CLIMATE ANALYTICS

DECARBONISATION PATHWAYS FOR THE EU POWER SECTOR

Policy framework, main drivers, case studies, and scenario analysis: lessons learned for alignment with the Paris Agreement

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POLICY FRAMEWORK, MAIN DRIVERS, CASE STUDIES & SCENARIO ANALYSIS: LESSONS LEARNED FOR ALIGNMENT WITH THE PARIS AGREEMENT

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Supporting science based policy to prevent dangerous climate change enabling sustainable development

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Summary of key findings

This report explores the current context and opportunities for emission reduction in the European power sector. It describes the political framework within which emissions reduction in the EU takes place and the key drivers determining the speed of emissions reduction in the power sector. These drivers are presented at the backdrop of three case studies, with potential lessons for other countries. It also assesses a suite of recently published scenarios resulting in an (almost) complete decarbonisation of the power sector from the perspective of compatibility with the Paris Agreement. On this basis, we list a number of policy repercussions and co-benefits resulting from transition towards a fully decarbonized power sector and provide a number of lessons learnt that can be used by other countries undergoing energy transition.

The European power sector is at the forefront of decarbonisation of the EU's economy. Between 1990 and 2019 greenhouse gas emissions from the sector decreased by 44%, with a significant acceleration even before the COVID-19-induced economic crisis. The share of renewables has almost tripled, from below 13% at the beginning of that period to almost 36% in 2019 and could even exceed 40% in 2020. These changes are the result of a governance framework which underwent numerous changes over the last three decades – especially since 2000.

The introduction of support mechanism for renewables, carbon pricing in the framework of the EU ETS, EU's air quality regulations, and more recent decisions of the majority of the EU member states to phase out coal, were the main drivers of these changes. **These drivers played different roles in different EU member states.** The introducion of feed-in tariffs was the main early driver of transformation in many countries. This was also the case in **Germany** and **Spain**, two out of three case studies we look into in more detail

Policy continuity and predictability is essential not only for moving the transformation forward but also decreasing its economic and social costs. A case in point is the experience in all three countries analysed in more detail in which radical policy change resulted in a significant slow down in new PV installations in Germany, and a collapse of domestic market for renewable energy industry Spain (for PV) and Poland (for wind) accompanied with job losses.

The assessment of the renewable energy development in the EU but even more clearly in the selected countries indicated **the importance of binding renewable energy goals**. It was often the belated realisation that the deadline for meeting EU's binding renewable energy goals for 2020 is approaching that resulted in EU member states improving the legal framework for the development of renewables. The lack of such binding commitments for 2030 – the EU 2030 goals for the share of renewables and improvement of energy efficiency has to be met at the EU level - may have negative repercussions for the prospects of meeting this goals.

Increasing momentum to move away from coal fired power generation resulted in an acceleration of transformation towards renewables in the late 2010s. **This acceleration resulted in the discussion around just transition away from coal becoming more prominent in all three countries but with different impacts on the situation on the ground.** In **Spain**, a comparatively short discussion – to some degree also reflecting comparatively small share of coal in the power sector – resulted in the adoption of a legal framework aiming to ensure that the people and regions affected by the phase out of fossil fuels can also benefit from the opportunities of the transformation. At the same time, share of coal in Spain's energy mix decreased from 17% in 2017 to 3% in 2020. In **Germany**, generous subsidies not only for the regions but also for the utilities operating coal power plants have been guaranteed in exchange for phasing out coal by 2038. The least consequential is the debate about coal phase out in

Poland, where it seems to be focused more on receving as much EU funds as possible than on the support of the people and regions affected. Nonetheless, also in this country electricity generation from coal decreased from 91% in 2009 to 74% in 2019 due to market pressures.

Despite the significant progress in transformation of the power sector over the last three decades, compatibility with the Paris Agreement temperature limit requires acceleration of the change in the sector. The importance of this sector in overall decarbonization of the energy sector is driven by two factors. First, the versatility of electricity makes it a central lever of emissions reduction in many other sectors, especially transport and buildings. Second, increasing competitveness of renewable energy in particular solar and wind, as well as storage technologies makes decarbonization of the power sector much easier. However, not all scenarios that result in zero or near zero GHG emissions in the power sector by 2050 can be considered compatible with the Paris Agreement as the pathway of reductions and timing of when zero emissions are met is important for meeting this Agreement's goals. Paris compatible emissions benchmarks for the power sector would result in emissions intensity decreasing from 265 gCO_2/kWh in 2019 to 75-80 gCO_2/kWh in 2030 and close to zero by 2040.

The major driver of this reduction of emissions should be coal phase out by around 2030 and an increase in the share of renewables to between 70-90% in 2030 and between 85-95% in 2040.

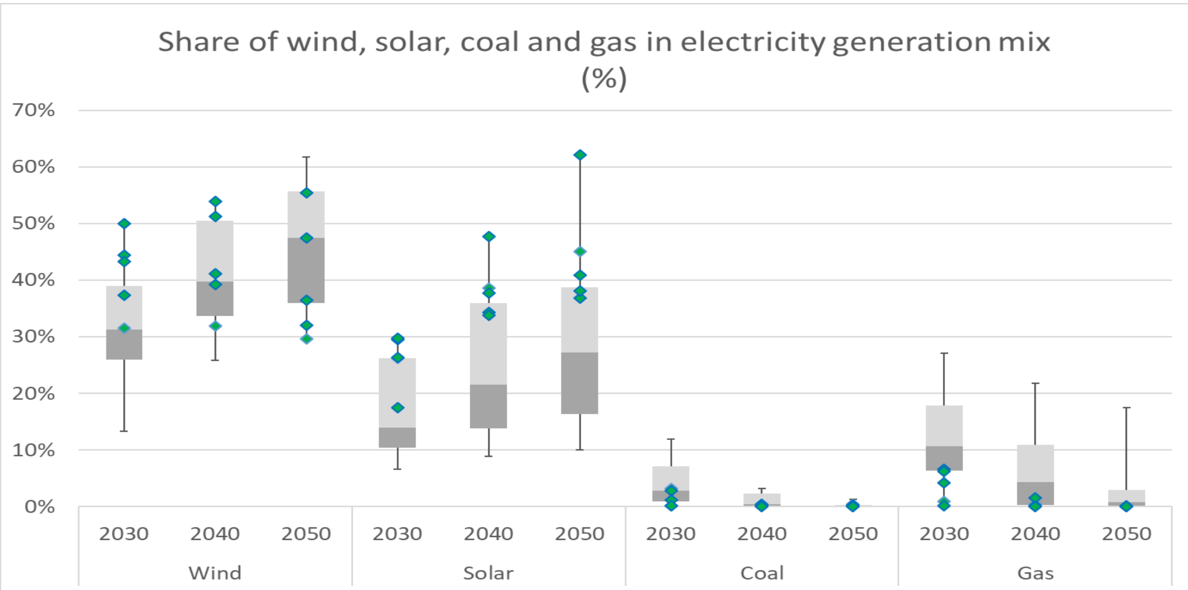

Figure 1 Share of wind, solar, coal and gas in electricity generation mix under different scenarios assessed in this study. The central line of the box plot represents the median (50th percentile), the other two lines below and above the median represent the first and third quartile respectively, and the whiskers cover the minimum and maximum values. The green markers in the box plot represent the values for the scenarios which meet the Paris Agreement compatibility benchmarks for the electricity generation mix. Own assessment of selected scenarios.

Only five out of 22 scenarios analysed in this report fulfill the benchmarks for Paris Agreement compatibility. They share some common characteristics, such as a rapid uptake of renewable energy technologies, especially wind and solar and high direct electrification rate across end use sectors such as industrial processes (heating, desalination) and transport. The electricity share in final energy demand reaches between 52% and 61% in 2050. The high electrification rate leads to massive efficiency gains, decrease in final energy demand but an increase in electricity generation demand. The electricity generation demand in 2050 increases by between 36% and 346% from 2019.

Another feature which is common among these scenarios is that all of them achieve net zero emissions from the power sector by 2050 without the application of CCS/BECCS technologies.

To accelerate the decarbonisation of the electricity sector, the already existing drivers of transformation need to be strengthened. This concerns especially carbon pricing via the EU ETS, creating favourable framework for deployment of renewables, and accelerating coal phase out. The EU ETS can be strengthened by increasing the annual reduction of the emissions cap to at least 4% starting in 2021 or reducing emissions in the base year by 300 $MtCO_2eq$. The situation is however complicated by the proposal of the Commission to expand the scope of the EU ETS to other sectors. The reform of the EU ETS that the Commission aims to present in the first half of 2021 should ensure that the risk of the price of allowances decreasing significantly as a result of a much faster than expected decarbonisation of the newly added sectors is avoided. This can be achieved by strengthening of the Market Stability Reserve (MSR) e.g. by increasing the share of oversupply of allowances taken from the market every year.

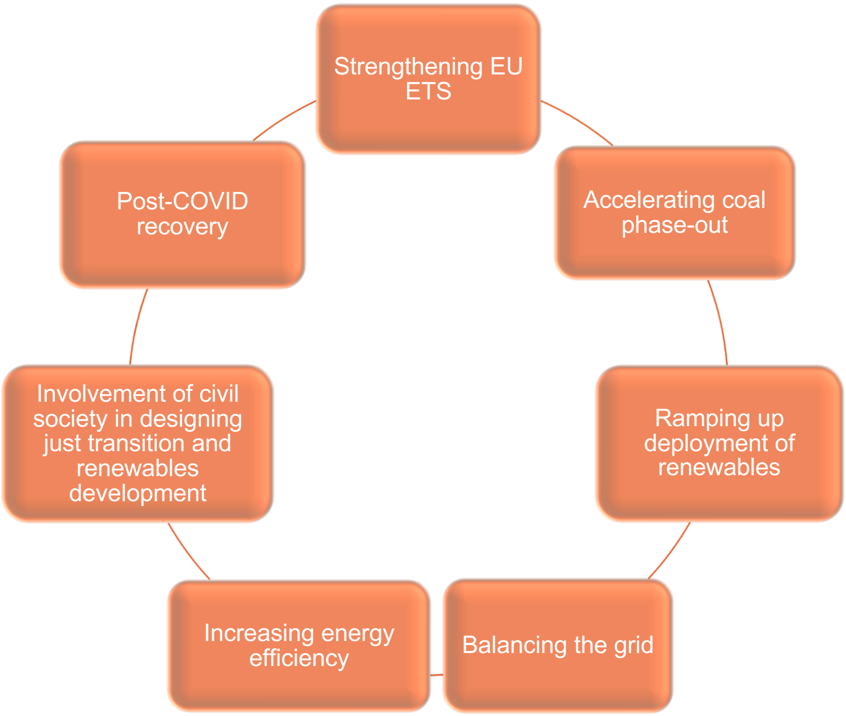

Figure 2 The main levers for decarbonization in the power sector

In addition to the need for all EU member states to commit to coal phase by 2030, deployment of renewables needs to be ramped up significantly. Our analysis of scenarios indicates that between 21 GW and 47 GW of wind (combined onshore and offshore) and between 20 GW and 109 GW of solar (combined utility scale and rooftop solar) needs to be installed every year until 2030. Increase of solar installations at the low end of the range would have to be accompanied with an increase of installed wind the high end of the range. Combined, between 44 and 171 GW of wind and solar would have to be installed annually in the Paris Agreement-compatible scenarios. This is much more than the capacity additions in the preceding years: in 2019 only around 11 GW of wind capacity and 10 GW of solar was installed, thus resulting in combined 21 GW of wind and solar, less than half of the low end of the range needed for Paris Agreement compatibility in the power sector (Solar Power Europe, 2020a; Wind Europe, 2020a). To meet these deployment pathways for renewables, the installed capacity auctioned for implementation in the EU member states needs to be significantly increased.

Smaller projects, especially those implemented by energy communities and prosumers, should be supported in the framework of feed-in tariffs. To increase the utilisation of the available roof space, small rooftop PV installations could be supported with a one-time grant instead of feed-in tariffs.

The significant share of variable renewables, especially wind and solar, which in 2030 may constitute up to 75% of electricity generation, requires adapting a number of measures to stabilise the electricity grid. Numerous options to balance the grid need to be considered – from storage and demand management, expanding transmission grids, through dispatchable renewables, to sector coupling and hydrogen – however their exact mix will be strongly influenced by the policies adopted. The need to rapidly ratchet up deployment of renewables requires an immediate deployment of the already available options for balancing the grid, while preparing infrastructure for deployment of the options that will be possible in the future.

Reaching 100% share of renewables will be easier if accompanied with a decrease in energy consumption. In addition to a significant potential for increasing energy efficiency in sectors that should be electrified, replacement of fossil fuels by renewables would already result in a significant reduction in energy demand. Additional savings can be achieved by leveraging electricity consumption via heat pumps for heating and cooling in the building sector.

The scale of the challenge requires an active involvement of the civil society. While the EU reserved significant resources to mitigate the impact of job losses resulting from phase-out of fossil fules, designing the transition plans jointly with those affected – both directly and indirectly – will increase the ownership of the plans, and increase the chances of their successful implementation. In addition, civil society should also play an active role in phasing in renewables. European legislation has already created a basis for increasing the involvement of civil society in electricity generation however many member states have failed to implement this legislation, despite the deadline approaching soon.

Few other sectors of the economy can contribute to such a rapid and widespread job creation as the development of renewable energy and improvement of energy efficiency. The European Union and itsmember states can seize the opportunity to recover their economies after the COVID-19-induced recession. This can include simple and unbureaucratic support for micro PV, e.g. in the form of one-time-grant, which can result in thousands of jobs in companies dealing with their installation and servicing. Investments in energy efficiency combined with electrification of heating can result in distributed job creation, decreasing the disparity not only between different countries in the EU, but also between different regions within the countries, especially between the rural and urban areas.

The study provides a range of lessons learned both for the future development in the EU and for other regions that are in the process of transforming their power sector. The EU approach of setting a combination of targets for greenhouse gas emission reductions, renewable energy and energy efficiency has been crucial to drive policy within the EU and EU member states. Targets have been adjusted to adapt to technological progress and policy demands in particular in relation to achievement of climate goals. Both the analysis for the EU and the Member state case studies show that timing and consistency of targets is important. Missing opportunities for adjusting targets or setting them at the adequate level in the first place can delay policy response and lead to lock-in effects. Managing the necessary transition challenges upfront with proactive stakeholder engagement, just transition processes and support for affected regions is instrumental to achieving political and societal buy-in.

Table of Content

1 Introduction

In the EU, as in the majority of other countries, the power sector is the largest greenhouse gas emitting sector and plays an important role in achieving early and fast emissions reductions, including emissions reductions in other sectors through electrification. It is also a sector that experienced the biggest changes in terms of the energy mix and the role of different players over the last two decades, thus providing lessons also for decarbonisation of other sectors. Understanding the drivers of these changes and the repercussions allows to draw some lessons, both in terms of the best practices and lessons learned as well as necessary steps ahead to implement the Paris Agreement.

The significant decrease in the costs of renewable sources of energy and the co-benefits of moving away from fossil fuels, such as a decrease in import dependency, improved air quality, opportunity to develop new branches of industry, and create numerous new jobs, makes climate change mitigation a major opportunity. This is especially the case at the backdrop of the COVID-19 induced ecnomic crisis: in many areas climate action results in a much bigger positive impact on the economy than investments in returning to fossil fuels-based economy. This results from higher job intensity of the low-carbon industries, distributed impact of the investment reflecting the scalability of renewable sources of energy, and improved trade balance resulting from a decrease of energy imports. Switch to renewable sources of energy, especially wind and solar, creates the opportunity to create new jobs in their installation but also in manufacturing. Contrary to fossil fuels, the siting of the manufacturing capacities (e.g. for solar panels and wind turbines) allows some flexibility, thus providing policy-makers with a tool to create jobs in the regions where these jobs are most needed – an essential tool in the post-COVID-19 recovery.

This report explores the current context and opportunities for mitigation in the European power sector. It describes the political framework within which emissions reduction in the EU takes place and the key drivers determining the speed of emissions reduction in the power sector. These drivers are presented at the backdrop of three case studies, with potential lessons for other countries. It also assesses a suit of recently published scenarios resulting in an (almost) complete decarbonisation of the power sector from the perspective of compatibility with the Paris Agreement. On this basis, we list a number of policy repercussions and co-benefits resulting from transition towards a fully decarbonized power sector and provide a number of lessons learnt that can be used by other countries undergoing energy transition.

After this introductory section, in Section 2 of the study shortly describes the broader framework within which policies affecting the power sector in the EU and its member states are taking place, including the division of powers between the European institutions and the member states. Subsequently, in Section 3, we describe the main drivers of transformation at the EU level, followed in Section 4 by a closer look at three EU member states with very different experiences in the transition from fossil fuels to renewables; Spain, Germany, and Poland. Section 5 looks at the recent scenarios considered as zero or near-zero emissions in 2050 and maps these against Paris Agreement benchmarks for the power sector. Based on the qualitative policy analysis in sections 3 and 4 and quantitative evaluation of Paris Agreement scenarios in Section 5, in Section 6 we investigate how the existing policies at the EU and national levels will have to change to reach Paris Agreement compatibility in the power sector and.present conclusions on lessons learned from our analysis.

2 Framework for emissions reduction in the EU power sector

2.1. Socioeconomic context and trends in the EU energy mix

Economy and GDP growth

With $15.6 trillion the EU27[1] was in 2019 the second largest economy in the world - after the United States ($21.4 trillion), but slightly ahead of China ($14.3 trillion). The average GDP per capita at $34,843 in 2019 was three times the world's average (The World Bank, 2020b). There are large differences between member states: GDP per capita in Eastern European countries that joined the EU in 2004 or afterwards are usually below the EU average, the lowest in Bulgaria (53% of the EU27 average) and Romania (69%). With the exception of Spain, Italy, and Portugal, all older EU member states are above or significantly above the EU's average GDP per capita. However, since 2000, mainly due to significant financial flows to the new member states, both in terms of public resources, but also private investment, the discrepancy between the richest and the poorest EU member states decreased considerably: in 2000 the weighted average GDP per capita of five of the poorest countries that later joined the EU was only 29% of the weighted avareged GDP of the EU27. By 2019 this indicator rose to 48% (See Figure 3) (Eurostat, 2020c).

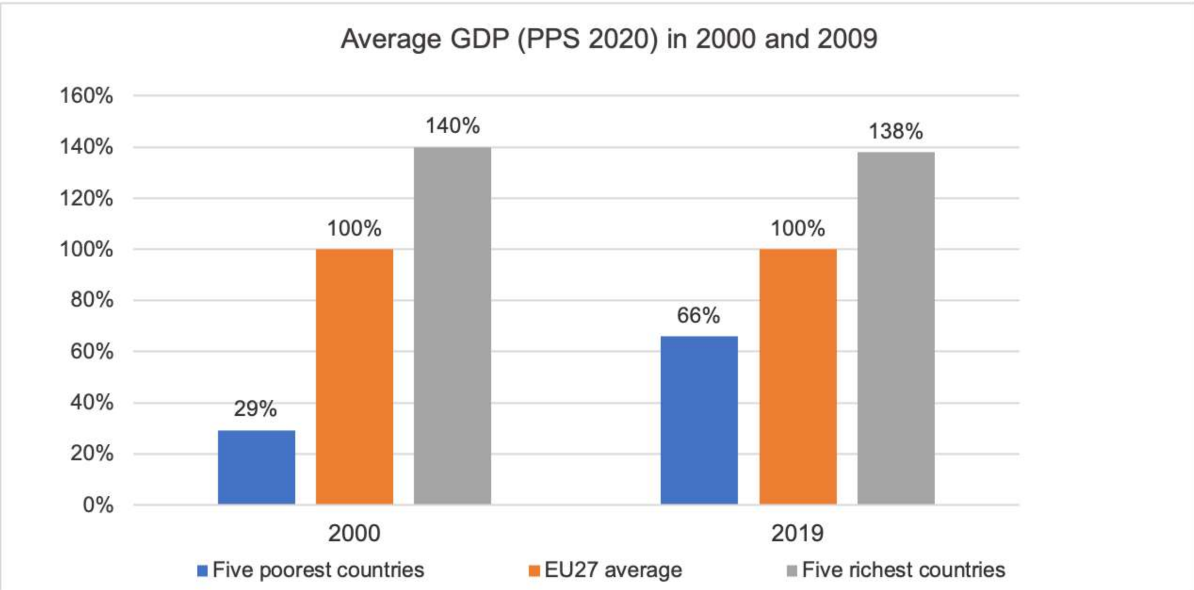

Figure 3: Increasing convergence between the EU member states. The weighted average of the five poorest and richest countries reflects EU membership after 31 January 2020. Own calculation based on (Eurostat, 2020c).

[1] Unless specified otherwise, the data applies to EU27. However, in many cases, especially for scenario analysis in Section 5, we had to rely on emissions for the EU27+UK.

This increasing economic convergence was largely due to rapid economic growth in the poorest EU member states. Between 2000-2019 Romania registered an average annual GDP growth of 4.1%. Bulgaria and Poland were not far behind with 3.6 and 3.8%, respectively. At the same time Germany and France, the two biggest EU economies, grew on average by 1.4% over the last two decades, which resulted in average of 1.7% growth for the EU. That was significantly below global average of 3.8%, however from a much higher starting base (IMF, 2020). With the full economic impact of the COVID-19 pandemic still not fully known, the European Commission's Summer Interim Forecast projects economic recession at 8.3% in 2020 before the economy bounces back in 2021 with economic growth at 5.8%. This is a deeper fall than the one affecting global economy, which is projected to fall by 3.9% in 2020, before it recovers 4.9% in 2021 (European Commission, 2020j).

The EU's economy is dominated by the services sector, which in 2017[2] contributed 65% to the EU's GDP. This is around the same share as the global average and exactly between the USA (77% share) and China (53% share). The share of industry in GDP generation in the EU was with 22% around 3%-points below global average, unchanged since 2014 – contrary to the global level, as well as the U.S.A and China where the share of industry in the GDP continued its decreasing trend. Agriculture generated 2% of the EU's GDP – above the USA, where it contributed less than 1% of the GDP but significantly below China, where 8% of the GDP was coming from this sector (The World Bank, 2020d).

Energy consumption and imports

EU's primary energy consumption per capita in 2015 was with 138 GJ per capita significantly above the world's or China's average at 80 GJ and 92 GJ, respectively, but half of the levels of the United States (The World Bank, 2020c). After a combined decrease by 4% in the early 1990s, resulting mainly from economic transformation in the Eastern European countries, primary energy consumption started to grow in 1995 until it peaked in 2006 at 63.3 EJ, or 11% above 1995 levels. By 2018 it fell to 57.6 EJ – only 0.6% higher than in 1990, however with a combined economc growth by 61% in the same period (European Commission, 2019d; Eurostat, 2020a).

In the same period, consumption of final energy increased by 3.9% and reached 43.4 EJ. This difference between an increase in final energy consumption and a slight decrease in primary energy consumption can be explained by an increasing role of renewables: whereas a significant share of primary energy included in fossil fuels is lost before the energy is transformed and transported to the final users, there are no energy losses in the case of energy (mostly electricity) generated from renewables such as wind and solar. This factor was complemented by higher efficiency of the fossil fuel plants in conventional and combined heat and power (CHP) plants, which increased from 42% in 1990 to almost 50% in 2016. Nonetheless, more than half of the primary energy included in fossil fuels was still wasted in 2016. (European Environment Agency, 2018).

[2] Whereas data for 2018 is already available for some countries, their lack for some countries results in misrepresentation for the global level, e.g. resulting in the share of services in contribution to the GDP decreasing by 5%-points between 2017 and 2018.

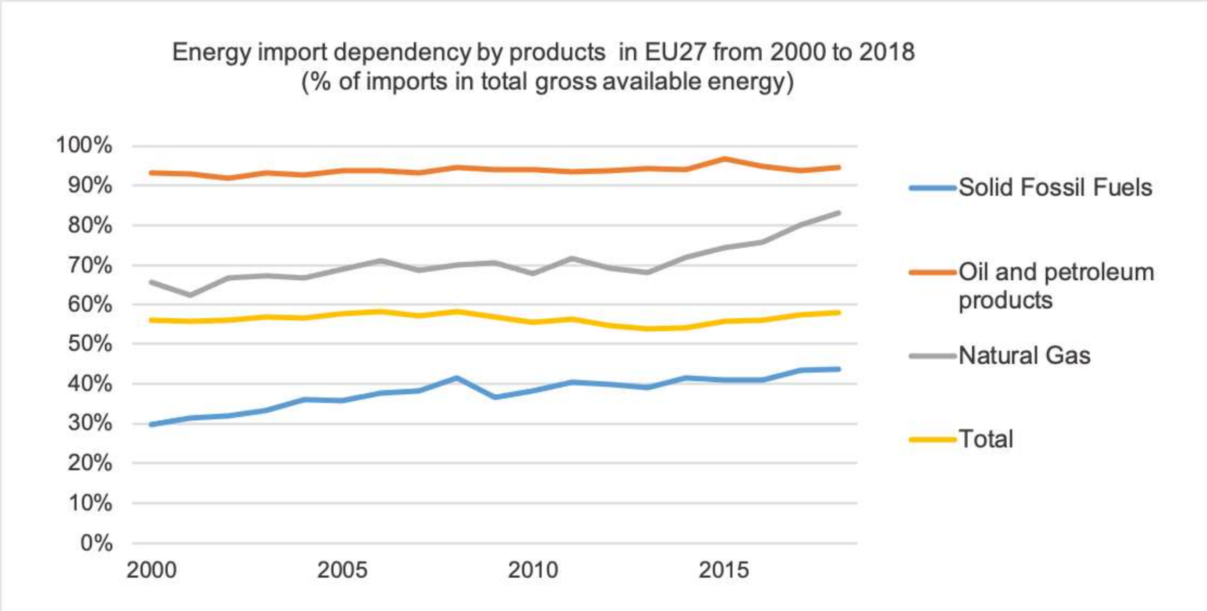

Figure 4: Energy import dependency by energy source in the EU between 2000-2018. Percentage of imports of different fuels in total gross available energy. Based on (Eurostat, 2020b).

A decrease in the consumption of primary energy and only slight increase in the consumption of final energy, combined with a significant growth of the European economy, indicate a substantial decrease of energy intensity of the economy, that is, emissions consumption per unit of GDP. In 2016 the EU consumed 67% less energy per unit of GDP than China, 40% less than the United States and 29% less than Japan. Except for some of its member states, the only other industrialised countries with lower energy intensity are Singapore, Switzerland, Norway, and the UK (The World Bank, 2020a).

Decreasing energy consumption and replacing mostly imported fossil fuels by domestic renewables is an important factor for the EU due to high and increasing dependence on fossil fuels imports. In 2018 over 58% of energy consumed in the EU was imported – an increase by percentage points since 1990 and one that is set to increase significantly as the Netherlands, one of the biggest EU producers of natural gas is planning to significantly decrease its gas extraction (Government of the Netherlands, 2018). Already in 2018 more than 83% of natural gas consumed in the EU27 was imported – an increase from 52% in 1990. The EU is also importing almost 96% of oil consumed (Eurostat, 2020b). The combined cost of energy imports to the EU (incl. the UK) amounted to €266 bn, equivalent of almost 2% of the EU28's GDP (European Commission, 2019b).

Energy mix

Most of the energy consumed in the EU27 is coming from oil combustion. However its share has decreased from 37% in 1990 to 33%. An even bigger decrease affected coal demand – its share has almost halved and reached 15% in 2018. These two sources of energy have been replaced by natural gas (+6 percentage points) and renewables (+10 percentage points). Whereas most of the increase in the share of natural gas occurred in the 1990s, the increase in the role of renewables accelerated after 2005. This is the only source of energy which share continued increasing steadily and provided more energy than coal starting in 2018. The share of oil decreased up to 2010 and stabilised at the current level in 2010.

These changes in the energy mix mirrors changes (or lack thereof) in the specific sectors of economy. The stabilisation of oil consumption reflects the lack of progress in decarbonisation of the transport sector. A decrease in the role of coal in the 1990s has mainly been due to the modernisation of the power sector and replacing coal with other fuels for individual heating. As a result, final coal consumption in the households decreased by 71% in the EU27 countries only in the 1990s. By 2018 almost over 70% of coal used in households in the EU was used in Poland representing slightly over 8% of the EU's population. The situation looked different in the power sector where only after 1999 it has steadily been replaced by renewables. Renewables have also been replacing nuclear energy especially in Germany after 2011 (Eurostat, 2020d).

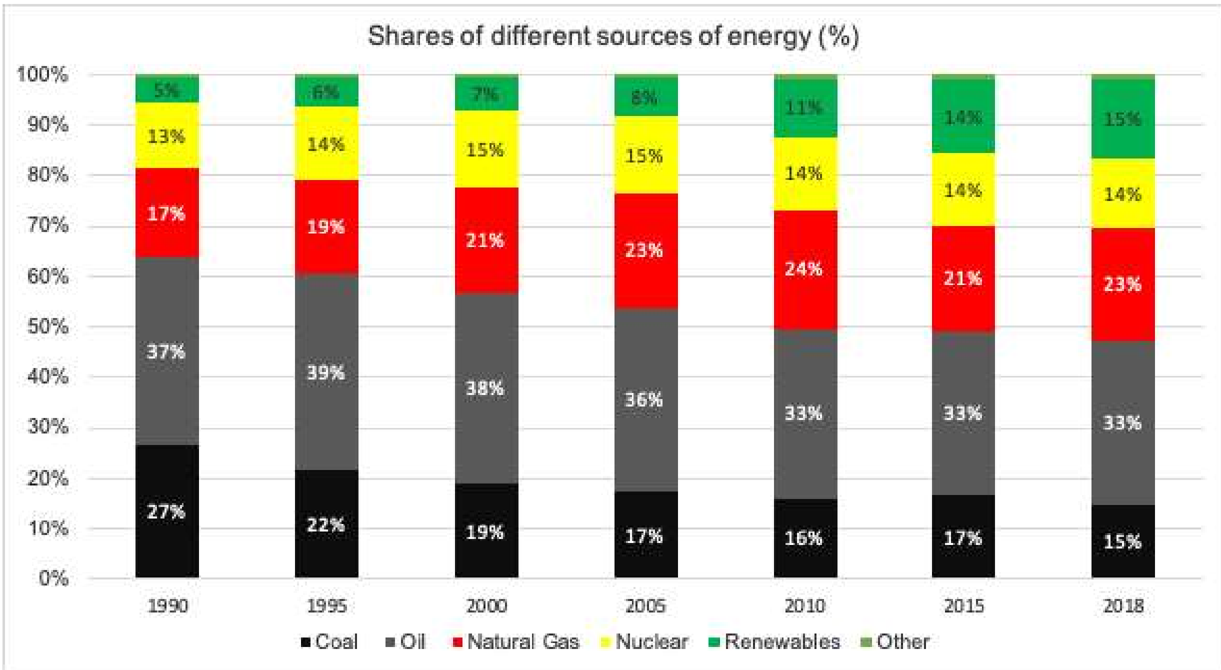

Figure 5: Share of different sources of energy in the EU27 total primary energy supply. Based on (Eurostat, 2020a).

The most important changes occurred in the electricity sector discussed later in the report. However, due to the fact that only a third of final energy is consumed in the form of electricity and associated heat (in CHP plants) (Eurostat, 2020a), these changes had only a limited impact on the changes of fuel mix in the primary energy (**Fehler! Verweisquelle konnte nicht gefunden werden.**).

2.2. The governance of the European Union

While formally merely an international organisation, the level of integration and the impact of the European institutions on the member states makes the EU a one-of-its-kind international body forming a political and economic union of currently 27 member states. Whereas in some areas (e.g. foreign policy) member states act independently, with rather loose coordination by the European High Representative for Common Foreign and Security Policy, in others the European Commission has significant competences (e.g. Common Agricultural Policy).

The European Commission is the only European institution empowered to present proposals for EU legislation in areas regulated by the treaties[3]. However, it often acts on the basis of suggestions of the European Council representing EU member states. The proposals are subsequently discussed by the Council of Ministers (the Council) representing specific representatives of the member states' governments, and the European Parliament. Both of these institutions consititute co-legislators in the framework of the ordinary legislative procedure. According to it, the European Parliament acts with simple (1st reading) or absolute (2nd reading) majority, whereas qualified majority is needed in the Council: only when legislation is adopted by representatives of at least 55% countries (currently 14 countries) representing at least 65% of the EU27 population (291 million citizens), it can enter into force.

Ordinary legislative procedure also applies to the area of energy. The Treaty on Functioning of the European Union[4] explicitly lists promotion of energy efficiency, development of renewable sources of energy, and combating climate change. However "measures significantly affecting a Member State's choice between different energy sources and the general structure of its energy supply" need to be adopted unanimously.

2.3. Climate change mitigation goals, architecture and governance

The recent history of the European climate change mitigation policy resulted in the creation of a framework within which the overall emissions reduction goals for the EU are set and their achievement ensured at the EU and national levels. The first major step in the creation of this framework was the establishment of the EU Emissions Trading Scheme (EU ETS), which entered into force in 2005. Since then it has been covering emissions from large installations, such as power sector, industrial installations, with aviation added in the reform of the EU ETS from 2009. Combined, this corresponded to around 45% of the EU's total emissions (European Parliament and the Council of the European Union, 2003, 2009d).

The EU headline emissions reduction targets and their distribution

In 2007 the European Council under German Presidency adopted the goal of reducing EU's overall emissions by 20% until 2020 in comparison to 1990. Part of this emissions reduction was to occur in the framework of the EU ETS. Emissions reduction in the sectors not covered by the EU ETS – mostly emissions from transport, buildings, and agriculture – was divided between member states with emissions reduction targets ranging between -20% and +20% taking into consideration their levels of economic growth and cost-effectiveness (European Parliament and the Council of the European Union, 2009a). Based on the name of the Effort Sharing Decision (ESD) that included the distribution of the emissions between the members states, the non-EU ETS emissions were also referred to as "ESD Sector". The emissions reduction agreed for the framework of the EU ETS was much stricter than in the non-EU ETS sector: While the former had to decrease by 2020 by 21%, the latter by only 10% (both with 2005 as base year).

[3] An EU treaty is a binding agreement between EU member states. See https://europa.eu/european-union/law/treaties_en

[4] See https://eur-lex.europa.eu/eli/treaty/tfeu_2012/oj

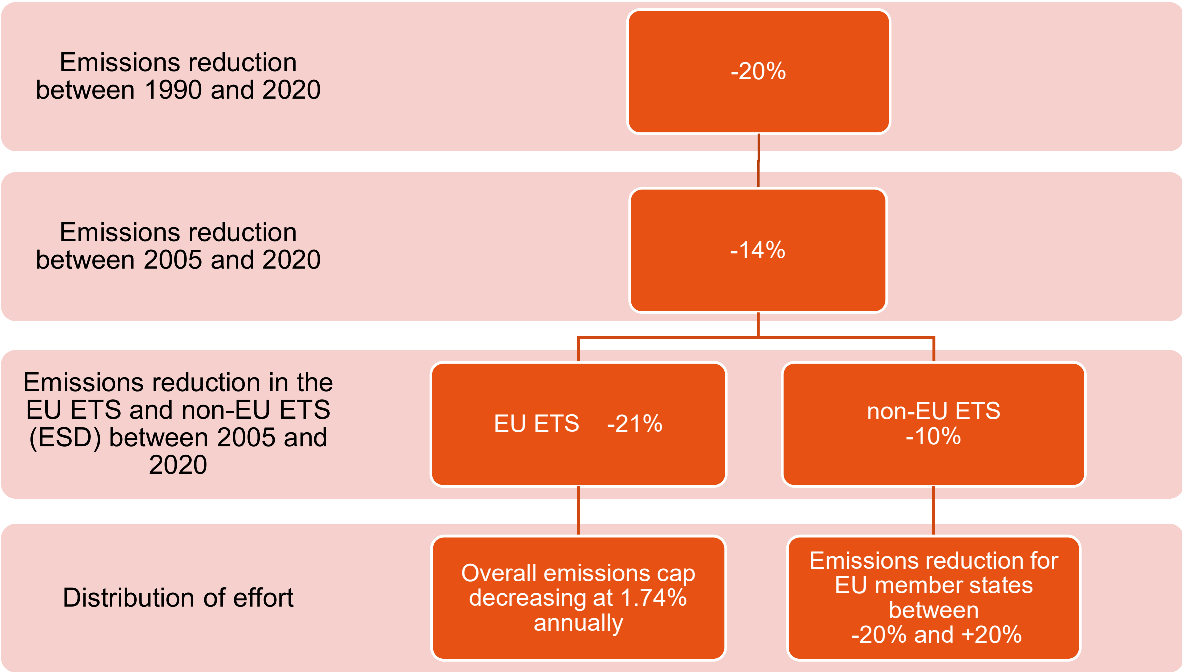

Figure 6:Disitribution of the overall EU greenhouse gas emissions reduction goal for 2020.

The way the 2020 emissions reduction goal was set (and met – with emissions reductions already at 23% below their 1990 levels in 2018) created a precedence for setting emissions reduction goals for 2030. In October 2014 the European Council adopted the goal of reducing emissions by "at least 40%" until 2030 from 1990 which was also enshrined in the first Nationaly Determined Contribution (NDC) of the EU to the Paris Agreement. This goal was to be achieved by reducing emissions by 43% in the EU ETS sectors and by 30% in the non-EU ETS sectors (European Council, 2014, 2015). Whereas in the case of the EU ETS sector this reflected the reduction of the overall emissions cap, in the latter case this goal was to be achieved by dividing it into national emissions reduction goals for sectors not covered by the EU ETS by between 0% and 40% taking into consideration the levels of economic growth and cost-effectieveness in different EU member states. Contrary to the distribution of the goals for 2020, no country was allowed to increase their emissions in 2030 in comparison to 2005. The goal was slightly weakened by the possibility to transfer emissions reduction in the LULUCF sector amounting to 280 $MtCO_2eq$ for all EU member states in the whole decade to the sectors covered by the Effort Sharing Regulation (ESR) (European Parliament and the Council of the European Union, 2018f) (Figure 7).

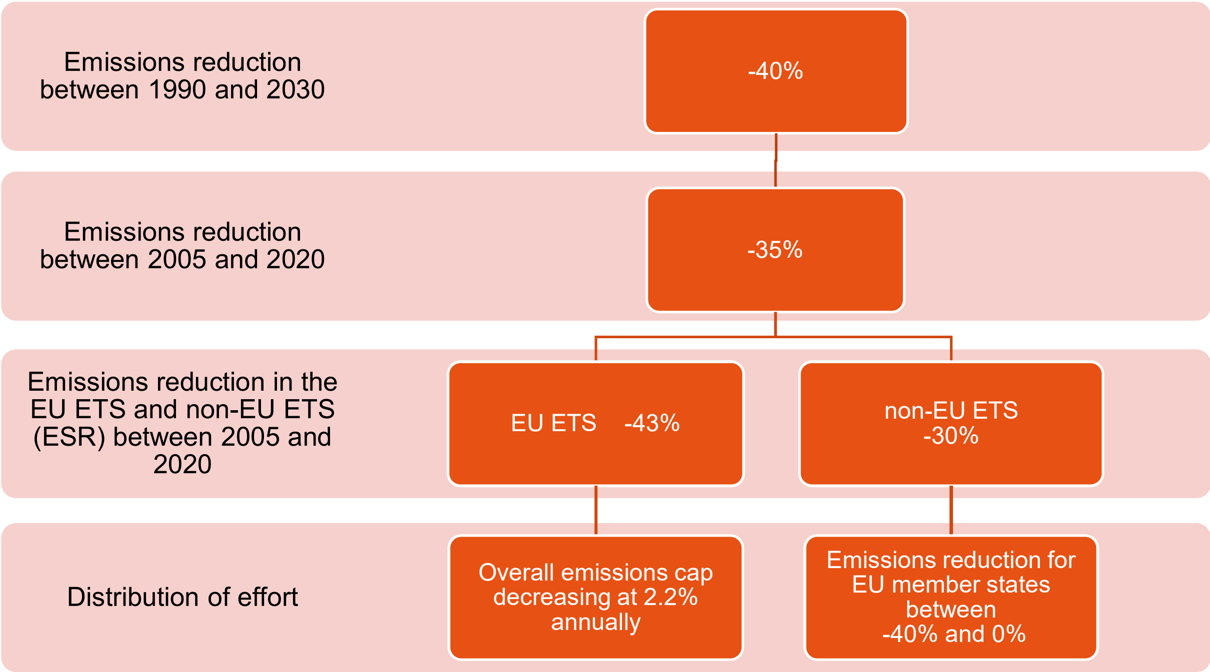

Figure 7: Distribution of the overall emissions reduction goal for 2030.

The EU is currently discussing how to ratchet up the 2030 target by the end of 2020, to bring it in line with the adopted long-term goal. In September 2020, the European Commission presented the proposal of increasing the EU's 2030 emissions reduction goal to "at least 55% below 1990 levels" to enable the EU to achieve the agreed greenhouse gas neutrality (or "climate neutrality") goal by 2050. Both, the 2030 and 2050 emissions reduction goal are to be enshrained in the European Climate Law the draft of which was tabled by the European Commission in March 2020 (European Commission, 2020o). The new proposal is a step-up from the previous target of at least 40% emissions reduction below 1990 levels adopted in 2014 and submitted as the first NDC to the Paris Agreement. However, the new proposal includes the Land use, Land-use change and forestry (LULUCF) sector both in the base year as well as in the target year, which would weaken the overall emissions reduction excluding LULUCF by around 2% (European Commission, 2020e, 2020m).

On 6th October 2020, the European Parliament (EP) voted to update the EU's climate target for 2030, backing a 60% GHG emissions reduction by 2030 below 1990 levels as compared to the existing 40% reduction target. The EP rejected the Commission's proposal to meet the 2030 climate target by means of carbon sinks such as the LULUCF sector. Further, the lawmakers voted in favour of proposing that each EU member state reaches carbon neutrality individually by 2050 (European Parliament, 2020a).

Three weeks later the Council of Ministers for Environment presented its amendments to the EU Climate Law, which were much weaker in comparison to those suggested by the Parliament. For 2030 the Council of Ministers kept the emissions reduction at "at least 55%" and stated that within six months of the 1st global stocktake due in 2023 the EU should set semissions reduction target for 2040 (Council of the European Union, 2020). In December 2020 European Council is set to agree on the 2030 emissions reduction goal. In its proposal to increase EU's 2030 emissions reduction goal, the Commission made also some suggestions that would substantially change the architecture of the EU's climate policy framework. In its Communication the Commision suggested to expand the EU ETS to cover all emissions from the combustion of fossil fuels and process emissions. Agriculture, which currently is covered by the Effort Sharing Regulation, would be merged with the LULUCF to create a new pillar. This would significanty reduce emissions covered by the ESR.

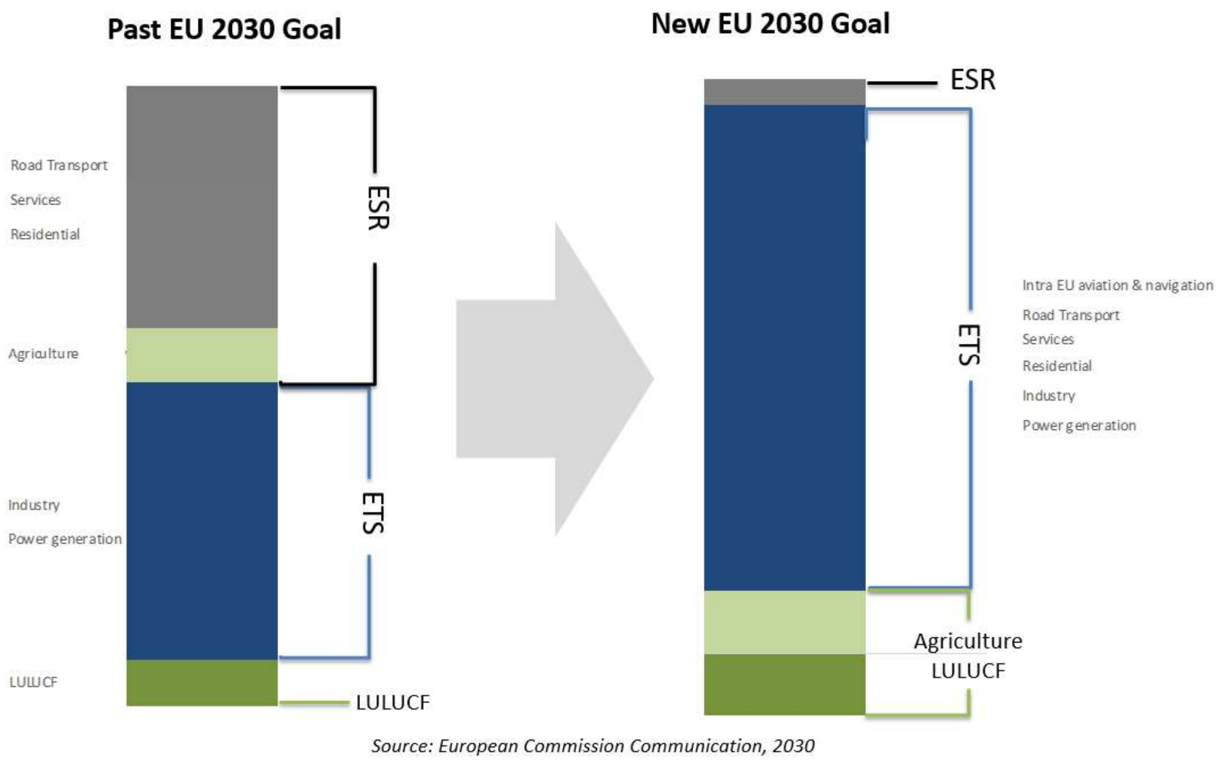

Figure 8: Proposed new climate policy architecture.

Energy targets and policies

Both for 2020 and in 2030, the EU has complemented greenhouse gas reduction goals with energy targets in their Climate and Energy Packages. The emissions reduction goal by 20% in 2020 adopted in 2007, was accompanied with the goals of improviding its energy efficiency by 20% that would result in the EU's energy consumption in 2020 not exceeding 1483 Mtoe (62.1 EJ) of primary energy or 1086 Mtoe (45.5 EJ) of final energy by 2020. At least 20% of this energy was to come from renewable sources of energy (European Parliament and the Council of the European Union, 2009c, 2012). Depending on where the remaining 80% will be coming from, this could reduce EU's emissions significantly below the 20% emissions reduction goal. In 2018 – the most recent year for which data are available at the time of writing – the share of renewables in the EU28 amounted to 18.9%. Primary energy consumption was with 1551 Mtoe (64.9 EJ) almost 4.6% e above the goal for 2020. The discrepancy between the final energy consumption and the 2020 goals was at 3.5%. Nonetheless, EU's emissions decreased by over 23% since 1990 (Eurostat, 2020e).

Similarly, the 2030 Climate and Energy Framework adopted in 2014 included a target to increase the share of renewable energy to 27% and to improve energy efficiency by 27%. As a first step of increased ambition, the EU, in 2018, adopted more ambitous energy targets, based on an assessment of reduced costs since the original framework was adopted in 2014. In 2018 the EU adopted the goal of increasing the share of renewables in the EU's to 32% of gross final energy consumption and the energy efficiency goal of improving energy efficiency by 32.5%, which translates into limiting energy consumption to 1273

Mtoe of primary or 956 Mtoe of final energy in 2030 for EU28 (European Parliament and the Council of the European Union, 2018d, 2018a).

Contrary to the renewable energy goal for 2020, the goal for 2030 has not been divided into binding national goals. Instead, countries have to commit their own national renewable energy goals and maximum energy consumption in 2030 in their National Energy and Climate Plans (NECP) (European Parliament and the Council of the European Union, 2018e). Though with some delay, so far all EU27 member states submitted their NECPs. The initial estimates of the contributions of the member states indicate that EU27 member states would underachieve the energy efficiency goal by reducing primary energy consumption by 29.7% instead of 32.5% in 2030 in comparison with Energy Baseline Scenario from 2007. National targets concerning the share of renewables would increase to 33.1% and 33.7%, thus overachieving he 32% goal (European Commission, 2020b).

Fulfilling the current two goals for renewable energy and energy efficiency would result in emissions reduction (excl. international aviation) by almost 48%[5]. This is already higher than the 40% emissions reduction that the EU commited to in 2015. Emissions in the EU ETS sector would decrese by almost 50% in comparison to 2005, instead of 43% resulting from the distribution of the 40% emissions reduction target (European Commission, 2019f).

Increasing EU's emissions reduction goal to at least 55% as suggested by the Commission in September 2020, will require further updating the renewable energy and energy efficiency goals. In one of the scenarios underpinning the Commission proposal, the share of renewables in the gross final energy consumption increases from the current goal of 32% to 38.5%. This would correspond to more than doubling the share of renewables in the EU's electricity sector to 64-65% and reduce emissions in the electricity sector by around 70% compared to 2015 (European Commission, 2020m).

The ground for ratcheting up EU's renewable energy goal has already been laid in the Renewable Energy Directive, which states that the currently binding goal should be reassessed, with the view of increasing if justified by "substantial costs reductions" of renewables, or "significant decrease in energy consumption" (European Parliament and the Council of the European Union, 2018c).

While the energy efficiency goal aims at reducing overall energy consumption, and renewable energy targets result in a steady increase in the share of zero carbon sources of energy, coal phase-out plans of some member states (see Section 3.4) reduce the role of the most carbon intensive source of energy in the remaining share of energy. According to estmates from early 2019, the implementation of the existing coal phase-out plans, combined with closing coal power in the remaining EU member states by 2040 would result in overall greenhouse gas emissions reduction by 53%. Accelerating coal phase-out to 2030, improving energy efficiency by 40% (instead of 32.5% as agreed) and increasing the share of renewables to 34% (which would be almost in line with what the member states committed to in their NECPs) would result in overall emissons reduction by 58% (Sandbag, 2019). Since the projection ws made a number of countries deciding to phase out coal before 2030 increased (e.g. by Hungary and Greece) and some countries either already switched off their last coal power plants (e.g. Austria and Sweden) or decided to do so much earlier than initially planned (e.g. Portugal).

[5] Own calculations based on (European Commission, 2019e)

Towards "climate neutrality" by 2050

In 2018 the European Commission published its vision of "climate neutral" European Union, accompanied with an in-depth assessment of decarbonisation options and eight different decarbonisation scenarios (European Commission, 2018b, 2018d). Only two of the scenarios – 1.5TECH and 1.5LIFE –could be considered as achieving this goal in 2050 – assuming the "climate neutral" goal refers to net zero emissions. However, the scenarios result in emissions reductions by only 89% and 90%, respectively, for greenhouse gas emissions, with the remaining gap to achieve net zero greenhouse gas emissions is covered by carbon removal technologies (additional reduction of net greenhouse gas emissions by 5 percentage points and 1 percentage point, respectively) and carbon uptake in the Land-use sector, e.g. through afforestation and reforestation (6 percentage points and 8 percentage points) (European Commission, 2018b).

In December 2019, all member states endorsed the objective of achieving "a climate-neutral EU by 2050". However, while supporting setting this goal for the EU, the Polish government stated that it could not commit to implementing this goal. The issue of lacking commitment on behalf of the Polish government was to be discussed during the meeting of the Council in June 2020 (European Council, 2019). Instead, the issue returned indirectly during the negotiations of the EU's Multiannual Financial Framework for 2021-2027 and the COVID-19 Recovery Package NextGenerationEU in July 2020. According to the conclusions from these negotiations, countries that fail to commit to implementing the goal of climate neutrality by 2050 will only be allowed to use 50% of the national allocation in the framework of the Just Transition Fund, of which Poland was to be the main beneficiary (European Council, 2020).

Achieving the goal of "climate neutrality" is the main objective of the European Green Deal (EGD) presented by the European Commission in December 2019. The accompanied timeline aimed at updating and complementing almost the enterity of the EU's climate-related legislation on the basis of the Commission's proposals to be presented in 2020 and 2021. In addition to the aforementioned reform of the EU ETS and revision of the Effort Sharing Regulation distributing the non-EU ETS goals between different member states, the timeline also includes new policy initiatives aiming at sectoral integration, preparing industry for meeting the "climate neutrality goals", and strategy for offshore wind development (European Commission, 2019a).

One of the main policy initiatives developed in the framework of the European Green Deal is the aforementioned draft of the European Climate Law presented by the European Commission in March 2020. If adopted as proposed, it would fundamentally change the process of setting new emissions reduction goals: Instead of these goals being the result of a political compromise between the EU member states the emissions reduction goals after 2030 would reflect the emissions trajectory leading to "climate neutrality" in 2050. When setting this trajectory – and the resulting emissions reduction goals – the Commission should take into consideration ten different elements, including cost-effectiveness, best-availabile technology, and the most recent science (European Commission, 2020o).

The implementation of the European Green Deal and reaching the goal of climate neutrality by 2050 has been defined as the main priority – next to digitalisation and resilience – in the EU27's Multiannual Financial Framework for 2021-2027[6] and the NextGenerationEU recovery fund, totalling over €1.8 trillion. According to the agreement of the heads of states reached in July 2020, at least 30% of the

[6] To avoid intensive and risky annual negotiations over the EU budget, the EU proceeds and spendings are planned in the framework of 7-year-long Multiannual Framework (MFF).

budget should be spent on meeting EU's climate objectives (European Council, 2020). The resulting amount of at least €547 billion, to spent largely in the early 2020s, will be significantly increased by the requirement engrained in many streams of funding to complement the expenditure by national resources.

3. The main drivers of decarbonisation in the power sector

The power sector has seen GHG emissions decrease in the EU27+UK by 34% between 1990 and 2018 – much faster than the EU's overall emissions which fell by 25% in the same period. As a result, the share of the power sector in total GHG emissions (excl LULUCF) fell from 25% in 1990 to 22% in 2018 (European Environment Agency, 2020b). Early estimates indicate an acceleration in the decrease from 6.5% in 2018 to 15% in 2019, which would indicate combined overall GHG emissions reduction by 44% in comparison to 1990 (European Commission, 2020f). A significant decrease in emissions from this sector is also expected in 2020. Emissions from the electricity sector in the 1st quarter of 2020, even before the main impact of the COVID-19-induced lockdown could be felt, are projected to have decreased by 20% (European Commission, 2020p).

This acceleration in emissions reduction before the COVID-19 induced lockdown and economic recession has been caused by the increasing role of renewables and market economics increasingly working against coal. The countries with the largest decrease in hard coal are the ones with the biggest increase in renewable energy (AgoraEnergiewende & Sandbag, 2020). Whereas the increasing role of renewable energy has been driven by support mechanisms for renewables, the fall of coal was also driven by carbon pricing, air quality regulations, and decisions of the majority of the European countries to phase out power generation in coal-fired power plants. The following subsections look at each of these factors independently, and also look into how the COVID-19 pandemic and the response to it has influenced these drivers.

Figure 9 shows how the electricity generation mix has changed in the EU27+UK historically between 1990 and 2019. The share of wind and solar has increased substantially in Europe in the past decade. From a share of 0% in 1990, 1% in 2000 and 5% in 2010, the share of these two sources of energy in the electricity generation mix rose steeply to 17% in 2019, or slightly more than half of all renewables Coal fired power generation fluctuated between 1.050 and 912 TWh between 1990 and 2007, with the share decreasing due to overall increase in electricity generation. It was then followed by two periods of decline – in 2008 and 2009, and after 2014 which continues until now following a significant acceleration in 2018. In 2019, about half of the fall in coal generation was offset by renewables, and the other half by gas. The share of renewable in electricity generation reached 35% in the EU28 in 2019 (Agora Energiewende and Sandbag, 2020a). It would need to increase to 57% in 2030 to be consistent with the current overall renewable energy target, and even further to 64-65% to be in line with the pathway to net zero emissions (European Commission, 2018e).

The short term impact of the COVID-19 pandemic is visible in the changes of the first half of 2020, when the share of renewable energy in the electricity generation increased to 40% in the EU-27, exceeding for the first time the share of all fossil fuels combined (34%). A 7% fall in electricity demand and the continued rise of renewable energy generation led to a dramatic fall of 32% of coal fired power generation, and a fall of 6% for gas generation, leading to a reduction of EU-27 power sector $C0_2$ emissions by about 23% (Ember, 2020).

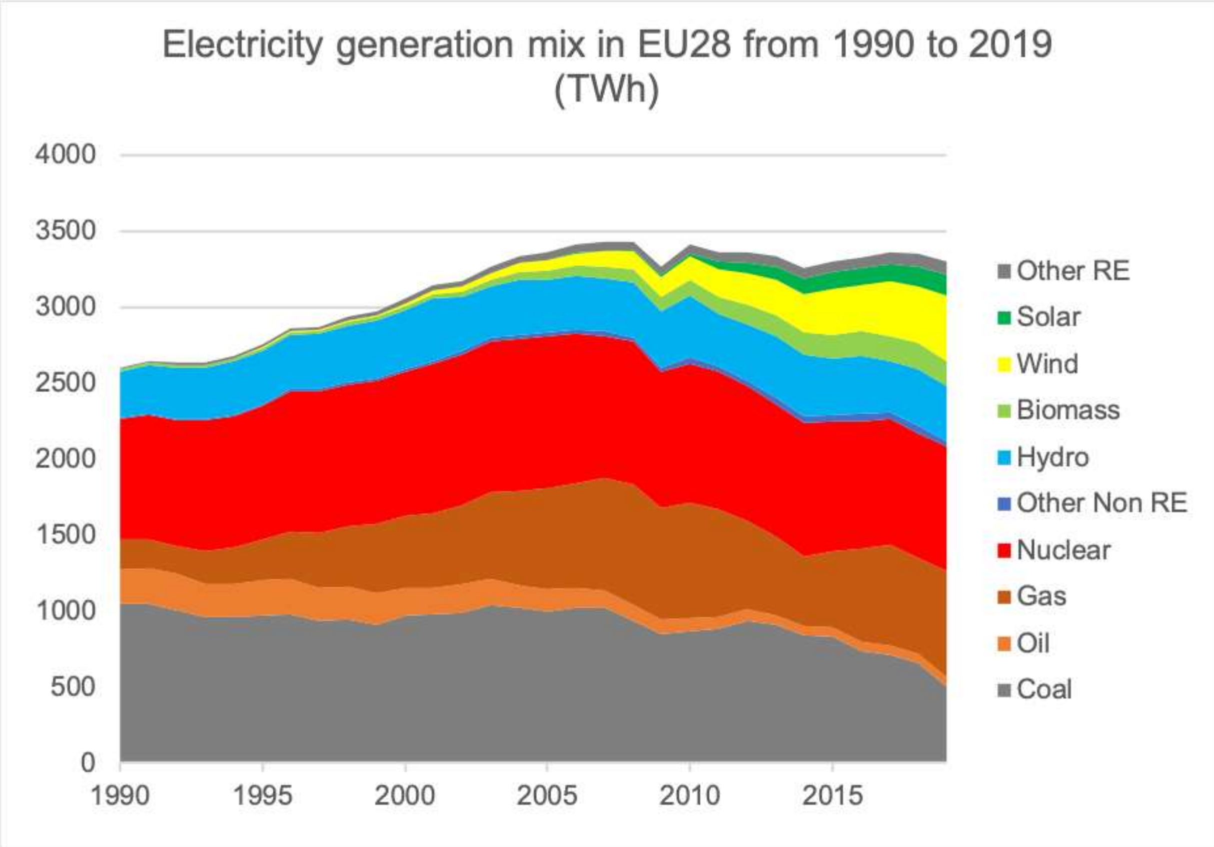

Figure 9: Historical electricty generation mix of EU27+UK. Data for the period 1990-2017 is based on (International Energy Agency, 2020). Data for 2018 and 2019 are based on harmonisation between (Agora Energiewende and Sandbag, 2020a; International Energy Agency, 2020).

3.1 Support for renewable sources of energy

While carbon pricing does increase the competitiveness of renewable sources of power, if not complemented by targeted measures it mostly results in switching to less carbon intensive sources of energy. This could be observed in the UK where the introduction of an additional carbon price floor in 2013 initially resulted in shift from coal mostly to natural gas. However, also in the UK, renewable generation excluding hydro increased by 78 TWh, compared to an increase in gas generation by a 30 TWh (Agora Energiewende and Sandbag, 2020a). Shift towards renewables did require additional measures to allow them to compete with encumbent power generators until they became competitive due to falling costs.

Already in the 1990s some EU member states introduced support measures for renewables energy sources. The most effective in increasing the role of renewables in the power sector were feed in tariffs introduced in Germany and Denmark (Bechberger, Mez and Sohre, 2008a). In 2001 the European Union adopted a directive wih indicative goals for the share of renewable energy in the electricity sector and the obligation to introduce support mechanism to reach those goals (European Parliament and the Council of the European Union, 2001b). As a result, all countries adopted various support mechanisms, which resulted in different dynamics for RES development, especially following their significant decrease in costs in the early 2010s.

The feed-in tariffs and feed-in premiums were the dominant ways to support development of renewables. While their exact design differed from country to country, they had one major thing in common: due to differentiated levels of support for different sources of renewable energy these mechanisms allowed development of sources of energy that would not have chance in competition with ways of generating electricity at a given point in time but offered a significant potential for decarbonisation in the future. One of the examples is solar energy, which in 2001 in Germany was offered six times higher support than wind energy (IWR, 2004). The on average higher levels of support per installed capacity for solar energy in comparison to wind started to decrease significantly after 2013, following a decrease in the costs of this technology (JRC, 2017).

In recent years, with maturing technologies and reducing costs, a clear trends towards auctioning has developed which does reflect European Commission's state aid guidelines adopted in 2014. These guidelines make approval of support mechanisms conditional on the aid being granted on the basis of "competitive bidding process". This condition excludes renewable energy installations smaller than 1 MW. For wind energy bidding is required for installations with installed capacity above 6 MW or 6 units (European Commission, 2014b).

The replacement of feed-in-tariffs by auctions – complemented with a significant decrease in the costs of renewable energy technologies - resulted in a significant decrease in the support granted. In Germany, after a decrease in feed-in-tariffs for large solar PV installations from 25 eurocent/kWh in 2015 to 9 eurocent/kWh, the auctions in February 2020 resulted in the lowest price noted so far of 3,5 eurocent/kWh (Fraunhofer ISI, 2020). The transition to auctions had also negative repercussions: the higher complexity and insecurity of investment despite the costs resulting from project development had a negative impact on smaller investors and local energy initiatives ("energy cooperatives"). This resulted in a decrease in acceptance, which affected especially wind energy in Germany – the biggest market for this source of energy in the EU (WWEA, 2019).

A significant decrease in the feed-in tariffs in many EU member states, abolishment of support mechanisms in some of them and even adoption of additional charges on solar energy in others (e.g. Spain, Germany) resulted in a significant slow down in development of renewables after 2015 (Deloitte, 2015). Despite the expectations, replacement of the feed-in tariffs by auctioning also did not reduce the costs of onshore wind by more than would have been the case with the projected decrease of the feed-in tariffs. Instead, it had a negative impact on acceptance and thus contributing to a significant decrease in installed capacity (Grashof *et al.*, 2020).

The situation started to improve only in 2018 due to decreasing costs of renewables and increasing levels of carbon pricing. After remaining constant at around 30%, the share of renewables in the power sector increased to 33% in 2018 and 35% in 2019 (AgoraEnergiewende & Sandbag, 2020). Most of this increase resulted from increased generation in wind power plants (+1.8 percentage points increase) and solar power plants (+0.3 percentage points) with stable contribution from biomass and decreasing generation from hydro power plants (Agora Energiewende and Sandbag, 2020b). In the first quarter of 2020, partly due to decreasing overall electricity demand, the share of renewables in the power sector increased to 40% (European Commission, 2020p).

With additional 9.5 GW of onshore wind energy in the EU28, the new installed capacity in 2019 was 28.2% higher than in 2018 and reached 192 GW. However, it was heavily centralized: in only four EU countries – Spain (2.3 GW), Sweden (1.6 GW), France (1.3 GW) and Germany (1 GW) was the installed capacity higher than 1 GW. Nine out of 13 countries that joined the EU in or after 2004, didn't add any new capacity in 2019. The new offshore wind capacity amounting to 3.6 GW in 2019 was even more centralized: new offshore wind power plants have only been installed in the UK (1.7 GW), Germany (1.1

GW), Belgium, and Denmark, with both around 370 MW (Wind Europe, 2020b). Solar PV registered a much more spectacular growth, with additional capacity more than doubling in the EU28 and reaching 16.7 GW (Solar Power Europe, 2020b). A significant part of this growth is due to removal of barriers introduced in the early 2010s to slow down the solar boom, decreasing costs, and simplification of the support programms

To ensure that the development of renewables follows the trajectory leading to at least 32% share of renewables – and the corresponding much higher share of renewables in the power sector – Governance Regulation adopted in 2018 creates the basis for the creation in 2021 of Renewable Energy Financing Mechanism. This mechanism will allow for the organization of European renewable energy auctions financed by “voluntary payments” by member states not able to meet their indicative trajectory. These resources may be complemented by European resources, thus allowing the EU to directly invest in development of renewable sources of power (European Parliament and the Council of the European Union, 2018d).

The EU is also taking steps to coordinate development of offshore wind between member states. By the end 2019 there were almost 10GW of offshore wind installed in the EU27, most (over 75%) in Germany. However, some countries are planning to increase their investment in this source of energy. In May 2020 Germany increased its 2030 goal from 15GW to 20GW installed capacity (ZfK, 2020b). Denmark announced its plans to build two “energy islands” consisting of offshore wind turbines with combined capacity of 4GW, with a potential to increase their capacity to 10 GW (REcharge, 2020).

However, this is still far below the 240 to 450 GW installed capacity which are according to the European Commission needed to reach the emissions neutrality goal by 2050 (European Commission, 2020n). Due to numerous exclusion zones, especially in the North Seas, up to 112 GW can be built cost effectively (WindEurope, 2020). To mitigate this issue, in October 2020 the European Communition will publish a Offshore Wind Strategy aiming among others at facilitative cooperation between member states in developing this source of energy (European Commission, 2020n).

3.2 The EU Emissions Trading Scheme

The EU Emissions Trading Scheme (ETS) has been the flagship of the European climate policy since 2005. By *partly* internalising the external costs of fossil fuels, it aims at reducing emissions in energy and industry sectors. While its introduction resulted in higher corporate awareness about emissions reduction possibilities (Anderson, Convery and Di Maria, 2011), the continued low prices of emisisons allowances between €3 and €6 in 2013, driven by their oversupply, resulted in doubts as to whether this instrument can be effective in driving meaningful emissions reduction (Laing *et al.*, 2013).

The reform process that started in 2014 with an agreement to postpone the auctioning of 900 million tCO_2, continued in 2015 with the decision to transfer the “backloaded” allowances to a newly created Market Stability Reserve, that was to start operating in 2019, and finished with the revision of the EU ETS Directive for Phase 4 between 2021 and 2030. This resulted in much higher prices of allowances (European Commission, 2014a; European Parliament and the Council of the European Union, 2015, 2018b). Between January and December 2018 the price of emisson allowances increased from below €8 to above €22, and averaged €25 in 2019. Differently from the trend observed during the economic crisis 2008/2009, the price of emissions allowances turned out to be much more stable and decreased only modestly during the COVID-19-induced recession and returned to the record levels at around €30 in summer 2020 (European Commission, 2020q).

This stability shows how successful the reform was: It is largely the result of moving theoversupply of allowances into the Market Stability Reserve: This is expected to amount to 24% of their oversupply annually in the period between 2019 and 2023. Subsequently, this share will decrease to 12% of the oversupply annually. This transfer of allowances takes place every year in which the number of allowances in circulation exceeds 833 million. So far allowances corresponding to over 995 $MtCO_2$ were taken or announced to be taken off the market between January 2019 and August 2021 (European Commission, 2018c, 2019c, 2020h).

It can be expected that further allowances are removed from the market as the oversupply exceeds the 833 million threshold. One of the major drivers of this continues oversupply is the slow decrease in the emissions cap. Between 2013 and 2020 it was decreasing by 1.74% annually, but just in 2019 emissions covered by the EU ETS fell by 8.7% (European Commission, 2020). This is more than the emissions reductions projected by the member states for the whole 2018-2030 period at 7% (European Environment Agency, 2019). In 2020 emissions from the sector are expected to decrease three times as fast – by over 24% or 388 milion compared to time before the COVID-19 crisis (ICIS, 2020).

With economic recovery in 2021 and 2022 some of this decrease may be mitigated. However, with the continued and even accelerated development of renewables, it can be assumed, that emissions in the EU ETS sector will stay significantly below the cap, despite a slight acceleration of its decrease to 2.2% annually post-2020. In addition, starting in 2024, the transfer of emissions allowances to the MSR is set to return to its "default" level of 12%. This may make it impossible to markedly decrease the oversupply of allowances and thus increase their price to the levels needed to fully internalize the external costs of fossil fuels. The revision of the EU ETS directive planned for June 2021 may mitigate the issue by significantly accelerating the rate at which the emissions cap decreases and increasing the uptake of emissions allowances by the MSR.

3.3 Air quality regulation

Emissions from the power sector have also been influenced by EU's air quality regulation, even if they didn't explicitly refer to GHG emissions. The most important in this regard was the Large Combustion Plants Directive (LCPD) from 2001 which among others applied to thermal power plants with the capacity exceeding 50 MW. Starting in 2008 these power plants had to fullfill requirements concerning emissions of SO_2, NO_x, and dust. Operators of these power plants could either modernise their plants by installing the filters required to meet the maxmimum emissions levels, or could opt-out of this obligations under the conditions of utilising their power plants a maximum of 20 000 hours between 1 January 2008 and 31 December 2015 and switching them off after this period (European Parliament and the Council of the European Union, 2001a). This meant maximum an average utilisation rate below 29%. A number of operators decided to take advantage of the opt-out, resulting in their closure after 2015. The majority of them were in the UK, where combined 8.8 GW of coal and 2.5 GW of natural gas power plants were taken offline (DECC, 2015).

In 2010 the LCPD has been replaced by the Industrial Emissions Directive (IED). The main difference in comparison to the LCPD was an integrated approach: instead of exact limits, the overall environmental performance of the plants was to be taken into consideration allowing some flexibility to national authorities to set less strict limits. Nonetheless, the power plants had to meet emissions limits defined by the Best Available Techniques (European Parliament and the Council of the European Union, 2010). These new standards, issued by the Commission in accordance with the IED have to be met by all coal-fired power plants by 2021, and were exceeded by 82% of the installations. The combined cost of was estimated at between €8-14.5 billion (DNV GL-Energy, 2017). Faced with such costs, and increasing competition from renewables, many operators decided to shut down their plants instead of upgrading them. This has been the case for seven of Spain’s 15 coal power plants which were closed at the end of June 2020 (Pais, 2020).

3.4 Coal phase out and just transition

Due to high emissions intensity and readily available alternatives, coal phase-out is one of the most effective ways of climate change mitigation. At the time of writing coal power plants have already been phased out completely in three Member States: Belgium, Sweden and Austria. Another eleven Member States announced a coal phase out, all but Germany before 2030, and the majority before 2025. In Czechia and Spain coal phase-out is under discussion, with 2025 discussed in the latter. Only five EU member states, all of which Eastern European ones, did not put this topic on their agenda. In all of them except for Poland coal playes a small role, with installed capacity between 125 MW in Croatia and 1.3 GW in Romania. The situation in Poland looks very different: with over 30 GW installed, it is responsible for 22% of total EU27 coal capacity, second only to Germany (Europe Beyond Coal, 2020).

Ongoing and planned coal phase out increases the potential for oversupply of emissions allowances in the ETS with the current cap, thus decreasing their price and risking to undermine decarbonisation in other countries without addressing this so-called “waterbed effect”. It has partly been addressed by the introduction of the MSR (MCC, 2018) as described in Section 3.2. Ahead of further necessary reform steps as outlined Section 3.2 (increasing uptake of emissions alloances in the MSR and accelerating the cap decrease), member states phasing out coal need to cancel an amount of allowances corresponding to the emissions of the installations to be prematurely closed (European Parliament and the Council of the European Union, 2018b).

To mitigate the impact of coal phase-out on affected communities, EU established, in 2017, the “Platform for Coal Regions in Transition” aiming at knowledge sharing and exchanges of experiences between the stakeholders in the regions affected (European Commission, 2020d). In early 2020 the European Commission suggested that this bottom up cooperation should be complemented with a “Just Transition Mechanism” that would mobilise at least €100 billion in the period between 2021 and 2027. The mechanism is to consist of three pillars.

The first of these pillars, the Just Transition Fund, is to be equipped with €7.5 billion. This amount was to be matched with at least the same amount from the other European funds and complemented with additional national resources. (European Commission, 2020l). In July 2020, the European Council (that is the EU heads of state) adopted the framework of the COVID-19 recovery programms and decided to increase the budget of the Just Transition Fund by an additional €10 billion.

The second pillar of the Just Transition Mechanism, InvestEU Just Transition Scheme, should complement the Just Transition Fund by supporting investments by private and public entities in the regions affected by coal phase-out via European Investment Bank Group or national bank or other lending institutions. In thd framework of the COVID-19 recovery programme the InvestEU scheme, is to be strengthened with additional €5.6 billion (European Council, 2020). The third pillar is the EIB public sector loan facility aimed at triggering investment worth between €25 and €30 billion of public investment in energy and transport infrastructure. It will consist of a grant component from the EU budget worth €1.5 billion, and €10 billion from the EIB own resources (European Commission, 2020i)

To benefit from the support granted in the framework of these three pillars, member states will need to develop territorial just transition plans for the regions affected by coal phase out. Access to the Just Transition Fund will be limited to 50% of the respective national allocation for those countries which did not commit to implement the objective of achieving the EU climate neutrality by 2050 goal. At the moment of writing this applies only to Poland.

4 Multiple speed transformation: Case studies

This section looks into three examples of countries with different approaches to the transformation of the power sector. It starts with Spain, which – jointly with Germany – initiated development of renewables already in the late 1970s and the 1980s, but experienced a major slowdown in the 2010s, until it strengthened its mitigation efforts in the late 2010s. This is followed by a short description of the transformation of the electricity sector in Germany, including the impact of the feed-in tariffs on decreasing the costs of solar and wind energy. Finally, we look into Poland, which since the beginning of its membership in the European Union made itself know as the laggard and blocker of the European climate policy, but had actually ambitious renewable energy goal in the 1990s. Poland and Germany have the largest shares of total coal fired power generation in the EU, leading to high emissions intensity of electricity generation. All three countries have regions with traditionally high dependency of employment fro coal fired power generation and mining (Figure 10), Spain is transitioning away from coal fired power generation at high speed, and Germany has adopted legislation for a coal phase out plan by 2038 the latest. With a relatively high share of renewable energy including hydro, Spain has a lower emissions intensity compared to the EU average, and a smaller contribution of electricity generation to overall greenhouse gas emissions.

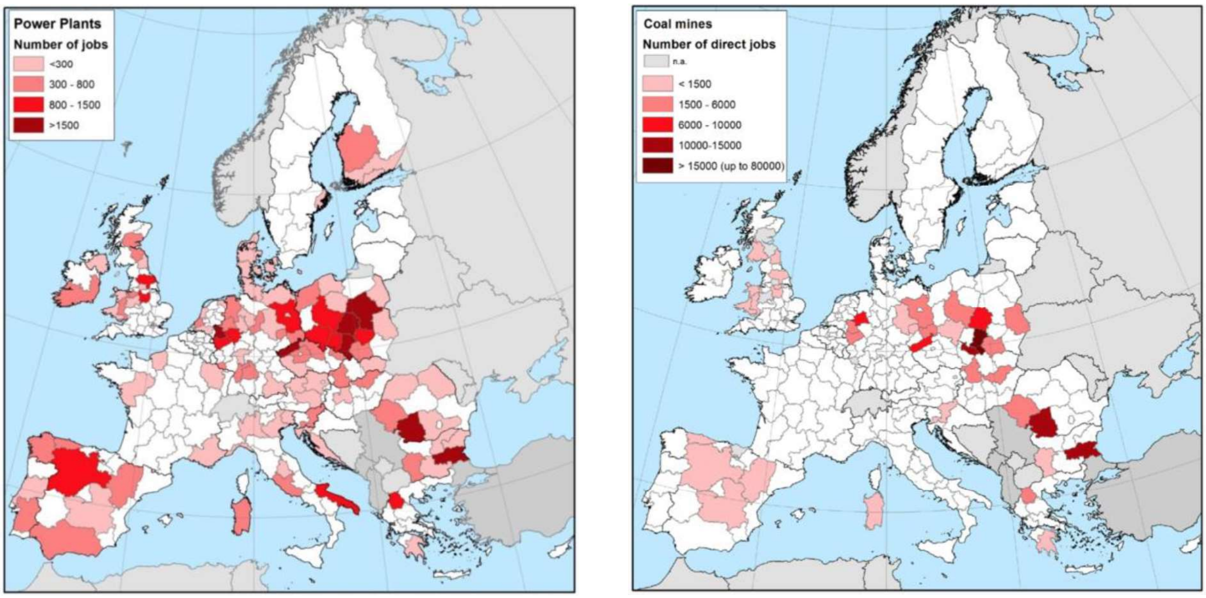

Figure 10 Estimated number of direct jobs in active coal power plants (left) and in coal mining (right). Source: (JRC, 2018).

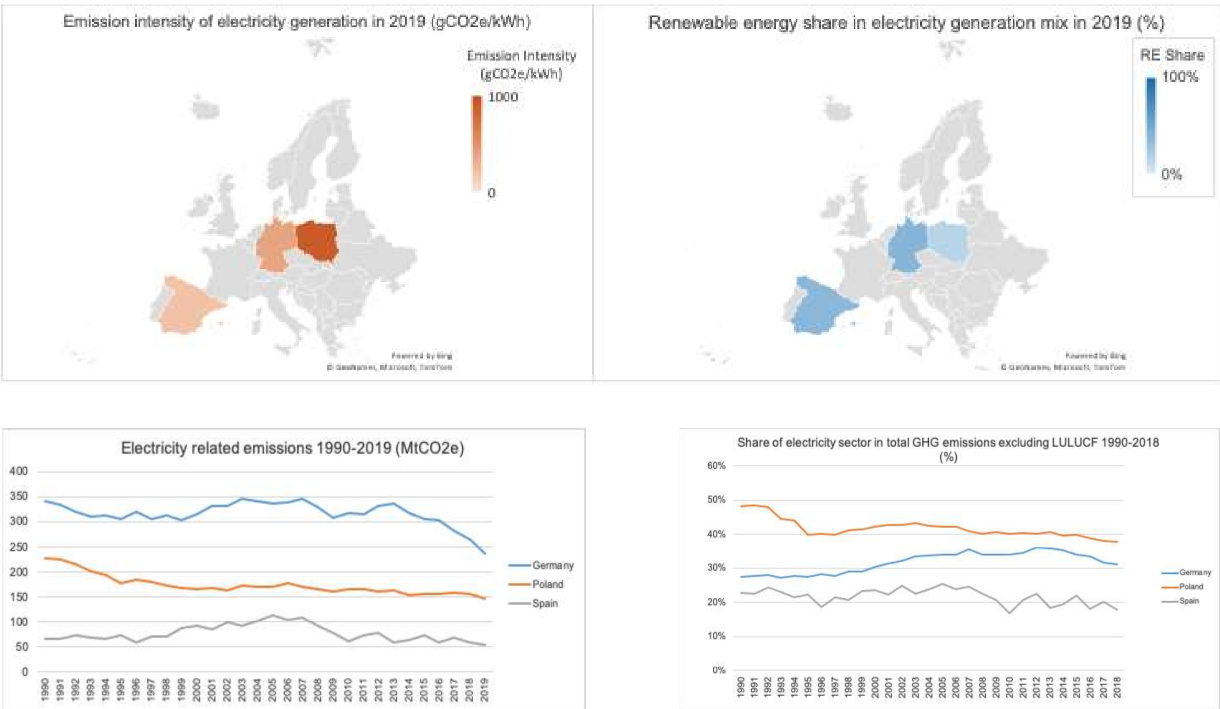

Figure 11 Top: Emissions intensity (left) of electricity generation and share of renewable energy (right) in electricity generation in the three countries selected as case studies: Spain, Germany, Poland. Bottom: electricity related emissions (left) and contribution of the electricity sector to total GHG emissions (right). The electricity generation mix for three countries are based on (BP, 2020). The generation mix for EU27+UK is based on (AgoraEnergiewende & Sandbag, 2020) and the emissions intensity of electricity sector for all countries/regions is based on (AgoraEnergiewende & Sandbag, 2020; European Commission, 2020k; European Environment Agency, 2020a)

Table 1: Main indicators for the electricity sector in the selected countries in 2019. The electricity generation mix for three countries are based on (BP, 2020). The generation mix for EU28 is based on (AgoraEnergiewende & Sandbag, 2020) and the emission intensity of electricity sector for all countries/regions is based on (AgoraEnergiewende & Sandbag, 2020; European Commission, 2020k; European Environment Agency, 2020a).

Indicators	**Spain**	**Germany**	**Poland**	**EU28**
Emission intensity of the electricity sector (gCO_2/kWh)	194	389	898	265
Share of renewables in the power sector	38%	40%	15%	35%
Share of coal in the power sector	5%	28%	74%	15%
Share of natural gas in the power sector	31%	15%	9%	22%
Share of nuclear in the power sector	21%	12%	0%	11%

4.1 Spain

Renewable energy: From boom to collapse and back again

With 300 days of sunshine per year, Spain has one of the largest potential of solar energy in Europe and is also blessed with good wind resources. Similar to some other renewable energy front, such as Germany and Denmark, Spain initiated support for renewables, in that case mostly wind energy, already in the late 1970s. In 1979 the Spanish Industry and Energy Ministry introduced a programme to develop a wind energy power installation with the capacity of around 100 kW as a first step towards MW-class installations. In 1980 the Energy Conservation Law provided renewable energy installations in Spain with guaranteed access to the grid. In addition, an Innovation Grant provided up to 30% of the investment value, and an annually adapted feed-in tariff for the surplus energy from the installations up to 5 MW was introduced. This legal framework, combined with an active participation of commercial actors, including electricity providers, resulted in a continuous development of wind energy, with capacity reaching 7.3 MW in 1991. In the subsequent year a further 38 MW were added (Bechberger, Mez and Sohre, 2008b).

Between the mid 1990s and 2008, Spain's renewable energy policy was characterised by significant policy innovation. In 1994 the country adopted feed-in tariffs (FITs) for different renewable energy technologies, which in 1998 were complemented with a system based on a premium in addition to the wholesale electricity price. As a result, renewable energy producers could choose between fixed tariffs and a system in which they received an additional premium to the proceeds from the sale of electricity at the stock exchange. The goal of these support mechanisms was to increase the share of electricity from renewable sources to 12% in 2010 (The Government of Spain, 1998).

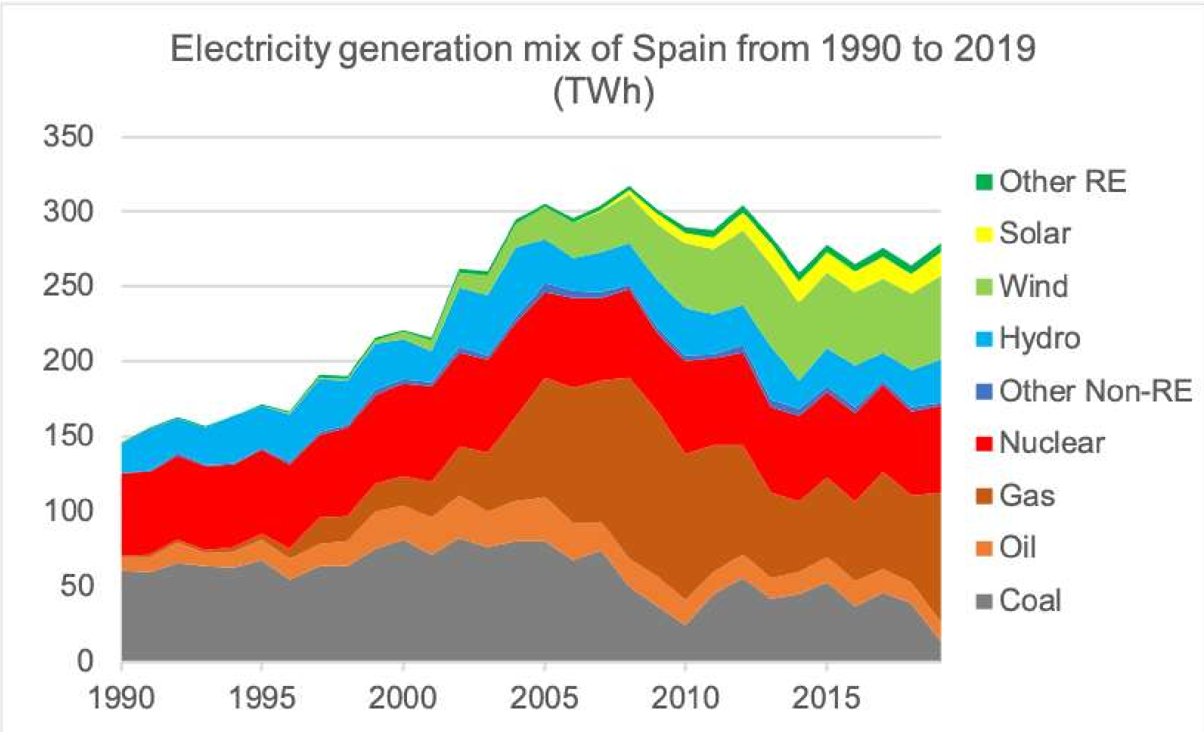

Figure 12: Electricity generation mix in Spain since 1990. Source (BP, 2020).

By 2007, Spain was the second biggest market in the EU for wind and solar behind Germany, with over 15 GW and 733 MW installed, respectively. It was also home to a third of solar thermal electricity generating capacity in the world (EurObserv'ER, 2009). In 2007 Royal Decree 661/2007 increased the feed-in tariffs for solar PV installations between 100 kW and 10 MW from around 23 €c/kWh to around 42 €c/kWh. At the same time, the costs of electricity generation decreased for two reasons. Firstly, increased efficiency of solar panels, combined with deployment of 1- or 2-axis tracking systems resulted in an increase in electricity generation per kW installed by 33%. Secondly, a weakening dollar made imports of solar PV much cheaper than expected. In addition, the first signs of stagnation at the housing market caused a flight of capital to more profitable investments – solar PV being one of the major opportunities. A delay in reporting of the administrative permits by the regional and local governments made it challenging for the government to understand the impacts of its policies (IISD, 2014). All the factors resulted in an explosion of new PV installations. After adding 590 MW in 2007, in 2008 Spain added 2.687 MW, by far the most in the EU (EurObserv'ER, 2010).

The government reacted to this unexpectedly rapid increase in installed capacity with a series of measures that brought this development to a halt and a collapse of renewable energy industry: Contrary to the changes in Germany, which were limited to a (significant) reduction of the feed-in tariffs, the Spanish government introduced a number of additional measures, e.g. a cap on the number of operating hours during which the installations could deliver electricity, imposing a moratorium on new projects, and making it more difficult to repower old projects. Especially disturbingly, most of the new legislation applied retroactively for existing projects, which had very negative impact on the security of investment (IISD, 2014). As a result of these measures, in 2009 the installed solar PV capacity amounted to only 39 MW – a decrease by almost 99% in comparison to the preceding year. The number of jobs in the PV industry fell from 30.000 in 2008 to 14.000 in 2009 (EurObserv'ER, 2010). To make matters even worse, in October 2015 the government introduced a tax on self-consumed electricity from PV installations. While this tax excempted installations smaller than 10kW, this exception was only temporary thus discouraging potential investors from installing smaller installations for self-consumption (El Periodico, 2018).

While the developments in the wind energy industry were less volatile, the recession, combined with administrative procedures, resulted in a significant decrease of new instllations in 2010 and 2011. A new law adopted in February 2013 abolished payment of the premium paid in addition to the wholesale market market price and retroactively forced all wind turbine operators to accept much lower feed-in tariffs (EurObserv'ER, 2011, 2013). As a result, by 2014 also the wind market collapsed with more wind turbines deinstalled than installed in that year (IRENA, 2020b).

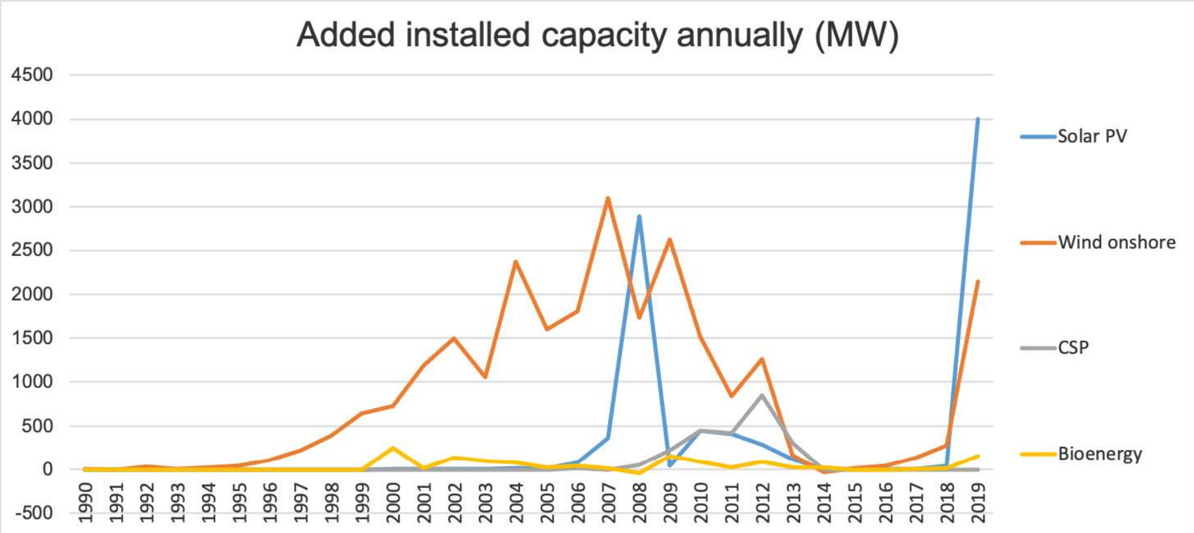

Figure 13: Annually added capacity for renewable energy in Spain. Own compilation based on (Bechberger, Mez and Sohre, 2008a; International Renewable Energy Agency, 2020).

Between 2014 and 2018 only around 564 MW have been installed in wind, solar (incl. solar thermal) and bioenergy, *combined* (see Figure 13). This was less than in any *single* year since 2000. The number of jobs in wind and solar energy industry fell from 67 300 in 2008 to 25 000 in 2015 (EurObserv'ER, 2009, 2017). Despite the collapse of the renewable energy industry, in 2015 a tax was introduced on electricity generated and *self-consumed* by the prosumers (PV-Magazine, 2015).

The new government under Pedro Sánchez, that came into power in June 2018, significantly improved the conditions for development of renewables in Spain. The need to meet EU's 2020 renewable energy goal, combined with the decreasing costs of renewables, were the main drivers motivating a significant improvement in the framework for renewable energy development.

Already in Spain's National Renewable Energy Action Plan submitted to the European Commission in 2010, describing how Spain aimed to reach EU's binding goal of generating 20% of energy from renewable sources, the governments indicated that by 2020 there should be 8.4 GW installed in solar PV, 5.1 GW in concentrated solar, and 35 GW of wind (including 3 GW of offshore wind) (The Government of Spain, 2010). At the end of 2018 these goals were met by 57%, 45%, 62%, respectively (IRENA, 2020a).

In 2017 the government conducted auctions for 5GW of renewables. Over 3.9 GW of the capacity was awarded to PV and the remaining 1.1 GW to wind energy (PV TECH, 2017). In April 2018 the Spanish government published a scenario according to which by 2030 the installed capacity in PV would reach 77 GW, with further 47.5 GW in wind energy (The Government of Spain, 2018a). This would mean a 16-fold increase in the installed capacity for solar PV and 2-fold for wind in comparison to the installed capacity when the report was published.

In October the widely criticised "sun tax" on self-consumed electricity was abolished (The Government of Spain, 2018b). Royal Decree 244/2019 adopted in April 2019 expanded the definition of self-consumption to a group of people, thus allowing neighbors and whole districts (with installed capacity up 100 kW) to share renewable energy while significantly simplying the administrative procedures: Small self-consumers (up to 100 kW without surplus) only have to notify the installation to their regional government (The Government of Spain, 2019b).

These changes – especially the implementation of the projects that won the auctions in 2017 – resulted in a significant increase in installed capacity: in 2019 almost 4 GW of solar PV and 2.1 GW of wind were added to the grid. The total solar PV installation in 2019 alone accounted for more capacity installations in Spain than the previous nine years of the decade combined (International Renewable Energy Agency, 2020). With favourable political support prospects, additional 17 GW of solar PV is projected to to be installed between 2020 and 2024 in Spain resulting in total installed capacity of about 27 GW by 2024 (GET Invest, 2020).

A Ministry for Ecological Transition works on a Strategic Energy and Climate Framework …

The change in government in 2018 led to a fundamental shift in priorities and framing of climate and energy policy, with the ambition of moving Spain from the position of a laggard to a leader in climate mitigation and energy transition," This represented a significant u-turn in priorities of the government.

A Ministry for Ecological Transition is responsible for environment, climate change, and energy, merging porfolios in previously separate departments for environment and for energy. It declared early on the need to phase out coal, combined with a strong focus on just transition, to "not leave anybody behind" (Euractive, 2018).

The government released the Strategic Energy and Climate Framework in February 2019, consisting of three elements (The Government of Spain, 2019a):

- Draft National Integrated Energy and Climate Plan (NECP) (as part of EU governance/obligation as described in Section 3),
- Draft Bill on Climate Change and Energy Transition (LCCTE) with the framework of domestic targets and policies, approved by cabinet in May 2020,
- and the "Just Transition Strategy" for Spain.

In its "Integrated National Energy and Climate Plan (NECP)" Spain set a 2030 target of achieving 42% share of renewables in the final energy consumption – that was a 7 percentage points higher target than the one suggested in the earlier draft of the NECP. The share of renewables in electricity generation was to increase to 74% from by 2030 – almost twice the level in 2019 when the share of renewables in the power sector reached 39%. This share will however be calculated from a higher base – contrary to the overall decrease in energy consumption, electricity consumption will increase due to the electrification of different sectors of the economy. As a result, electricity generation from renewables will need to increase by 113% (REE, 2020a; The Government of Spain, 2020).

These targets where also included in the draft Bill on Climate Change and Energy Transition as aspirational goals or ambitous end of target ranges. Nuclear energy is not specifically mentioned in the draft Bill, while earlier drafts had included the aim to close all seven of Spains nuclear plants between 2025 and 2035. The draft bill includes the aim to achieve 100% renewable energy based electricity generation, implying a phase out of nuclear energy by 2050.

… and puts it into the heart of the COVID-19 recovery strategy

Spain was hit particularly hard by the COVID-19 pandemic, reacting with one of the hardest lockdowns within the EU. This was followed by a deep economic crisis for a country with high dependency oon the tourism sector.

Development of renewables and investment in energy efficiency is perceived in Spain as part of the recovery strategy from the COVID-19 induced economic crisis. In May 2020, the Spanish cabinet approved the draft of Climate Change and Energy Transition Bill. which would, if adopted ban all new coal, oil and gas extraction projects and set the goal of greenhouse gas neutrality of the whole economy, and a 100% renewable electricity system by 2050 (EVWind, 2020). The government aims to make Spanish climate and energy targets and policies consistent with an enhanced EU climate target and the pathway to net zero emissions by 2050 (Farand, 2020).

The use of EU funds for recovery as approved in July by EU heads of state in June 2020 is seen by the government as a central element for implementing these goals and boosting employment through the energy transition. Recently, Spanish authorities announced a 181 million Euro spending on renewable energy projects, to boost a clean economic recovery by creating employment and reducing carbon emission (ENDS Europe, 2020)

Coal phase out and just transition, plus the ETS and air pollution regulation driving coal out of electricity generation

Coal phase out is an important element of decarbonisation of the Spanish economy. The share of coal in electricity generation decreased rapidly in the recent years: from 16.5% in 2017, to 14.3% in 2018 and only 4.2% in 2019 (REE, 2019, 2020b). This decrease was driven mainly by the increasing costs of emissions allowances in the framework of and the EU ETS. The profitability of the remaining coal-fired power plants decreased further due to the fall in the wholesale electricity prices resulting from the COVID-19 induced economic crisis and significantly increasing share of renewables, which in the second quarter of the year reached on average 50% (European Commission, 2020r). As a result, in the first half of 2020 only 2.6% of electrity generated was coming from coal-fired power plants (Global Data, 2020).

The Air Quality Regulations mentioned in Section 3.3 added to the challenges facing the coal sector in Spain. Instead of refurbishing the coal-fired power plants, operators of seven of them with combined capacity at 4.6 GW, decided to switch them off on 30 June 2020. As a result, only five coal units with combined capacity of 3.3 GW remained connected to the grid. Spain is expected to be coal free by 2025 (electrek, 2020; European Commission, 2020r; Global Data, 2020).

To increase social acceptance for the transformation away from fossil fuels, the Spanish government developed a Just Transition framework that aims to ensure that the people and regions affected by the phase out of fossil fuels can also benefit from the opportunities of the transformation. The aforementioned Climate and Energy Transition Bill obliges the government to adopt five-year Just Transition Strategies, which among other elements, should put forward adequate support policies for affected regions. Such policies should ensure that affected regions and rural areas benefit from the most job creation in the areas contributing to climate change mitigation, e.g. building renovation, renewables and storage development, or electric mobility (Ministry for Ecological Transition., 2019).

The Just Transition Strategy also creates the basis for the negotiation and adoption of Just Transition Agreements and provide support for their implementation. The Agreements are much more targeted and detailed tools aimed at countervailing the social and economic impacts of the transformation. They should include and specific, measurable targets, such as the number of jobs and businesses created and maintained. The drafting and implementation of the Just Transition Strategies will be supported by the Just Transition Institute created for this purpose (Ministry for Ecological Transition., 2019).

4.2 Germany

Renewable Energy: An early success story

Germany has a long-established postion as a leader in development of renewable sources of energy. Already in the 1980s German government funded the development of a number of large scale wind-turbines. The most popular of which was GROWIAN which went online in 1983. With the capacity of 3MW was at that time by far the largest operating wind energy turbine in the world. However, due to numerous technical issues, it was taken offline only 4 years later (Hauschildt and Pulczynski, 1995). At the same time amateur engineers and farmers were developing wind turbines for self-consumption relying on already tested solutions in the neighboring Denmark, that were steadily scaled up (Tacke, 2004; Bechberger, Mez and Sohre, 2008b).

Since the end of the 1980s the government supported wind energy development in the framework of a "100 MW Wind" program, later scaled up to 250 MW. The support was granted either in the form of investment grants amounting to 60% of the costs, or fixed premium additional to the income from the sale of electricity (Bechberger, Mez and Sohre, 2008b). This supported led to a boom of new installations: between 1989 and 1992 installed wind energy capacity increased almost 10-fold: from 18 MW to 172 MW (Hoppe-Kilpper, 2004).

The development of wind energy accelerated further with the adoption of the Electricity Feeding Act (*Stromeinspeisungsgesetz*) which obliged operators of the electricity grid to purchase electricity from renewable energy installations at a certain price, which for solar and wind energy amounted to 90% of the electricity price for consumers (Deutscher Bundestag, 1990). This increased the security of investment and drove innovation. Thus, between 1991 and 2000, the number of installed wind turbines in Germany increased 12-fold: from 769 to 9.375 (Byzio, Heine and Mautz, 2002).

Renewable Energy Act – successful export product boosting uptake of renewable energy

The adoption of the Renewable Energy Act (*Erneuerbare Energien Gesetz*) in 2000 and its revision from 2004 were the milestones for the development of renewables in Germany and beyond. It introduced fixed cost-covering tariffs for each kilowatt hour generated from renewables for the period of 20 years. The tariffs differentiated between different sources of energy to reflect their respective costs. To mobilise innovation, for wind and PV installations connected to the grid in subsequent years the tariffs were decreasing by 5% annually. The second pillar of the support mechanism for renewables was the obligation of the network operators to purchase the electricity from renewables at the respective price (Deutscher Bundestag, 2000). The revision of the Law from 2004 differentiated the decrease of the tariffs between wind energy (decrease by 2% annually) and solar energy (decrease by 6.5% annualy, starting in 2006) (Deutscher Bundetsag, 2004) reacting to the fast decrease in costs. Due to its simplicity and impact on the development of renewables, the cornerstones of the law: the feed-in tariffs and the obligation to purchase electricity from renewables, was subsequently adopted by over 100 countries and has been referred to as Germany's most successful export product (Steinbacher, 2016).

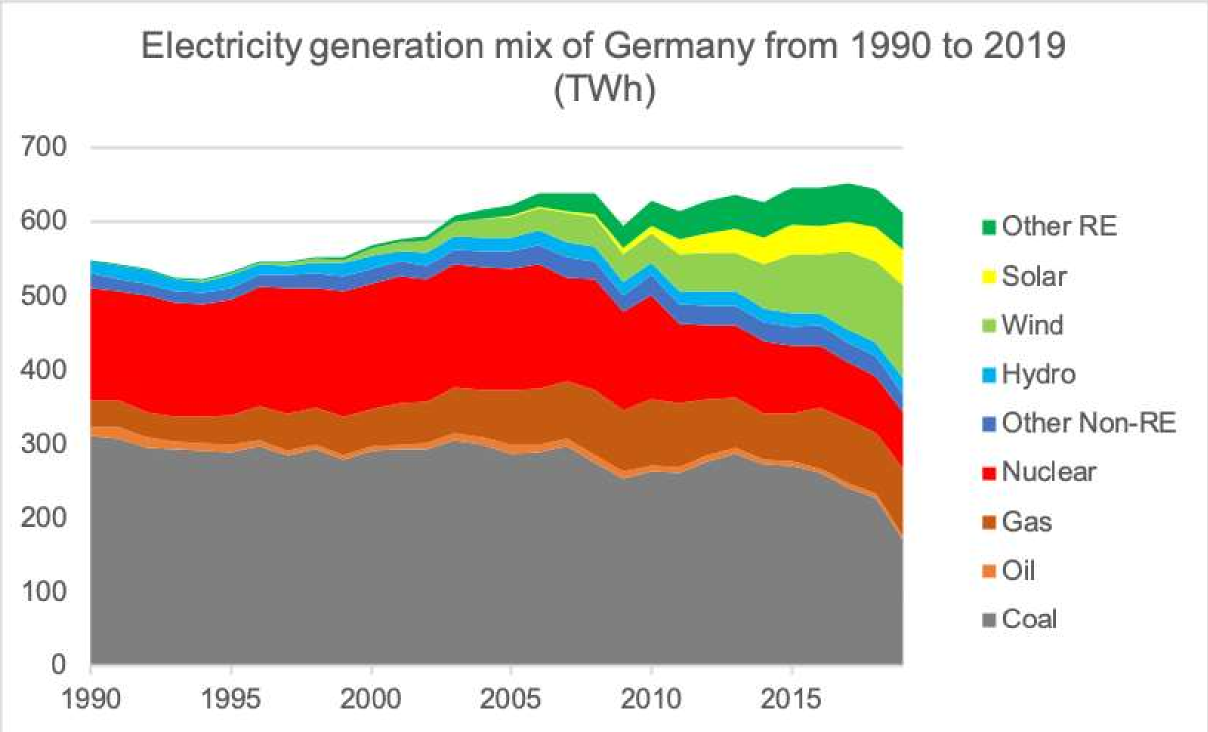

Figure 14: Electricity generation mix in Germany since 1990. Source: (BP, 2020).

During the 2000s the share of electricity from renewables in Germany has almost tripled from 6.3% in 2000 to 17% in 2010 (BMWi, 2020a). This increase was mainly driven by a 4-fold increase in electricity generation from onshore wind during that decade, especially before 2007. In 2010 almost 39 TWh, or 7.2% of all electricity generated in Germany was coming from this source of energy. The increase in electricity generation from solar PV was even more spectacular but from a lower base. In 2010 slightly over 2.2% of electricity generated in Germany was coming from this source of energy (Fraunhofer ISE, 2020a).

The following decade witnessed an acceleration in the development of solar energy. The significant decrease in costs without an accompanied decrease of the rates of the feed-in tariffs increased the profitability of the investment in PV installations. Between 2010 and 2012 the installed capacity exceeded 7 GW annually. With additions from wind and bioenergy, in 2011 and 2012 almost 11 GW of renewables were added, each (see Figure 15).

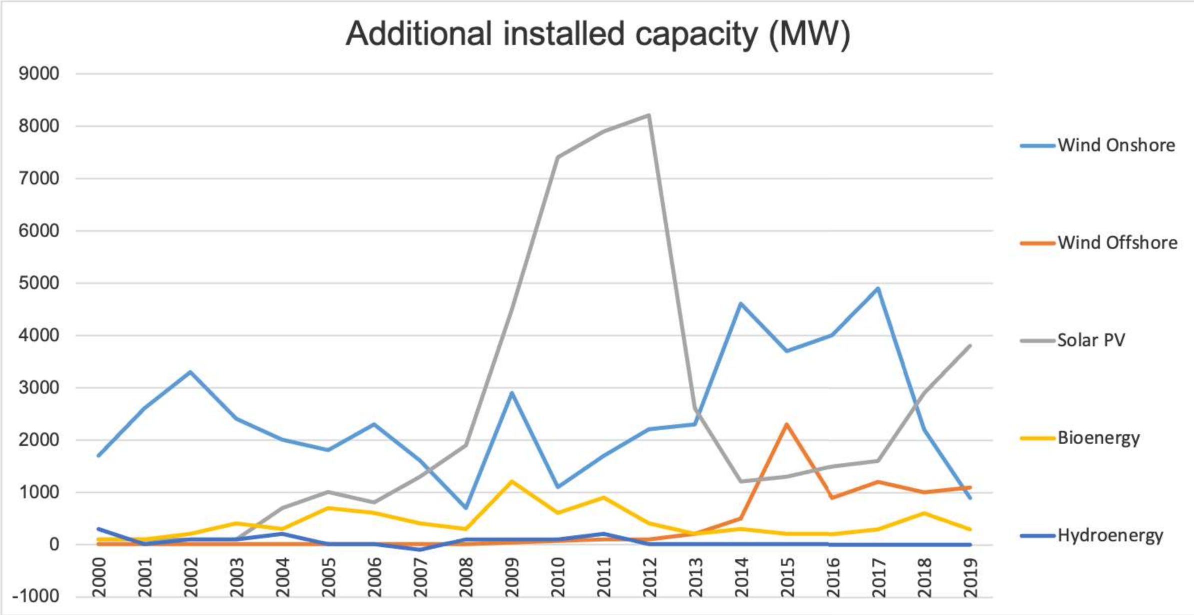

Figure 15: Additional installed capacity in renewables between 2000 and 2019 (BMWi, 2020b; Fraunhofer ISE, 2020b).

In reaction to the accelerated development of solar PV, and the increase in cost covered by electricity consumers through the EEG surcharge, in June 2012, the German Parliament adopted significant changes to the Renewable Energy Law in relation to solar PV. The modification included a significant, one time, decrease in the level of the feed-in tariffs by between 20 and 30% - depending on the size of the installations. The regular decrease of the level of the feed-in tariffs was accelerated and linked with the installed capacity in the preceding quarter. Should the installed capacity remain in the target correidor between 2500-3500 MW annually, the feed-in tariffs would decrease by 11.4% annually. Should annual installations exceed 7.5 GW, they would decrease by 29% in that year. If less than 1000 MW were installed, the feed-in tariffs would actually increase by 6%. The changes to the Renewable Energy Law also added a cap of 52 GW of installed capacity. As soon as the cap is reached, the support for solar PV in “its current form” was to expire (Deutscher Bundestag, 2012).

The changes led to a significant decrease in the installed capacity. The combined installed capacity in the five years following these changes was around the same as installed in 2012 only. In addition to the collape of the domestic market, German PV industry had to face competition from other countries, especially China. These two factors resulted in a wave of bankruptcies in the sector. The number of jobs in the PV industry fell from 110.090 in 2012 to 31.600 in 2015 (Augsburger Allgemeine, 2015).

The boom and bust development repeated itself in the case of wind energy. In 2014 the installation of onshore wind doubled in the comparison to the preceding year and reached 4.6 GW. It remained at between 3.7 and 4.9 GW until around 2017 before it fell to 2.2 GW, complemented with additional 1 GW offshore in 2018. With only 0.9 GW onshore wind installed in 2019, the installed capacity in this source of energy fell to its second lowest level since the introduction of the Renewable Energy Act (Fraunhofer ISE, 2020a).

This significant decrease in the installed capacity was the result of a major overhaul of the Renewable Energy Act in 2016 aiming to curbing costs and controlling the expansion of renewable energy which replaced fixed feed-in tariffs with auctioning and introduced an overall cap on expansion of renewable energy capacity. This change, combined with opposition to wind energy in some regions, and moratorium on wind energy development in some parts of Germany (Süddeutsche Zeitung, 2019; ZfK, 2020a) has led to a decrease in installed wind capacity. In addition, introduction of a minimum distance from the nearest residential buildings of 1000 Meter or even 10-times of the height of the wind turbine as in the federal state of Bavaria, significantly reduces the amount of available space for onshore wind development (Umwelbundesamt, 2019).

The worsening crisis in the wind energy sectory, combined with the pressure to strengthen climate action, resulted in some small improvements in the framework shaping the development of renewable energy sources in Germany. Even before these improvements had an impact and largely due to improved weather conditions, in 2019, the share of renewable energy has reached 46% up from 19% in 2010, with wind energy is the largest source of electricity generation, contributing a quarter of total generation, with offshore wind energy developing into a major cornerstone (Wehrmann, 2019)

Towards emissions neutrality by 2050

In September 2020 a draft of the recast of the Renewable Energy Law was published due to enter into force in early 2021. It is now aiming for an increase in ambition to achieve a goal of reaching 65% share of renewables in the electricity sector by 2030 (up from a previously agreed target of 50%) and emissions neutrality of the electricity sector by 2050. The draft also abolishes the 52 GW limit on the support for solar PV and sets specific goals for each source of energy for 2030 (see Figure 16), including almost doubling solar PV and more then doubling offshore wind (BMWi, 2020c).

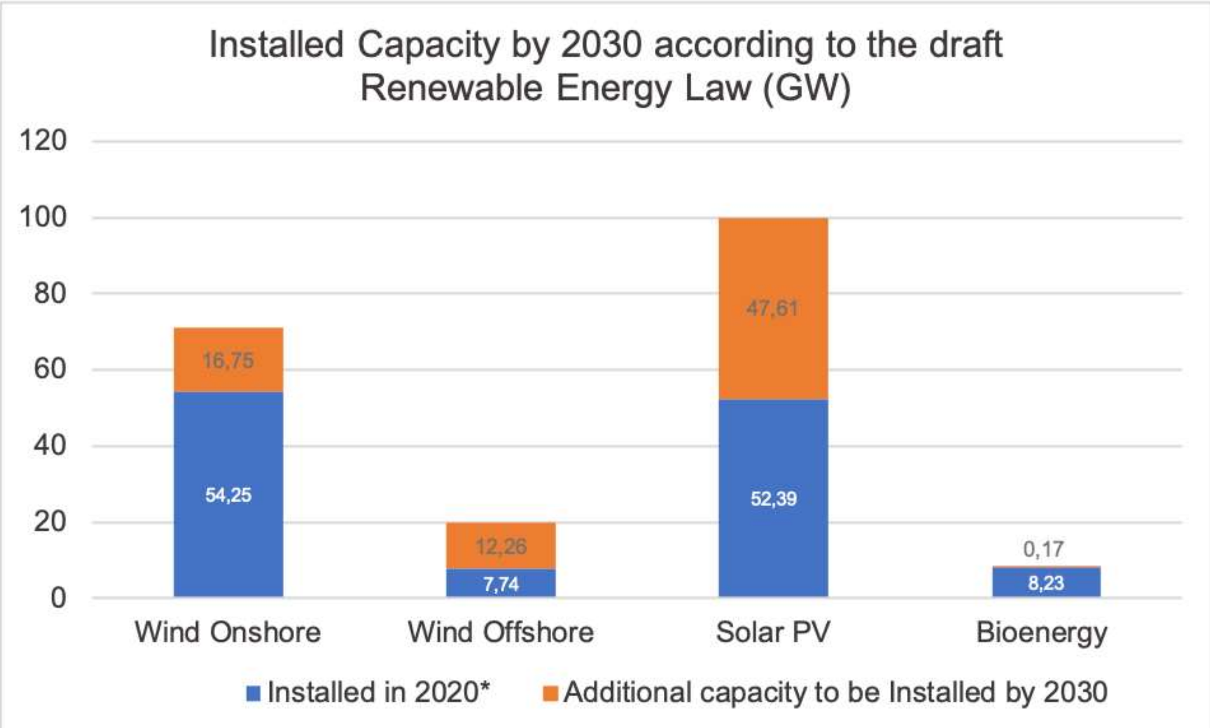

Figure 16: Capacity to be installed according to the draft of the recast of the Renewable Energy Law from September 2020 (BMWi, 2020c; Fraunhofer ISE, 2020b).

The draft includes a regular monitoring and refers to the goal of increasing the share of renewables in the power sector to 65% as a minum target. A review is envisaged in 2023 and includes the need to review tendering volumes in the light of a re-assessed overall electricity demand. The goal of increasing the share of renewables to 65% is only 13% percentage points away from the share of renewables in

2020, which indicates slowing down development of renewables in comparison to the average over the preceding two decades. In addition, the targeted installed capacity results from only modest projected increase in gross electricity demand – from 569 TWh in 2019 to 580 in 2030 (Agora Energiewende, 2020; BMWi, 2020d). While the overall energy demand is indeed projected to decrease, the electrification of different sectors, especially ransport and heating, will result in a much higher electricity demand – thus also much higher generation from renewables to meet the 65%-goal. In addition, the share will need to be adjusted to a ratcheting up of the EU 2030 target, which would impliy the need to ratchet up the domestic reduction targets, and therefore also the sectoral targets.

The Amendment of the Renewable Energy Law is an element of implementation of the sectoral 2030 greenhouse gas reduction target adopted with the Climate Action Plan 2050 in 2016 by cabinet, and since enshrined in the Climate Change Act adopted by parliament and entered into force in 2019 as part of an energy and climate package to reach the 2030 greenhouse gas reduction targets (Appunn and Wettengel, 2020). With the Climate Change Act, a target of greenhouse gas neutrality by 2050 was adopted, and an expert commission on climate issues established. The Climate Change Act enshrines the overall current domestic greenhouse gas reduction target of 55% by 2030 compared to 1990 and the split into sectoral targets, with responsibility for ministries to achieve these targets. The Act also allows for the 2030 target to be ratcheted up (Der Bundestag, 2019). This will be necessary with a ratcheted up EU target.

Coal phase out and support for regions

In July 2020 German parliament adopted the Coal Phase-out Law. The contentious coal phase out decision was preceded by a discussion process involving affected regions and stakeholders. The so called coal commission ("Commission on Growth, Structurcal Change, and Employment") was established in 2018, after the approval of the Climate Action Plan 2050 in 2016. In its final report released in January 2019, it made recommendations for a coal phase out by 2038, including elements of compensation of owners for early shut down, as well as support for regions affected by the coal phase out (Kommission Wachstum Strukturwandel und Beschäftigung., 2019). This led to the Coal phase out legislation passed by the German Parliament in 2020. The basis for the recommendation and in fact the mandate for the commission's work was the adopted 2030 sectoral target for the energy sector. It did not take into account the need to ratchet up the 2030 targets to bring them in line with the Paris Agreement long-term temperature goal.

According to the Coal Phase-out Law, the installed capacity of the coal power plants is to be reduced to 15 GW for hard coal and lignite each by 2022. By the end of the decade the installed capacity is to be reduced to 8 GW of hard coal and 7 GW of lignite, before coal is completely phase-out from the electricity grid in 2038. The Law includes the option of bringing the coal phase-out date to 2035, depending on the review of the situation in 2026, 2029 and 2032. Operators of the coal power plants are to be compensated for switching off their respective coal power plants before 2027, with the compensation amounting to maximum €155.000/MW for closing the coal power plant in 2020 and decreasing steadily to a maximum of €89.000/MW for closures in 2026 and 2027 (Deutscher Bundestag, 2020).

The date of the coal phase-out is significantly after what is considered as compatible with the Paris Agreement. It is also an outlier in comparison to other coal phase out dates agreed in almost all other EU member states. Due to its heavy carbon intensity and availability of low carbon alternatives, moving away from coal is one of the low-hanging-fruits of climate change mitigation. To leave room for more challenging sectors, coal needs to be phased out by 2030 in all OECD countries and EU member states to be in line with the Paris Agreement long-term temperature goal (Climate Analytics, 2018, 2020).

In fact, the coal phase-out may happen earlier driven by market forces. With a competition from renewables and the aforementioned increase of the price of emissions allowances, the competitiveness of the coal fired-power plants has already decreased substantially. This led to a fall in the share of coal in electricity generation from 37.4% in 2018 to 29.3% in 2019. The COVID-19 induced economic crisis and lower electricity prices further dampened electricity consumption from coal-fired power plants, which in the first 10 months of 2020 reached 22.2% (Fraunhofer ISE, 2020a).

While economic recovery may result in higher electricity prices, electricity generation in the coal-fired power plants may decrease even further. Some of them may operate only due to the emissions allowances purchased cheaply before 2018 and have been kept online in expectation of a compensation in the case of a regulatory coal phase-out. With the adoption of the Coal Phase-out Law in, this incentive for operating unprofitable coal ower plants may disappear and lead to shutting down of the last coal fired plant much earlier than the 2038 deadline (Bloomberg, 2020).

With plans for nuclear and coal phase out, Germany is increasing its dependency on natural gas. The share of electricity generated from this sources of energy has more than doubled from 5.5% in 2015 to almost 12% in the first 10 months of 2020 (Fraunhofer ISE, 2020a). The political support for Nordstream II will further increase German dependency on the imports of Russian gas, potentially increasing the stranded assets (Euractiv, 2018).

4.3 Poland

Poland has been considered a laggard in terms of climate action, not only hesitant to reduce its emissions, but also blocking a more ambitous policy at the European level (Skjærseth, 2018). However, it has not always been the case. In the early 1990s, Poland did have ambitious goal for the development of renewable sources of energy. These were driven on the one hand by the need to curb air pollution, an on the other hand, by the prospects to eventually join the European Union. Between 1990 and 1995 emissions from the power sector in Poland decreased by almost 22%. However, this reduction in emissions was driven by transformation from centrally planned economy to a free market one, which led to the closure of the most inefficient coal mines and power plants. As a result, employment in the coal mining sector decreased from 388 thousand in 1990 to 275 thousand in 1995 (Bluszcz, 2014; NETTG, 2020a).

At the same time the government defined the support for local actions aimed at increasing energy efficiency and development of renewable sources of energy as one of the most urgent tasks (Sejm RP, 1990). Between 1993 and 1999 there even were feed-in tariffs for units generating electricity from renewable sources with installed capacity below 5 MW. The main drawback was that the tariffs were only around 30% above the electricity market prices and were announced by the Ministry of Finance only one year in advance, thus making it impossible to plan long-term investments (Ancygier, 2013).

An ambitous early Renewable Energy Strategy and challenges with implementation

Despite the challenges with implementation, the government set renewable energy goals that were ambitious for those times. In July 1999 the Polish parliament almost unanimously obliged the government to introduce legal and financial conditions which would make it possible for companies, individuals, local communities and NGOs to actively participate in the development of the renewable energy sector (Parliamentary Environmental Committee, 1999; Sejm RP, 1999). In reaction to that, in 2000 the Polish government adopted its Renewable Energy Strategy with the goal of increasing the share of renewables in the overall energy consumption to 7.5% in 2010 and 14% in 2020 (EC BREC, 2002).

The situation for renewable sources of energy worsened significantly throughout the 2000s despite the introduction of support mechanism of renewables. The quota support mechanism relying on Green Certificates required energy generators to either generate a certain share of electricity from renewable sources or purchasing Green Certificates to fulfil this obligation. This share was defined regularly by the Ministry of Economy. The Green Certificates were sold by the operators of renewable installations and constituted an additional source of income. However the price of the certificates was very volatile and dependent on political decisions (or lack theoreof). The extremely low price of the certificates resulting from low level of the obligation and the oversupply of "green" energy generated from biomass co-firing led to numerous bankrupcies and insecurity on the market. In addition, the new conservative PiS-led government introduced additional limits on new wind energy installations in 2015 thus halting their development.

Shifting focus to biomass and wind

The focus shifted from solar and wind towards bioenergy cofiring in coal-fired power plants. The latter was perceived as a way to create new jobs especially in the farming sectors (GIPH, 2003). Due to relatively low cost, it was the major beneficiary of the quota support mechanism which did not differentiate between the sources of energy. Between 2005 when the support mechanism was introduced and 2011 when energy from biomass co-firing peaked, the amount of electricity generated in this way increased 7-fold and constituted almost half of the "renewable" energy sources generated in Poland (URE, 2020a). However, the economic and environmental impact of biomass co-firing was very negative: according to the government's own estimates, in 2011 around 1.7 million tonnes of co-fired biomas was imported from over 50 mostly distant countries (Ministry of Economy, 2012).

In the following years the support for biomass co-firing was scaled down and finally abolished. In 2018 only 4% of renewables supported in the framework of the quota mechanism was biomass co-firing. Instead, wind energy started to dominate and in 2016 constituted more than 60% of the renewable energy generated in Poland and the installed capacity reached 5.8 GW. Generation in solar PV constituted less than 0.4% of total renewable energy generation with less than 100 MW installed (URE, 2020b, 2020a).

New focus on nuclear and gas slowing down wind and other renewable energy

In the meantime the government brought two other sources of energy into focus: In his exposé in 2006 Prime Minister Jarosław Kaczyński presented the idea of building a nuclear power plant in Poland (Bankier, 2006). These plans were followed by his successor, Donald Tusk, who added the prospect of repeating the U.S. experiences with shale gas. Its commercial exploitation was to start in 2014 and by 2035 Poland was to become self-dependent in terms of natural gas consumption (Newsweek, 2011).

Not only did the plans to build nuclear power plant and exract any meaningful amounts of shale gas failed to materialize, but after coming in the power of the conservative PiS government in 2015, legislation was introduced that made construction of new onshore wind turbines very difficult. This concerned especially the requirement that new wind turbines should not be built closer that 10-times their hights from even single households or nature protected areas (Sejm RP, 2016). Between 2016 and 2018, only 59 MW of new onshore wind were installed (URE, 2020b).

A breeze of change – incentives for households

As a result of these changes, Poland risked missing its binding renewable energy goal within the EU framework of generating at least 15% of gross final energy from renewables by 2020 (European Parliament and the Council of the European Union, 2009b). In 2018 this share was only 12.7% and in absolute terms energy generation from renewables was lower than in any year since 2015 (GUS, 2019). Already in 2016 the Polish government organised the first auctions for renewable energy, however it was only in 2018 that the volume of the electricity that was to be generated in renewable energy installations became meaningful. As a result, between 2016 and 2019 the construction of renewable energy capacity of 3.4 GW for wind and 1.7 GW for solar PV was auctioned (URE, 2020c). In addition, in 2019 the government introduced the unbureacratic support mechanism for small PV installations “Moj Prad” [My Electricity] that resulted in over 130.000 of new household installations built in only 8 months after the programm was introduced. As a result the share of renewables in electricity generation increased from 12.7% in 2018 to 15.4% in 2019 (Forum Energii, 2019, 2020).

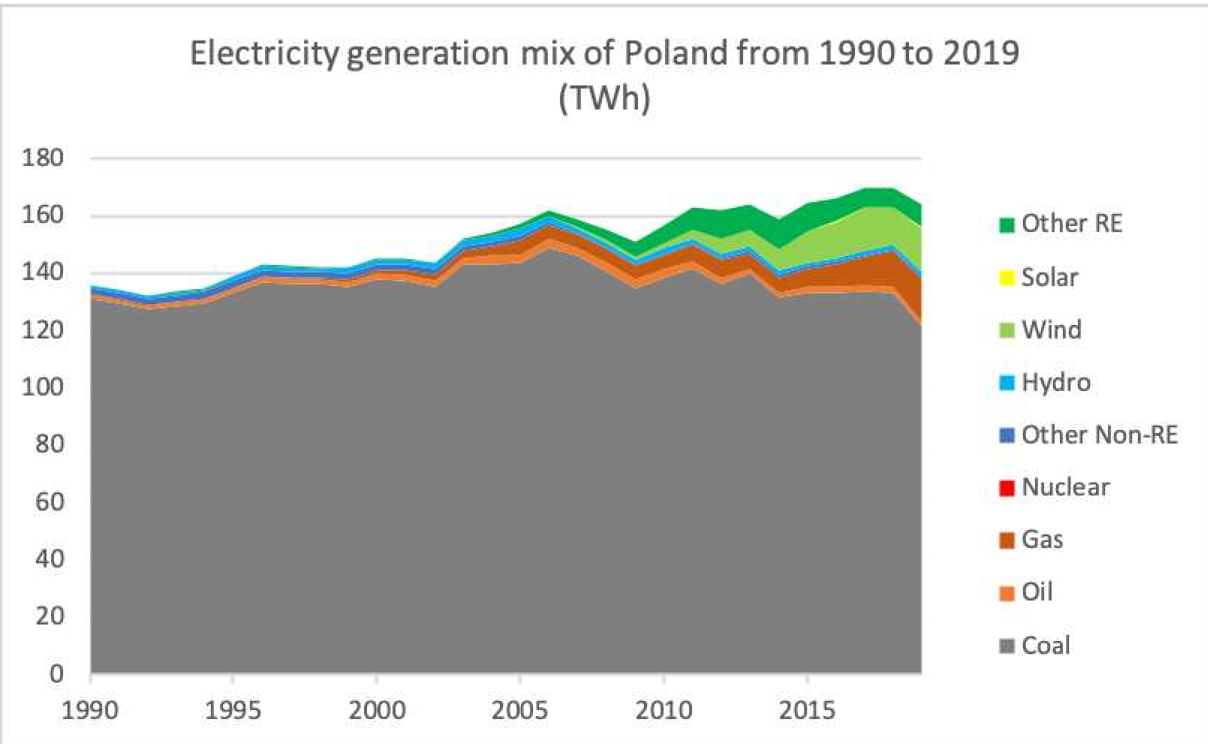

Figure 17: Electricity generation mix in Poland since 1990. Source (BP, 2020).

Diminishing role of coal, but no coal phase out plan

In the meantime, the role of coal in the power sector kept decreasing. Initial estimates for 2019 indicate the share of coal in electricity generation falling to 74% from 91% in 2009. In absolute terms, hard coal power plants generated 5% less electricity than in 2018, whereas generation in lignite-fired power plants fell by 15%. At the same time the share of renewables reached 15.4% (Wysokie Napięcie, 2020a). One of the main reason for this decrease was much higher wholesale electricity price in comparison to neighboring countries. In the last quarter of of 2019 the average wholesale electricity price in Poland was the highest in the EU, and over 20% above the wholesale electricity prices in Germany and Sweden (European Commission, 2020q). This resulted in an increase in electricity imports: in 2019 Poland imported over 17.3 TWh of electricity, or around 10% of its consumption and exported 6.7 TWh. This constituted a major change in comparison to the 2000s, when Poland exported over 11 TWh (Wysokie Napięcie, 2019).

Decrease in coal consumption for electricity generation worsened the situation of the coal *mining* industry, which also had to compete with cheaper coal from imports – especially Russia (Money, 2019). Extraction of domestic hard coal fell from 147 million ton in 1990 and 102 million ton in 2000 to 62 million ton in 2019 (Wysokie Napiecie, 2020). The situation looks significantly worse in 2020, when the mining industry not only had to deal with decrease in electricity consumption and coal prices at the lowest levels in 17 years (NETTG, 2020b), but also the COVID-19 pandemic which affected coal-mining regions in Poland especially badly and resulted in weeks-long closure of the coal mines.

Decreasing coal consumption also resulted in a decrease of employment in the sector – from 275 thousand in 1995 to 160 thousand in 2000 before it fell below 100 thousand at the beginning of the 2010s (Bluszcz, 2014). By the end of 2019 there were 83 thousand people working in the coal mining sector (NETTG, 2020a). To improve the rapidly worsening economic situation in the mining industry, the government was planning to close the most unprofitable coal plants. At the time of writing, this decision was still not implemented due to the opposition from the representatives of the coal mining industry. Instead, the government was aiming for building new storage for coal that could not be burnt. In mid 2020 there were combined 21 million tonnes of coal stored at the coal power plants, sold but due to lacking space not yet picked up next to the coal mines, as well as at the central "emergency" storage (Wysokie Napięcie, 2020b, 2020c).

In September 2020 a representative of Polish Ministry for State Assets signed an agreement with the coal miners workers unions according to which coal *mining* in Poland should be phased-out by 2049. The agreement included a timeline of closure of the coal mines, with only three out of 15 coal mines to be closed in the 2020s. In exchange for agreeing to coal phase-out, Polish government is to subsidize coal mining in Poland, conditional on the agreement by the European Commission (Ministry of State Assets, 2020). Such an agreement by the European Commission would is not only improbable but would in fact be illegal.

The future – coal reduction, increasing renewable enrgy, including offshore wind

In its NECP sent to the European Commission in early 2020, the Polish government projected increasing the share of renewable energy in electricity generation to 32%. Most of this increase is to be driven by increasing the installed solar PV capacity to 7.3 GW and building 3.8 GW of offshore wind. The installed capacity of onshore wind – the cheapest source of energy - is to increase by only 3 GW and reach 9.6 GW. Whereas the installed capacity of solar PV and offshore wind are to increase further by 2040 – by additional 8.7 GW and 4.2 GW, respectively, onshore wind is to remain at the same level as in 2030. This is explained by the "lacking corellation between electricity generation and demand" and "differentiated level of acceptance for [onshore] wind by local communities" (Ministry of Climate, 2020a).

Most of the assumptions and projections mentioned in Poland's NECP were repeated in the draft of the Polish Energy Policy until 2040 presented by the Polish Ministry of Climate in September 2020. The main difference concerned the speed of moving away from coal: According to the NECP, by 2030 the share of coal in the Polish power sector should still be at between 56-60%. The draft of the Polish Energy Policy sets 56% as the top of its range for 2030, which starts at 37%. By 2040 the share of coal should fall to between 11% and 28%. By then a large share of coal power plants should be replaced by nuclear: between 2033 and 2043 six nuclear power plants are planned to start generating electricity in Poland (Ministry of Climate, 2020b). The lack of any meaningful progress concerning the construction of the nuclear power plant 14 years after this source of energy has been presented as one of the options for Poland, combined with a decreasing costs of renewables and their incompatibility with nuclear, makes the realisation of this projections rather unrealistic.

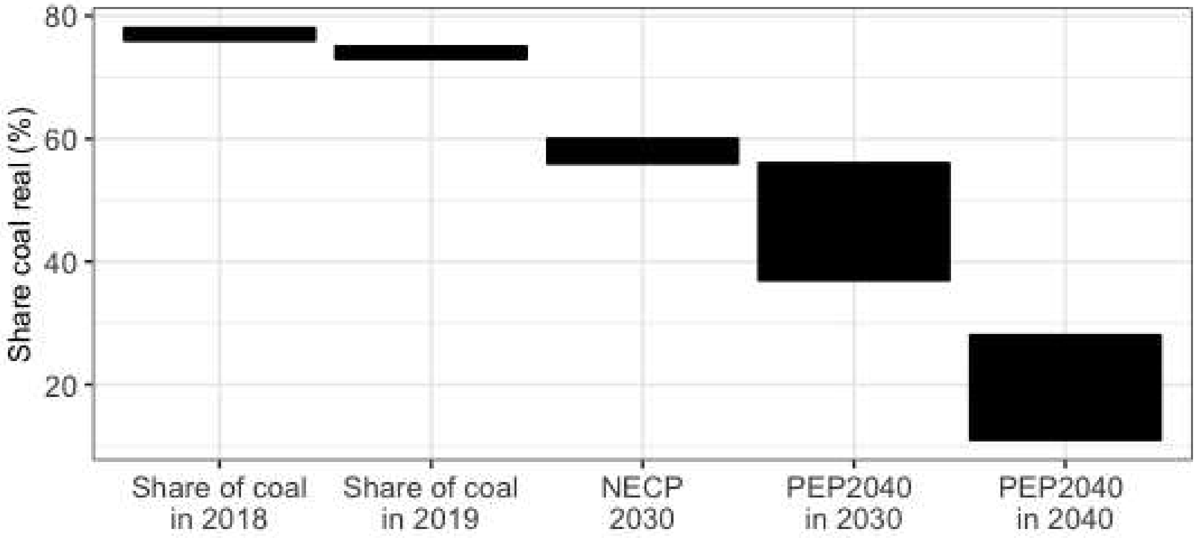

Figure 18: Coal in Poland: historic and projections in the National Energy and Climate Plan (NECP 2030) and draft of the Polish Energy Policy 2040 (PEP2040). Source (Ministry of Climate, 2020c, 2020a).

4.4 Conclusions

Due to the differences in their approach to climate policy, Spain, Germany, and Poland offer important conclusions and lessons learnt for the process of decarbonisation that may also go beyond the power sector. These lessons can be summarized in three groups focusing on the relationship between the policies and the technological development, socioeconomic opportunities and impacts of decarbonization, and the role of external drivers on decarbonisation processes.

Despite significant differences between them, all three countries exemplify the challenge of **adapting the policies to the status of the technological development** in a way that would allow for the development of renewables in an effective and efficient way. The feed-in tariffs introduced in Poland in the 1990s were too low and unpredictable to instigate a growth in renewables. On the other hand, for almost a decade the feed-in tariffs introduced in Germany with the Renewable Energy Act in 2000 allowed for a steady development of different kinds of renewables. However, the decrease in their costs exceeded most of the expectations and resulted in windfall profits for some investors in the early 2010s. Instead of an adequate decrease in the levels of renewables, the German government adopted a a massive reduction in the support which led to a collapse of the solar energy industry in the country. An even more extreme case of the boom and bust approach took place in Spain: The very generous feed-in tariffs were abolished around a year after their introduction. Subsequently, the PV solar market was frozen for almost a decade. It could be asked, whether a more stable and predictable policy-making process could be adopted that on one hand better reflects the costs of renewable energies, while on the other ensure enough predictability for investors.

Another lesson learnt that can be drawn from the experiences of these three countries is the close relationship between the changes in the energy sector and the **socioeconomic repercussions of this change**. In Germany and Spain, wind and solar energy developed as a result of bottom-up initiatives and created new substantial industry sectors[7]. Its successful development in Germany was the result of

[7] The bottom-up development of wind energy is especially clearly seen in the case of Denmark, which however has not been the subject of the assessment.

the active role of energy cooperatives, developed due to the simple and predicatble support mechanism based on fixed feed-in tariffs. The increasing complexity and decreasing predictability of the support mechanism in Germany resulted in decreasing involvement of citzens' energy and also increasing opposition to new projects. In Poland, the unbureaucratic support for micro PV resulted in an explosion of prosumerism and numerous new jobs created within less than a year. In addition, Polish citizens leveraged the resources made available for the transformation in ration 4 to 1, thus increasing also their ownership in the transformation.

At the same time, Poland is also an example of failing management of the transformation away from coal. The structural unemployment in cities and regions affected by the closure of coal mining resulted in a significant opposition to the plans of coal phase-out. In this case, Spain offers an excellent example how the transformation can be conducted in a way which leaves no one behind and prioritizes those affected the most by the transformation in benefiting from the opportunities resulting from the transformation and aligning the transformation planning with the need to enhance ambition in line with the Paris Agreement. For its part, German government has shown the willingness to compensate the communities affected by the coal phase-out generously, however the date of the coal phase-out is far behind what is required by science and made possible by the rapid decline in the costs of renewables. Lack of alignment early on leads to the need for more adjustments later on thus decreasing the benefit of long-term planning security. This shows, that the transformation away from fossil fuels towards renewables needs to take into consideration the impact on and the opportunities for different groups of actors. Getting them involved in the discussion and offering them a stake in the transformation significantly influenced the chances of its success.

The **final lesson concerns the importance of external factors**: be it the rapidly decreasing costs of renewables or the external commitments – in this case the EU renewable energy and greenhouse gas reduction goal. The same government that in 2015 defended coal as the backbone of the Polish economy is currently suggesting limiting its share to as low as 11% by 2040 and introduced measures which resulted in a Poland becoming one of the biggest markets for PV solar. In Spain, the conservative government that brought solar PV development to a halt in the early 2010s, in 2017 presented a scenario resulting in the capacity of solar PV increasing 16-fold. While in both cases a much more rapid change was needed – and is indeed occurring in Spain after the change of the government – these developments show that countries can hardly oppose megatrends, such as decreasing costs of renewables, or international commitments, especially if this would have high economic costs.

5 Scenario analysis

In this section, we review recently published long-term scenarios with a focus on the European power sector and assess them in particular regarding their compatibility with benchmarks consistent with the Paris Agreement long-term temperature goal.

This selection has been conducted in two steps. In the first step, we selected scenarios that aimed at zero or near zero GHG emissions from the power sector. We identified 22 scenarios from 18 literature sources published since 2016. The overview of the scenarios identified and assessed is shown in Annex 1. In the second step, we assessed the scenarios against Paris Agreement-compatibility benchmarks in terms of emissions intensity of electricity, coal phase out, and share of renewable based generation (Climate Action Tracker, 2020). The majority of the scenarios analyzed in this study have EU27+ the UK in their geographical coverage. The remaining scenarios also cover additional neighbouring countries in their modelling.

5.1 Characteristics of low carbon scenarios for power sector

The scenarios reviewed in this study show the following general characteristics:

- Most scenarios show an increase in electricity demand, driven by a trend towards electrification of end use sectors such as transport and industry;
- All scenarios show an increase in generation from renewable energy, in particular wind and solar, and hence an increase in installation of these renewable energy sources;
- Many scenarios analyse the increasing role of storage as well as transmission grids and flexibility options to enhance integration of variable renewable energy.
- Scenarios diverge in terms of the future role of nuclear energy.

Electrification of end use sectors increases electricity demand and supports flexibility

In 2017, the share of electricity amounted to approximately 21% in overall final energy consumption in the EU27+UK. Over a third of final energy in industry sector was consumed as electricity. The share in residential and commercial sector was at approximately 33%. In transport sector, less than 2% of the final energy was consumed as electricity. This share has increased only slightly over the past three decades (International Energy Agency, 2020). According to the scenarios reviewed as part of this study, the electricity share in final energy consumption increases from 21% today to between 24% and 56% in 2030 and between 34% and 63% in 2050, with a median of 27% in 2030, 39% by 2040 and 45% by 2050.

For a majority of the scenarios, gross electricity generation increases from current levels, with most scenarios showing an increase between 23% and 112% compared to 2019 levels. An exception from this rule apply to scenarios that focus on demand side management, efficiency improvements, circular economy and behavioural change. This group of scenarios leads to decrease in the overall energy demand, including electricity consumption (European Climate Foundation, 2018). The opposite trend in terms of electricity demand could be observed in the scenarios prepared by (Energy Watch Group and Lappeenranta University of Technology, 2019; Gerbaulet *et al.*, 2019) which show an increase in electricity demand by more than 200%.

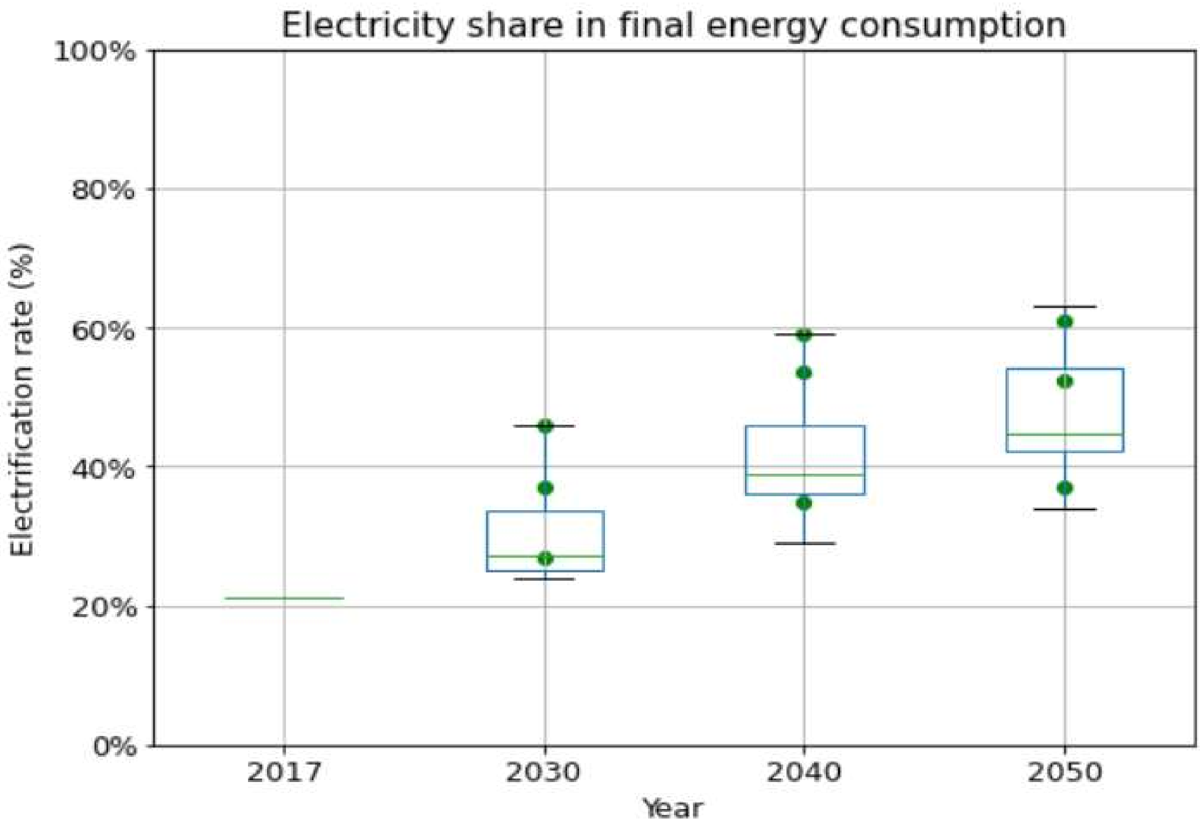

Figure 19: Electrification rate in EU27+UK current (2017) and projected under the scenarios assessed in this study. The central line of the box plot (green color) represents the median (50^{th} percentile), the other two lines below and above the median represent the first and third quartile, respectively, and the whiskers cover the minimum and maximum values. The green dots in the box plot represent the values for the scenarios which meet the benchmarks for Paris Agreement compatibility as assessed in section 5.2. Data for 2017 based on (International Energy Agency, 2020), projections based on assessment of selected scenarios.

Direct electrification of end-use sectors such as industry, buildings and transport, is an essential element of the decarbonisation strategy. It also contributes to energy efficiency improvement and reduction of final energy demand. Indirect electrification via green hydrogen or synthetic hydrocarbons, including e-fuels derived from green hydrogen, help decarbonise hard-to-abate sectors such as iron and steel, ammonia, freight transport (e.g. fuel cell electric vehicles), shipping and aviation as well as industry processes that cannot readily be electrified, such as high temperature industry processes.

The role of the novel fuels, including hydrogen and synthetic hydrocarbons based on renewable electricity, becomes more prominent from 2030 onward and plays a more important role in recently published scenarios. Earlier modelling in particular for scenarios that underpin most of current EU and member states targets do not yet include this option in a significant way. This reflects the very dynamic recent technology development and increasing policy interest in green hydrogen and zero carbon fuels derived from hydrogen (Bloomberg New Energy Finance, 2020). The demand for these novel fuels is another driver of higher electricity generation projections towards the mid-century in recent scenarios.

Wind and solar become dominant sources, coal and gas phased out

On average, the scenarios reviewed project an increase in the share of variable renewable energy **(VRE) to about 75% in the electricity generation mix by 2050** from approximately **18%** today. In most of the scenarios, **onshore wind would be the dominant source of electricity generation in Europe by 2050** due to its high potential and declining costs. The share of wind in electricity generation mix is highest in two scenarios[8], wherein the share reaches 62% in 2050. Offshore wind plays an important role in countries surrounding the North Sea and Baltic Sea. In other two scenarios[9] solar PV becomes the dominant form of generation technology by 2050 owing to the lower cost assumptions.

All scenarios project a rapid decline in coal-based generation and its complete phase out by 2050 at the latest, in some cases between 2030 and 2040. While all the scenarios project an eventual decline in the gas share in the European power sector, they show much higher variation compared to the share of coal. The scenarios reviewed also have divergent assumptions with regard to the application of Carbon Capture and Technology (CCS) in power sector. Eight of the scenarios assessed assume the application of this technology, particularly in natural gas power plants. This explains why the median share of gas in electricity generation mix doesn't reach zero but is marginal in 2050. Further description of the assumptions on the role of CCS technologies in the power sector is given towards the end of this section. The median share of natural gas-based generation in the electricity generation mix is projected to decline to 12%, 4% and 1% by 2030, 2040 and 2050 respectively.

The share of bioenergy is projected to be in the range of **200 and 450 TWh per year over the entire projection period** in the scenarios assessed. This is close to the current biomass-based generation level of 200 TWh**.**Massive instalations of wind and solar needed

All the scenarios reviewed project the installed capacity of wind and solar to continue rising from 191 GW in wind and 132 GW in Solar PV installed in 2019 in the EU27+ UK (International Renewable Energy Agency, 2020). Onshore wind have higher installed capacity projections than offshore wind in all scenarios. This is in line with the potential of onshore wind and offshore wind for the region identified in various studies. The study by (Dalla-Longa *et al.*, 2017) quantifies the potential for onshore and offshore wind power installation capacities at 4750 GW and 3800 GW, respectively in the most unrestrictive case in the region. Either of these capacities are sufficient to fulfil the entire current electricity demand in the region. The projection for onshore wind installed capacity for 2050 ranges between 404 GW[10] and 760 GW[11] in scenarios analysed in this study. Offshore wind installed capacity projection for 2050 ranges between 71 GW[12] and 451 GW[13] in 2050. The projections of **total** wind power installation capacities range from **467 GW** to **over 1200 GW (**Figure 21**)**.

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[8] Oeko 2017: Vision scenario (Oeko-Institut, 2017) and Gerbaulet 2019: Default scenario (Gerbaulet *et al.*, 2019).

[9] Scenarios EWG & LUT 2019: 100% renewable energy scenario and Child 2019: Area and Region scenarios, both of which are modelled using the LUT energy system transition model (Child *et al.*, 2019; Energy Watch Group and Lappeenranta University of Technology, 2019).

[10] IEA ETP 2017: B2DS (International Energy Agency, 2017)

[11] Gaffney 2020: High VRE scenario (Gaffney *et al.*, 2020) and EC 2018: 1.5 Tech scenario in 2050 (European Commission, 2018a)

[12] in IEA ETP 2017: B2DS (International Energy Agency, 2017)

[13] in EC 2018: 1.5TECH scenario (European Commission, 2018a)

In the global context, offshore wind technology is almost an exclusive European development. The UK boasts of the world's largest offshore wind market and installed capacities followed by Germany, China, Denmark, Netherlands, Belgium and Sweden (Global Wind Energy Council, 2017). The Internationa Energy Agency projects offshore wind technologies to be cost-competitive with fossil fuels as well as other renewables including solar PV within the next decade (International Energy Agency, 2019). An important characteristic of offshore wind is higher utilisation rate (with recent projects showing capacity factors as high as 40-50%) as compared to onshore wind and solar PV technologies. This means that offshore wind technologies can provide system flexibility by acting as "variable baseload" technology. Areas with abundant offshore wind resources (e.g. in the North Sea) and with proximity to grid close to industrial buyers are also suitable for production of hydrogen/synthetic fuels (European Commission, 2018a).

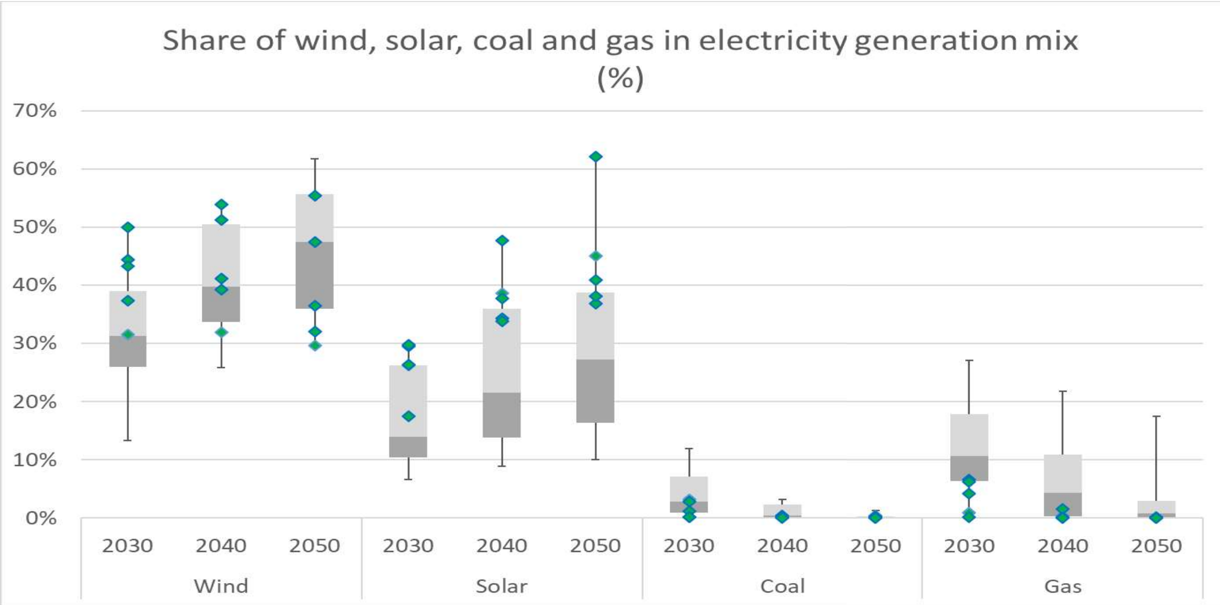
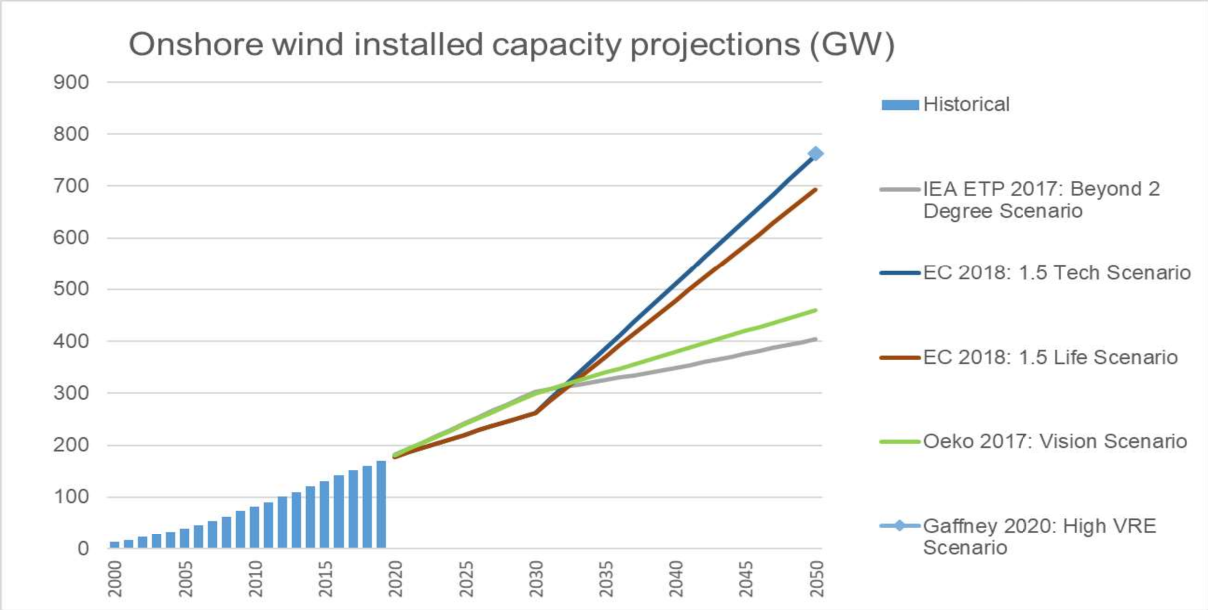
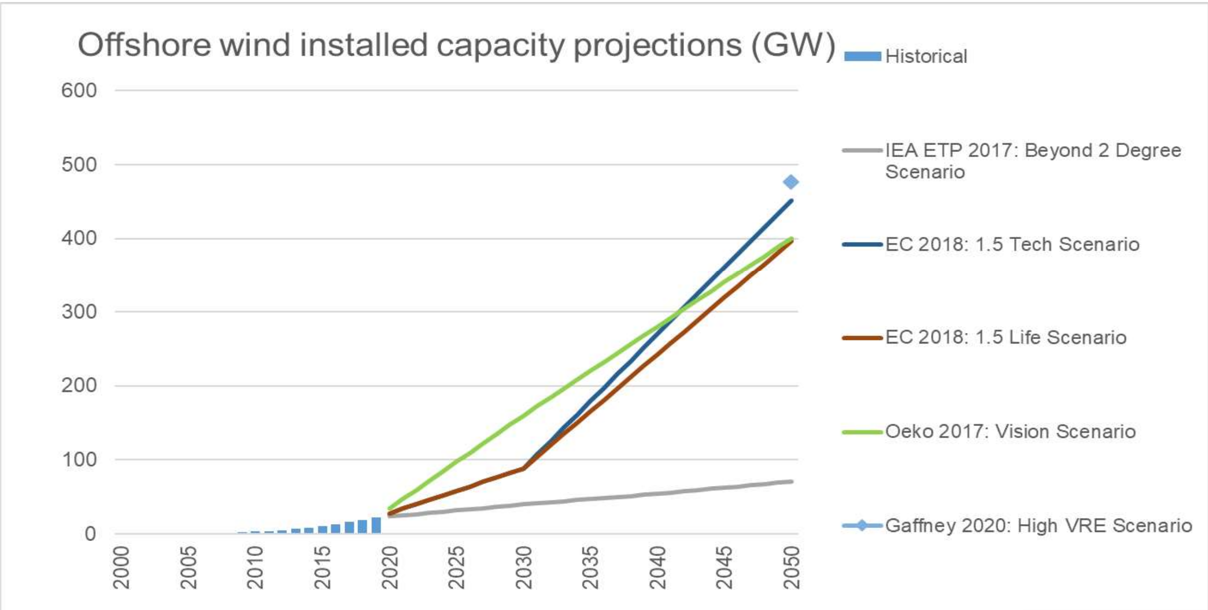


Figure 20: Share of wind, solar, coal and gas in electricity generation mix under different scenarios assessed in this study. The central line of the box plot represents the median (50th percentile), the other two lines below and above the median represent the first and third quartile, respectively, and the whiskers cover the minimum and maximum values. The green markers in the box plot represent the values for the scenarios which meet the Paris Agreement compatibility benchmarks for the electricity generation mix. Own assessment of selected scenarios.


Onshore wind installed capacity projections (GW)
900
800
700
600
500
400
300
200
100
0
2000
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
Historical
IEA ETP 2017: Beyond 2 Degree Scenario
EC 2018: 1.5 Tech Scenario
EC 2018: 1.5 Life Scenario
Oeko 2017: Vision Scenario
Gaffney 2020: High VRE Scenario


Offshore wind installed capacity projections (GW)
600
500
400
300
200
100
0
2000
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
Historical
IEA ETP 2017: Beyond 2 Degree Scenario
EC 2018: 1.5 Tech Scenario
EC 2018: 1.5 Life Scenario
Oeko 2017: Vision Scenario
Gaffney 2020: High VRE Scenario

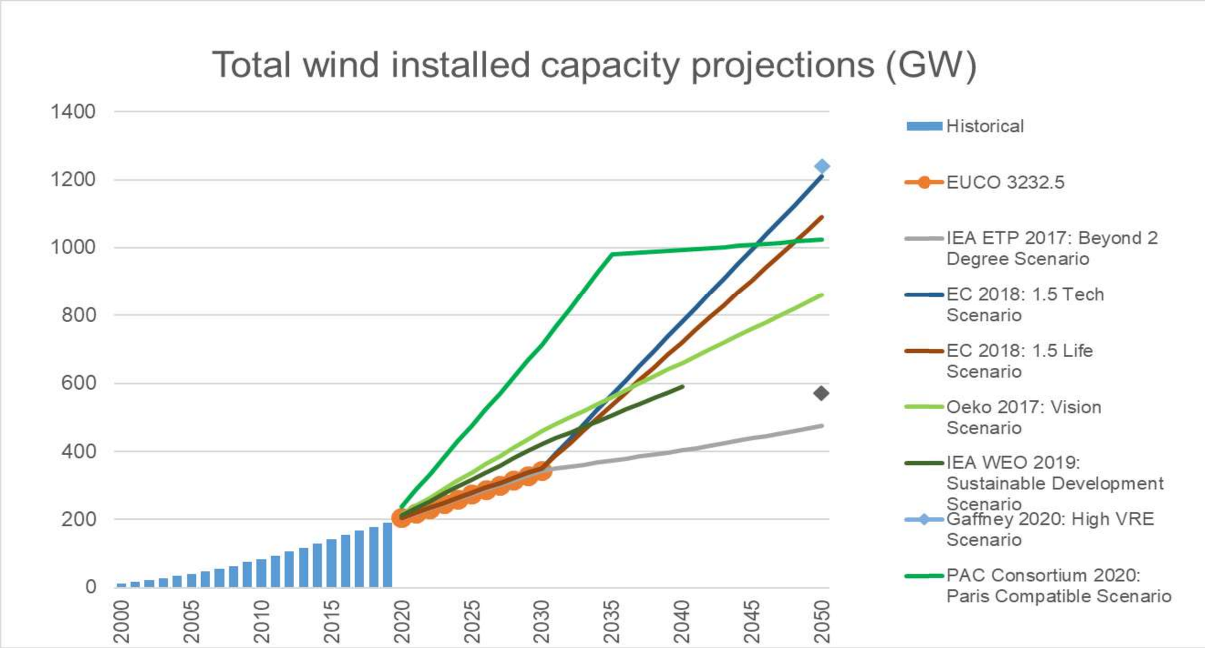


Figure 21 Installed capacity projections for Onshore (top), offshore (middle) and total (bottom) wind capacity in scenarios analysed in this study, where data are available. The green lines represent the values for the scenarios which meet the Paris Agreement compatibility benchmarks for the share of renewables in electricity generation mix. Historical capacities are based on (International Renewable Energy Agency, 2020)

Solar PV is in many cases the cheapest renewable technology and easiest to scale up. Due to the declining trend of its installation costs, it forms one of the largest share in total capacity installations in EU27+UK in 2050 among the scenarios reviewed. Acoording to the scenario by (Energy Watch Group and Lappeenranta University of Technology, 2019) solar PV will play a significant role in 2050 in the 100% renewable energy scenario, with utility scale PV becoming dominant form of electricity generation. The study by (Child *et al.*, 2019) shows that the development of rooftop solar PV compared to utility solar PV depends on the level of interconnection, with higher shares of rooftop solar for lower levels of interconnection. Utility scale PV forms the largest share in the total installed capacities of all the 100% renewable energy scenarios in the study by (Zappa, Junginger and van den Broek, 2019), with rooftop solar PV only installed in appreciable amounts once the best PV utility sites are exploited due to higher cost assumptions. The capacity of solar PV is projected to reach between 214 GW (237 GW including CSP)[14] and 1906 GW[15]. In 2019, the total installed capacity of Concentrated Solar Power (CSP) technologies in EU27+ UK region was 2.34 GW, most of which (over 98%) was installed in Spain, with small scale installations in Italy, France, and Portugal (International Renewable Energy Agency, 2020).

[14] in IEA 2017: B2DS (International Energy Agency, 2017)

[15] in PAC Consortium 2020: Paris Compatible Scenario (Climate Action Network Europe and European Environmental Bureau, 2020)

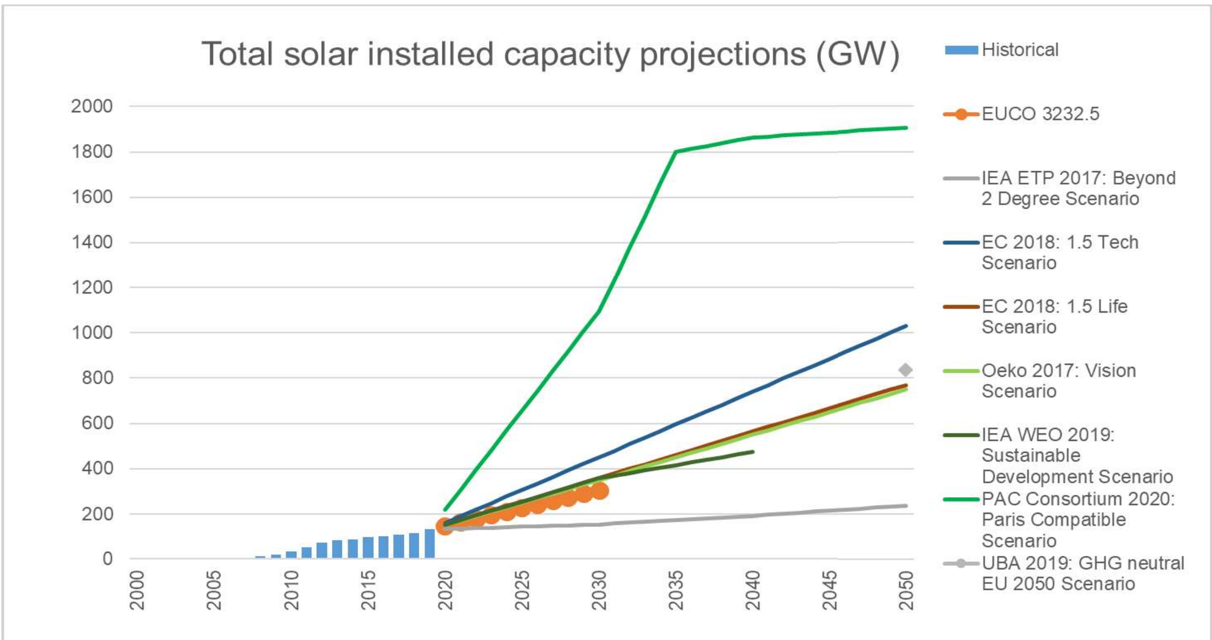


Figure 22: Total installed capacity historical and projected in scenarios analysed in this study. The green lines represent the values for the scenarios which meet the Paris Agreement compatibility benchmarks for the share of renewables in electricity generation mix. Historical capacity is based on (International Renewable Energy Agency, 2020)

Scenarios project the installed capacity of hydropower to remain relatively consistent with the current levels (**131 GW in 2019**). Scenarios project only limited but not drastic addition of new hydropower capacities in the years to come.

Nuclear energy does not show any significant increase in capacity in any of the studies analysed. it stays either at the same level or increase only slightly compared to current capacity in scenarios attributing a larger role to nuclear energy for decarbonisation such as the IEA and EC scenarios. Other scenarios[16] assume no new installations of nuclear energy in Europe due to their high investment costs, as well as risks and uncertainities involved. These scenarios assume a stepwise decommissioning of existing capacity.

[16] the UBA 2019: GHG neutral EU2050 Scenario, DIW Berlin 2020: Paris Scenario, PAC Consortium 2020: Paris Compatible Scenario and Gaffney 2020: High VRE scenario (Umweltbundesamt, 2019; Climate Action Network Europe and European Environmental Bureau, 2020; Deutsches Institut für Wirtschaftsforschung, 2020; Gaffney *et al.*, 2020).

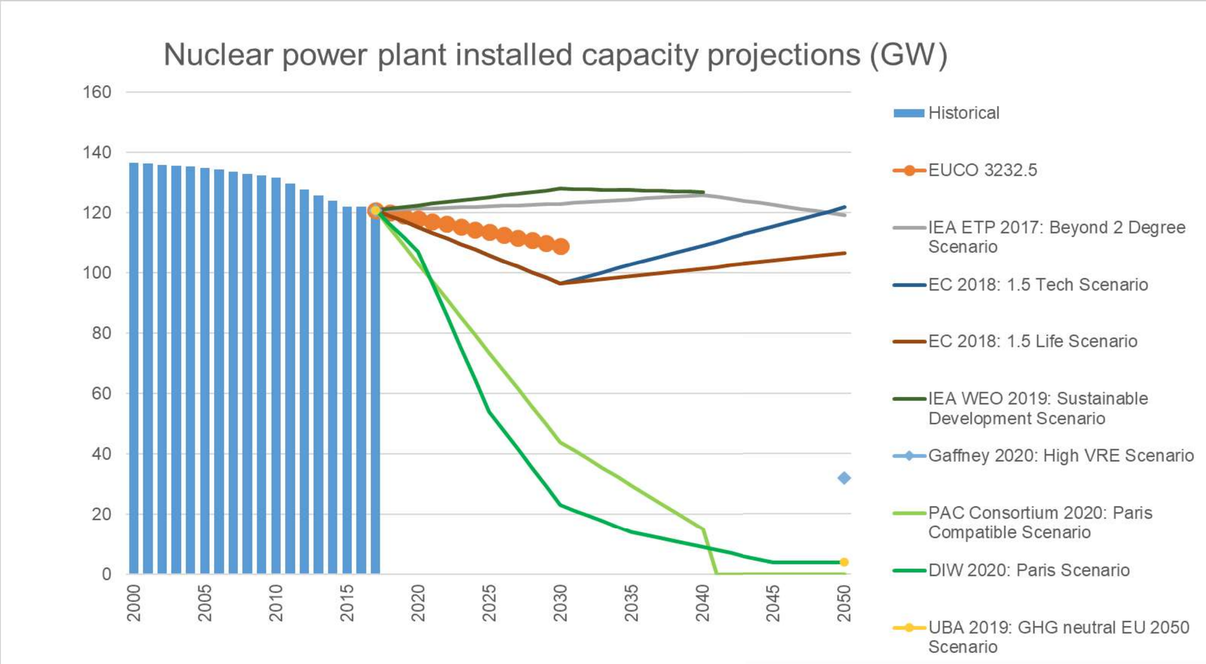


Figure 23: Installed capacity for nuclear power – historical and projected in scenatrios analysed in this study. The green lines represent the values for the scenarios which meet the Paris Agreement compatibility benchmarks for the share of renewables in electricity generation mix. Historical capacity is based on (European Commission, 2020k).

A power system which is dominated by renewables, particularly variable renewables, requires high degree of flexibility in order to integrate them by maintaining a balance between supply and demand at different time scales. The flexibility options, which help to prevent shortages or curtailment, can be provided by several measures such as expansion of transmission grid and interconnection capacity, smart electrification, sector coupling, power-to-X technologies or demand response management. There is also a **trade-off between these flexibility options**, for example between more decentralized storage capacity and an increased EU-wide integration and exchange of electricity.

Transmission …

All scenarios analysed here show that the expansion of transmission and interconnector capacities is one of the key enablers to integrate higher shares of variable renewable energy in the power sector. The level of cross-border transmission capacity expansion varies in the scenarios as there is trade-off with generation and other flexibility options. In reality, this also depends on technology reliability and regulations.

In the Eurelectric scenario, the transmission capacity in Europe needs to be expanded by **63% between 2015 and 2045 (57 GW to 93 GW)** in order to satisfy the regional supply peaks (Eurelectric, 2018). An even higher increase – to as much as 200 GW – is considered necessary in the study by (Zappa, Junginger and van den Broek, 2019) to accommodate electricity sector relying exclusively on renewables. The study also stresses the importance of reliability of the transmission line in order to maintain security of supply.

The majority of this interconnections are established in areas rich in wind resources (e.g. the UK, Ireland, Norway and Denmark), rich in solar resources (e.g. Italy) or with extensive hydropower resources (e.g.

Norway and Sweden). In addition the interconnections are important in densely populated or industries areas (e.g. Germany, France). The interconnection capacity across the region is projected **to rise to 20% of the regional peak load** in (Teske, 2019).

According to a recent system needs study by ENTSO-E, the cross-border transmission capacity needs to reach **188 GW by 2040 in a cost-optimal pathway** to meet the EU Green Deal goal of climate neutrality by 2050 (European Network of Transmission System Operators for Electricity, 2020).This is also in line with the projections in the Child 2019: Area Scenario (Child *et al.*, 2019).

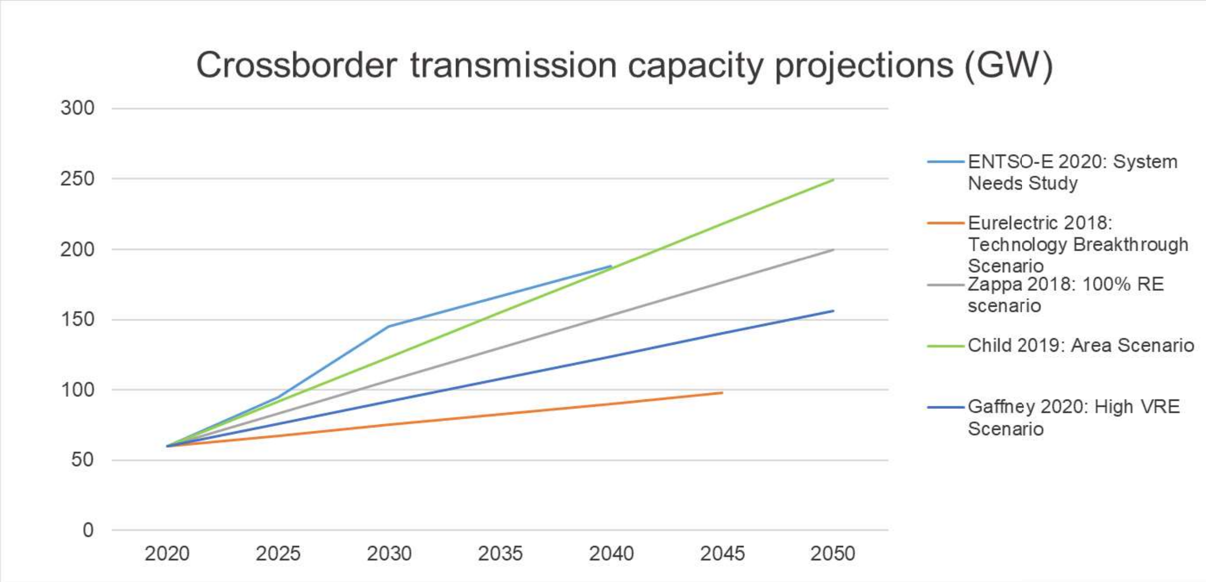


Figure 24: Crossborder transmission capacity projected in range of scenarios analysed in this study. The green line represents one of the scenarios, which meet the benchmarks for Paris Agreement compatibility in our scenarios assessment. Baseline value is based on (Eurelectric, 2018).

… and storage play an increasing role

Storage technologies store electricy during times of high energy availability and low demand, and release it when electricity demand exceeds electricity generation. This need to balance the supply and demand will increase substantially as the share of VRE increases. Storage can be provided in many forms and scales. Pumped hydropower storage, batteries and Demand Side Management (DSM) measures are the key providers of storage analysed in the context of the European power system. Many studies demonstrate that electricity storage needs remains relatively low until the renewable energy penetration in the generation crosses the 80% mark, when the need of storage for balancing rises substantially (Schill, 2020). This has been presented in the case of Germany in (Schill and Zerrahn, 2018), the USA in (Ziegler *et al.*, 2019) and overall Europe in (Child *et al.*, 2019). According to (Energy Watch Group and Lappeenranta University of Technology, 2019), the share of electricity demand covered by storage in Europe increases over time reaching 17% by 2050.

The studies by (Child *et al.*, 2019; Gerbaulet *et al.*, 2019; Climate Action Network Europe and European Environmental Bureau, 2020) suggest that the storage capacity of pumped hydro would stay relatively consistent over the transition period. According to (Gerbaulet *et al.*, 2019), the potential of new pumped hydro storage is negligible in Europe. Pumped hydro storage could provide balancing needs spanning days and even weeks, but is not deemed economically feasible to be utilised for seasonal storage from the viewpoint of grid operator or utility (Gaffney *et al.*, 2020). According to (European Commission, 2018a; Climate Action Network Europe and European Environmental Bureau, 2020; Deutsches Institut für Wirtschaftsforschung, 2020), the total installed capacity of pumped hydropower storage grows very slowly and remains at about 52 GW, contributing to the storage of about 54 TWh of electricity in 2050.

Batteries are effective in providing active power in shorter timescales (Gaffney *et al.*, 2020). Although the total installed capacity of batteries remain negligible currently, studies by (International Energy Agency, 2019; Deutsches Institut für Wirtschaftsforschung, 2020) state that **batteries are the fastest growing source of flexibility** today worldwide **and would remain so in the next two decades driven by their falling costs**. According to the above-mentioned studies, batteries (mainly lithium-ion) would obtain majority of the new investments to offer short-term storage (from hours to days). According to (Child *et al.*, 2019), the use of batteries particularly by solar PV prosumers is projected to rise quite strongly in the coming years, especially after 2025. Batteries provide 70% of the storage need in the all the scenarios of (European Commission, 2018a) and 83% of the total electricity storage output by 2050 in (Teske, 2019). Acording to the scenario by (Deutsches Institut für Wirtschaftsforschung, 2020) there is a strong correlation between the growth of solar PV and battery capacities. The solar PV battery capacity reaches up to 343 GW by 2050 in the PAC Scenario which stores 76 TWh of electricity (Climate Action Network Europe and European Environmental Bureau, 2020).

Demand response also plays an important role in meeting the rising flexibility needs by shaving the peak demand and redistributing electricity to times of smaller load and cheaper prices. Demand side flexibility (demand side management, DSM) schemes incentivise consumers to shift their demand to times of oversupply. However, the role of DSM in providing system flexibility is in general considered to be limited in comparision to stoarge. According to (Gerbaulet *et al.*, 2019), DSM measures would play only a marginal role for storage, offering 3% of system flexibility.

Green hydrogen – decarbonising some enduse and providing additional flexibility

There is a general consensus among recent scenarios that green hydrogen produced via electrolysers and synthetic fuels derived from green hydrogen would play a pivotal role in decarbonisation of the processes that cannot normally be decarbonised by means of direct electrification. Hydrogen could mainly be employed in steel and ammonia industries, as well as fuel cell electric vehicles. Synthetic fuels could be utilised in aviation and navigation. According to the scenarios reviewed, the demand for these fuels would become more prominent from 2030 onward. As energy carriers, green hydrogen and novel fuels have large load shifting potential and could offer seasonal storage as well as offer flexibility and reliability to the power system.

Not all the scenarios consider the added electricity demand with relation to production of hydrogen or novel fuels. The amount of additional electricity required for production of novel fuels depends not only on quantity, but also on the composition of fuel itself (e.g. hydrogen, liquid or gaseous hydrocarbons).

The additional electricity demand for the production of hydrogen/novel fuels in 2050 in scenarios that do include this range between **830 TWh**[17] **to 2000 TWh** [18]**.**

The Power-to-Gas technologies offer the option of seasonal storage by converting curtailable electricity into storable gas or liquid form. Hydrogen has the potential of substituting natural gas for power generation in combined-cycle or open-cycle gas turbines, providing renewable yet dispatchable generation (Gaffney *et al.*, 2020). Some scenarios assume the usage of hydrogen in electricity generation. The share of hydrogen in electricity generation in 2050 ranges from less than **1%**[19] **to 10%**[20].

Sector coupling provides additional flexibility and decarbonisation of end-use sectors

In the Connolly 2016: 100% renewable energy scenario, the cross-sectoral integration of electricity sector with heating/cooling and transport sectors provides additional flexibility in the power system. This enables penetration of over 80% variable renewables in the power system (Connolly, Lund and Mathiesen, 2016). Accoridng to a scenario by DNV GL and WIndEurope the major source of flexibility in the future European power system would come from sources such as heat pumps and smart charging infrastructure both of which have load shifting potential (DNV GL and WindEurope, 2018).

Based on the modelling work done, (Deutsches Institut für Wirtschaftsforschung, 2020) suggests that sector coupling is imperative in an ambitious scenario in order to achieve climate neutrality. This in turn also increases the overall electricity demand. The use of electric vehicles in a smart manner could help shift demand and reduce the investment in battery technologies for short-term storage. However, it would require incentives that would influence the behaviour of the vehicle owners.

Dispatchable power plants

Dispatchable power plants can provide flexibility by ramping up and ramping down output, shutting down and starting up near-instantaneously. Further, they can adjust their output levels depending on the load as well as periods with high wind/high solar. In a 100% renewable energy scenario, the residual demand which is not met by variable renewable energy supply must be met either by dispatchable renewable generators or storage. Among these technologies, hydropower is the most flexible one. Other dispatchable renewable generators to balance variable renewables analysed in scenarios (Zappa, Junginger and van den Broek, 2019) and (Child *et al.*, 2019) include biomass, concentrated solar power, and geothermal energy.

Role for Fossil fuels and CCS in the power sector?

Integrated Assessment Model (IAM) scenarios evaluated in the IPCC as well as energy system scenarios such as those published by the IEA typically underestimate the political, economic, social and technical feasibility of solar energy, wind energy, and electricity storage technologies. These renewable and storage technologies have improved dramatically over the past few years, with costs dropping rapidly and corresponding growth trajectories much faster than expected over the last years. These trends are expected to continue. The IPCC SR1.5 has shown that CCS in the electricity sector have not

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[17] Oeko 2018: Vision scenario (Oeko-Institut, 2017).

[18] UBA 2019: GHG neutral EU 2050 scenario (Umweltbundesamt, 2019). 1150 TWh in PAC Consortium 2020: Paris compatible scenario (Climate Action Network Europe and European Environmental Bureau, 2020).

[19] in both DIW Berlin 2020: Paris scenario (Deutsches Institut für Wirtschaftsforschung, 2020) and PAC Consortium 2020: Paris compatible scenario (Climate Action Network Europe and European Environmental Bureau, 2020).

[20] in both JRC LCEO 2018: Zero carbon scenario (Nijs *et al.*, 2018) and Teske 2019: 1.5 C compatible scenario (Teske, 2019), 5% in ECF 2018: Technology scenario (European Climate Foundation, 2018).

shown similar improvements. The costs of CCS have not come down over the last decade despite large funding efforts from some governments.

CCS is typically deployed in IAM pathways beyond 2030, reflecting that it is currently not a commercially viable option. Despite strong support for CCS by some governments, there are currently only twenty-one large-scale CCS facilities in operation, around the world, and only three in construction (Global CCS Institute, 2020). Only two of the currently operating facilities are linked to power stations, and one of these has recently been mothballed (Institute for Energy Economics and Financial Analysis, 2020). There is only one CCS facility in construction linked to power generation, which is the ZEROS project in the USA (Global CCS Institute, 2020). However, fossil fuel fired power plants with CCS have been so far been used for Enhanced Oil Recovery and therefore not stored carbon dioxide in a secure geological reservoir.

The adverse economics of CCS power plants require them to operate at a capacity factor close to 90% which is increasingly unlikely, under pressure from cost effective renewable energy options. Together with the large co-benefits of renewable energy, this adverse cost trend makes CCS technologies increasingly unlikely to be able to compete with renewable energy and storage, a fundamental economic dynamic which is not reflected in many energy-economy models (Schaeffer *et al.*, 2019).

The majority of scenarios (total of 11 studies) assessed here do not see any role for fossil fuels with CCS to decarbonise the power sector. According to (Connolly, Lund and Mathiesen, 2016) the role of CCS is not suitable in a 100% renewable energy system dominated by variable renewables. This is because the thermal power plants, which act as base load generation, consume additional fuels in combination with CCS making the overall system more expensive. The same view is also reiterated by (Child *et al.*, 2019) and (Climate Action Network Europe and European Environmental Bureau, 2020). (Oeko-Institut, 2017) states that the role of CCS is important in medium term, but only in so called hard to abate sectors with less mitigation alternatives, for example cement and steel industry, but not in the power sector that we focus on here. According to the assessment by (Deutsches Institut für Wirtschaftsforschung, 2020) CCS is not a technically and economically viable option for decarbonisation and it therefore does not assume CCS technologies in their scenarios, referring to the example of several unsuccessful CCS projects worldwide and specifically in Europe, concluding that so far the step from small-scale pilot projects to large-scale demonstration plants has not succeeded.

The Zero Carbon scenario in (Nijs *et al.*, 2018) assumes no underground storage but rather reuse of 50% of captured CO_2, based on the assessment that the European Directive on the geological storage of CO_2 makes large scale deployment of CCS rather unlikely in Europe. Some EU member states, such as Austria, Croatia, Estonia, Finland, Ireland, Latvia, Luxembourg and Slovenia or regions such as the Brussels capital region of Belgium restrict the geological storage of CO_2 (Nijs *et al.*, 2018). The Netherlands, the UK and Sweden restrict the geological storage only to offshore areas. In other member states there are restrictions in time (Czech Republic), in quantity (Germany) or for demonstration purposes only (Poland).

The role of fossil-fuel (particularly gas-fired power plants) in combination with CCS has been assessed in numerous studies, and has been emphasized to eliminate residual emissions from the power sector during the transition period. In the study by (European Commission, 2018a), the installations of fossil fuels with CCS rises from zero in 2030 to 16 GW by 2050 in 1.5TECH scenario and 2.5 GW by 2050 in

1.5LIFE Scenario[21]. ECF 2018 Shared effort scenario and Technology Scenario assume that 100% of new gas fired power plants are equipped with CCS from 2030. The IEA ETP 2017: B2DS assumes a share of natural gas with CCS for the region, generating 3 TWh by 2030 (capacity of 1.44 GW), and 9 TWh by 2040 (1.44 GW) but no generation in 2050. Coal with CCS does not get applied in this region in the scenario.

(DNV GL and WindEurope, 2018) states that CCS would become economically attractive at a carbon price of 90 €/tCO_2. In the Eurelectric scenario the carbon price needs to reach 130 €/tCO_2 by 2045 in their Technology Breakthrough scenario to make CCS competitive (Eurelectric, 2018) in which case it would abate 50% of remaining emissions from power sector in 2050[22]. The provision of carbon pricing allows for the extensive use of natural gas in these studies. In (Eurelectric, 2018), up to 15% of gas capacity is equipped with CCS in the Technology Breakthrough scenario in 2050. In the modelling work done in (Gaffney et al., 2020), the high VRE Scenario also assumes the usage of natural gas equipped with CCS.

5.2 Benchmarks for Paris Agreement Compatibility

For the power sector, we look into benchmarks for the following three indicators;

- electricity emission intensity (gCO_2/kWh);
- share of coal in electricity generation mix;
- share of renewables in electricity generation mix.

for 2030, 2040 and 2050 based on the Paris Agreement Compatible Sectoral Benchmarks report (Climate Action Tracker, 2020). These indicators were chosen in order to provide both a general overview (electric emissions intensity) of where the electricity sector needs to be in the milestone years of 2030, 2040, and 2050, as well as a more granular description of how much the build-up of renewables (reflected by RES-E share) and phase-out of fossil fuels (reflected by the share of coal) needs to have progressed in each country (Climate Action Tracker, 2020).

Emissions intensity of the power sector is a clear and direct measure of decarbonisation of the power sector. The share of coal and renewable energy are relevant for policy decisions in relation to target setting for the power sector. The Paris Agreement compatible benckmarks derived in (Climate Action Tracker, 2020) for the power sector in the European Union[23] are shown in Table 2. The analysis is based on downscaled Integrated Assessment Model (IAM) results as well as based on recent global energy system modelling exercise leading to full decarbonisation (EWG-LU, 2017) which is also one of the scenarios analysed here for the EU. The (EWG-LU, 2017) study finds that a 100% renewable energy electricity system is feasible by 2050 in the EU and in other regions, and provides the upper bound in the share of renewable energy benchmark. This is substantiated further with other literature including the literature evaluated in this study. In (Climate Action Tracker, 2020) it is pointed out that every region can achieve an electricity system with an emissions intensity of 0g CO_2/kWh by 2050 which is used to substantiate the findings from downscaling global IAM pathways that emissions intensities need to be, and can feasibly be, negative by 2050 in each country to be consistent with the Paris Agreeement.

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[21] While not stated explicitely in the report, we assume this implies gas-fired power plants with CCS and not coal-fired power plants with CCS because the share of coal reaches 0% in generation mix in 2050.

[22] Likely also applying to gas which still has a share of 17% in generation mix in 2050 generating 1057 TWh while the coal share is 0%.

[23] The European Union in this report refers to the EU27 plus the UK, denoting the status before Brexit.

Table 2: Benchtablemarks for Paris Agreement compatibility for power sector based on (Climate Action Tracker, 2020).

Indicator	2030	2040	2050
GHG emisisons intensity of power generation (gCO_2e/kWh)	75-80	0-5	<0
Share of coal in power generation	0%	0%	0%
Share of renewables in power generation	70-90%	85-95%	98-100%

It is important to note that the benchmarks used here are consistent with the finding that emission need to be reduced substantially in the short term, with coal phased out by 2030 in the EU, and emissions intensity reduced substantially already by 2030, reaching zero or almost zero by 2040 and becoming negative by 2050. The benchmark analysis also suggests that to be Paris Agreement-compatible and reach complete decarbonisation by 2050, the most promising option is to fully transition the electricity sector to 100% renewable sources using variable and dispatchable sources, firm biomass capacity, all storage options and flexible electricity demand, given other alternative low-carbon technologies are not expected to compete economically with renewable energy and storage where costs are falling and are expected to continue to fall. Therefore the lower bound for renewable energy generation in 2050 is derived from the lowest country-specific renewables penetration rate from global study of EWG/LUT (Zappa, Junginger, & van den Broek, 2019) which most closely aligned with recently observed developments in the renewable energy space, and reflects the abovementioned uncertainties.

We filter the set of scenarios analysed and described in section 5.1 and annex I based on these benchmarks, in order to use a reduced number of scenarios to derive policy conclusions. For the share of renewables and GHG emission intensity of electricity generation, we use the lower end in terms of ambition of the benchmarks. For the coal share in electricity generation, we use 5% as benchmark for 2030 and 1% for 2040. This approach enables the selection of a subset of scenraios that have developments broadly consistent with the Paris Agreement benchmarks in order to derive policy relevant conclusions in relation to the future power sector development. Results are shown in Table 3, Table 4, Table 5, as well as Figure 25.

Table 3: Comparison of the scenario indicators against the Paris Agreement compatible benchmarks for emissions intensity.The green cell denotes that the indicators are compatible, while the red cell denotes that they are not. The blue cell denotes that the data is not available.

Paris Agreement Compatibility Check	GHG emissions intensity (gCO_2/kWh)		
Scenarios	**2030**	**2040**	**2050**
PSR Benchmark Upper	75	0	0
PSR Benchmark Lower	80	5	0
EUCO 3232.5	169	n.a.	n.a.
Connolly 2016: 100% Renewables Scenario	n.a.	n.a.	n.a.
IEA ETP 2017: Beyond 2 Degree Scenario	78	27	-30
DNV GL 2018: Paris Compatible Scenario	n.a.	n.a.	n.a.
Eurelectric 2018: Technology Breakthrough Scenario	146	36	0

ECF 2018: Shared Effort Scenario	104	22	-2
ECF 2018: Demand Scenario	93	27	19
ECF 2018: Technology Scenario	121	29	-1
EC 2018: 1.5 Tech Scenario	170	0	0
EC 2018: 1.5 Life Scenario	168	4	0
JRC 2018: Zero Carbon Scenario	n.a.	n.a.	n.a.
Oeko 2017: Vision Scenario	143	50	0
Child 2019: Region Scenario	26	2	0
Child 2019: Area Scenario	0	0	0
EWG & LUT 2019: 100% Renewables Scenario	41	8	0
Gerbaulet 2019: Default Scenario	153	70	4
UBA 2019: GHG neutral EU 2050 Scenario	n.a.	n.a.	2
IEA WEO 2019: Sustainable Development Scenario	106	50	n.a.
Teske 2019: 1.5 C Compatible Scenario	65	17	0
DIW 2020: Paris Scenario	45	0	0
Gaffney 2020: High VRE Scenario	n.a.	n.a.	-1
PAC Consortium 2020: Paris Compatible Scenario	n.a.	n.a.	n.a.

Table 4: Comparison of the scenario indicators against the Paris Agreement compatible benchmarks for the share of coal in the power sector.The green cell denotes that the indicators are compatible, while the red cell denotes that they are not. The blue cell denotes that the data is not available

Paris Agreement Compatibility Check	**Share of coal (%)**		
Scenarios	**2030**	**2040**	**2050**
PSR Benchmark Upper	0%	0%	0%
PSR Benchmark Lower	5%	1%	0%
EUCO 3232.5	12%	n.a.	n.a.
Connolly 2016: 100% Renewables Scenario	n.a.	n.a.	0%
IEA ETP 2017: Beyond 2 Degree Scenario	0%	0%	0%
DNV GL 2018: Paris Compatible Scenario	2%	0%	0%
Eurelectric 2018: Technology Breakthrough Scenario	8%	2%	0%
ECF 2018: Shared Effort Scenario	5%	2%	1%
ECF 2018: Demand Scenario	5%	3%	0%
ECF 2018: Technology Scenario	8%	3%	1%
EC 2018: 1.5 Tech Scenario	n.a.	n.a.	0%
EC 2018: 1.5 Life Scenario	n.a.	n.a.	0%
JRC 2018: Zero Carbon Scenario	1%	0%	0%
Oeko 2017: Vision Scenario	7%	0%	0%
Child 2019: Region Scenario	3%	0%	0%
Child 2019: Area Scenario	0%	0%	0%
EWG & LUT 2019: 100% Renewables Scenario	3%	0%	0%
Gerbaulet 2019: Default Scenario	11%	3%	1%
UBA 2019: GHG neutral EU 2050 Scenario	n.a.	n.a.	0%
IEA WEO 2019: Sustainable Development Scenario	2%	1%	n.a.

Teske 2019: 1.5 C Compatible Scenario	1%	0%	0%
DIW 2020: Paris Scenario	1%	0%	0%
Gaffney 2020: High VRE Scenario	n.a.	n.a.	0%
PAC Consortium 2020: Paris Compatible Scenario	0%	0%	0%

Table 5: Comparison of the scenario indicators against the Paris Agreement compatible benchmarks for the renewables in the power sector. The green cell denotes that the indicators are compatible, while the red cell denotes that they are not. The blue cell denotes that the data is not available.

Paris Agreement Compatibility Check	**Share of renewables (%)**		
Scenarios	**2030**	**2040**	**2050**
PSR Benchmark Upper	90%	95%	100%
PSR Benchmark Lower	70%	85%	98%
EUCO 3232.5	56%	n.a.	n.a.
Connolly 2016: 100% Renewables Scenario	n.a.	n.a.	100%
IEA ETP 2017: Beyond 2 Degree Scenario	59%	67%	71%
DNV GL 2018: Paris Compatible Scenario	54%	66%	77%
Eurelectric 2018: Technology Breakthrough Scenario	60%	79%	86%
ECF 2018: Shared Effort Scenario	63%	84%	93%
ECF 2018: Demand Scenario	66%	82%	91%
ECF 2018: Technology Scenario	64%	90%	97%
EC 2018: 1.5 Tech Scenario	n.a.	n.a.	86%
EC 2018: 1.5 Life Scenario	n.a.	n.a.	86%
JRC 2018: Zero Carbon Scenario	55%	81%	95%
Oeko 2017: Vision Scenario	70%	85%	100%
Child 2019: Region Scenario	86%	96%	99%
Child 2019: Area Scenario	90%	98%	100%
EWG & LUT 2019: 100% Renewables Scenario	86%	96%	99%
Gerbaulet 2019: Default Scenario	54%	81%	97%
UBA 2019: GHG neutral EU 2050 Scenario	n.a.	n.a.	99%
IEA WEO 2019: Sustainable Development Scenario	61%	73%	n.a.
Teske 2019: 1.5 C Compatible Scenario	74%	94%	100%
DIW 2020: Paris Scenario	82%	100%	100%
Gaffney 2020: High VRE Scenario	n.a.	n.a.	94%
PAC Consortium 2020: Paris Compatible Scenario	89%	98%	100%

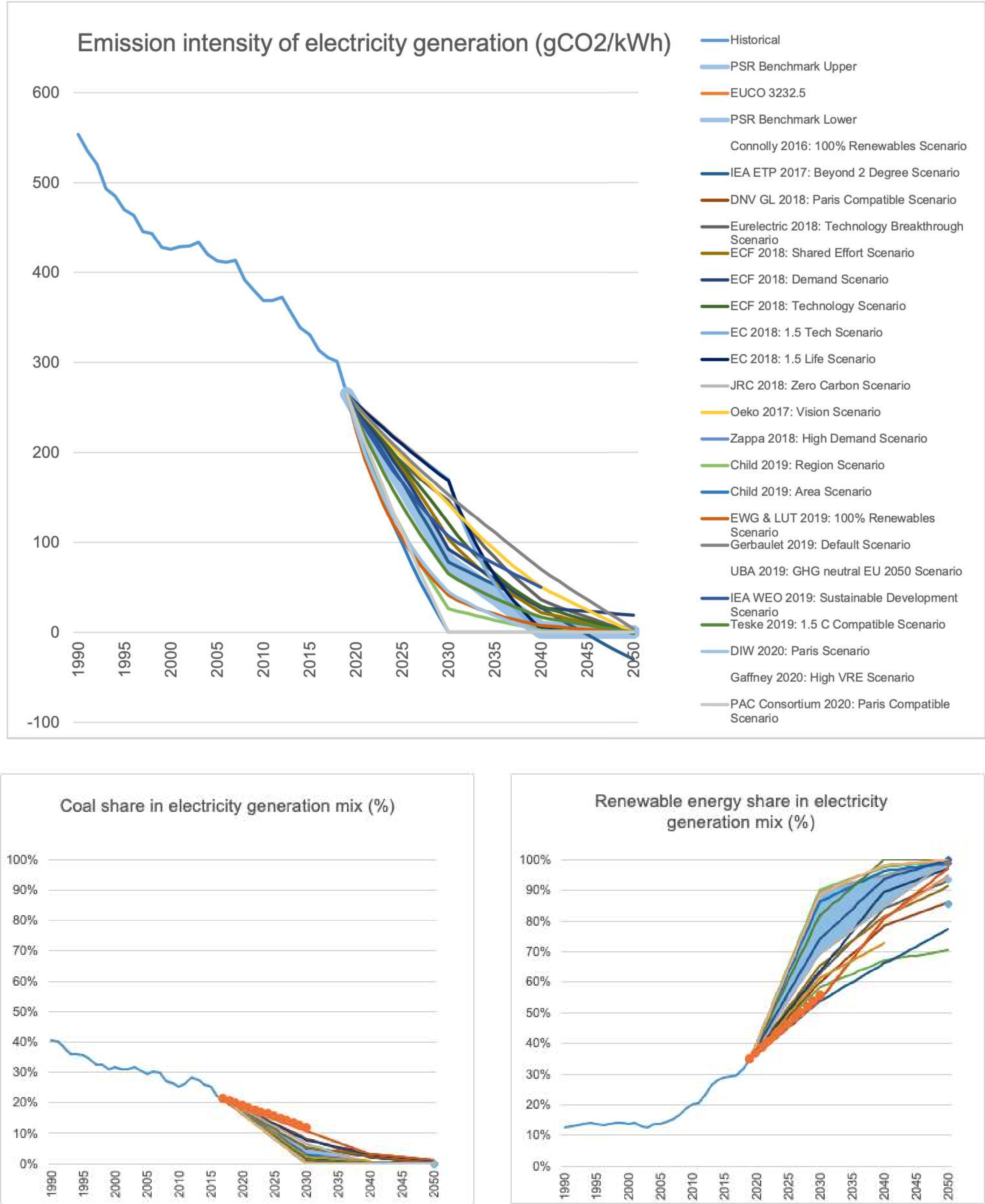

Figure 25: Benchmarks for Paris Agreement compatibility based on GHG emissions intensity (top), coal and renewable energy share in electricity generation mix (bottom). Source: own evaluation.

Based on the above mapping exercise, we determine following scenarios as the ones which meet all or majority of the benchmarks for a Paris Agreement-consistent power sector pathway for the EU:

- **PAC Consortium 2020: Paris Compatible Scenario**. Our mapping exercise finds the PAC Consortium 2020: Paris Compatible Scenario as the **most ambitious scenario** of all scenarios analysed. This scenario achieves 65% emissions reduction by 2030 as compared to 1990 levels, with a share of 89% of renewable energy in 2030, and net zero emissions from the overall energy system by 2040. There is a swift ramping up of domestic renewable energy use (particularly solar PV and wind), with the renewable electricity generation tripling between 2020 and 2030. Coal is phased out in the electricity generation mix by 2030, whereas fossil gas follows by 2035 and oil by 2040. Most nuclear power plants would also be shut down by 2040.
- **DIW Berlin 2020: Paris Scenario.** This scenario also shows an ambitious approach to reach climate neutrality in Europe by 2040. Cross-sectoral integration and increase in electrification rate across sectors lead to more than doubling of *electricity demand* between 2020 and 2050 in this scenario. However, energy efficiency improvement and change in behaviour pattern leads to overall decrease in *primary energy demand* by 50% when compared to 2015. The fossil fuels and nuclear are stepwise scaled down and completely phased out and replaced by renewables mainly onshore wind, solar PV and offshore wind which reach 82% in 2030 and 100% in 2040.
- **Teske 2019: 1.5℃ Compatible Scenario.** In this scenario, the rise in electrification rate increases the *electricity demand* by 78% while the efficiency gain reduces the *final energy demand* by 45% by 2050 as compared to 2015 levels. The power system transformation is characterized by a dynamically growing demand for renewable energy. The share of wind and solar PV complemented by biomass, CSP, ocean energy and geothermal increases continuously in this scenario reaching 74% in 2030 , 94% in 2040 and 100% share by 2050.
- **EWG & LUT 2019: 100% Renewable Energy Scenario.** This scenario developed using the LUT energy system transition model is based on the premise that global energy transition is not a matter of technoeconomic feasibility, but rather a matter of political will. The study depicts that a faster and more rigorous uptake of renewable technologies could trigger a dynamic technology development globally without depending on fossil fuels, nuclear or CCS technologies. The high electrification rate across this scenario leads to high energy efficiency and significant energy savings. Solar PV is the most dominant form of electricity generation in Europe in this scenario contributing 62% to electricity mix, followed by wind contributing one-third and the rest by other renewable technologies. This scenario was used in (Climate Action Tracker, 2020) to identify the benchmarks for renewable energy.
- **Child 2019: Area and Region Scenarios.** The study presents two 100% renewable energy scenarios when the regions are modelled independently in Region Scenario and with consideration of transmission interconnection between regions in Area Scenario. The energy transition in Europe is facilitated by lowering cost of renewable energy, flexible generation, storage technologies and interconnection between regions. These scenarios emphasize the role of flexibility options such as batteries, pumped hydro storage and dispatchable hydropower to balance the intermittent generation of wind and solar in the grid.

Common characteristics of the scenarios that meet the PA compatibility benchmarks

- Consistent with the definition of the benchmark, all of the scenarios, which meet the Paris Agreement compatibility benchmarks, achieve **100% renewable energy based power generation by 2050**. While the scenarios by PAC and DIW achieve 100% renewable energy share in electricity generation mix by 2040 itself, other scenarios achieve around 95% renewable energy share by 2040 and 100% by 2050.

- There is a **rapid uptake of renewable energy technologies, especially wind and solar from the base year** itself in all the scenarios. The share of VRE in electricity generation mix reaches up to 70% in Teske et al, three quarters in both the Child 2019 scenarios, 84% in DIW 2020: Paris Scenario and approx. 93% in PAC Consortium Scenario, and 94% in EWG & LUT 2019 Scenario.
- Another commonality of these scenarios is the **high direct electrification rate** across end use sectors such as industrial processes (heating, desalination) and transport. The electricity share in final energy demand reaches up to 52% in Teske 2019 and 61% in PAC Consortium Scenario. The high electrification rate leads to massive efficiency gains, decrease in final energy demand but an increase in electricity generation demand. The electricity generation demand in 2050 increases between 36% in Child 2019 and 346% in EWG & LUT 2019 Scenario.
- Another feature which is common among these scenarios is that all of them **achieve climate neutrality from the power sector by 2050 without the application of CCS/BECCS technologies**.

Some of the scenarios reviewed as part of our study present the status of power system for 2050 only, however, they don't provide the transition pathways leading to 2050. These scenarios include Connolly 2016: 100% renewable energy scenario, UBA 2019: GHG neutral EU 2050 scenario and Gaffney 2020: High VRE Scenario. These scenarios are not taken into consideration as they do not provide a basis to derive policy relevant conclusions for the pathway towards net zero emissions/100% renewable enrgy.

The JRC LCEO 2019: Zero Carbon Scenario is an ambitious scenario in terms of climate ambition and emission reduction. In 2050, the electricity generation mix in this scenario is composed of 95% renewables, but it only achieves 55% renewable energy in 2030, leaving a large share of gas and nuclear energy.

The European Commission's 1.5TECH and 1.5LIFE scenarios also have quite significant share of nuclear in electricity generation mix which is about 12% share in 2050 in both the scenarios. The share of fossil fuels (mainly coal) remains at a high level of 24% in 2030 in these scenarios. This results in higher emissions from the power sector during the transition period.

5.3. Employment impact of an increase in renewable energy share in power generation

An increase in the share of renewable energy to 75% in 2030[24], based on the electricity mix projection from the 'ADV ER Scenario' by (Greenpeace, 2015) as analysed in (Climate Action Tracker, 2018) would create, on average, around 350 000 more direct jobs between 2020 and 2030 in the electricity sector in the EU27+UK than in a reference scenario that would only lead to 43% of renewable energy, particularly through the increase in wind and solar energy use. The net employment benefit, estimated here only for direct jobs based on an employment-factor approach, would be much higher if indirect and induced jobs were taken into consideration. Employment through other measures in the sector such as grid development, storage and other flexibility measures are not taken into account in this estimate. In 2025, the estimated direct job creation in renewable energy is still estimated to be six times higher than the

[24] The Paris Agreement consistent scenario analysed in (Climate Action Tracker, 2018) is based on the 'ADV ER Scenario' by (Greenpeace, 2015). The RE share of 75% is at the lower end of the Paris Agreement consistent benchmark as described in chapter 5.

reduction in fossil-based jobs for the same year compared to the reference scenario (Climate Action Tracker, 2018).

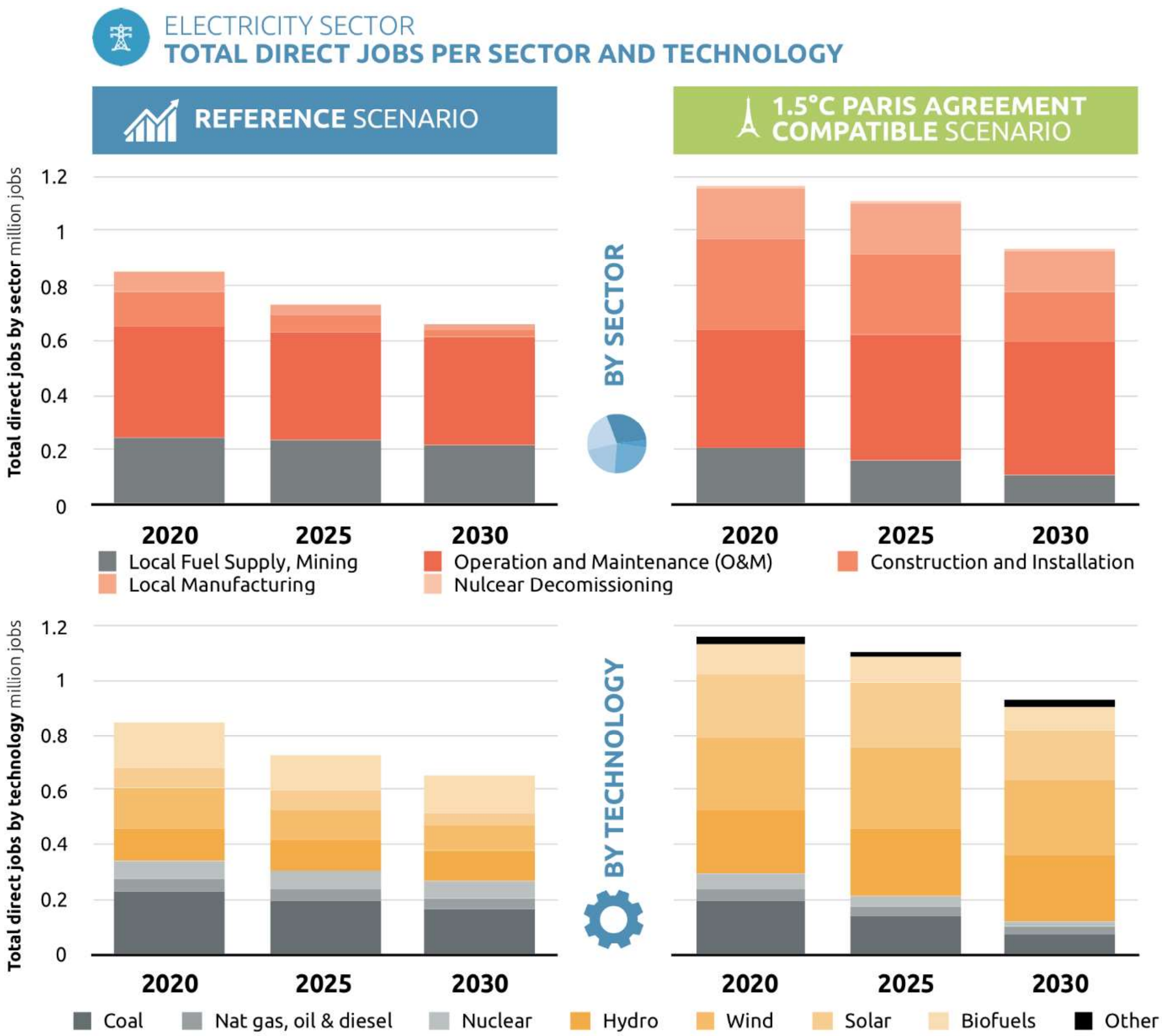

Figure 26: Employment impact of an increase of the share of renewable energy in the EU power sector, by sector (above) and technology/energy source (below), comparing a Paris Agreement compatible scenario (share of 75% of renewable energy in 2030) with a reference scenario (47% share). Source: (Climate Action Tracker, 2018).

Scenarios with a stronger reliance on natural gas or nuclear power create fewer jobs than scenarios that are more ambitious in terms of building up new renewable energy capacities, especially in solar and wind energy, as manufacturing as well as construction and installation of renewable energy facilities is generally more job intensive (Climate Action Tracker, 2018). The number of local jobs depends on the share of local manufacturing and bioenergy supply, which highlights that measures supporting local expertise and skills for manufacturing and the development of a local manufacturing value chain could support the transition away from coal and the generation of local high quality jobs in the renewable energy sector. The distributed character of renewables may be expected to enhance the impact on the creation of local jobs, especially in rural areas (Climate Action Tracker, 2018).

It should be noted that the scenario analysed in (Climate Action Tracker, 2018) which was at the most ambitous end in the available literature at the time of that analysis, is now at the lower end of ambition of Paris Agreement compatible scenarios of energy transition. This shows the significant increase in ambition that is possible due to recent technology developments and related cost reductions.

5.4. Conclusions

While an increasing number of countries and regions adopt the goal of emissions neutrality by the middle of the century, a full decarbonisation of the electricity sector must happen well ahead of that deadline. This is driven mainly by the fact that electricity plays an essential role as enabler and lever of decarbonisation in the other sectors. By 2050 at least 52% of energy – in the case of many scenarios much more - will be consumed in the form of electricity – a significant increase from 21% of energy consumed as electricity in 2017. Emissions pathways resulting in 100% share of renewables in electricity generation cannot be considered compatible with the Paris Agreement, unless accompanied with a significant decrease in emissions intensity in the current decade, driven mostly by coal phase-out by around 2030.

Few scenarios fulfil these criteria. Those that do require a significant uptake of renewables amounting to installing between 21 GW and 47 GW of wind (combined onshore and offshore) and between 20 GW and 109 GW of solar (combined utility scale and rooftop every year until 2030, and even more afterwards. Increase of solar installations at the low end of the range would have to be accompanied with an increase of installed wind the high end of the range. Combined, between 44 and 171 GW of wind and solar would have to be installed annually in the Paris Agreement-compatible scenarios. This is at least 2-fold increase in comparison to the average in the 2010s, accompanied with a significant strengthening of energy efficiency. However, a significant decrease in the costs of both technologies makes it possible to achieve such an acceleration in the deployment of renewables. This is in fact already happening: with 17 GW of solar PV installed in 2019 the EU is on pathway toward a virtuous cycle of increasing capacity and decreasing costs.

This increasing share of renewables, especially variable renewables, such as wind and solar, needs to be accompanied with measures aiming to adapt the grid. Already existing solutions, such as storage and grid development, should be accompanied by taking advantage of the opportunities resulting from electrification of other sectors. As pointed out in some scenarios, sector coupling may provide new sources of flexibility in the future European power system, e.g. by utilization of heat pumps and charging infrastructure, both of which have load shifting potential. In addition, development of green hydrogen can allow indirect utilization of electricity in more challenging sectors and would offer almost unlimited possibilities for electricity storage.

Ratcheting up development of renewables in the power sector would also result in significant job creation. According to a scenario at the lower end of ambition of Paris Agreement compatible scenarios which would result in 32 percentage point higher share of renewables in the power sector, around 350.000 more direct jobs can be created between 2020 and 2030 in the electricity sector in the EU27+UK. Thus, an accelerated decarbonisation of the power sector can also be an important instrument in the post-COVID-19 recovery efforts.

6 Conclusions and lessons learnt

The following conclusions and lessons learnt can be drawn from the analysis of current drivers of decarbonisation in the EU and its member states, as well as from the analysis of scenarios to achieve Paris Agreement compatible benchmarks to reduce emissions intensity in power generation expanding the the share of renewable energy and phasing out fossil fuels, in particular coal.

The scenario analysis shows that the key driving policies (EU ETS, coal phase out plans, ramping up of renewable energy) that are already in place need to be strengthened and accelerated as well as (in the case of coal phase out and renewable energy support) expanded across the EU. Further, policies for the power sector need to take into account its important role in decarbonising end use sectors through (direct and indirect) electrification and how this impacts on expected electricity demand, and at the same time support enhanced uptake of variable renewable energy sources in particular wind and solar. This makes the continuation and strengthening of efforts to increase energy efficiency even more important,

In addition, the analysis of current drivers and trends, including case studies for individual member states shows that strengthening the role of civil society and taking into account how measures impact on all parts of society and manage the transition in a way that ensures participation of affected regions in benefits for employment and income (just transition) is an important success factor to ensure support for adequate climate policy. Finally, enhancing synergies between green COVID-19 recovery and climate policy is an important factor that can also be expanded and strengthened. Figure 24 provides an overview of the key levers that we describe in more detail in the following subsections.

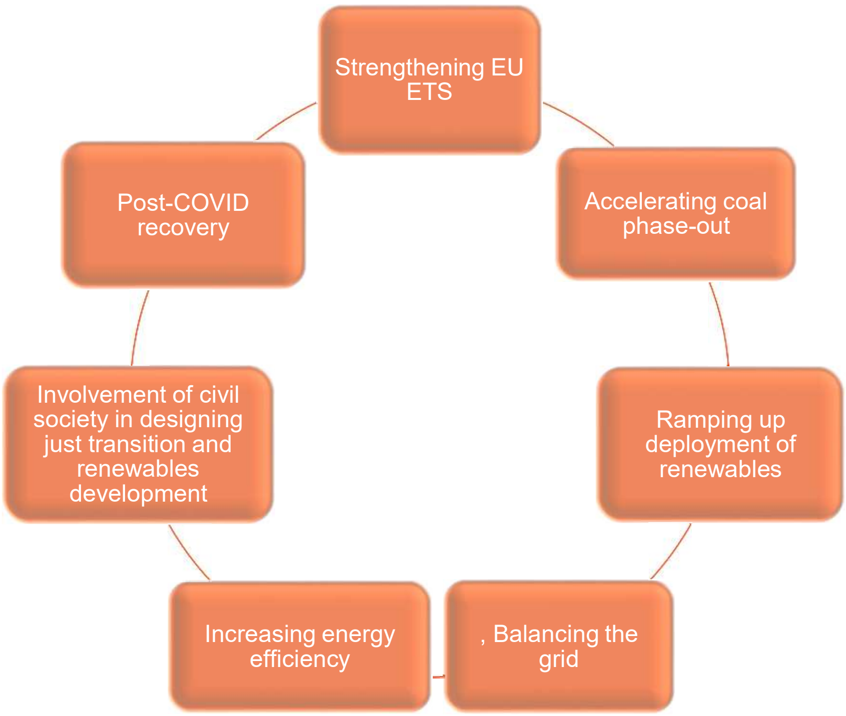

Figure 27: The main levers for decarbonisation of the power sector.

Strengthening the EU ETS

The 2030 **EU ETS** emissions reduction goal at 43% below 2005 levels, needs to be adapted to reflect the need to ratchet up the **overall** emissions reduction goal to be Paris compatible and to accelerate reducing emissions intensity of the power sector in particular. Depending on the scenario and scope (e.g. inclusion or exclusion of the LULUCF, aviation), the overall 55% emissions reduction goal suggested by the Commission would require strengthening the emissions reduction in the EU ETS sector for stationary installations to between 64 and 69% (European Commission, 2020s). Increasing the emissions reduction goal to 60%, as suggested by the European Parliament, would require strengthening the EU ETS to between 66 and 71% (Umweltbundesamt, 2020). To put this into context of scenarios consistent with the Paris Agreement analysed in Section 5: The PAC Scenario results in **economy wide GHG emissions reductions of 65% below 1990 levels by 2030 excluding LULUCF.**

The EU ETS can be strengthened by increasing the Linear Reduction Factor (LRF), which is the annual reduction of the emissions cap, from 2.2% to 4% starting in 2021. This would reduce the cap from around 1.800 $MtCO_2eq$ in 2021 to 930 $MtCO_2eq$ in 2030 (Zaklan, Wachsmuth and Duscha, 2020). Another approach would reduce the cap by reducing the level of emissions taken as the basis for the cap calculations (rebasing) (Oeko-Institut, 2020). Whereas the first approach would result in a much steeper reduction in the cap, the latter would flatten the curve but starting at a much lower level than in the year preceding the reform: reducing emissions in the base year by 300 $MtCO_2eq$ would only require an increase of the LRF by 2.69% - only modestly above the current level – starting in 2023 to allow for enough time for the adoption of the EU ETS reform (Oeko-Institut, 2020).

The situation is however complicated by the proposal of the Commission to expand the scope of the EU ETS to other sectors. To increase the EU ETS' efficiency the reform should take into consideration the different levels at which carbon pricing triggers decarbonisation in different sectors. It should also avoid the risk of the price of allowances decreasing significantly as a result of a much faster than expected decarbonisation of the newly added sectors. This can especially be the case if the projections for decarbonisation e.g. in the building sector are on the conservative side to reflect more the slow progress in the past than the significant emissions reduction potential. This potential can be trigged e.g. as a result of the implementation of the EU Renovation Wave (European Commission, 2020a). While a significant acceleration in decarbonisation of the EU's building stock is of great importance, it is very important that this does not result in a decrease in the level of carbon pricing in the power sector, which would slow overall decarbonisation.

Strengthening of the Market Stability Reserve (MSR), which already turned out to be an effective way to stabilise the price of the emissions allowances, could be considered as a way to avoid the risk of watering down carbon pricing resulting from inclusion of other sectors. This strengthening could take the form of increasing the share of oversupply of allowances taken from the market every year. While certain share of these allowances could be returned to the market if the oversupply decreases below a certain level – as is the case currently – the amount of allowances stored in the MSR should be reduced as well, with the rest deleted permamently.

Planned coal phase out

As mentioned in Section 5, coal phase-out by around 2030 is one of the requirements of the power sector for Paris Agreement compatibility. This is driven by the high emissions intensity of this source of energy and the readily available alternatives. As pointed out in Section 3.4, the majority of the EU member states have already set a date for coal phase out by that deadline. This does not apply to

Poland and Germany, the largest consumers of coal in the EU. Whereas Germany plans to phase out coal by 2038, Poland has no commitmentt to phase out coal.

As mentioned in Section 4.2, decreasing competitiveness of coal in comparison to renewables, combined with carbon pricing, makes a much earlier coal phase out in Germany much more probable. On its part the Polish government is running out of options to subsidise existing coal mines and space to store coal which cannot be consumed. However, leaving the process of coal phase-out exclusively to market forces may result in negative socio-economic repercussions. For Poland, where in 2019 almost three quarter of electricity was still generated in coal power plants, an unplanned collapse of the coal industry may also have disastrous repercussion for the electricity system. Both kinds of impacts can be mitigated if coal phase out is planned ahead of market forces and accompanied with ramping out of alternatives. Just transition mechanisms and support for affected regions are an important element of such a planned phase out.

Support mechanisms for renewable energy ramped up

To replace coal, natural gas and nuclear energy, EU and its member states need to ramp up development of renewables and associated grid and market design changes to support high penetration of variable renewable energy. A key lesson from comparing current trends with Paris Agremeent consistent benchmarks and related scenarios is the need to substantially accelerate the increase in deployment of renewable energy, in particular wind and solar energy.

To be make EU's power sector compatible with the Paris Agreement, between 21 GW and 47 GW of wind (combined onshore and offshore) and between 20 GW and 109 GW of solar (combined utility scale and rooftop needs to be installed every year until 2030, and even more afterwards. This is much more than the capacity additions in the preceding years: Only slightly less than 11 GW of wind capacity and around 10 GW of solar was installed in the 2010s. Combined, between 44 and 171 GW of wind and solar would have to be installed annually in the Paris Agreement-compatible scenarios (Solar Power Europe, 2020a; Wind Europe, 2020a).

The five-fold increase in the deployment of renewables is possible but requires changes to the existing support mechanisms for renewables in the power sector, that would include among others a significant increase in the installed capacity auctioned for implementation in the EU member states. The auctioned amount should take into account that some projects will not be implemented. EU member states could cooperate to implement large-scale projects, especially offshore wind farms. This cooperation can be coordinated by the European Commission.

As described in Section 3, the rapid decrease in the costs of renewables caught the governments of Germany and Spain off guard in terms of adapting the level of feed-in tariffs to reflect the technological developments. However, instead of learning on the mistakes and improving this mechanism to take advantage of its strengths, these governments – and many others in the EU – decided to abolish it completely. This represents a lost opportunity: due to its predictability and simplicity, the feed-in tariff system facilitated the participation of civil society in energy transformation. As mentioned earlier, its replacement with much more complicated and unpredictable auctioning mechaniims decreased the role of civil society and with it also acceptance for renewables. To accelerate the development of renewables smaller projects, especially those implemented by energy communities and prosumers, should be supported in the framework of feed-in tariffs. At a level around 85% below the feed-in tariffs introduced in Germany in 2004 (Deutscher Bundetsag, 2004; Bundesnetzagentur, 2020), there is almost no risk of windfall profits. Nonetheless, the decrease in the level of the feed-in tariffs should be much closer correlatated with technological developments.

To increase the utilisation of the available roof space small rooftop PV installations could be supported with a one-time grant instead of feed-in tariffs. This could mitigate the problem of relatively high upfront investments and reduce the administrative burden. While the existence of feed-in tariffs makes it easier to get a loan to cover the investment, it nonetheless requires additional time and effort which may discourage some home owners. In addition, instead of receiving compensation for electricity fed into the grid, part of that electricity (e.g. 70-80%) could be used by the homeowners or tenants within a specific period of time (e.g. one year). This could on one hand encourage electricity consumers to whenever possible shift electricity consumption (e.g. charing EVs) thus contributing to grid stabilization.

Balancing the grid

As described in section 5, variable renewables (VRE) will play a dominant role in the Paris Agreement-compatible electricity sector and cover around 75% of the electricity generation in 2050. Numerous options to balance the grid need to be consired – from storage and demand management, through dispatchable renewables, to sector coupling and hydrogen – however their exact mix will be strongly influenced by the policies introduced. Subsidies for small scale, household batteries, offer the potential to balance electricity generated and consumed in short term, diurnal time scale. Smart sector coupling, for example applying dynamic electricity pricing, could utilise the potential for demand shifting in other sectors, e.g. heating, cooling, or transport. It could thus reduce the costs of balancing the grid at the larger scale and in longer term. Faciliatating development and deployment of hydrogen requires significant investments, but also offers the potential of long-term electricity storage and indirect usage of green electricity in areas in which energy density exceeding what can be provided by batteries, plays a decisive role, e.g. aviation, shipping or heavy duty transport.

The need to rapidly ratch up deployment of renewables requires an immediate deployment of the already available options for balancing the grid, while preparing infrastructure for deployment of the options that will be possible in the future. A case in point is the installation of smart meters and charging stations in the households that will make it possible to use EVs as grid stabilizers even if dynamic electricity tariffs are not yet available. Electrolysers for hydrogen generation should be installed even if they cannot be fully utilized yet and thus (initially) unprofitable. Such inefficiencies are necessary to avoid carbon lock-in resulting e.g. from increasing dependency on fossil gas to stabilize the grid which would either hinder change or result in stranded assets.

Decrease energy demand

While ratcheting up deployment of renewables is essential to meeting the Paris Agreement temperature limit, reaching 100% share of renewables will be easier if accompanied with a decrease in energy consumption. In addition to a significant potential for increasing energy efficiency in sectors that should be electrified, especially heating and cooling in building sector (European Parliament, 2020b), replacement of fossil fuels by renewables would already result in a significant reduction in energy demand. As mentioned in Section 2.1, more than half of the primary energy included in fossil fuels consumed for electricity generation was still wasted in 2016 (European Environment Agency, 2018). Electrification of transport would result in additional reduction in energy consumption due to energy efficiency of the electric vehicles which can be between 2.5 and 6-times higher than that of combustion vehicles (U.S. Department of Energy, 2020).

EU modelling of the 55% emissions reduction goal indicates reduction in primary energy consumption by between 40% and 41% in comparison to the Commissions' projection for 2030 from 2007. Higher emissions reduction goals result in even deeper reduction in energy consumption. The PAC Scenario which results in **65% economy wide GHG emissions reductions below 1990 levels by 2030**

excluding LULUCF, leads to at least **45% energy savings** (Climate Action Network Europe and European Environmental Bureau, 2020).

Significant savings could be achieved in the building sector. These savings are essential if fossil fuels directly used for heating are to be replaced by electricity, especially from wind and solar: the amount of energy needed, especially in times of the year when electricity generation from solar PV is limited, would be challenging especially in the case of older, inefficient building stock. Thus, in addition to homes insulation – which would reduce energy demand not only for heating but also for cooling – the energy generated from electricity could be leveraged be up to the fact of four via heat pumps (Geothermal Communities, 2013).

Involvement of civil society in designing just transition and development of renewables

Moving away from fossil fuels towards renewables has significant socioeconomic repercussions. While deployment of renewable energy provides opportunities for an overall increase in employment for the EU, phasing out coal will likely impact on employment in regions currently concentrating most of the employment in mining or coal fired power generation as pointed out in Section 3.3. Thus, unless mitigated with additional measures, coal phase-out by the end of the decade can result in significant job losses in affected regions, which would also affect local economy and can result in long-term, structural unemployment. This can be especially the case if no or few alternatives exist or are developed specifically in the region.

While the EU reserved significant resources for a Just Transition mechanism, the way these resources are spent will to a large degree depend on the member states. This creates the potential that the resources may be used in a way which only to a limited degree benefit those affected or the impact is limited in time, e.g. if the support is limited to generous, one-time-payments. Instead, governments and especially local authorities, can learn from successful experiences of other countries and involve local communities in designing the respective transition strategies. While certain solutions may be common to most regions (e.g. early pensions, re-training, siting of new industries), they also need to be adapted to the specific circumstances. Most of all, designing the transition plans jointly with those affected – both directly and indirectly – will increase the ownership of the plans, and increase the chances of their successful implementation.

Civil society should not only be involved in the process of *phasing out* one source of energy, but should also be playing an active role in *phasing in* its replacement. The scalability of renewables creates numerous opportunities to invove members of civil society: starting from electricity generation from PV installations, through participation in the renewable energy cooperatives, to investments in large scale decarbonisation projects via pension funds. Energy communities can also play an important role in coming up with ideas concerning the ways in which increasing shares of variable renewables can be balanced using storage, demand management, and sector coupling.

European legislation has already created a basis for increasing the involvement of civil society in electricity generation. The Renewable Energy Directive introduces the definition of *renewable energy communities* which are given certain rights and obligations, e.g. member states have to ensure that renewable energy communities can participate in the support mechanisms for renewables on an equal footing with commercial participants. They can also introduce additional measures to balance the weaker positions of such communities resulting from weaker financial buffers, risk aversion, or smaller or completely lacking experience in participating in the bidding process. The law also obliges member states to ensure that renewable energy communities are allowed to share energy produced by the community-owned installations among themselves. The directive also bans the introduction of additional charges on the self-generated electricity (this would apply to the “solar tax” introduced in Spain in 2015). In terms of obligations, the law states that energy communities should not be exempt from charges and costs borne by customers who are not members of the community, e.g. grid charges whenever public grid infrastructure is used and should ensure that they contribute to fighting energy poverty by enabling the participation of vulnerable consumers and tenants (European Parliament and the Council of the European Union, 2018c).

Recently developed European legislation can still be improved, for example in relation to consistency across Directives: The Energy Market Directive introduces a definition of citizens energy communities with slightly different rights and obligations to the Renewable Energy Directive which unnecessarily complicates the situation (The European Parliament and the Council of the European Union, 2019). However it presents a major step forward in recognizing the role that civil society has already played in the transformation of the electricity sector.

Unfortunately, the elements of the directive referring to renewable energy communities have rarely been implemented in the national legislation in the majority of the member states, despite the deadline for its transposition approaching soon. This is especially surprising for Germany, where community based renewable energy generation has been an important factor supported through the feed-in tariffs, but the recent major revision of the Renewable Energy Act which is about to be adopted, fails to implement this part of the European legislation.

Use the opportunity of post-COVID-19 recovery

As the European Union and the EU member states try to recover their economies after the 7.8% economic contraction in 2020 (European Commission, 2020c), they can seize the opportunity offered by development of renewable sources of energy and improvement in energy efficiency. Few other sectors of the economy can contribute to such a rapid and widespread job creation as these two sectors. Ratcheting up development of renewables in the power sector to match a Paris Agreement emissions pahway in the sector would result in around 350.000 more direct jobs created the electricity sector in the EU27+UK in the 2020s (Climate Action Tracker, 2018).

Simple and unbureaucratic support for micro PV, e.g. in the form of one-time-grant, can result in thousands of jobs in companies dealing with their installation and servicing. Ensuring that the demand for PV panels will continue (e.g. by setting an annual goal of prosumers) will ensure that these jobs will be permanent instead of resulting in a boom and bust observed in the Spain and Germany. This can especially provide an opportunity for countries in the south of Europe strongly affected by the pandemic, and subsequently by the decrease in tourism resulting from travel restrictions. The weather conditions which made them the hotspot for tourism in the EU, make them also optimal destination for distributed PV electricity generation. At the same time, large scale wind and solar energy projects will ensure a continued demand for renewable energy installations and in this way facilitate development of manufacturing facilities in the respective regions and countries. Governments may influence where these jobs will be created by providing support if they are sited in places affected by phase out of fossil fuels. Employment is also provided through the continued need for operation and maintenance.

Similarly, investments in energy efficiency combined with electrification of heating, e.g. via heat pumps, can result in distributed job creation, decreasing the disparity not only between different countries in the EU, but also between different regions within the countries, especially between the rural and urban areas. However, differently from solar PV, which constitutes a comparatively smaller investment, for which the rate of return can be easily understood and calculated, electrification of the heating system combined with the essential home insulation and possibly also installation of charging system for electric vehicle, constitutes a much bigger and complicated investment decision. In the situation of the economic crisis-driven insecurity, few home owners would be ready to go ahead with such a decision. To facilitate change in this regard, governments need to facilitate creation of companies or specialized departments in the local public authorities, that will make such investments as simple, transparent, and attractive as possible. This should include supporting such investments with grants combined with low-interest-rates loans that would replace the annual energy costs.

Lessons learned

The study provides a range of lessons learned both for the future development in the EU and for other regions that are in the process of transforming their power sector. The EU approach of setting a combination of targets for greenhouse gas emission reductions, renewable energy and energy efficiency has been crucial to drive policy within the EU and EU member states. Targets have been adjusted to adapt to technological progress and policy demands in particular in relation to achievement of climate goals. Both the analysis for the EU and the Member state case studies show that timing and consistency of targets is important. Missing opportunities for adjusting targets or setting them at the adequate level in the first place can delay policy response and lead to lock-in effects. Managing the necessary transition challenges upfront with proactive stakeholder engagement, just transition processes and support for affected regions is instrumental to achieving political and societal buy-in.

Annex 1. Overview of scenarios reviewed

Author and Scenario	Geographic Coverage	Scenario definition, narratives and assumption
Connolly 2016: 100% Renewables Scenario (Connolly, Lund and Mathiesen, 2016)	EU27+ the UK	• EnergyPLAN simulates electricity, heating/cooling and transport sectors with an hourly resolution over a year (here 2050) and optimizes the overall energy system. Incorporates the intermittency of Variable Renewable Energy (VRE) and demand, and regulations to maintain grid stability • Developed using the Smart Energy System approach in a series of steps: decommissioning nuclear power, heat savings, electrification of passenger car fleet, providing heat in rural areas with heat pumps and in urban areas with district heating, switching fuel in heavy duty vehicles to renewable electrofuel and replacing natural gas with methane • Sector coupling leads to over 80% VRE penetration in power system in 2050
IEA ETP 2017: Beyond 2 Degree Scenario (B2DS) (International Energy Agency, 2017)	Global model disaggregated into 28 to 39 subregions including the EU27+ the UK	• Softlinking of four different models. ETP-TIMES energy conversion model is based on bottom-up approach. The models for transport, industry and buildings are based on optimization approach • Technological deployment, improvement and innovation pipeline seen to be "pushed to maximum practical limits" at the time of publication, resulting in cumulative emissions from the global energy system of 750 $GtCO_2$ between 2015 and 2060 • Net-zero emissions achieved in 2060 with significant amount of BECCS
DNV GL 2018: Paris Compatible Scneario (DNV GL and WindEurope, 2018)	EU27 +the UK, Iceland, Norway, Liechtenstein, Switzerland	• Least cost optimization model that covers electricity, transport and buildings sectors • Besides electrification of end use sectors and energy efficiency, phasing out of coal based generation by 2030 and increase in the sectoral coverage of carbon pricing are the key scenario elements • CO_2 price of €90 per tonne over the projection period
Eurelectric 2018: Technology Breakthrough Scenario (Eurelectric, 2018)	EU-27 + the UK and the EEA countries[25]	• The Global Energy Perspective model (developed by McKinsey&Company) utilizes granular multi-factor approach to analyse economic and political parameters that influence demand for transport, buildings and industry secttors until mid-cenutury. The least cost optimization approach is utilized to model the power system.

[25] EEA (European Economic Area) countries include the countries in the European Union plus Iceland, Norway and Liechtenstein

		• The outcomes are driven by early technology breakthrough, commercialization of novel technologies and deployment at scale before 2040 via global coordination. This enables economy wide emissions reduction of 95% below 1990 levels well before 2050 • High rate of electrification up to 60% in 2050, transmission expansion, deployment of demand side management measures, power-to-X and CCS lead towards near full decarbonisation
ECF 2018: Shared Effort, Demand Focus &Technology Focus Scenarios (European Climate Foundation, 2018)	EU27 + the UK	• Simulation approach. Scenarios are constructed with the Climate Transparency Initiative (CTI) tool by setting the "levers" for power, transport, buildings, industries, AFOLU and other sectors. • Shared effort scenario is driven by evenly distributed mitigation effort across all sectors. Demand-focus scenario is driven by demand side interventions such as materal efficiency, recycling, as well as social and behavioural change. Technology scenario is driven by electrification and efficiency measures, innovation and larger deployment of novel technologies such as hydrogen and CCS. • Energy demand reduction by between 41% in technology scenario and 62% in demand-focus scenario between 2010 and 2050.
European Commission 2018: 1.5 Tech & 1.5 Life scenarios (European Commission, 2018a)	EU27 + the UK	• The PRIMES partial equilibrium modelling system simulates an energy system equilibrium in the European Union and its member states. The model covers the interaction between major sectors including LULUCF. Out of the eight scenarios, two scenarios which achieve net-zero emissions by 2050 are: 1.5LIFE and 1.5TECH. • The 1.5 Tech scenario relies completely on the innovative technology options and deployment of BECCS to realize net zero GHG emissions by 2050. • The 1.5 Life scenario assumes that a drive by EU businesses and awareness in its citizens towards sustaible life style, low carbon intensive diets, consumer choices and circular economy leads to the abatement of emissions, which is complemented by the land-use sink.
Gerbaulet et al., 2018: Default Scenario and Budget Scenario (Gerbaulet *et al.*, 2019)	EU27+ the UK, Norway, Switzerland, Serbia, Albania, Montenegro	• Dynamic partial equilibrium model (dynELMOD) of the European power sector. It determines least cost investment decisions for conventional and renewable generation, storage, including demand side management and development of transmission grid. • No new investment on fossil fuel plants from 2025 onwards, with complete phase-out of coal and gas by 2040. Due to the high cost of nuclear, renewables constitute the most to decarbonization. • Default Scenario envisions a moderate electricity demand increase and near complete decarbonization of the European power sector by 2050. Budget Scenario is based on the power sector emissions budget of 22.5 $GtCO_2$ between 2015 and 2050, leading to zero emissions by 2050.

JRC LCEO 2018: Zero Carbon Scenario (a variant of ProRES) (Nijs *et al.*, 2018)	EU-27+ the UK, Switzerland, Iceland, and Norway	• Partial equilibrium optimization model (JRC-EU-TIMES). Global energy scenarios are translated to the EU level to explore the impact of policy and technology drivers to 2050 • Zero Carbon scenario that achieves 95% energy-related emissions reduction in 2050 below 1990 levels. Due to decentralization trends, VRE become more prominent and other renewable technologies act as complementary • Electricity demand is driven by the direct electrification of transport and the demand for the production of green hydrogen in electrolysers
Oeko 2017: Vision Scenario (Oeko-Institut, 2017)	EU-27 + the UK	• Carbon budget of 61.5 $GtCO_2$ between 2015 and 2050 is the main constraint in the model that determines the future pathways. An hourly modelling exercise is perfomed for the analysis of the power sector in member state level • Substantial tightening of the cap on EU ETS leads to full decarbonisation of ETS regulated installations by 2050 • The scenario assumes sustainability limits on biomass based generation; and no new nuclear reactor installations. Green hydrogen plays a significant role for full decarbonisation by 2050
Zappa et al., 2018: 100% Renewable Energy Scenario (Zappa, Junginger and van den Broek, 2019)	EU27+ the UK, Norway, Switzerland	• Long-term capacity expansion optimization model (Plexos). The model provides least cost generation technologies and transmission infrastrucuture portfolio for given overall demand. Only results for 2050 are presented in the study • To generate 100% of power from renewables, the total installed capacity of generation technologies should reach at least 1.9 TW in 2050 from 1 TW in 2015, and the transmission capacity needs to expand to at least 200 GW in 2050 from 60 GW in 2015.
Child et al., 2019: Region & Area scenarios (Child *et al.*, 2019)	EU27+ the UK, Norway, Iceland, Switzerland, Turkey, the Balkan region, Ukraine, Moldova	• Based on least cost optimization model (LUT energy system model), which is run in hourly resolution for 5-year time intervals between 2015 and 2050 and taking into account the current age and capacities of power plants. • The study shows that a 100% renewable based power system is technically and economically feasible in Europe even before 2050. This is facilitated by the lowering costs of renewable technologies, flexible generation, storage and enhanced interconnection between regions • The transmission capacity increases fourfold in the Area Scenario, and it is more cost effective with lower need for generation and storage capacities, and lower LCOE as compared to Region Scenario
EWG & LUT 2019: 100% Renewable Energy Scenario	Global energy system model covering nine	• The global-local energy system transition model towards 100% renewables is based on prosumer cost optimization approach. This

(Energy Watch Group and Lappeenranta University of Technology, 2019)	major regions including Europe as a continent	is simulated in hourly resolution for the transition period from 2015 to 2050 across power, heat, transport and desalination sectors • Characterized by 100% renewables based energy system that are technically feasible and economically viable on national level based on cost-benefit analysis. Variable renewables dominate the generation side in the future • High electrification rate leading to massive gain in efficiency and significant energy savings
UBA 2019: GHG neutral EU2050 scenario (Umweltbundesamt , 2019)	EU27+UK	• Detailed bottom-up analysis for electricity, heating, transport, buildings and industries. Projections based on decomposition analysis for 2050 only • Virtually all energy carriers in the scenario come from renewable sources: either direct or indirect renewable electricity or other renewable fuels • Added electricity demand due to production of hydrogen (within Europe) and novel fuels (in or outside of Europe)
IEA WEO 2019: Sustainable Development Scenario (SDS) (International Energy Agency, 2019)	Global model disaggregated into 21 regions including EU27+UK	• Global simulation model. It has three main modules for energy supply, conversion and final energy consumption • Charactertized by policies that achieve the global goals for sustainable energy, climate and air quality • Defined by measures such as staggered CO_2 price, increased low carbon power supply, energy efficiency and fuel switching that lead to sharp emissions reduction.
Teske 2019: 1.5 ℃ compatible scenario (Teske, 2019)	Global model disaggregated into ten regions including OECD Europe[26]	• Hybrid of top-down and bottom-up approaches. A cluster of models for energy system, power system, transport, climate and simplified land based sequestration • Based on plausible techno economic pathways and a global energy-related CO_2 emissions budget of 450 $GtCO_2$ between 2015 and 2050 • Immediate uptake of the renewable energy and energy efficiency potential
German Institute for Economic Research (DIW) Berlin 2020: Paris scenario (Deutsches Institut für Wirtschaftsforschu ng, 2020)	EU27 + the UK, Norway, Switzerland, Turkey and the Balkan region	• GENeSYS-MOD uses top-down approach to provide least cost trajectories. This is processed by anyMOD model using bottom-up approach to get hourly supply and demand profile for key years. Encompasses electricity, transport, heating and industry sectors under strict climate constraints • The scenario is characterized by significant efficiency improvement, certain behavioral parameters and high electrification that leads to decline in primary energy demand and decarbonization of the energy system.

[26] https://www.oecd.org/about/members-and-partners/

		• The high electrification rate due to sector coupling leads to more than doubling of the electricity demand between 2020 and 2050.
Gaffney 2020: High VRE Scenario (Gaffney *et al.*, 2020)	EU27 + the UK	• Linear programming approach (PLEXOS model) provides optimal dispatch of thermal, renewable and storage capacity to meet the overall hourly demand. It has high technical and temporal resolution • Relies heavily on enabling technologies such as power-to-gas and interconnection that facilitiate higher share of VRE generation capacity. • It results in 72% VRE, 94% RE, 4.5% nuclear and only 1.5% fossil based generation in 2050.
PAC Consortium 2020: Paris Compatible Scenario (Climate Action Network Europe and European Environmental Bureau, 2020)	EU27 + the UK	• Using a bottom-up research assessment it compares and adopts elements from existing models. • Scenario leads to 100% renewable energy supply and net zero energy systems by 2040 • Driven by mobilisation of energy savings potential, swift ramping up of domestic renewable energy use, electrification of end-use sectors and quick phase out of fossil fuels.

Bibliography

Agora Energiewende (2020) *Die Energiewende im Stromsektor: Stand der Dinge 2019*. doi: 088/01-A-2016/DE.

Agora Energiewende and Sandbag (2020a) 'The European Power Sector in 2019', p. 49.

Agora Energiewende and Sandbag (2020b) 'The European Power Sector in 2019', p. 49. Available at: https://www.agora-energiewende.de/en/publications/the-european-power-sector-in-2019/.

AgoraEnergiewende & Sandbag (2020) *The European Power Sector in 2019*, *Agora Energiewende and Sandbag*. Available at: https://www.agora-energiewende.de/en/publications/the-european-power-sector-in-2019/.

Ancygier, A. (2013) 'Misfit of Interests instead of the "Goodness of Fit"? Implementation of European Directives 2001/77/EC and 2009/28/EC in Poland'.

Anderson, B., Convery, F. and Di Maria, C. (2011) 'Technological Change and the EU ETS: The Case of Ireland', *SSRN Electronic Journal*. doi: 10.2139/ssrn.1855495.

Appunn, K. and Wettengel, J. (2020) 'Germany's Climate Action Law'. Available at: https://www.cleanenergywire.org/factsheets/germanys-climate-action-law-begins-take-shape.

Augsburger Allgemeine (2015) 'Der Niedergang der deutschen Solarwirtschaft'. Available at: https://www.augsburger-allgemeine.de/wirtschaft/Der-Niedergang-der-deutschen-Solarwirtschaft-id41477701.html.

Bankier (2006) 'Expose Jarosława Kaczyńskiego z 19.07.2006'. Available at: https://www.bankier.pl/wiadomosc/Expose-Jaroslawa-Kaczynskiego-z-19-07-2006-7329166.html.

Bechberger, M., Mez, L. and Sohre, A. (2008a) *Windenergie im Ländervegleich*. Peter Lang GmbH, Internationaler Verlag der Wissenschaften.

Bechberger, M., Mez, L. and Sohre, A. (2008b) *Windenergie im Ländervergleich. Steurungsimpulse, Akteure und technische Entwicklungen in Deutschland, Dänemark, Spanien und Großbritannien*. Frankfurt am Main: Peter Lang GmbH, Internationaler Verlag der Wissenschaften.

Bloomberg (2020) 'Germany's Coal Power Could Shut Down a Decade Early'. Available at: https://www.bloomberg.com/opinion/articles/2020-07-06/germany-s-coal-power-could-shut-down-a-decade-early.

Bloomberg New Energy Finance (2020) *Hydrogen Economy Outlook*. Available at: https://about.bnef.com/blog/hydrogen-economy-offers-promising-path-to-decarbonization/#:~:text=Hydrogen Economy Outlook%2C a new,industry – at a manageable cost.

Bluszcz, A. (2014) 'Proces przemian struktury zatrudnienia w górnictwie węgla kamiennego*'.

BMWi (2020a) 'Entwicklung der erneuerbaren Energien in Deutschland im Jahr 2019'. Available at: https://www.erneuerbare-energien.de/EE/Navigation/DE/Service/Erneuerbare_Energien_in_Zahlen/Entwicklung/entwicklung-der-erneuerbaren-energien-in-deutschland.html.

BMWi (2020b) 'Entwicklung der erneuerbaren Energien in Deutschland im Jahr 2019'.

BMWi (2020c) 'Entwurf eines Gesetzes zur Änderung des Erneuerbare-EnergienGesetzes und weiterer energierechtlicher Vorschriften'.

BMWi (2020d) 'Entwurf eines Gesetzes zur Änderung des Erneuerbare-EnergienGesetzes und weiterer energierechtlicher Vorschriften'. Available at: https://www.bmwi.de/Redaktion/DE/Downloads/Gesetz/referentenentwurf-aenderung-eeg-und-weiterer-energierechtlicher-vorschriften.pdf?__blob=publicationFile&v=4.

BP (2020) *Statistical Review of World Energy, 2020 | 69th Edition*.

Bundesnetzagentur (2020) 'EEG-Re-gis-ter-da-ten und -För-der-sät-ze'. Available at: https://www.bundesnetzagentur.de/DE/Sachgebiete/ElektrizitaetundGas/Unternehmen_Institutionen/ErneuerbareEnergien/ZahlenDatenInformationen/EEG_Registerdaten/EEG_Registerdaten_node.html;jsessionid=82EF4DF3EDF9AC2D1FE7A0760BC1CB70.

Der Bundestag (2019) 'Gesetz zur Einführung eines Bundes-Klimaschutzgesetzes und zur Änderung weiterer Vorschriften'. Available at:

https://www.bgbl.de/xaver/bgbl/start.xav?startbk=Bundesanzeiger_BGBl&start=//*[@attr_id=%27bgbl119s0010.pdf%27]#__bgbl__%2F%2F*%5B%40attr_id%3D%27bgbl119s2513.pdf%27%5D__1605178915647.

Byzio, A., Heine, H. and Mautz, R. (2002) 'Zwischen Solidarhandeln und Maktorientierung'.

Child, M. *et al.* (2019) 'Flexible electricity generation, grid exchange and storage for the transition to a 100% renewable energy system in Europe', *Renewable Energy*. Elsevier Ltd, 139, pp. 80–101. doi: 10.1016/j.renene.2019.02.077.

Climate Action Network Europe and European Environmental Bureau (2020) *Building a Paris Agreement Compatible (PAC) energy scenario: CAN Europe/EEB technical summary of key elements*. Available at: https://www.pac-scenarios.eu/fileadmin/user_upload/PAC_scenario_technical_summary_fin.pdf.

Climate Action Tracker (2018) *Scaling up climate action: European Union*. Available at: https://climateactiontracker.org/documents/505/CAT_2018-12-06_ScalingUp_EU_FullReport.pdf.

Climate Action Tracker (2020) *Paris Agreement Compatible Sectoral Benchmarks: Elaborating the decarbonisation roadmap*. Available at: https://climateactiontracker.org/documents/753/CAT_2020-07-10_ParisAgreementBenchmarks_FullReport.pdf.

Climate Analytics (2018) 'Science based coal phase-out pathway for Germany in line with the Paris Agreement 1.5°C warming limit', (October). Available at: https://climateanalytics.org/media/germany_coalphaseout_report_climateanalytics_final.pdf.

Climate Analytics (2020) 'Germany's coal exit law, or the politics of inertia'. Available at: https://climateanalytics.org/blog/2020/germanys-coal-exit-law-or-the-politics-of-inertia/.

Connolly, D., Lund, H. and Mathiesen, B. V. (2016) 'Smart Energy Europe: The technical and economic impact of one potential 100% renewable energy scenario for the European Union', *Renewable and Sustainable Energy Reviews*. Elsevier, 60, pp. 1634–1653. doi: 10.1016/j.rser.2016.02.025.

Council of the European Union (2020) 'Outcome of Proceedings'.

Dalla-Longa, F. *et al.* (2017) *Wind potentials for EU and neighbouring countries - Input datasets for the JRC-EU-TIMES Model*. doi: 10.2760/041705.

DECC (2015) 'Large Combustion Plant Directive (LCPD): Running hours during winter 2014/15 and capacity for 2015/16'.

Deloitte (2015) 'European energy market reform. Country Profile: Spain'. Available at: https://www2.deloitte.com/content/dam/Deloitte/global/Documents/Energy-and-Resources/gx-er-market-reform-spain.pdf.

Deutscher Bundestag (1990) 'Stromeinspeisungsgesetz'.

Deutscher Bundestag (2000) 'Erneuerbare-Energien-Gesetz (EEG) vom 25.02.2000'. Available at: http://www.iwr.de/re/iwr/info0005.html.

Deutscher Bundestag (2012) 'Gesetz für den Vorrang Erneuerbarer Energien (Erneuerbare-Energien-Gesetz - EEG)'. Available at: https://www.clearingstelle-eeg-kwkg.de/sites/default/files/EEG2012_juris_120817.pdf.

Deutscher Bundestag (2020) 'Kohleausstiegsgesetz', 2020(37), p. 202. Available at: https://www.bmwi.de/Redaktion/DE/Downloads/A/abschlussbericht-kommission-.

Deutscher Bundetsag (2004) 'Gesetz für den Vorrang Erneuerbarer Energien (Erneuerbare-Energien-Gesetz - EEG)'. Available at: https://www.clearingstelle-eeg-kwkg.de/sites/default/files/EEG_2004_letzte_Fassung_061107.pdf.

Deutsches Institut für Wirtschaftsforschung (2020) *Make the European Green Deal Real- Combining Climate Neutrality and Economic Recovery*. Available at: https://www.diw.de/documents/publikationen/73/diw_01.c.791736.de/diwkompakt_2020-153.pdf.

DNV GL-Energy (2017) 'Hard coal / lignite fired power plants in EU28. Fact-based scenario to meet commitments under the LCP BREF'. Available at: https://europeanclimate.org/wp-content/uploads/2017/06/16-1213-rev2-DNV-GL-report-ECF-BREF-LCP2.pdf.

DNV GL and WindEurope (2018) *Breaking new ground: Wind energy and the electrification of Europe's energy system*. Available at: https://windeurope.org/wp-content/uploads/files/about-wind/reports/WindEurope-breaking-new-ground.pdf.

EC BREC (2002) 'Executive Program to the Strategy for the Developmnet of Renewable Sources of Energy'.

electrek (2020) 'The demise of coal in Spain'. Available at: https://electrek.co/2020/07/01/spain-closes-nearly-half-of-its-coal-fired-power-stations/.

Ember (2020) 'Renewables beat fossil fuels. A half-yearly analysis of Europe's electricity transition'.

ENDS Europe (2020) 'Spain to offer €181 million in renewable energy subsidies'. Available at: https://www.iisd.org/sustainable-recovery/news/clean-recovery-spain-offers-eur-181-million-for-renewable-energy-projects/.

Energy Watch Group and Lappeenranta University of Technology (2019) *Global Energy System based on 100% Renewable Energy*, *Energy Watch Group*. Available at: http://energywatchgroup.org/new-study-global-energy-system-based-100-renewable-energy.

Euractiv (2018) 'EU's Cañete warns gas pipelines risk becoming "stranded assets"'. Available at: https://www.euractiv.com/section/energy-environment/news/eus-canete-warns-gas-pipelines-risk-becoming-stranded-assets/.

Euractive (2018) 'Spain to lead the energy transition in Europe?' Available at: https://www.euractiv.com/section/energy/opinion/spain-to-lead-the-energy-transition-in-europe/.

Eurelectric (2018) *Decarbonisation pathways Full study results Part 1 - European economy Part 2- European power sector*. Available at: https://cdn.eurelectric.org/media/3558/decarbonisation-pathways-all-slideslinks-29112018-h-4484BB0C.pdf.

EurObserv'ER (2009) 'The State of Renewable Energies in Europe. The 9th EurObserv'ER Report'.

EurObserv'ER (2010) 'The State of Renewable Energies in Europe'.

EurObserv'ER (2011) 'The State of Renewables in Europe.'

EurObserv'ER (2013) 'The State of Renewable Energies in Europe'.

EurObserv'ER (2017) 'The state of renewable energies in Europe - Edition 2017, 17th EurObserv'ER Report'.

Europe Beyond Coal (2020) 'Overview: National coal phase-out announcements in Europe. Status February 2020.' Available at: https://beyond-coal.eu/wp-content/uploads/2019/02/Overview-of-national-coal-phase-out-announcements-Europe-Beyond-Coal-March-2019.pdf.

European Climate Foundation (2018) 'Net Zero by 2050: From Whether to How', (September). Available at: www.lindsayynobledesign.com.

European Commission (2014a) *Commission Regulation (EU) No 176/2014 of 25 February 2014 amending Regulation (EU) No 1031/2010 in particular to determine the volumes of greenhouse gas emission allowances to be auctioned in 2013-20*. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32014R0176&from=EN (Accessed: 29 November 2016).

European Commission (2014b) 'Guidelines on State aid for environmental protection and energy 2014-2020', *Official Journal of the European Union*, C 200/1, pp. 1–55. doi: 10.1016/j.nucengdes.2011.01.052.

European Commission (2018a) *A Clean Planet for all. A European long-term strategic vision for a prosperous , modern , competitive and climate neutral economy.* Available at: https://ec.europa.eu/clima/sites/clima/files/docs/pages/com_2018_733_analysis_in_support_en_0.pdf.

European Commission (2018b) 'A Clean Planet for all. A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy'. Available at: https://ec.europa.eu/clima/sites/clima/files/docs/pages/com_2018_733_en.pdf.

European Commission (2018c) *ETS Market Stability Reserve will start by reducing auction volume by almost 265 million allowances over the first 8 months of 2019*. Available at: https://ec.europa.eu/clima/news/ets-market-stability-reserve-will-start-reducing-auction-volume-almost-265-million-allowances_en.

European Commission (2018d) *In-depth analysis in support of the Commission Communication COM(2018)773 A Clean Planet for all.* Available at: https://ec.europa.eu/clima/sites/clima/files/docs/pages/com_2018_733_analysis_in_support_en_0.pdf.

European Commission (2018e) *In-depth analysis in support of the Commission Communication COM(2018)773 A Clean Planet for all.*

European Commission (2019a) 'Communication from the Commission: The European Green Deal', *COM(2019) 640 final*, p. p24. doi: 10.1017/CBO9781107415324.004.

European Commission (2019b) 'Energy prices and costs in Europe'. Available at: https://ec.europa.eu/energy/sites/ener/files/epc_report_final_1.pdf.

European Commission (2019c) *ETS Market Stability Reserve to reduce auction volume by almost 400 million allowances between September 2019 and August 2020*. Available at: https://ec.europa.eu/clima/news/ets-market-stability-reserve-reduce-auction-volume-almost-400-million-allowances-between_en.

European Commission (2019d) 'EU greenhouse gas emissions down 23% since 1990, still implementation will have to be further accelerated to reach current 2030 targets'.

European Commission (2019e) *Results of the EUCO3232.5 scenario on Member States*. Available at: https://ec.europa.eu/energy/sites/ener/files/technical_note_on_the_euco3232_final_14062019.pdf.

European Commission (2019f) 'Technical Note. Results of the EUCO3232.5 scenario on Member States', (December), p. 62. Available at: https://ec.europa.eu/energy/en/data-analysis/energy-modelling/euco-scenarios.

European Commission (2020a) 'A Renovation Wave for Europe - greening our buildings, creating jobs, improving lives'.

European Commission (2020b) 'An EU-wide assessment of National Energy and Climate Plans'.

European Commission (2020c) 'Autumn 2020 Economic Forecast: Rebound interrupted as resurgence of pandemic deepens uncertainty'.

European Commission (2020d) 'Coal regions in transition'. Available at: https://ec.europa.eu/energy/topics/oil-gas-and-coal/EU-coal-regions/coal-regions-transition_en.

European Commission (2020e) *Communication: Stepping up Europe's 2030 climate ambition Investing in a climate-neutral future for the benefit of our people*. Available at: https://ec.europa.eu/clima/sites/clima/files/eu-climate-action/docs/com_2030_ctp_en.pdf.

European Commission (2020f) 'Emissions trading: greenhouse gas emissions reduced by 8.7% in 2019'.

European Commission (2020g) 'Emissions trading: greenhouse gas emissions reduced by 8.7% in 2019', pp. 1–5. Available at: https://ec.europa.eu/clima/news/emissions-trading-greenhouse-gas-emissions-reduced-87-2019_en.

European Commission (2020h) *ETS Market Stability Reserve to reduce auction volume by over 330 million allowances between September 2020 and August 2021*. Available at: https://ec.europa.eu/clima/news/ets-market-stability-reserve-reduce-auction-volume-over-330-million-allowances-between_en.

European Commission (2020i) 'EU budget for recovery: Questions and answers on the Just Transition Mechanism'.

European Commission (2020j) 'European Economic Forecast. Summer 2020 (interim)'. Available at: https://ec.europa.eu/info/sites/info/files/economy-finance/ip132_en.pdf.

European Commission (2020k) *Eurostat Database*. Available at: https://ec.europa.eu/eurostat/data/database (Accessed: 15 August 2020).

European Commission (2020l) 'Financing the green transition: The European Green Deal Investment Plan and Just Transition Mechanism'. Available at: https://ec.europa.eu/regional_policy/en/newsroom/news/2020/01/14-01-2020-financing-the-green-transition-the-european-green-deal-investment-plan-and-just-transition-mechanism.

European Commission (2020m) *Impact Assessment; Stepping up Europe's 2030 climate ambition. Investing in a climate-neutral future for the benefit of our people*. Brussels: European Commission. Available at: https://ec.europa.eu/clima/policies/eu-climate-action/2030_ctp_en.

European Commission (2020n) 'Onshore and offshore wind'. Available at: https://ec.europa.eu/energy/topics/renewable-energy/onshore-and-offshore-wind_en.

European Commission (2020o) 'Proposal for a Regulation of the European Parliament and of the Council establishing the framework for achieving climate neutrality and amending Regulation (EU) 2018/1999 (European Climate Law)'.

European Commission (2020p) 'Quarterly Report on European Electricity Markets'. Available at: https://ec.europa.eu/energy/sites/ener/files/qr_electricity_q1_2020.pdf.

European Commission (2020q) 'Quarterly Report on European Electricity Markets', 12(4). Available at: https://ec.europa.eu/energy/sites/ener/files/quarterly_report_on_european_electricity_markets_q_4_2019_final.pdf.

European Commission (2020r) 'Quarterly Report on the European Electricity Market. Q2 of 2020.' Available at: https://ec.europa.eu/energy/sites/ener/files/documents/quarterly_report_on_european_electricity_markets_q_2_2020.pdf.

European Commission (2020s) *Stepping up Europe's 2030 climate ambition Investing in a climate-neutral future for the benefit of our people*. Brussels, Belgium. doi: 10.1017/CBO9781107415324.004.

European Council (2014) 'Conclusions on 2030 Climate and Energy Policy Framework', 2014(October 2014), pp. 1–10.

European Council (2015) *Submission by Latvia and the European Commission on behalf of the European Union and its Member States: Intended Nationally Determined Contribution of the EU and its Member States*.

European Council (2019) 'European Council meeting (12 December 2019) - Conclusions'. Available at: https://www.consilium.europa.eu/media/41768/12-euco-final-conclusions-en.pdf.

European Council (2020) 'Conclusions adopted by the European Council'. Available at: https://www.consilium.europa.eu/media/45109/210720-euco-final-conclusions-en.pdf.

European Environment Agency (2018) 'Efficiency of conventional thermal electricity and heat production in Europe'.

European Environment Agency (2019) 'The EU Emissions Trading System in 2019: trends and projections', *EEA report*, pp. 1–8. doi: 10.2800/324887.

European Environment Agency (2020a) *EEA Greenhouse Gas- data viewer*. Available at: https://www.eea.europa.eu/data-and-maps/data/data-viewers/greenhouse-gases-viewer (Accessed: 18 August 2020).

European Environment Agency (2020b) 'EEA greenhouse gas - data viewer'.

European Network of Transmission System Operators for Electricity (2020) *Completing the map: Power system needs in 2030 and 2040 About ENTSO-E*. Available at: https://eepublicdownloads.azureedge.net/tyndp-documents/IoSN2020/200810_IoSN2020mainreport_beforeconsultation.pdf.

European Parliament (2020a) 'Amendments adopted by the European Parliament on 8 October 2020 on the proposal for a regulation of the European Parliament and of the Council establishing the framework for achieving climate neutrality and amending Regulation (EU) 2018/1999 (European Cli'.

European Parliament (2020b) 'European Parliament resolution of 17 September 2020 on maximising the energy efficiency potential of the EU building stock'.

European Parliament and the Council of the European Union (2001a) 'Directive 2001/80/EC of the European Parliament and of the Council of 23 October 2001 on the limitation of emissions of certain pollutants into the air from large combustion plants'.

European Parliament and the Council of the European Union (2001b) 'Directive 20011/77/EC of the European Parliament and of the Council of 27 September 2001 on the promotion of electricity produced from renewable energy sources in the internal electricity market', *Communities*, 6, pp. 12–25. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32001L0077&from=EN.

European Parliament and the Council of the European Union (2003) 'Directive 2003/87/EC of the European Parliament and of the Council as of 13 October 2003 establishing a scheme for greenhouse gas emission allowance trading within the Community and amending Council Directive 96/61/EC', *Official Journal of the European Union*.

European Parliament and the Council of the European Union (2009a) 'Decision No 406/2009/EC of the European Parliament and of the Council of 23 April 2009 on the effort of Member States to reduce their greenhouse gas emissions to meet the Community's greenhouse gas emission reduction commitments up to 2020'.

European Parliament and the Council of the European Union (2009b) 'Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009', *Official Journal of the European Union*, 140, pp. 16–62. doi: 10.3000/17252555.L_2009.140.eng.

European Parliament and the Council of the European Union (2009c) 'Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC'. Available at: http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32009L0028&from=EN.

European Parliament and the Council of the European Union (2009d) 'Directive 2009/29/EC of the European Parliament and of the council of 23 April 2009 ammending Directive 2003/87/EC', *Official Journal of the European Union*, 140, pp. 63–87.

European Parliament and the Council of the European Union (2010) 'Directive 2010/75/EU of the European Parliament and of the Council of 24 November 2010 on industrial emissions (integrated pollution prevention and control) (Recast)'.

European Parliament and the Council of the European Union (2012) 'Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency', *Official Journal of the European Union Directive*, (October), pp. 1–56. doi: 10.3000/19770677.L_2012.315.eng.

European Parliament and the Council of the European Union (2015) 'Decision (EU) 2015/1814 of the European Parliment and of the Council of 6 October 2015 concerning the establishment and operation of a maerket stability reserve for the Union greenhouse gas emission trading scheme and amending Directive 2003/87/EC', *Official Journal of the European Union*, L264(9.10.2015), pp. 1–5. doi: 10.1007/s13398-014-0173-7.2.

European Parliament and the Council of the European Union (2018a) *Directive (EU) 2018/2001 of the European Parliament and of the Council on the promotion of the use of energy from renewable sources*, *Official Journal of the European Union*. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32018L2001&from=EN.

European Parliament and the Council of the European Union (2018b) 'Directive (EU) 2018/410 of the European Parliament and of the Council of 14 March 2018 amending Directive 2003/87/EC to enhance cost-effective emission reductions and low-carbon investments, and Decision (EU) 2015/1814', *Official Journal of the European Union*, L76(October 2003), pp. 3–27. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32018L0410&from=DE.

European Parliament and the Council of the European Union (2018c) 'Directive 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources (recast)'.

European Parliament and the Council of the European Union (2018d) 'Regulation (EU) 2018/1999 of the European Parliament and of the Council of 11 December 2018', *Official Journal of the European Union*, 328(1), pp. 1–77. doi: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32018R1999&from=EN.

European Parliament and the Council of the European Union (2018e) 'Regulation (EU) 2018/1999 of the European Parliament and of the Council of 11 December 2018 on the Governance of the Energy Union and Climate Action.'

European Parliament and the Council of the European Union (2018f) 'Regulation (EU) 2018/842 of the European Parliament and of the Council of 30 May 2018 on binding annual greenhouse gas emission reductions by Member States from 2021 to 2030 contributing to climate action to meet commitments under the Paris Agreement.' Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2018.156.01.0026.01.ENG.

Eurostat (2020a) 'Complete energy balances [nrg_bal_c]'.

Eurostat (2020b) 'Energy imports dependency [nrg_ind_id]'.

Eurostat (2020c) 'Purchasing power parities (PPPs), price level indices and real expenditures for ESA 2010 aggregates'.

Eurostat (2020d) 'Supply, transformation and consumption of solid fossil fuels'.

Eurostat (2020e) 'Tables on EU policy'.

EVWind (2020) 'Spain rolls out ambitious new climate legislation'. Available at: https://www.evwind.es/2020/05/26/spain-rolls-out-ambitious-new-climate-legislation/74862.

Farand, C. (2020) 'Spain unveils climate law to cut emissions to net zero by 2050'. Available at: https://www.climatechangenews.com/2020/05/18/spain-unveils-climate-law-cut-emissions-net-zero-2050/.

Forum Energii (2019) 'Transformacja energetyczna w Polsce. Edycja 2019'.

Forum Energii (2020) 'Transformacja energetyczna w Polsce. Edycja 2020'.

Fraunhofer ISE (2020a) *Net installed electricity generation capacity in Germany*. Available at: https://energy-charts.de/power_inst.htm (Accessed: 1 June 2020).

Fraunhofer ISE (2020b) *Net installed electricity generation capacity in Germany*.

Fraunhofer ISI (2020) 'Aktuelle Fakten zur Photovoltaik in Deutschland', 1(99), pp. 1–99. Available at: https://www.ise.fraunhofer.de/content/dam/ise/de/documents/publications/studies/aktuelle-fakten-zur-photovoltaik-in-deutschland.pdf.

Gaffney, F. *et al.* (2020) 'Comparing negative emissions and high renewable scenarios for the European power system', *BMC Energy*. BMC Energy, 2(1), pp. 1–13. doi: 10.1186/s42500-020-00013-4.

Geothermal Communities (2013) 'Geothermal Systems and Technologies'. Available at: https://geothermalcommunities.eu/assets/elearning/6.22.Shallow Geothermal SYstems.pdf.

Gerbaulet, C. *et al.* (2019) 'European electricity sector decarbonization under different levels of foresight', *Renewable Energy*. Elsevier Ltd, 141, pp. 973–987. doi: 10.1016/j.renene.2019.02.099.

GET Invest (2020) *Global Market Outlook for Solar Power/ 2020-2024*. doi: 10.4018/978-1-7998-4607-9.ch006.

GIPH (2003) 'Węgiel i biomasa', *Biuletyn Górniczy*. Available at: http://www.giph.com.pl/bg/2003_05-06/biomasa.html.

Global CCS Institute (2020) *CCS Facilities Database*. Available at: https://co2re.co/FacilityData (Accessed: 9 November 2020).

Global Data (2020) 'Spain's remaining coal-fired plants likely to be phased out by 2025'. Available at: https://www.globaldata.com/spains-remaining-coal-fired-plants-likely-to-be-phased-out-by-2025/.

Global Wind Energy Council (2017) 'GWEC Global Wind 2017 Report - A snapshot of top wind markets in 2017: Offshore wind', pp. 54–63. doi: 10.1021/jp0213102.

Government of the Netherlands (2018) 'Dutch Cabinet: termination of natural gas extraction in Groningen'.

Grashof, K. *et al.* (2020) 'Long on promises, short on delivery? Insights from the first two years of onshore wind auctions in Germany', *Energy Policy*, 140(C). doi: 10.1016/j.enpol.2020.111240.

Greenpeace (2015) *Energy [R] Evolution*, *Energy [R]Evolution*.

GUS (2019) 'Energy statistics in 2017 and 2018'.

Hauschildt, J. and Pulczynski, J. (1995) 'Growian: Zielbildung für bedeutende Innovationsvorhaben'. Available at: https://web.archive.org/web/20100704221230/http://www.offshore-wind.de/page/fileadmin/offshore/documents/TU-Berlin_GroWiAn.pdf.

Hoppe-Kilpper, M. (2004) 'Perspektiven der Windenergienutzung in Deutschland'.

ICIS (2020) *European power and carbon markets affected by COVID-19 – an early impact assessment*, *Indipendent Commodity Intellegence Services*. Available at: https://www.icis.com/explore/resources/news/2020/03/27/10487371/european-power-and-carbon-markets-affected-by-covid-19-an-early-impact-assessment.

IISD (2014) 'A Cautionary Tale. Solar PV Investment Bubble.'

IMF (2020) 'IMF Data Mapper'.

Institute for Energy Economics and Financial Analysis (2020) *Petra Nova Mothballing Post-Mortem: Closure of Texas Carbon Capture Plant Is a Warning Sign*. Available at: https://ieefa.org/wp-content/uploads/2020/08/Petra-Nova-Mothballing-Post-Mortem_August-2020.pdf.

International Energy Agency (2017) *Energy Technology Perspectives (ETP).* Paris, France. Available at: https://www.iea.org/reports/energy-technology-perspectives-2017.

International Energy Agency (2019) *World Energy Outlook 2019*. doi: 10.1049/ep.1977.0180.

International Energy Agency (2020) *Data and Statistics*. Available at: https://www.iea.org/data-and-statistics/?country=EU28&fuel=CO2 emissions&indicator=CO2 emissions by sector (Accessed: 18 August 2020).

International Renewable Energy Agency (2020) *Data and Statistics*. Available at: https://www.irena.org/Statistics (Accessed: 15 July 2020).

IRENA (2020a) *Renewable Capacity Statistics 2020*. Abu Dhabi.

IRENA (2020b) 'Trends in Renewable Energy'. Available at: https://public.tableau.com/views/IRENARETimeSeries/Charts?:embed=y&:showVizHome=no&publish=yes&:toolbar=no.

IWR (2004) 'EEG-Vergütungssätze (2000 - 2004)'.

JRC (2017) *Renewables in the EU: an overview of support schemes and measures*, *JCR Science for Publicy Report*. doi: 10.2760/69943.

JRC (2018) 'EU coal regions: opportunities and challenges ahead'.

Kommission Wachstum Strukturwandel und Beschäftigung. (2019) 'Abschlussbericht'. Available at: https://www.bmwi.de/Redaktion/DE/Downloads/A/abschlussbericht-kommission-wachstum-strukturwandel-und-beschaeftigung.pdf?__blob=publicationFile.

Laing, T. *et al.* (2013) 'Assessing the effectiveness of the EU Emissions Trading System', *CCCEP Working Paper No. 126*, (126), p. 35. Available at: http://www.lse.ac.uk/GranthamInstitute/publications/WorkingPapers/Papers/100-109/WP106-effectiveness-eu-emissions-trading-system.pdf.

MCC (2018) 'Five myths about an EU ETS carbon price floor', *CEPS Policy Insights*, (October), pp. 1–14.

Ministry for Ecological Transition. (2019) 'The Just Transition Strategy within the Strategic Energy and Climate Framework'. Available at: https://www.miteco.gob.es/en/prensa/etj-english-interactive_tcm38-505653.pdf.

Ministry of Climate (2020a) 'Krajowy plan na rzecz energii i klimatu na lata 2021-2030'.

Ministry of Climate (2020b) *Polityka energetyczna Polski do 2040 r.* Available at: https://www.gov.pl/web/klimat/minister-kurtyka-polityka-energetyczna-polski-do-2040-r-udziela-odpowiedzi-na-najwazniejsze-wyzwania-stojace-przed-polska-energetyka-w-najblizszych-dziesiecioleciach.

Ministry of Climate (2020c) *Polityka energetyczna Polski do 2040 r.*

Ministry of Economy (2012) 'Justification of the draft of the Renewable Energy Law'. Available at: https://www.igwp.org.pl/images/pliki/naszaaktywnosc/legislacja/oze/9102012uzasadnienie.pdf.

Ministry of State Assets (2020) 'Porozumienie w sprawie transformacji i przyszłości górnictwa podpisane'.

Money (2019) 'Padł rekord importu węgla. 70 proc. pochodzi z Rosji'.

NETTG (2020a) 'Górnictwo: W kopalniach węgla kamiennego zatrudnienie stoi w miejscu'.

NETTG (2020b) 'Węgiel: tak niskie ceny dla indeksu CIF ARA były siedemnaście lat temu'. Available at: https://nettg.pl/news/168548/wegiel-tak-niskie-ceny-dla-indeksu-cif-ara-byly-siedemnascie-lat-temu#:~:text=- Ceny spot węgla w portach,dla całego roku 2018 r.

Newsweek (2011) 'Tusk: Gaz z łupków już w 2014 roku'. Available at: https://www.newsweek.pl/tusk-eksploatacja-gazu-lupkowego-od-2014-roku/p8yfnb2.

NFOŚiGW (2020) '100 000 wniosków w rządowym programie „Mój Prąd"'.

Nijs, W. *et al.* (2018) *Deployment Scenarios for Low Carbon Energy Technologies,*. Petten, Netherlands. doi: 10.2760/249336.

Oeko-Institut (2017) *The Vision Scenario for the European Union 2017 Update for the EU-28*. Available at: https://www.greens-efa.eu/en/article/document/the-vision-scenario-for-the-european-union-7659/.

Oeko-Institut (2020) 'How to Raise Europe's Climate Ambitions for 2030'.

Pais, E. (2020) 'Spain to close half its coal-fired power stations'. Available at: https://english.elpais.com/economy_and_business/2020-06-29/spain-to-close-half-its-coal-fired-power-stations.html.

Parliamentary Environmental Committee (1999) 'Meeting of the Parliamentary Environmental Committee from 16

Mar. 1999', *Biuletyny Komisji Sejmowych*.

El Periodico (2018) 'La breve historia del "impuesto al sol"'. Available at: https://www.elperiodico.com/es/mas-innovacion/20181017/la-breve-historia-del-impuesto-al-sol-7093609.

PV-Magazine (2015) 'Spain's government approves the "sun tax'. Available at: https://www.pv-magazine.com/2015/10/09/spains-government-approves-the-sun-tax_100021485/.

PV TECH (2017) 'Winners of Spain's 5GW renewables auction announced'. Available at: https://www.pv-tech.org/news/winners-of-spains-5gw-renewables-auction-announced.

REcharge (2020) 'Denmark confirms massive wind plans for "world's first energy islands" in North Sea and Baltic'. Available at: https://www.rechargenews.com/wind/denmark-confirms-massive-wind-plans-for-worlds-first-energy-islands-in-north-sea-and-baltic/2-1-812707.

REE (2019) 'The Spanish Electricity System. Preliminary Report'. Available at: https://www.ree.es/sites/default/files/11_PUBLICACIONES/Documentos/InformesSistemaElectrico/2019/Avance_ISE_2018_en.pdf.

REE (2020a) 'Renewable energy already exceeds the installed power capacity of other sources of energy on the Spanish peninsula'. Available at: https://www.ree.es/en/press-office/news/press-release/2020/03/renewable-energy-already-exceeds-installed-power-capacity-of-other-sources-of-energy-on-the-Spanish-peninsula.

REE (2020b) 'The Spanish Electricity System. Preliminary Report'. Available at: https://www.ree.es/sites/default/files/11_PUBLICACIONES/Documentos/InformesSistemaElectrico/2020/avance_ISE_2019_EN.pdf.

Sandbag (2019) 'Halfway There'. Available at: https://sandbag.org.uk/wp-content/uploads/2019/04/Halfway-There-March-2019-Sandbag.pdf.

Schaeffer, M. *et al.* (2019) *Insights from the IPCC Special Report on 1.5°C for preparation of long-term strategies*. Berlin/Perth. Available at: https://climateanalytics.org/media/climateanalytics_ipcc-lt-leds_report_april_2019.pdf.

Schill, W.-P. (2020) 'Electricity Storage and the Renewable Energy Transition', *Joule*. Elsevier Inc., pp. 1–6. doi: 10.1016/j.joule.2020.07.022.

Schill, W. P. and Zerrahn, A. (2018) 'Long-run power storage requirements for high shares of renewables: Results and sensitivities', *Renewable and Sustainable Energy Reviews*. Elsevier Ltd, 83(September 2016), pp. 156–171. doi: 10.1016/j.rser.2017.05.205.

Sejm RP (1990) 'Uchwała w sprawie założeń polityki energetycznej Polski do 2010 r.', *Monitor Polski*, 43(332).

Sejm RP (1999) 'Rezolucja Sejmu Rzeczpospolitej Polskiej z dnia 8 lipca 1999 r. w sprawie wzrostu wykorzystania energii ze źródeł odnawialnych', *Monitor Polski*, 25(365).

Sejm RP (2016) 'Ustawa z dnia 20 maja 2016 r. o inwestycjach w zakresie elektrowni wiatrowych'. Available at: https://sip.lex.pl/akty-prawne/dzu-dziennik-ustaw/inwestycje-w-zakresie-elektrowni-wiatrowych-18320622.

Skjærseth, J. B. (2018) 'Implementing EU climate and energy policies in Poland: policy feedback and reform', *Environmental Politics*, 27(3). doi: https://doi.org/10.1080/09644016.2018.1429046.

Solar Power Europe (2020a) 'Global Market Outlook For Solar Power for 2020 - 2024'.

Solar Power Europe (2020b) 'Global Market Outlook For Solar Power for 2020 - 2024'. Available at: https://www.solarpowereurope.org/wp-content/uploads/2020/07/31-SPE-GMO-report-hr-hyperlinks.pdf?cf_id=16358.

Steinbacher, K. (2016) *Exporting the Energiewende*. Springer Berlin / Heidelberg.

Süddeutsche Zeitung (2019) 'Der große Blackout'. Available at: https://www.sueddeutsche.de/wirtschaft/enercon-stellenabbau-krise-windenergie-1.4673755.

Tacke, F. (2004) *Windenergie: die Herausforderung: gestern, heute, morgen*. VDMA-Verlag.

Teske, S. (2019) *Achieving the Paris Climate Agreement Goals*, *Achieving the Paris Climate Agreement Goals*. doi: 10.1007/978-3-030-05843-2.

The European Parliament and the Council of the European Union (2019) 'Directive (EU) 2019/944 of the European Parliament and of the Council of 5 June 2019 on common rules for the internal market for electricity and amending

Directive 2012/27/EU'.

The Government of Spain (1998) 'Royal Decree 2818/1998, of December 23, on the production of electrical energy by facilities supplied by renewable energy sources or resources, waste and cogeneration.'

The Government of Spain (2010) 'Spain's National Renewable Energy Action Plan 2011-2020'. Available at: http://pvtrin.eu/assets/media/PDF/EU_POLICIES/National Renewable Energy Action Plan/202.pdf.

The Government of Spain (2018a) 'Análisis y propuestas para la descarbonización'. Available at: http://www6.mityc.es/aplicaciones/transicionenergetica/informe_cexpertos_20180402_veditado.pdf.

The Government of Spain (2018b) 'Royal Decree-law 15/2018 on urgent measures for energy transition and consumer protection'. Available at: https://climate-laws.org/geographies/spain/policies/royal-decree-law-15-2018-on-urgent-measures-for-energy-transition-and-consumer-protection.

The Government of Spain (2019a) 'Government presents Strategic Energy and Climate Framework'. Available at: https://www.lamoncloa.gob.es/lang/en/gobierno/councilministers/Paginas/2019/20190222framework.aspx#:~:text =The minister explained that the,private%2C public and joint investment.&text=This reduction will allow a,the years 2020 and 2030.

The Government of Spain (2019b) 'Royal Decree 244/2019 regulating the administrative, technical and economic conditions of the self-consumption of electric energy'. Available at: https://climate-laws.org/geographies/spain/policies/royal-decree-244-2019-regulating-the-administrative-technical-and-economic-conditions-of-the-self-consumption-of-electric-energy.

The Government of Spain (2020) *Integrated national energy and climate plan 2021-2030*. Available at: https://ec.europa.eu/energy/sites/ener/files/documents/es_final_necp_main_en.pdf.

The World Bank (2020a) 'CO2 emissions (kg per PPP $ of GDP)'.

The World Bank (2020b) 'Data for European Union, United States, China'.

The World Bank (2020c) 'Energy use (kg of oil equivalent per capita) - European Union, World, United States, China'.

The World Bank (2020d) 'Services, value added (% of GDP) - European Union, World, United States, China'.

U.S. Department of Energy (2020) 'All-Electric Vehicles'.

Umwelbundesamt (2019) 'Geplante Abstandsregeln für Windräder gefährden Klimaziele'. Available at: https://www.umweltbundesamt.de/themen/geplante-abstandsregeln-fuer-windraeder-gefaehrden.

Umweltbundesamt (2019) *GHG-neutral EU2050 -a scenario of an EU with net-zero greenhouse gas emissions and its implications*. Available at: https://www.umweltbundesamt.de/publikationen/ghg-neutral-eu2050.

Umweltbundesamt (2020) 'Raising the EU 2030 GHG Emission Reduction Target'.

URE (2020a) 'Ilość energii elektrycznej wytworzonej z OZE w latach 2005-2019 potwierdzonej wydanymi świadectwami pochodzenia'.

URE (2020b) 'Moc zainstalowana (MW)'.

URE (2020c) 'System aukcyjny dla odnawialnych źródeł energii ma 5 lat'.

Wehrmann, B. (2019) 'German wind power industry anxious as technology tops power mix'. Available at: https://www.cleanenergywire.org/news/german-wind-power-industry-anxious-technology-tops-power-mix.

Wind Europe (2020a) 'Wind energy in Europe in 2019'.

Wind Europe (2020b) 'Wind energy in Europe in 2019'. Available at: https://proceedings.windeurope.org/biplatform/rails/active_storage/disk/eyJfcmFpbHMiOnsibWVzc2FnZSI6IkJBa DdDRG9JYTJWNVNTSWhObTg0Y0RaNGMyc3dPV0ZwYm14dmVHbDNaelZ2WWpaa1lYSmxid1k2QmtWVU9o QmthWE53YjNOcGRHbHZia2tpZFdsdWJHbHVaVHNnWm1sc1pXNWhiV1U5SWxkcGJtUkZkWEp.

WindEurope (2020) 'Our energy, our future'. Available at: https://windeurope.org/wp-content/uploads/files/about-wind/reports/WindEurope-Our-Energy-Our-Future.pdf.

WWEA (2019) 'Bürgerwind im zweiten Jahr der Ausschreibungen : Viel Schatten, wenig Licht', *WWEA Policy Paper Series*, (Mai). Available at: http://www.wwindea.org/download/WWEA_Burgerwindstudie_2019_Web.pdf.

Wysokie Napiecie (2020) 'Wydobycie węgla w Polsce bliżej końca niż mówią politycy'.

Wysokie Napięcie (2019) 'Rekordowy import prądu w 2019 roku: ponad 10 TWh za 2 mld zł'. Available at: https://wysokienapiecie.pl/25377-rekordowy-import-pradu-w-2019-roku-ponad-10-twh-za-2-mld-zl/.

Wysokie Napięcie (2020a) 'Produkcja prądu najniższa w dekadzie. Udział węgla najmniejszy w historii'.

Wysokie Napięcie (2020b) 'Rząd szykuje kolejny magazyn węgla za 130 milionów zł'.

Wysokie Napięcie (2020c) 'Zwały węgla w Polsce sięgają już 20 mln ton. Co dalej?'

Zaklan, A., Wachsmuth, J. and Duscha, V. (2020) 'EU ETS up to 2030: Adjusting the Cap in light of the IPCC1.5°C Special Report and the Paris Agreement'.

Zappa, W., Junginger, M. and van den Broek, M. (2019) 'Is a 100% renewable European power system feasible by 2050?', *Applied Energy*, 233–234(January 2018), pp. 1027–1050. doi: 10.1016/j.apenergy.2018.08.109.

ZfK (2020a) 'Oberverwaltungsgericht bestätigt Windenergie-Moratorium'. Available at: https://www.zfk.de/politik/deutschland/artikel/5f94de9f6d6e95ce815e0ce93a98cf69/oberverwaltungsgericht-bestaetigt-windenergie-moratorium-2020-02-27/.

ZfK (2020b) 'Offshore-Wind: Einigung auf 20-GW-Ausbau bis 2030'. Available at: https://www.zfk.de/politik/deutschland/artikel/05d477339537f63960e806f4f36792a5/offshore-wind-einigung-auf-20-gw-ausbau-bis-2030-2020-05-10/.

Ziegler, M. S. *et al.* (2019) 'Storage Requirements and Costs of Shaping Renewable Energy Toward Grid Decarbonization', *Joule*, 3(9), pp. 2134–2153. doi: 10.1016/j.joule.2019.06.012.