the ECF, the share of hydro remains high in the IEA-ETP scenario, while the number for PV (12%) in the 60% RES ECF scenario tends to be significant. The 80% RES scenario of the ECF can be considered as sort of an outlier, with especially the high number for solar PV that catches the eye. In terms of nuclear, there seems to be a consensus among the different scenarios to about 30%. In the 60 and 80% RES scenarios of the ECF, the number for nuclear is lower, being 20 and 10%, respectively. Recall that these numbers for nuclear in the ECF scenarios are postulated, and do not result from an optimization. When considering the amount of fossils, the Eurelectric scenario features about 30%, almost equally spread between coal and gas. This corresponds to the (postulated) 40% RES scenario of the ECF. The IEA-ETP scenario has a considerably lower amount of fossils, with remarkably low numbers for natural gas (which might lead to questions concerning dynamic balancing of the system to cope with the large fraction of intermittent generation, see further).

As a comparison to current numbers, the projected electricity generation in 2010 (see first column) for the European (EU-27) consists of about 20% RES, (mainly hydro, accounting to 10%-pts of overall generation, followed by wind with about 5%-pts), 28% nuclear and a little over 50% fossil fuels, with a total generation of about 3090 TWh (Eurelectric, 2010). Taking into account the expected increase in demand for electricity towards 2050, this means that in a scenario with 40% RES, the amount of electricity generated by RES would have to be multiplied by 4 in the period 2005 – 2050, i.e., a spectacular increase, taking into account that the easy part (being hydro) is already exploited. The amount of nuclear would have to be maintained and even increased (up to as high as 40%), while the generation by fossils will decrease.

Note that all these numbers are for generation [TWh] (expressed in relative terms). The relative share of installed capacity of, e.g., RES will have to be much higher compared to nuclear and fossil fuel plants, given the low load factors of, e.g., wind compared to nuclear and coal with CCS. The installed capacity in 2050 amounts to the following:

- Eurelectric: 1318 GW
- ECF, 40% RES: 1280 GW
- ECF, 60% RES: 1700 GW
- ECF, 80% RES: 2020 GW
- IEA-ETP: 1350 GW

The installed capacity of the Eurelectric scenario, the ECF scenario with 40% RES and the IEA-ETP scenario are comparable. As a comparison, the installed capacity in the EU-27 in 2007 amounted to 795 GW (Eurelectric, 2009), while the 2010 capacity is projected to be 813.8 GW (Eurelectric, 2010). The increased amount of installed capacity in the 60% RES and 80% RES scenarios of the ECF are due to the increased required amount of solar, wind and back-up plants. This is illustrated by the values presented in Table 2. The first column again presents projected values for 2010 (Eurelectric, 2010).

Table 2. Installed capacity [GW] of PV and wind, in the envisaged scenarios of the considered studies.

	2010	2050				
		Eurelectric	ECF			IEA-ETP
			40%RES	60% RES	80% RES	
	[GW]	[GW]	[GW]	[GW]	[GW]	[GW]
Solar PV	16	125	195	555	815	125
Wind onshore	80	257	140	165	245	259
Wind offshore	4	125	25	130	190	99

Note the relatively low numbers for wind capacity in the ECF scenarios, possibly due to the relatively high load factors assumed, i.e., 35% and 45% for new build onshore and offshore, respectively, in 2050.

2.3 Matching demand and supply

A European zero carbon power system in 2050 will still need to match demand and supply with a combination of backup power, grid expansion, storage and demand response. This balancing will be a key issue. In what follows we introduce these options and then compare which are taken in the scenarios of the three studies.

2.3.1 Introducing the options

First option is back-up power. This is basically installing a certain amount of conventional (dispatchable) power for every MW of installed non-dispatchable capacity. This back-up power ensures that electricity can be generated when it is needed and when the non-dispatchable sources are generating insufficiently. Second option is expanding the grid. Assuming that the wind will always blow somewhere, and that the sun will always shine someplace, expanded interconnections can transport the power to where it is needed. Third option is storage, which allows capturing the power when generated, storing it (energy) and releasing it back when necessary (when there is demand). Fourth option is demand response, which shifts demand to match supply (e.g., consume when power from non-dispatchable renewables is available). Note that for the integration of all these options combined with the massive amount of variable sources, smart grids will play a crucial role.

2.3.2 Scenario comparison

Of the four considered options regarding flexibility and supply/demand matching, all studies put emphasis on the electric network. The Eurelectric study uses a DC load flow approximation to model transmission. The model covers 241 existing and new lines (exogenously imposed). The cross-border transmission capacities amount to an aggregated value of 179 GW in 2005. This is expected to increase to 245 GW in 2020, to 253 GW in 2030, and to remain stable thereafter. Expressed in relative terms, the increase in cross-border capacity amounts to about 40% (2005-2050).

The ECF puts great emphasis on the future development of the grid. A major expansion of interconnection capacity between national transmission networks is required, to integrate the proposed amounts of RES, to allow sharing reserves and to reduce curtailment. The model employed covers 15 major interconnections between so-called ‘centers of gravity’, spread over Europe. The aggregated capacity on these interconnections is currently 34 GW and increases (by 2050) with following amounts in the different scenarios:

- 40% RES: 56 GW
- 60% RES: 103 GW
- 80% RES: 166 GW

In relative terms, this represents additional capacity of about 65%, 200% and 390%, for the three scenarios respectively.

Demand response can be introduced by the deployment of smart grids. Examples include efficient charging of electric vehicles (no vehicle-to-grid storage has been assumed) and use of heat pumps. This demand response can reduce the need for transmission and backup services. The ECF study features a ‘20% demand response’ option for the three different scenarios (i.e., 20% of daily electricity demand can be shifted within a 24-hour period), which lowers the needs for transmission investment and back-up generation to some extent, especially in the scenarios with more RES.

2.4 Costs

In all projections, a zero carbon electricity system by 2050 will require much higher capital costs and hence upfront investments. This is due to the important role of RES, CCS and nuclear, all characterized by high capital costs (compared to more fossil fuels – without CCS – in the baseline) and to the fact that the overall installed capacity will be higher, because of the limited load factors of RES (e.g., wind, PV), as demonstrated earlier. In the Eurelectric scenario, investment in power generation amounts to 1.75 T€ (12% higher than the baseline scenario)[5]. The investment in the power grid is also substantial, resulting in 1.5 T€ (which is reported to be 35% or some 400 G€ higher than baseline). Hence, the total additional investment cost in the power sector (i.e., generation and transmission) is about 25% or 600 G€ higher than the baseline. In the ECF report, the investment in power generation in the baseline ranges from about 27 (2010) to 35 (2050) G€/year. In the zero carbon pathways, these investments significantly increase to about 55-70 G€/year in the period 2025-2035, after which they slightly decrease. The investment in transmission (aggregated 2010-2050) lies at levels of about 53 G€ up to 182 G€, which is significantly higher than the reference case (10 G€). Investment in back-up generation is reported to be about 93 G€ to 131 G€, again well above the baseline (32 G€). In the IEA-ETP scenario, additional investment in the power sector is 780 G$ over the period 2010-2050.

The additional investments are reported to be offset by lower fuel cost (RES and nuclear). The average price of electricity in the Eurelectric scenario is practically the same as in the baseline (significant increase during 2010-2025); from 95 €/MWh (2005) up to 145 €/MWh in 2050 (in 2005 €). The ECF presents an integrated cost of electricity, which is about 10% higher than base case (77 €/MWh) in 2050, and practically equal in all three zero carbon scenarios: 85 €/MWh (40% RES pathway), 85 €/MWh (60% RES pathway) and 83 €/MWh (80% RES pathway)[6]. This integrated cost includes generation (investment + operation) and grid costs (HV transmission investment, back-up capacity, balancing).

However, projected costs strongly depend on the assumptions made related to the grid, back-up, storage and demand response. The most optimistic cost estimate is obtained when assuming a well integrated EU electricity system, allowing for the option of cheap and unrestrained network expansion. Grid reinforcements and expansion indeed lower the need for back-up capacity (the wind will always blow somewhere, goes the argument, as discussed above). However, such an approach lacks possible practical difficulties with this network expansion and does not account for the costs associated with these difficulties (feasibility, licensing, conflicting incentives of member state versus EU wide approach). The other extreme, i.e., the most pessimistic estimate, considers local regions and attributes high back-up capacity and corresponding costs to the deployment of RES. Note also that the investment cost for the massive grid expansion as proposed by the ECF (53 – 182 G€, for an expansion of 65% - 390%) is lower than the number proposed by Eurelectric (1.5 T€, for an expansion of 40%). Given these differences, it is clear that the overall cost of electricity in these scenarios deserves more detailed scrutiny and study.

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[5] T€ stands for Tera or 10^{12} €, while G€ indicates Giga or 10^{9} €.

[6] It is remarkable that the reported integrated costs are practically the same for the three considered ECF pathways, given the different assumptions of these pathways. This aspect might require further study.

3. Policy recommendations

In what follows, we first discuss what the policy recommendations of the three studies have in common, to then highlight their differences.

3.1 Similarities in the three studies

The main similarities in the three studies are first the importance of grid reinforcement, expansion and planning they demonstrate and second the central role of the EU ETS they express.

3.1.1 Importance of grid reinforcement, expansion and planning

The importance of grid reinforcement, expansion, and planning is emphasized in all three studies. RES are typically characterized by a variable and to some extent unpredictable profile, and are only limited dispatchable. The existing European grid and balancing mechanisms have been able to absorb the current amount of RES. However, given the expected levels of RES deployment towards 2050, the electricity grid will play a crucial role. The network will have to be fundamentally expanded, both on the transmission (high voltage) side (increase cross border interconnections towards an integrated European system) and on the distribution level (enable increasing amount of distributed generation and demand side management). Evolving towards a so-called ‘smart-grid’ is a further important step. The increasing amount of variable sources will call for more balancing requirements and an increasingly important role for storage, so as to keep the system reliability at the proper levels. Rules for grid access together with a clear regulation framework for renewables integration must be set up. A ‘smart’ connection between supply and demand will be necessary. The enrollment of smart grids will be crucial in this regard, calling for coordination and standardization. Significant R&D investment efforts in these areas are required. The need for additional balancing requirements and regulation needs to be identified and addressed. A European strategy for network reinforcements and development will have to be developed. Rather than aggregating national action plans, a plan with EU-vision has to be set up. Appropriate licensing and permitting procedures will prove crucial for timely investments.

All three surveyed studies mention the importance of ensuring enough grid investment. The ECF recommends expanding ACER/ENTSO-E to develop a strategic interconnection plan. The IEA-ETP similarly calls for a roadmap for improving electricity and gas interconnections.

3.1.2 Central role of the EU-ETS

The EU has set up the European Union Emission Trading Scheme (EU ETS), initially as an instrument to meet its obligation under the Kyoto protocol. As from 2005, this cap and trade system entered into force.

The EU ETS is currently Europe’s main instrument in the fight against climate change. According to economic theory, a cap-and-trade system with a cap progressively decreasing and effectively going to zero in 2050 would set an appropriate price on CO_2 and thereby would trigger the optimal amount of investment in and deployment of low-carbon technologies. This would yield the optimal (lowest cost) carbon free generation mix. A consistent price for CO_2 is an important and crucial requirement in the path of decarbonization.

When considering the three studies discussed throughout the paper, all recognize EU ETS as central key instrument, to be set in line with the 2050 target. The Eurelectric study calls for well functioning carbon and electricity markets so as to deliver carbon reductions at least cost. On a broader scale, all sectors should internalize the cost of greenhouse gas emissions. The report supports a carbon price as sole driver (over time) for low carbon investments. A carbon price of 103.2 €/ton (€ 2008) is projected in 2050. The ECF recommends to "*set EU ETS in line with 2050*", while the IEA-ETP calls for "*a strengthening of the EU ETS*".

3.2 Main difference in the three studies

In the Eurelectric scenario, "no binding RES-targets are set after 2020", while "RES support mechanisms remain fully in place until 2020 and are then gradually phased out during 2020-2030". This means there is a sole reliance on the EU ETS CO_2 price (as from 2030) for the deployment of low-carbon technologies. The ECF and the IEA-ETP on the other hand do consider continuing with targets for RES in combination with a more harmonized EU RES trading scheme. In what follows we introduce the main risks of relying solely on the EU-ETS, and the arguments for taking additional measures.

3.2.1 Introducing the main risks of relying solely on the EU-ETS

The main risks include windfall profits, over-allocation, the allocation process in itself, price volatility and lock-in. Some of these risks are often expressed as critiques on the EU ETS (for an overview, see Ellerman and Joskow (2008)). The introduction of a price for carbon may yield so-called windfall profits. Three different kinds of windfall profits are identified by Lévêque et al. (2009). The first type relates to the impact on short and long-run equilibria of electricity market. In the short-run (with current technologies in place), profits of different types of power plants can change due to a change in merit order and a different market clearing price (accounting for the price of carbon). In the long-run however, the price for carbon will affect the optimal generation mix, where in the optimal solution revenues will equal costs (zero windfall profit). The latter effect is the desired effect of a carbon price. The second type of windfall profit relates to imperfect market conditions. If certain technologies are constrained in deployment, the optimal generation mix can not be reached. Hence, these constrained technologies will enjoy a scarcity rent (this will be explained below). The third type of windfall profit concerns the allocation mechanism. A constraint on CO_2 emissions creates a scarcity rent. If allowances are initially allocated for free, this rent is captured by the generators and hence represents a windfall profit.

Windfall profits (of the first and third type) have been reported (Sijm et al., 2006). The first type is inherent to the introduction of a carbon price, and windfall profits in this case are limited in time. They might be taxed so as to recover them. Concerning the third type (related to initial allocation), allowances will be auctioned in the power sector as from 2013 (main rule with some exceptions), instead of allocating them for free to the generators. Especially the second type of windfall profit is relevant in the 2050 context. After all, the electricity market faces several constraints and has several market imperfections: difficulties arise related to planning and licensing. Especially some types of RES and nuclear (public acceptance) face severe permitting and licensing restrictions, preventing them from free deployment. If the carbon price is the sole driver towards low carbon, the marginal abatement cost might become very high if expensive technologies are needed to respect the cap[7]. With the CO_2 price being set by the marginal technology, significant windfall profits will be made by, e.g., operators of constrained technologies like nuclear or wind turbines. Taxation of these profits might be an option but could become practically difficult.

Avoiding this high equilibrium CO_2 price by, e.g., imposing RES targets might be a possibility (note that if certain types of RES become competitive, some of such targets might even be exceeded).

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[7] A well interconnected European system reduces possible impediments of deployment of certain technologies, as it covers a larger geographic area and combines various MS policies. Hence, this also reduces the risk of facing the second type of windfall profits.

In the 2050 framework, it has been demonstrated that RES will play a crucial role. The low or zero carbon technologies are characterized by high investment costs compared to relatively low variable costs. Carbon prices in the current range (10-20 €/ton) seem not sufficient to trigger such investments[8]. Furthermore, the increase in electricity demand due to the shift from the other sectors will only occur on the longer term, thereby not providing the current incentives needed.

The EU ETS further does not prevent investments in CO_2 intensive technologies “locking in” carbon emissions for a long time span. Especially in the 2050 framework, investing now in carbon intensive technologies imposes a significant lock-in and stranded costs in the future. This inherently poses difficulties with future claims from the industry (indicating so-called “negative windfall profits”). A typical example is building a new coal plant (without CCS) with a lifetime of typically 40-60 years[9]. Several Member States, however, already announced or implemented restrictions on the use of carbon intensive technologies (like coal) or on the building of new capacity, for example obliging new coal plants to be equipped with CCS on part of their output, and with the option to employ CCS on the full capacity.

3.2.2 Additional policy recommendations in the studies

In the Eurelectric scenario, no binding RES targets are set after 2020, and RES support is gradually phased out in the period 2020-2030. After 2030, the carbon price becomes the sole driver for the deployment of low carbon technologies. The ECF on the other hand does consider implementing complementary measures to invest in low carbon. The EU should *“request MS to come forward with long term targets for deployment of key renewable generation technologies and adopt parallel measures for CCS”*. The IEA-ETP calls for a harmonized trading system for RES.

Concerning lock-in, substantial early retirement of capital stock might already even be required (IEA, 2008). Therefore, strong signals on a long term climate policy should be provided. Restrictions on new carbon intensive capacity might be a necessity. The ECF explicitly mentions the option of ruling out investment in carbon-rich generation. They furthermore call for a review of the wholesale market arrangements, to ensure proper incentives for demand side resources and system balancing.

4. Summary and conclusions

The challenge faced to limit climatic change to acceptable levels is huge. The EU will have to move to a practically zero carbon energy system by 2050. This paper has focused on the impact of such a transition on the demand for electricity, the composition of the generation mix, on the corresponding balancing of this demand and supply, and on the cost, together with policy implications. Three main reference studies have been used throughout the paper: The Power Choices study by Eurelectric, The Roadmap 2050 by the European Climate Foundation and the Energy Technology Perspectives by the IEA, all released in 2010.

Due to electrification of both transport and heating/cooling, the electricity demand is projected to increase substantially towards 2050 despite a higher overall efficiency both at the demand and generation side, with up to 50% compared to current levels. Basically three technology options are available in a zero carbon system: RES, nuclear and fossil fuels with CCS. The amount of RES faces a lower limit of 40% over the different studies, ranging up to as high as 80% in one of the scenarios of the ECF. Assuming 40% of the electricity generation in 2050 by RES, this means a multiplication of

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[8] Towards 2050, carbon prices will increase. However, at this moment, sufficient investment is already required, to benefit from learning and to stay in line with the 2050 target.

[9] One should, however, account for the option of a coal plant being ‘CCS-ready’, or for the option of fuel switching, to transform the plant to run on biomass.

the current RES generation by a factor of 4. Especially wind energy is projected to increase and contribute significantly to this number. Given the limited load factors of RES, the installed capacity in the European power system is almost double of the current level, already in the 40% RES case. The role of the electric network will be crucial, although numbers tend to differ significantly among the studies. Especially the grid extension and balancing requirement deserve further investigation. The low or zero carbon technologies (RES, nuclear, CCS) are characterized by high investment costs. All studies report a significantly higher investment burden compared to the baseline cases. This additional upfront cost is, however, offset by savings in fuel cost, resulting in a levelized cost of electricity comparable to the baseline. The fact that the cost of electricity generation in the three ECF scenarios is about the same might require further study.

In this transition, EU ETS will play an important role. Relying solely on a carbon price, however, might not be sufficient. Although comparable in outcome, the Eurelectric study does advocate this sole reliance on carbon pricing, while the ECF and the IEA-ETP call for RES targets and a harmonized RES trading scheme. Lock-in of carbon intensive technologies might be another aspect deserving attention. Finally, significant investment in the grid will be required, to move towards a well interconnected European power system. This is emphasized by all three studies.

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Authors contacts:

Erik Delarue and William D’haeseleer

University of Leuven (K.U.Leuven)

Energy Institute, TME branch (Applied Mechanics and Energy Conversion),

Celestijnenlaan 300A - post box 2421

B-3001 Leuven (Heverlee)

Email: erik.delarue@mech.kuleuven.be

Email : william.dhaeseleer@mech.kuleuven.be

Leonardo Meeus

Research Fellow at Florence School of Regulation (and Associated Professor at KULeuven)

European University Institute, RSCAS

Villa Malafrasca, Via Boccaccio, 151

I-50133 Firenze

Email: leonardo.meeus@eui.eu

Ronnie Belmans
Professor at University of Leuven
Energy Institute, ELECTA branch (Electric Energy and Computer Architectures)
10 Kasteelpark Arenberg 10 box 2445
3001 Leuven (Heverlee)
Belgium
Email: ronnie.belmans@kuleuven.be

Jean-Michel Glachant
Director of the Florence School of Regulation and of the Loyola de Palacio Chair
European University Institute, RSCAS
Villa Malafrasca, Via Boccaccio, 151
I-50133 Firenze
Email jean-michel.glachant@eui.eu

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