CLIMATE ANALYTICS

A STRESS TEST FOR COAL IN EUROPE UNDER THE PARIS AGREEMENT

SCIENTIFIC GOALPOSTS FOR A COORDINATED PHASE-OUT AND DIVESTMENT

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Coal excavator from above
Photo © Curioso

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EXECUTIVE SUMMARY

The long-term temperature goal adopted under the Paris Agreement of holding temperature increase to "well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels" requires a rapid decarbonisation of the global power sector and the phase-out of the last unabated coal-fired power plant in the EU by around 2030.

While moving away from coal is required to achieve the transformation in line with the Paris Agreement long-term temperature goal, a fast coal phase-out strategy in the European Union represents not only a necessity but also an opportunity when considering other policy goals beyond climate change. There are numerous alternatives to coal and their development is gaining momentum, **many bringing benefits beyond emissions reductions, such as cleaner air, energy security, and distribution.**

Currently hard coal and lignite jointly provide over a quarter of electricity generated in the EU. While the EU has achieved significant reductions in coal use for other purposes in the last decades, reductions in the use of coal in power plants were more modest at 11% below 2000 levels in 2014**.** However, the importance of these fuels varies significantly across the member states. Just two states - Germany and Poland - are jointly responsible for 51% of the EU's installed capacity and 54% of the emissions from the coal-fired power plants **but seven others have no coal-fired power plants in their electricity mix.**

There is an increasing disparity between EU member states in their approach towards the future role of coal. While some have significantly decreased their power production from coal in recent years and announced phasing out coal completely in the coming 10-15 years (e.g. the UK, Finland, France), **others are building or planning to build new coal-fired power plants** (e.g. Poland, Greece).

While the role of coal has been decreasing in the European Union electricity mix, a much faster coal phase-out is necessary to remain within a Paris Agreement-compatible emissions budget for coal in the electricity sector. We have calculated this budget to be around 6.5 GtCO2 by 2050. **Should existing coal-fired power plants continue their operation as planned, this CO2 emissions budget will be exceeded by 85% by 2050.** If CO2 emissions from planned and announced plants are added, cumulative emissions will be almost twice as high as the coal emissions budget.

To stay within the Paris Agreement temperature limit, a quarter of the coal-fired power plants already operating in the EU would need to be switched off before 2020; **a further 47% should go offline by 2025**. If the EU is to meet its commitments under the Paris Agreement, any investments in new plants and most investments in existing power plants will not be recovered by investors.

This report and its associated webpage: climateanalytics.org/hot-topics/eu-coal-phase-out.html present two scenarios for phasing out coal. Our first approach, the **Regulator perspective**, aims to phase out plants with the highest emissions intensity first. In our second approach, the **Market perspective**, the economic value of the plant is prioritised over its emissions intensity. Both approaches yield a phase-out of coal by 2030, which is in line with the Paris Agreement, and differ only in the order, in which coal power plant units go offline. While both perspectives mean strictly the same for the environment, the Regulator perspective may better reflect what could happen in reality as countries phase out coal through a mix of regulations both at the EU as well as at the national level.

The main differences between the Regulator and Market perspectives concern Poland, Czech Republic, Bulgaria and Denmark. Under the Market perspective, Poland and Denmark would have to shut down most of their plants by around 2025. Under the Regulator perspective some plants can stay online until the end of the decade before shutdown by 2030. In Czech Republic and Bulgaria, a large part of the total capacity needs be shut down already around 2020 under the Regulator perspective, showing the high emissions intensity of plants in these countries. In Germany, a similar amount of capacity would run until 2030 under both the Market and Regulator perspectives, but which specific plants go offline by when differs quite significantly between the two approaches, with different potential impacts on different regions within the country.

Regardless of the retirement schedule implemented in the European Union, the coal phase-out needs to be complemented by measures that increase the predictability and decrease the economic, social and environmental costs of the energy transition. This concerns especially regions heavily dependent on jobs in the coal sector.

A number of **developments and policy instruments at both the national and European level** could play an important role in facilitating coal phase-out compatible with the target of the Paris Agreement, **however most of them need to be strengthened or scaled up to achieve a fast coal phase-out**.

One of the most critical developments in the recent years is the significant **decrease in the costs of renewable energy sources, which has decreased the cost of a coal phase-out**. Even though wind and solar energy come with their own challenges, a number of options exist to cope with these issues. At the same time renewables come with the benefits of being inexhaustible and scalable thus allowing completely new business models and leading to job creation, including in areas which will be affected by coal phase-out.

An accelerated energy transition towards renewable energy sources in the EU can be supported by policies such as a more ambitious renewable energy target than currently planned, intensified investment in efficiency and grids or market design reformed to prioritise demand response.

The **EU-ETS**, introduced in 2005, is one of the flagship instruments of European climate policy. However, its effectiveness has been far lower than expected when it was initially introduced and in its present state **this instrument does not provide a strong enough incentive to lead to coal phase-out compatible with the Paris Agreement goal**.

Phasing out coal by regulation is an effective way to achieve emissions reduction targets at a lower cost, while providing stakeholders with certainty to ensure a smooth transition to alternative power sources in regions where coal currently plays an important role. Many European countries have either announced coal phase-out dates or created specific national regulations to achieve this goal. These plans create an environment of certainty for energy sector investors and allow better national planning to avoid strong economic shocks (mostly in terms of regional tax revenue and employment) created by the spontaneous closure of coal power plants due to market forces.

Stricter environmental regulations, resulting from e.g. the new Best available technologies Reference documents (BREFs) regulations and the National Emission Ceilings Directive, will decrease the competitiveness of the coal sector. Whereas some power plants may operate after costly retrofitting, additional investments to meet these directives would increase the value of stranded assets and hence the costs of coal phase-out. **A clear phase-out schedule would allow for reducing these costs by switching off the more emissions intensive plants first and consequently avoiding the need for retrofitting.**

Bełchatów Power Station and lignite coal mine. This 5400 MW lignite-fired power station in central Poland is the largest in the EU. Photo © NV77

BACKGROUND AND OBJECTIVE

At the 21st session of the Conference of Parties (COP21) in December 2015, 195 parties to the UNFCCC adopted the Paris Agreement, including mitigation and other commitments for signatories to strengthen their efforts in fighting against climate change and its consequences.

At its core the Agreement includes a goal **to hold "the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C"**. This long-term temperature goal is linked to another goal of bringing global greenhouse gas (GHG) emissions to zero in the second half of the 21st century. The exact timeframe is to be developed on the basis of the best available scientific evidence. The Paris Agreement has been ratified in record time and entered into force on 4 November 2016.[1]

The technologies needed for reducing emissions to limit global warming to 2°C are the same as those necessary to limit global warming to maximum 1.5°C by 2100 but they need to be deployed faster and be complemented by actions further decreasing energy demand (Schleussner et al., 2016). According to the most recent scientific literature[2], meeting the Paris Agreement goal requires a rapid decarbonisation of the global power sector. As a consequence, the share of unabated coal, i.e. coal-fired power plants without carbon capture and storage, should decline rapidly from today's levels until this source of energy is phased out completely around mid-century (IPCC, 2014a; Rogelj et al., 2015).

The need for a quick coal phase-out stands in stark contrast to the current[3] and planned coal-based generation capacity globally. A recent Climate Analytics analysis of the implications of the Paris Agreement for coal use in the power sector (Rocha et al., 2016) shows that existing coal-fired power plants around the world would produce twice the amount of emissions allowed under scenarios consistent with the long-term temperature goal in the Paris Agreement.

The report finds that the EU and OECD would need to stop using coal for electricity generation by 2030, China by 2040 and the rest of the world, including the majority of emerging economies, would need to phase out coal by 2050. Any delay in phasing out coal globally before 2050 will mean that the reliance on negative emissions technologies in the second half of the century will be higher to compensate for lack of climate action. Should the availability of negative emissions options be limited due to technological or sustainability reasons, coal phase-out will be necessary much earlier to achieve the Paris Agreement's long-term temperature goal.

Regarding the EU, the analysis shows that while a large part of its coal-based power capacity is already close to the end of its economic lifetime (European Environment Agency, 2016), currently operating power plants will still emit over their remaining lifetime 70% more than what would be consistent with meeting the EU's required emissions reductions under the Paris Agreement (Rocha et al. 2016). The report also clearly indicates that existing coal power plants jeopardise the EU's emissions reduction target communicated to the UNFCCC before COP21 in Paris (European Union, 2015b). Coal-fired power plants have long lifetimes - the average operating lifetime of a coal-fired power plant in the EU is 46 years. This means that any new installations in the EU — or in other regions —

1 As of 12 January 2017, 194 parties signed the Agreement, meaning these countries are now obliged to refrain from acts that would defeat the treaty's object and purpose; another 123 parties both signed and ratified, thereby signaling their intent to be legally bound by the terms of the treaty.

2 Scenarios consistent with limiting warming to below 2°C or 1.5°C in the IPCC Fifth Assessment Report (IPCC, 2014a)

3 We define *current* capacity as the sum of *operating* capacity and capacity *under construction*. Coal power plants under construction are usually associated with large sunk cost that would occur regardless of their construction being completed.

Kraftwerk Neurath at night. The 4400 MW lignite-fired power station in Neurath, North Rhine-Westphalia, Germany is the second largest in the EU. The five units on the left were built in the 1970's and the two 1100 MW units on the right were completed in 2012. Photo © r.classen

risk locking in emissions that are inconsistent with the Paris Agreement's long-term temperature goal.

These findings demonstrate a need for a clear coal exit strategy that avoids wasting additional capital and creating stranded assets (Carbon Tracker Initiative, 2013). Such a strategy should also help the EU member states and utilities to reconcile emissions commitments with actual energy planning. The Paris Agreement provides new and additional momentum for formulating such a strategy.

This report contributes to conceptualising such strategy by **providing a science based shutdown schedule of the coal-fired power plant fleet in the European Union and its member states in line with the Paris Agreement's long-term temperature goal (and, for comparison, with the previous below 2°C target)**.

1 COAL IN THE EU AND COAL EMISSIONS REDUCTION POLICIES

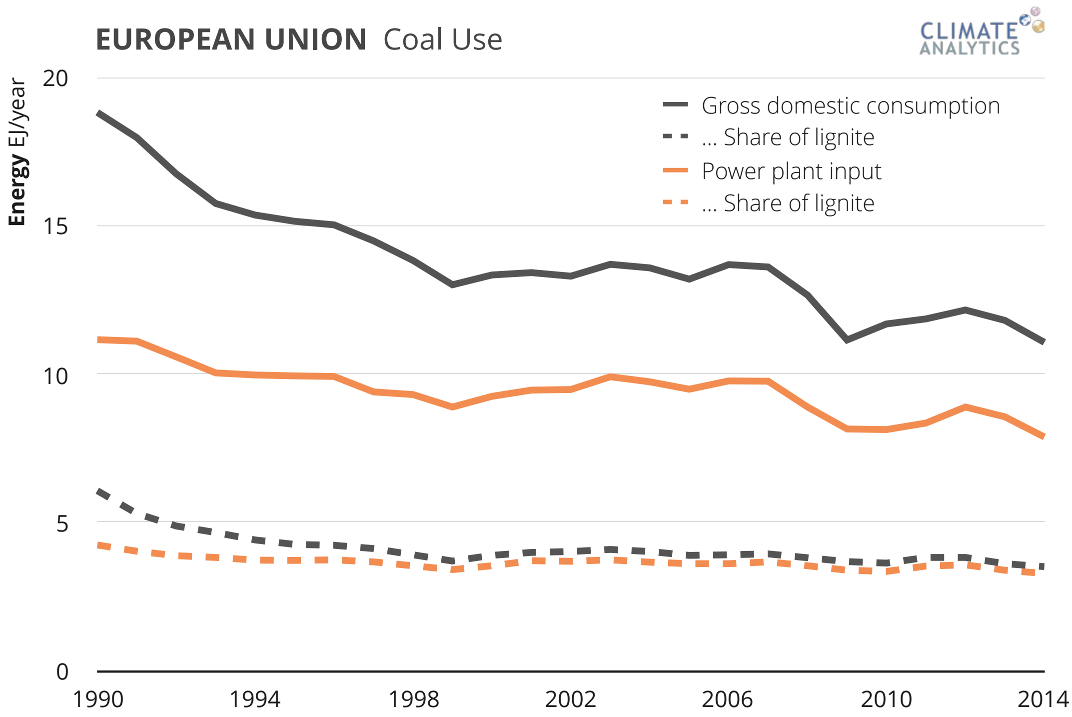

Figure 1: Coal use (hard coal and lignite) in the European Union. Source: Eurostat, own calculations

The current state of coal-fired power generation in the EU shows the scale of the challenge of reducing emissions from coal power plants to levels consistent with the Paris Agreement.

Coal is used as fuel for power plants, both as a reactant and to provide heat in industrial processes and for domestic heating. Figure 1 shows that most of the coal in the EU is used as fuel for power plants. The role of coal across all sectors in the EU has been decreasing steadily since 1990. Altogether coal consumption decreased by over 40% between 1990 and 2014 in the region.

This trend has not been uniform for all member states. While some have more than halved their coal consumption in this period, e.g. Belgium[4] (-69%), Denmark (-60%), Spain (-55%) or the UK (-54%), decrease in other countries has been less significant, e.g. in Poland (-29%) and Bulgaria (-12%). In Germany, responsible for about a third of the EU's coal consumption, it decreased by 47%. Contrary to this trend, coal consumption in two EU countries has even slightly increased: by 3% in Portugal and 6% in the Netherlands (Eurostat, 2016a).

In 2014, around a quarter of gross electricity generated in the EU came from coal (EEA, 2016). Figure 1 shows significant reductions in coal use for other purposes but reductions in the use of coal in power plants, both hard coal and lignite, are more modest, at 11% below 2000 levels in 2014. In that same year, emissions from coal-fired power plants constituted almost 77% of total power sector emissions and 28% of the energy sector emissions (IEA, 2016). Coal power stations in five countries contributed more than a quarter to total national GHG emissions: 28 % in Germany, 33 % in Poland and in Czech Republic, 34 % in Greece and as much as 44 % in Bulgaria (Jones & Gutmann, 2015).

4 Belgium has no coal power plants; the remaining coal is used for the other stated purposes.

The present lack of a clear and coherent plan to reduce coal-related carbon emissions not only hinders the EU in fulfilling its requirements towards achieving the Paris Agreement's long-term temperature goal, but also jeopardises its leadership in setting the global climate agenda.

In the Presidency Conclusions adopted in 2009, the EU outlined the target for developed countries as a group to reduce GHG emissions by 80-95% below 1990 levels by 2050 (European Council, 2009a). In 2014, EU heads of state adopted a binding emissions reduction target of "at least 40%" below 1990 levels by 2030 (European Council, 2014). Policies, pathways, and directives for achieving these goals are yet to be defined. A few key policies in the EU's climate and energy policy architecture could potentially offer solid ground for addressing the needed coal emissions reductions. In their current state, however, they fall short of what is needed:

- The **EU Emissions Trading Scheme (EU ETS)**, originally heralded as the cornerstone of European climate policy, has ceased to function as an effective mechanism to spur low-carbon or carbon-neutral investment, with prices collapsing below €5/tonne of CO_2 in 2016 (compared to €30/tonne at its launch in 2005). To make the EU ETS more effective, a series of reforms have been introduced with each phase of the Scheme. These include replacing the provision of free emissions allowances, or so called "grandfathering,"[5] with auctioning; increasing the annual reduction rate of the emissions cap and creating the Market Stability Reserve in 2018, which is to become operational in 2019. However, the overall effectiveness of these reforms remains to be seen, given that the structural oversupply of allowances in the region is foreseen to continue.

- The **Renewable Energy Directive** includes a target of increasing the share of renewables in the energy sector to at least 20% (European Union, 2009). In November 2016, the Commission proposed a recast of the Renewable Energy Directive with a binding target of at least 27% (European Commission, 2016b). However, due to the low price of carbon allowances in the EU ETS, rather than replacing coal, a big share of the new renewable energy capacity has replaced more expensive energy sources like gas, leading to a slower than required decrease in the power sector's carbon intensity.

- The **Energy Efficiency Directive** adopted in 2012 includes some binding measures to increase energy efficiency by 20% in 2020 compared to baseline projections. An effective implementation of this directive will also reduce electricity demand and thus decrease coal consumption (European Council, 2012). The Commission's proposal, presented in November 2016, includes a more ambitious energy efficiency target of 30% by 2030 (European Commission, 2016a).

- Air quality legislation could make the operation of coal-fired power plants increasingly expensive. The recently released **BREF-Standards under the Industrial Emissions directive** will affect new and existing power plants (EPPSA, 2016). But without a clear perspective of a coal phase-out in the coming years, this would still allow some plants to be retrofitted and new plants fulfilling the strict criteria be built, thus contributing to a carbon emissions lock-in.

Increasing the effectiveness and ambition of each of these policies should be part of a broader framework for tackling emissions from coal-fired power plants and coal phase-out in line with the Paris Agreement's long-term temperature and emissions goals. But such a framework requires a clear strategy with a coal phase-out timeline and different policies to replace coal with other energy sources.

This reports aims to contribute to conceptualising such a strategy. In addition to design-

5 Grandfathering means allocation of emissions for free based on historical demand. This practice is still used for allowances in such sectors as aviation or some energy intensive industries.

Drax, a 3960 MW coal-fired power station in North Yorkshire, England. It is the EU's third largest thermal power station by nameplate capacity and generates around 7% of UK's electricity. In 2012 the conversion to full biomass firing for three units was announced to be completed in 2013, 2014 and 2017 respectively. Photo © Neil Mitchell

ing an emissions reduction trajectory for coal and for the entire power sector in the EU, the shutdown schedule proposed here articulates some important policy-relevant aspects, such as efficiency and carbon intensity of plants, and aims to provide a basis to forward discussions on the subject.

This focus of this report is on the emissions reductions needed to stay in line with the Paris Agreement's long-term temperature limit. However, a fast coal phase-out strategy in the European Union is in itself desirable when considering other policy goals beyond the climate change.

There is scientific consensus today on the multiple immediate national and regional incentives to undertake a coal phase-out from the European electricity mix. One of the very important incentives is the significant reduction in air pollution and the mitigation of associated negative health impacts (International Energy Agency (IEA), 2016). It has been estimated that in the European Union alone, these cause 18 000 premature deaths, about 8500 new cases of chronic bronchitis, and over 4 million lost working days annually (Huscher, Smith, Holland, & Jensen, 2013).

Additional benefits of a quick coal phase-out include lowering the cost energy transition to renewable sources (Jones & Gutmann, 2015, (Schaeffer et al., 2016)), and boosting employment and growth opportunities (Schaeffer et al., 2016) (Pollitt et al., 2016) and increasing energy independence (Schaeffer et al., 2016).

2 TOTAL EMISSIONS AND COAL-RELATED EMISSIONS IN LINE WITH THE PARIS AGREEMENT

2.1 TRANSLATING THE PARIS AGREEMENT GOAL INTO EMISSIONS SCENARIOS

More than two decades of international climate negotiations laid the groundwork for the Paris Agreement and its objective of holding global warming to "**well below 2°C"** and **"pursuing efforts to limit" global warming to 1.5°C**.

Scientific literature provides ample energy-system emissions scenarios consistent with holding warming to below 2°C, with various degrees of likelihood.[6] This reflects the uncertainty surrounding the temperature response of the Earth system to changes in concentrations of GHGs in the atmosphere. The long-term temperature goal of holding warming **below 2°C,** included in the Cancun Agreements, is interpreted consistently with **scenarios that have a "likely chance" of 66%, or greater, of staying below a 2°C global mean warming** above pre-industrial levels throughout the 21st century (UNEP, 2016).

The Paris Agreement's long-term temperature goal is more stringent than the earlier 2°C goal of the Cancun Agreements. While the range and depth of literature available for the evaluation of the 1.5°C goal is not as ample as for the "likely below" 2°C class of scenarios, sufficient scenarios are available to allow a robust first order analysis of the difference between these two temperature goals.

Based on an assessment of the scenario literature, we have used an available scenario which holds warming below 2°C with 85% probability or greater, and remains below 1.5°C by 2100[7] with a more than 50% chance as a proxy for the Paris Agreement long-term temperature goal (UNEP, 2016).

The Paris Agreement's long-term temperature (Article 2) and emissions (Article 4) goals (UNFCCC, 2015) have specific implications for global emissions and energy transition pathways. The interpretation of the Paris Agreement's temperature goal that is applied here requires global GHG emissions to be reduced by 70-95% (65-90%) below 2010 (1990) levels by 2050, and to reach globally aggregated zero emissions by 2060-2080. In contrast, the Cancun Agreements goal implied that global GHG emissions need to be reduced by 40-70% below 2010 levels (35-55% below 1990 levels) in 2050 and reach globally aggregated zero emissions by 2080-2100.[8]

To ensure maximum relevance of this analysis for policy makers, we opt for scenarios with global emissions in 2020 as close as possible to current projections, often referred to as "delayed action" scenarios (UNEP, 2014). These scenarios usually assume that countries will meet their 2020 mitigation pledges, before beginning deeper action to meet a long-term temperature goal. In contrast, so-called "immediate action" scenarios assume strong global concerted climate action starting already in 2010.[9]

6 These energy-system scenarios come from Integrated Assessment Models (IAMs). IAMs combine the current knowledge of energy systems and climate-model projections to identify economically and technologically feasible emissions pathways consistent with a given climate target, while minimising global costs. These are the so-called optimal "least-cost" or "cost-optimal" pathways. See more on the IAMs in Annex I.

7 The 1.5°C consistent scenarios published to date overshoot a 1.5°C global mean warming above pre-industrial during the 21st century by about 0.1°C to 0.2°C, before returning to 1.5°C or below in 2100 with a 50% likelihood (median warming in 2100 of 1.4°C) and have simultaneously a probability of about 85% to hold warming below 2°C during the 21st century.

8 These numbers are drawn directly from the IPCC AR5 Working Group III Summary for Policymakers (IPCC, 2014b). The other numbers in this section draw from all scenarios assessed by the IPCC Fifth Assessment Report and the 2014 UNEP Emissions Gap Report (UNEP, 2014) and follow the methodologies of the 2014 UNEP Emissions Gap Report.

9 IAMs usually compute results at a five or ten year resolution. MESSAGE operates on a 10-year resolution from 2010 onwards. Since the scenarios prepared for AR5 where run before 2014 – the year when AR5 was published – the first period for which immediate climate policy is assumed is 2010, whereas it is 2020 for delayed climate policy.

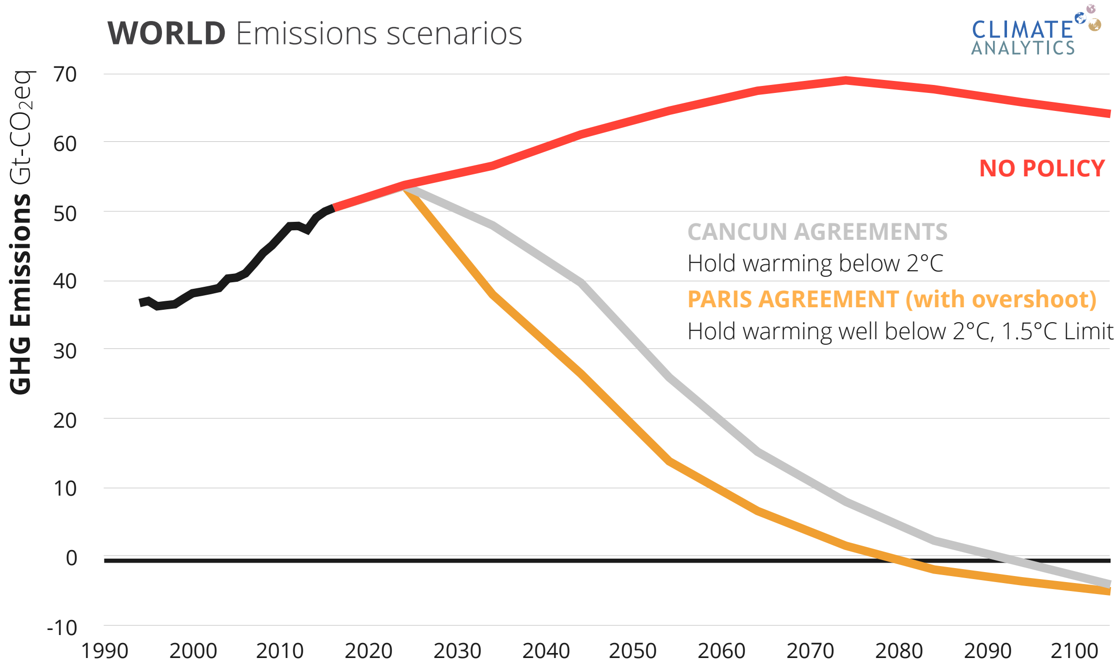

Figure 2: Global policy-relevant emissions scenario cases. GHG emissions, including LULUCF.
Source: IIASA/(Rogelj et al., 2015)

For more detailed information on the scenario selection refer to Annex III: Integrated Assessment Model scenarios selection.

Based on these considerations, we selected the following two scenarios from the Integrated Assessment Model MESSAGE (IIASA, 2016), shown in Figure 2, to be the basis of this analysis:

- **Paris Agreement 1.5°C scenario with overshoot**: Pathway that accelerates global action from 2020 onwards and temporarily allows temperature increase to exceed 1.5°C during the 21*st* century. However, due to reduction in emissions and later CO_2 removal from the atmosphere, the global mean temperature rise is brought to 1.5°C by 2100 with 50% probability.

- **Cancun Agreements 2°C scenario**: Pathway that accelerates global action from 2020 onwards in order to hold warming to below 2°C by 2100, with at least 66% probability.

2.2 COAL EMISSIONS PATHWAYS IN LINE WITH THE PARIS AGREEMENT

Based on the global emissions scenarios introduced above, we derived cost-optimal pathways for electricity generation from coal globally and for the EU in particular, in line with the Paris Agreement's 1.5°C temperature goal (and for comparative purposes also for the Cancun Agreements 2°C goal) (Figure 3).

IAMs achieve emissions reductions through the deployment of a number of technologies. Among these technologies, the model includes the use of carbon capture and storage (CCS) in coal power stations. In this report, we focus on the relevance of coal-fired power stations for Earth's climate.

The MESSAGE model used in this work assumes that coal power plants with CCS emit no CO_2 into the atmosphere, so within the model they are not relevant for emissions budget considerations. In reality, coal power plants with CCS are very likely to emit around a tenth[10] of the average emissions compared to an installation without CCS. We consider that deployment of CCS for fossil fuel power plants at scale is unlikely, given the very small number of current and planned coal power plants retrofitted

10 http://www.iea.org/topics/ccs/

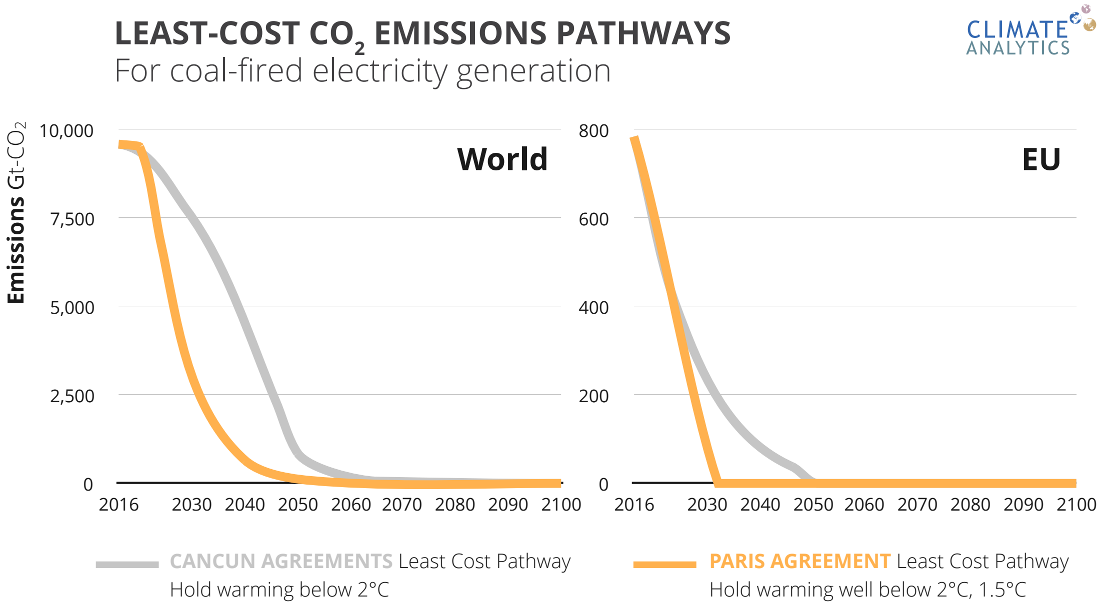

Figure 3: CO_2 emissions from coal-fired electricity generation globally and in the European Union in line with the Paris Agreement and with the Cancun Agreements. Source: IIASA/Rogelj et al. (2015) (World) and own calculations based on Rogelj et al. (2015) and Annex IV: SIAMESE.

with CCS, resulting reduced plant efficiency by adding CCS and its high costs. The high cost is considered especially in the context of rapidly decreasing costs of alternatives.

While global pathways are a direct output of the MESSAGE model, an aggregate pathway for the 28 EU member states is calculated using Climate Analytics' SIAMESE model (Simplified Integrated Assessment Model with Energy System Emulator). This tool downscales the aggregated coarse IAM regions to subregions and then re-aggregates them again to custom regions (in this case the EU28).

SIAMESE results are the outcome of numerical simulations and are based on MESSAGE results prior to the publication of the IPCC's AR5 in 2014. To make those simulation results more relevant for policy makers, we post-processed the cost-optimal pathways for the EU in two ways.

First, we adjusted them to match historical emissions in 2016. Second, for numerical reasons, emissions from coal always stay just above zero in SIAMESE. Therefore, we understand a "complete" phase out of coal power plants as an emissions reduction by more than 95% below 2010 levels. While doing these adjustments, we made sure that the emissions budget for the adjusted pathway is the same as for the original pathway.

For more details on the SIAMESE model, see Annex IV: SIAMESE.

The least-cost emissions pathways show that coal-related emissions approach zero by 2050 globally to remain in line with the Paris Agreement, and by around 2060 to be in line with the Cancun Agreements.

In the EU, emissions decrease steeply in the coming years and reach zero already shortly after 2030. Under the Cancun Agreements, emissions for this region become zero about 20 years later. In the second half of the century, coal-related emissions are zero globally, regardless which temperature goal is considered.

BOX 1 - SCENARIO LIMITATIONS

Our approach has some limitations that should be taken into account when interpreting the results.

Firstly, IAMs use a very simplified representation of the global economy based on neoclassical theories. They collectively provide state-of-the-art knowledge of the energy system, and are the basis of the scientific work supporting the adoption of long-term temperature goals, using a global cost-optimal approach to mitigation.

IAMs assume the availability of relatively cheap mitigation options in today's low-income countries, which lower the need to rapidly reduce emissions in rich countries. The necessary funds are transferred from rich to poor countries by means of the perfect capital market. Without such options, mitigation would need to happen much quicker in comparatively rich regions like the European Union.

The least-cost approach does not explicitly take into account burden-sharing regimes that account for historical responsibility or capability. Rich regions bear more responsibility and have higher capability to mitigate emissions, and IAMs account for that by assuming financial transfers from these regions to other parts of the world. By considering only emissions, this overall effort required of rich regions remains underestimated.

Other energy-system models offer different approaches, which are also interesting to policy-makers. Models the WEO (IEA, 2015), IRENA (2016) and Greenpeace Revolution (Greenpeace, 2015) use different assumptions to achieve emissions reductions and can yield considerably different regional results from IAMs.

Secondly, we use just a single scenario from a single IAM for each temperature goal (Paris Agreement and Cancun Agreements). It is well known that there is quite some inter-model variation between IAMs, which is precisely why IPCC's AR5 relied on a range of scenarios from different models to build consensus on what is needed to achieve different temperature goals. However, currently the number of publicly available scenarios meeting the criteria necessary to deliver on Paris commitments is too small to provide this kind of analysis. Researchers are working on releasing such scenarios in 2017/2018.

The advantage of our approach is that it allows for a comparison of scenarios with the same or at least very similar assumptions e.g. regarding population development or availability of certain mitigation options (BECCS, nuclear, among others) for one temperature goal, thereby giving confidence in the robustness of results.

The numbers and trends provided here represent first order indications, not precise values cast in stone. It must be noted that at this time, only IAMs have produced the data on 1.5°C scenarios currently available in the scientific literature. Other sources (e.g. IRENA, IEA) are in the process of producing new scenarios and are expected to deliver full, or partial assessments of 1.5°C in the course of 2017, alongside an expected much broader assessment base of the IAM "community". Also, IAMs are the only tools that provide a good representation of the interlinkages and trade-offs present in the real world and will always remain valuable tools to evaluate possible solutions to the problem of climate change on a global and aggregate regional scale.

3 COAL EMISSIONS IN THE EUROPEAN UNION

In order to estimate emissions from currently operating and planned coal power plants in the EU, we used the Global Coal Plant Tracker (GCPT) data, which provides information on every known coal-fired power generation unit, including its location, status, operator, capacity, combustion technology[11] and fuel, year of opening and planned retirement (not for all units). For additional characteristics like observed historical load factors and fuel use, which allow for a more accurate estimation of the emissions from each plant, we merged the GCPT data with information provided by the European coal power plant database hosted and coordinated by the Climate Action Network (CAN) Europe (CAN Europe, 2016).

There are other datasets that contain coal power plant information at a comparable level of detail. Commercial examples are Platt's World Electric Power Plants database [12] or ENERDATA's power plant tracker[13]. Other, non-commercial datasets are the outcome of EU level regulation and related reporting requirements – e.g. the EU-ETS. However, these datasets have drawbacks - they are either very costly or not always transparent, or contain only resolution to the level required by the respective regulation (the EU-ETS only includes plants above a certain capacity).

Many plants consist of several subunits, each one consisting of a steam generator, turbine and electricity generator. Since each of these units is able to operate independently from others and often units are added subsequently, we conduct our analysis at the unit level. The dataset we use distinguishes between units deactivated, retired, cancelled, shelved, operating, under construction, permitted, pre-permitted and announced. For this report, we exclude the first four categories, since these plants are already inactive.

Based on the information provided in the GCPT and CAN Europe's databases, we estimate the CO_2 emissions from the current and planned coal power plants, differentiating for each power plant unit.

For more information on the databases and emissions calculations see Annex V: Estimating CO_2 emissions from coal plants.

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11 The database distinguishes between different combustion technologies in the following categories: subcritical, supercritical and ultra-supercritical without or with CCS, ranking from least to most efficient respectively. For example, MIT's "Future of Coal" study (Massachusetts Institute of Technology, 2007) estimated the following representative efficiencies for plants burning Illinois #6 coal, a bituminous grade of coal with 25,350 kJ/kg heat rate: Subcritical: 34.3%; Supercritical: 38.5%; Ultra-supercritical: 43.3%. We do not consider coal-fired power plants retrofitted with CCS technology in our analysis.

12 http://www.platts.com/products/world-electric-power-plants-database

13 http://www.enerdata.net/enerdatauk/knowledge/subscriptions/research/power-plant.php

EUROPEAN UNION Coal Power Plant Unit Age

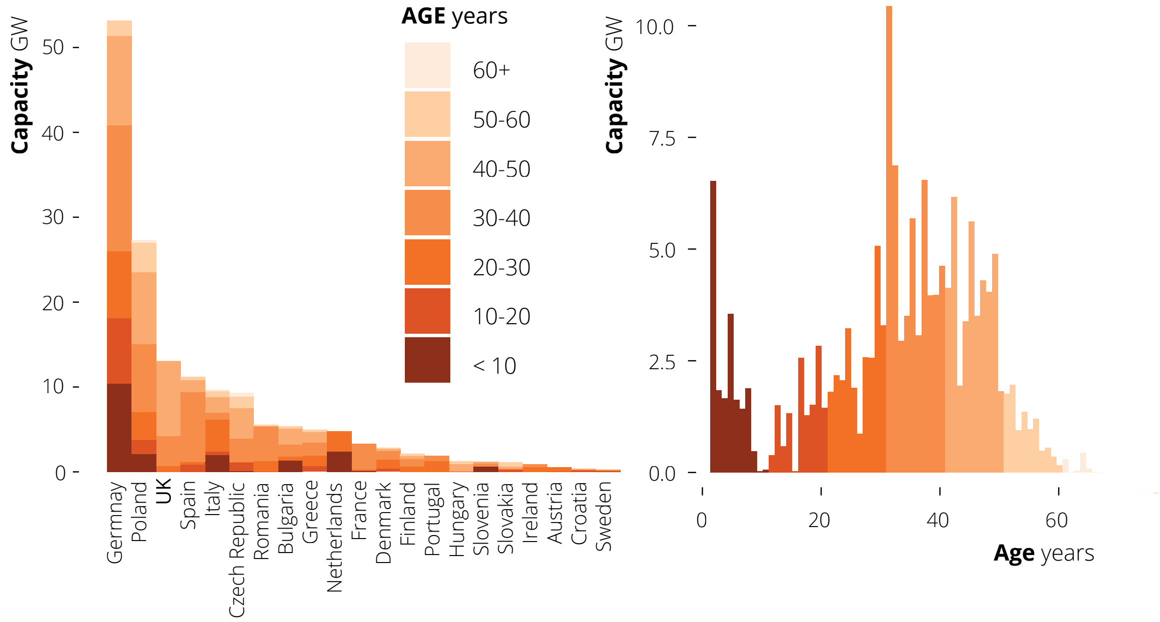

Figure 4: Age structure and capacity by country (left panel) and total age structure (right panel) of the EU's coal power plant unit fleet. Source(s): GCPT, CAN Europe.

3.1 CURRENTLY OPERATING CAPACITY

Our dataset contains 727 operating coal-fired power generation units, located in 315 coal power plants[14] in 21 member states of the European Union[15] with combined installed capacity of 161 GW. Additional 11 units, representing nearly 7 GW of new combined capacity, are currently under construction.

Figure 4 summarises the national distribution of operating coal-fired power plants in the EU as well as their age structure. Table 1 provides more detailed information also on the number, estimated emissions and the average age of units.

Germany and Poland alone account for nearly half of EU's installed capacity (51%) and more than half of yearly emissions (54%) of all coal-fired power plants. Other big coal users in terms of capacity (emissions) are Czech Republic, Spain, Italy and the United Kingdom, with a share of 6.4% (6.2%), 6.7% (4.9%), 5.7% (5.1%) and 7.8% (7.5%) respectively[16]. Most smaller coal using countries have hardly built any new power plants in the last decade. As a result, a large part of their current capacity is already more than 30 years old.

Comparatively little new capacity came online during the 1990s and early 2000s (Figure 4, right panel) but in the last decade a considerable amount of new capacity has been built in Poland, the Netherlands, Italy and especially Germany. In Germany alone new capacity commissioned in the last decade is comparable with the total capacity of Spain or Italy (Figure 4, left panel). Unless these plants are retired before the end of their lifetime, emissions will be locked into the system longer than what would be consistent with the EU's GHG emissions reduction targets.

14 Some units of different plants are on the same "site" or in the same "complex". Sometimes they are considered different plants - sometimes with different owners - and in other cases they are considered the same plant. The 315 "plants" is an estimate derived from the Global Coal Plant Tracker database as of July 2016. While every effort to ensure accuracy has been made, we cannot guarantee there are no errors, especially with financial ownership shifts after July 2016. The number of units and their total capacity is the basis of this reports analysis and not the number of "plants".

15 States that do not have any operating power plants are Belgium, Cyprus, Estonia, Latvia, Lithuania, Luxembourg, and Malta.

16 The differences between capacity and emissions shares are partially due to differences in emissions intensities but mainly due to differences in actual capacity usage between countries. Actual usage was calculated based on a comparison of actual fuel usage in 2013 compared over maximum theoretical fuel usage if a unit was running at 100 percent of rated capacity 365 days a year.

Table 1: Country level distribution of current coal power plant capacity (operating and under construction). Emissions are estimated based on 2013 fuel use data. Source: GCPT, CAN Europe

COUNTRY	TOTAL UNITS	SHARE OF TOTAL- EU	TOTAL CAPACITY	SHARE OF TOTAL- EU	ESTIMATED YEARLY EMISSIONS	SHARE OF TOTAL- EU
	Unit	%	MW	%	Mt CO_2	%
Austria	4	0.5	800	0.5	1	0.1
Bulgaria	36	4.9	5 372	3.2	29.7	3.6
Croatia	2	0.3	335	0.2	1.6	0.2
Czech Republic	123	16.7	10 693	6.4	51	6.2
Denmark	9	1.2	2 837	1.7	17.7	2.2
Finland	16	2.2	2 119	1.3	8.4	1
France	10	1.4	3 312	2	15.8	1.9
Germany	154	20.9	53 597	32.0	284.2	34.8
Greece	17	2.3	4 925	2.9	24.2	3.0
Hungary	12	1.6	1 274	0.8	8.3	1.0
Ireland	3	0.4	915	0.5	4	0.5
Italy	32	4.3	9 640	5.7	41.6	5.1
Netherlands	8	1.1	5 860	3.5	32.4	4.0
Poland	182	24.7	31 675	18.8	156.3	19.1
Portugal	6	0.8	1 878	1.1	9.8	1.2
Romania	29	3.9	5 535	3.3	18.3	2.2
Slovakia	13	1.8	1 133	0.7	4.6	0.6
Slovenia	6	0.8	1 194	0.7	5.8	0.7
Spain	40	5.4	11 179	6.7	40.1	4.9
Sweden	5	0.7	296	0.2	1	0.1
United Kingdom	31	4.2	13 100	7.8	61.6	7.5
EU	**738**	**100**	**167 670**	**100**	**817.2**	**100**

3.2 PLANNED COAL CAPACITY

Our dataset distinguishes between announced, pre-permitted and permitted installations. Of the EU's total planned capacity, one unit has been announced in Poland, only two units have been permitted in the UK and Greece, and additional eight have a pre-permitted status (mostly in Poland and Germany). These 11 planned power plants represent around 9 GW of new capacity and would be a potentially wasteful investment because they would need to be retired long before the end of their economic lifetime. Table 2 shows plant-level data of planned capacity in the EU.

As shown above, more than half of all planned coal-based power generation capacity in the region is in Poland, followed by Germany and the United Kingdom. However, it is not certain whether these planned units will actually come online, taking into account that an increasing number of coal-fired power plants in the region has been cancelled for reasons including competition with renewables and environmental concerns (Shearer, Ghio, Myllyvirta, & Nace, 2015). 129 coal-based generation units, with

Table 2: National distribution of planned coal-based capacity

LOCATION	UNIT NAME	SPONSOR	STATUS	TOTAL CAPACITY	COMMENTS
				MW	
Poland, Pomorskie	Północ Power station Unit 1	Polenergia	pre-permit development	800	As of January 2017, the website of Polenergia still includes the plans to commission by 2020 two units of 800 MW each. However, the units' construction permits were revoked in December 2016, which raises questions about the feasibility of the project and makes the 2020 date unlikely.
Poland, Pomorskie	Północ Power station Unit 2	Polenergia	pre-permit development	800	
Poland, Śląskie	Zabrze Power Station	Fortum	pre-permit development	220	The cornerstone for the new Fortum CHP plant in Zabrze, Poland, was laid on 13 June 2016. This new plant is expected to have a production capacity of 220 MW and will replace the existing plant, which was built in the 1950s.
Poland, Lubuskie	Gubin Power Project	PGE	announced	3 000	In 2014, PGE announced the construction of a lignite mine in Gubin in 2018 and an accompanying coal plant with capacity of 2700 - 3000 MW to be completed in 2030. In August 2016, plans for the lignite mine were suspended by an administrative decision of the Regional Directorate for Environmental Protection. This raises questions about the feasibility of the project.
Germany, Lower Saxony	Stade Dow Chemical	Dow Deutschland Anlagengesellschaft mbH	pre-permit development	920	The power plant project of Dow is criticised by citizens' initiatives and environmental protection associations, who submitted a lawsuit against the city in October 2015 for the permissions given to the construction of this plant. However both the company and the city still have the intention to carry out the project.
Germany, North Rhine-Westphalia	Niederaussem Unit L (BoAplus)	RWE Power AG	pre-permit development	1 100	Unit K was the first Braunkohlenblock mit optimierter Anlagentechnik (BoA) unit, an optimised, highly efficient steam-electric unit design. A second BOA unit (Unit L) is planned. It is still not clear yet whether RWE will be allowed to build unit L. A decision is likely in 2017. Only then RWE will decide based on economic considerations
United Kingdom, Firth of Forth, Scotland	Captain Clean Energy Project	Summit Power	pre-permit development	570	The Captain Clean Energy Project is a proposed "commercial-scale" carbon capture and storage CCS coal-fired plant. In March 2015, the project got £4.2 million funding for research and feasibility studies. Technical assessments have been largely complete by the end of 2016 and commercial analysis is ongoing.
United Kingdom, Yorkshire	C.GEN North Killingholme Power Project	CGEN	permitted	470	In September 2014 the UK Government approved C.GEN's plans to build a 470MW power station, complete with CCS technology. However, after the UK Government announced in November 2015 that it will cancel the funds for the CCS competition the project has had financial difficulties. As of December 2016, there has been no progress on this project in over two years, which suggests the project has been shelved or abandoned.
Greece, West Macedonia	Ptolemaida-V	Public Power Corp.	under construction	660	Ptolemaida V will be the fifth coal-fired unit at the Ptolemaida power station, with a generating capacity of 660MW. The project was permitted in 2013 and began construction in September 2016, with estimated construction duration of 70 months. Given its early stage of construction, it is unclear whether his unit will actually come online. We therefore opted to exclude it from our analysis.

LOCATION	UNIT NAME	SPONSOR	STATUS	TOTAL CAPACITY	COMMENTS
				MW	
Hungary, North-Hungary	Matra power station Unit 6 (renewed proposal)	Matrai Eromu	pre-permit development	500	The original project, cancelled in 2010, was a 440MW unit to be added to the Matra coal plant. The new 2015 project consists in a 500MW supercritical unit, which has already started the process of getting construction permits.
Italy, Carbonia-Iglesias	Sulcis Power Station	Enea	pre-permit development	350	The project is a proposed 350-megawatt (MW) coal-fired power plant with carbon capture and storage (CCS) supported by a government programme for development and demonstration of CCS. However, no developments have been observed in the project since February 2014, which suggests the plans for the plant have been deferred or abandoned.

a total planned capacity of 92 GW, have been either cancelled or shelved in the EU between 2010 and 2016.

It is expected that almost all of future coal-related CO_2 emissions in the EU will come from existing coal-fired power plants and not from new capacity. If currently operating units would follow the historically observed national average lifetime, the last coal-fired power plant would go offline only in the late 2060s, assuming that no additional capacity beyond what is currently known is added.

3.3 EMISSIONS FROM CURRENTLY OPERATING AND PLANNED COAL CAPACITY

We estimate CO_2 emissions from currently operating and planned capacity in the EU based on the methodology described in detail in "Annex V: Estimating CO_2 emissions from coal plants." Our analysis shows that even with no new coal power plants coming online, cumulative CO_2 emissions from current coal-based electricity generation capacity would exceed both the Cancun Agreements and the Paris Agreement compatible cost-optimal emissions budgets for the remainder of the century (Figure 5).

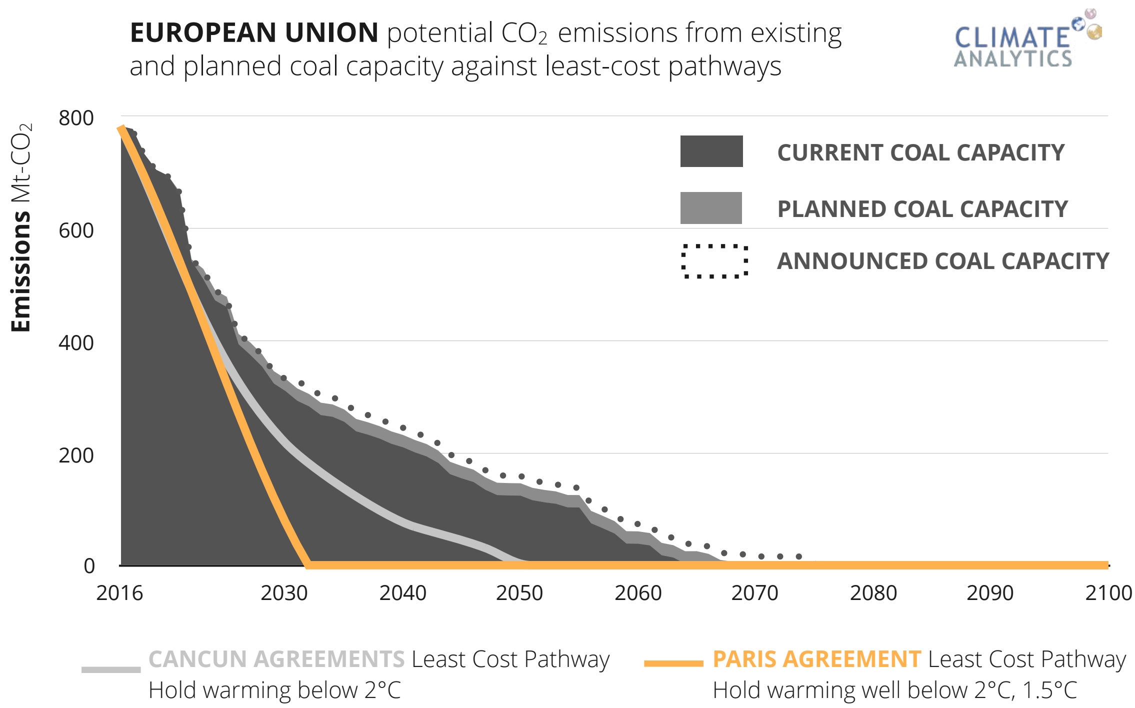

Figure 5 Emissions from existing and planned coal-fired power plants compared with the coal emissions budget according to the Cancun and Paris temperature goals. Sources Rogelj et al. (2015), GCPT, CAN Europe, own calculations.

In order to achieve the Paris Agreement's long-term temperature goal, our results show that EU member states will need to implement early retirement[17] of currently operating power plants and/or dramatically reduce their utilisation rate (not directly assessed here). Opening new power plants is out of the question.

EU's coal-related CO_2 emissions are projected to fall in the following decades even without additional policies. This is because a large share of the EU's coal power stations are already relatively old and at the end of its economic lifetime (see section 3.1). Moreover, this can also be attributed to already implemented policies such as the EU-ETS, the feed-in tariff scheme for renewable energy sources in many European countries, air pollution regulations, and energy efficiency directives. However, if the speed of coal retirements continues at its historical pace, currently operating capacity would emit much more than what would be in line with the Paris Agreement. More precisely, as shown in Table 3, current **cumulative emissions** will exceed budgets in line with the Paris Agreement for the European Union by 85% until 2050 and 99% until 2100.

Table 3: Cumulative CO_2 emissions form currently operating and planned coal power plants (Mt CO_2e) and relation to Paris and Cancun Agreements cost-optimal budgets. Source: IIASA/Rogelj et al., (2015b), GCPT, CAN Europe, own calculations

	CUMULATIVE EMISSIONS	SURPASSES THE PARIS AGREEMENT BUDGET BY	SURPASSES THE CANCUN AGREEMENTS BUDGET BY	CUMULATIVE EMISSIONS	SURPASSES THE PARIS AGREEMENT BUDGET BY	SURPASSES THE CANCUN AGREEMENTS BUDGET BY
	Mt CO_2	%	%	Mt CO_2	%	%
EU current	12 145	85%	37%	13 039	99%	47%
+ planned	12 755	95%	44%	14 036	114%	58%
+ announced	13 019	99%	47%	14 617	123%	65%

17 We use planned retirement date where available or average country level historical lifetimes or EU level lifetimes (46 years) where there are too few observations to calculate these. For details refer to Annex V: Estimating CO_2 emissions from coal plants.

4 COAL SHUT DOWN SCHEDULE

This report is accompanied by the webpage climateanalytics.org/hot-topics/eu-coal-phase-out.html **that provides a dynamic visualisation of the results shown here.**

In this section, we explore the timeline of coal capacity decrease required year-by-year at the unit level to achieve coal emissions pathways in line with the Paris Agreement temperature goal. With this in mind, we developed a methodology to determine which European power plants need to shut down when in order to fit the CO_2 coal emissions in line with commitments made in Paris.

The results of this analysis allow a regional level visualisation of what the current national phase-out plans could look like and highlight the phase-out speed needed in each country.

4.1 WHICH UNITS NEED TO RETIRE FIRST?

The main outcome of this analysis — a phase-out schedule for coal power plants in the EU —relies on some key assumptions about the sequence in which the different European plants will need to be retired. The critical question is which criteria should determine which plant units are switched off and when. If we only look at climate considerations, this choice is irrelevant as long as emissions are being reduced over time. However policy makers, plant market and other stakeholders will have different perspectives.

Power plant **owners and holding operators** will aim to maximise the revenue that they can generate from their assets. Therefore, they would prioritise the operation of those units that generate the highest net revenue for as long as possible, regardless of their emissions intensity.

Local policy makers may aim to keep local plants online as long as possible but support shutting down those not located in their area. This is especially the case for some regions in Europe, which are economically highly dependent on the vertically integrated energy companies consisting of open pit mines and associated power plants. These include, for example, lignite areas close to Cologne and in Lusatia in Germany, Upper Silesia in Poland and Ostrawa in Czech Republic.

National policy makers might be driven by very similar incentives as local ones, but on a larger scale. If coal mining does play a significant role in a nation's economy, fears of economic losses associated with shutting down power plants might greatly hinder effective national climate policy.

EU level regulators focus on finding the common denominator, taking into account EU level environmental and economic issues and also the EU's responsibility on a global scale.

Taking all these views into account, we consider two approaches to determine the phase-out schedule that aim to encompass different aspects of these views:

- **Regulator perspective:** it adopts an environmental integrity approach and prioritises the shutdown of the least efficient units, while also taking into account the revenue they can generate. For this perspective, units are sorted primarily according to their carbon intensity (amount of CO_2 emitted per unit of electricity generated). To reduce the overall economic loss of the phase-out, and given that many generation units have similar carbon intensity characteristics, a secondary sorting is applied where priority for phase-out is given to the units with less economic value in each of the carbon intensity ranges. The measure used to estimate the economic value of a power generation unit is the Net Present Value (NPV) per MW, which is the present value of the anticipated future cash flows of each unit during its remaining lifetime, after controlling for unit size.

For detailed information on the approach followed to calculate the NPV refer to Annex VI: Calculating the Net Present Value of coal power plants.

- **Market perspective:** keeping in line with the priorities of plant owners and operators, it aims to reduce the overall cost of the shutdown strategy for the whole EU by keeping units with higher economic value online as long as possible. Similarly to the Regulator perspective, the sorting of the units is done using a two-step approach. First, units are sorted according to their profitability (NPV/MW) and the least-profitable units are phased-out first. Secondly, for units within the same range of economic value, priority for phase-out is given to the units with the highest carbon intensity. Including efficiency considerations in the Market perspective does not only reflect the fact that inefficient units have usually higher fuel and carbon price costs, but also accounts for the fact that national regulations concerned with issues like air quality and GHG emissions will affect those units first, making them more risky assets for investors than more efficient units.

The shutdown is performed in a stepwise manner. For each year in which the sum of emissions from coal plants is above levels consistent with the long-term goal in the Paris Agreement, plants need to be shut down until the emissions are at or below this level. Coal power plants are sorted as explained above and those plants with highest priority will be shut down in a certain year, as depicted schematically in Figure 6 with the grey units being those that are shut down in a specific year.

Both views are based on a static approach, which ranks units according to their NPV and emissions intensity as of 2016 and assumes this rank to remain constant during the whole projection period. Although a dynamic approach with a changing ranking — in which emissions intensity and economic value are calculated each year taking into account the previous year's retirements and technology improvements in the units — would be ideal to determine the optimal retirement schedule, there is high uncertainty surrounding projections of many of the variables considered. For instance, investments in technology improvements to comply with emissions and air quality standards will depend on the stringency of the standards, special exceptions or time extensions to comply with the standards at the national level, and the technology prices, all of which are very challenging to project.

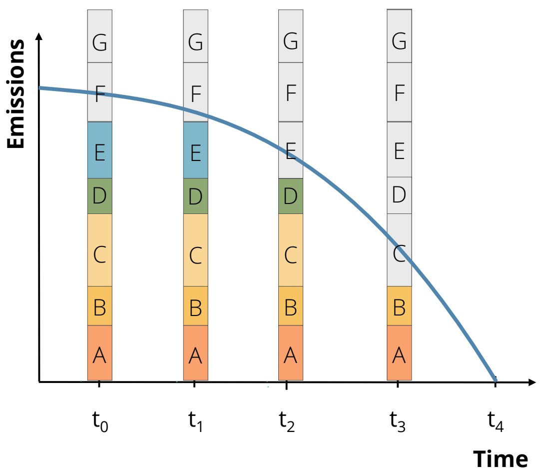

Figure 6: Schematic overview of methodology. Each of the boxes labelled A to G shows emissions from a power unit. The blue line indicates IAM derived cost-optimal coal emissions pathways in line with the Paris Agreement long-term temperature goal, and t0 through t4 depict the time steps (years). If we assume that our shutdown regime starts in t1, this means that plants G and F need to shut down – as indicated by the grey colour. In t2 plant E needs to be shut down under a least-cost strategy and in t3 only plants A and B may remain in operation. In t4 all remaining plants need to be shut down, as emissions need to reach zero to comply with the Paris Agreement's long-term temperature goal.

Further developments of our current methodology could include a dynamic modelling that takes into account changes in country level information due to unit retirement and other national characteristics, such as subsidies.

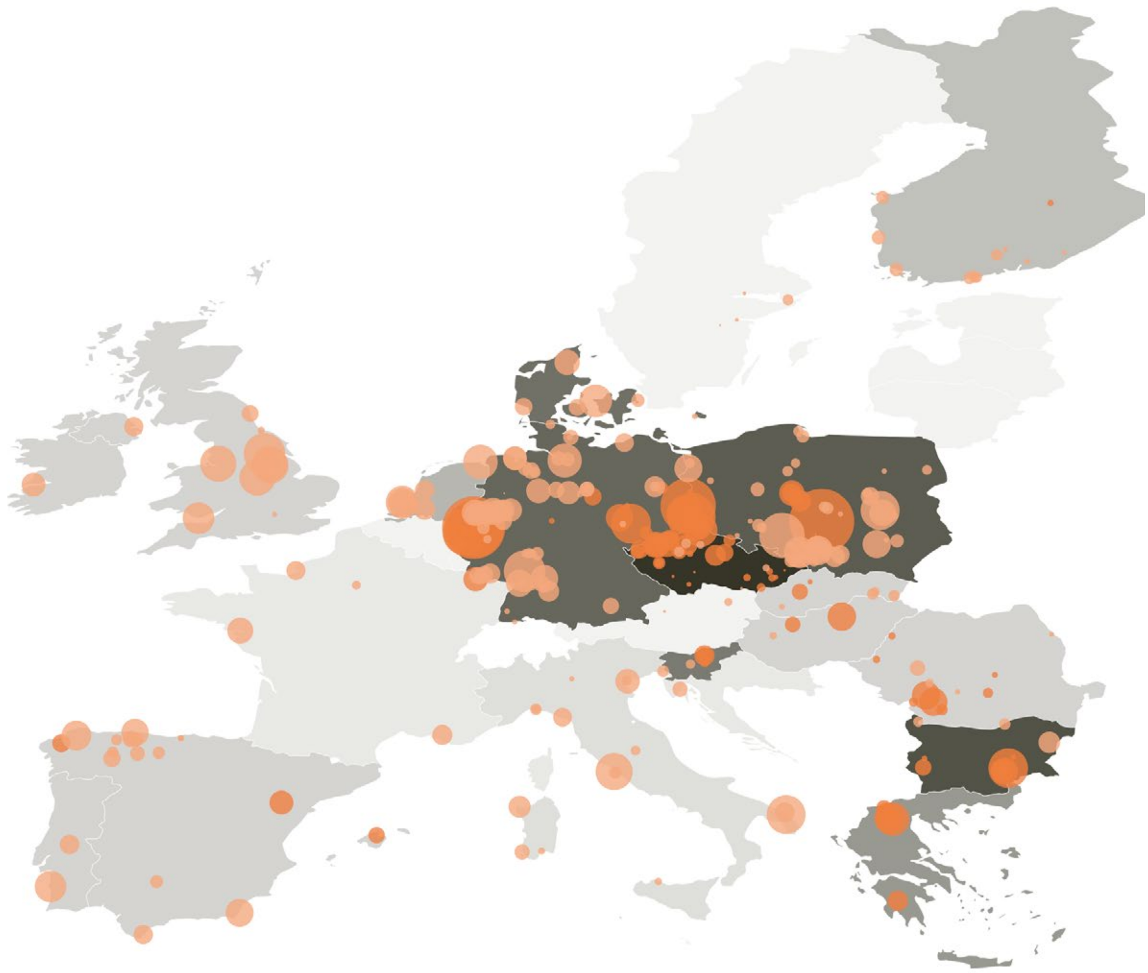

Figure 7: Location of coal power plants in the EU in 2016. Circle diameter indicates capacity. Country colours depict coal use per capita (darker shading indicates higher coal use per capita). Source: GCPT, CAN Europe, SSP, own calculations

4.2 THE STARTING POINT FOR OUR ANALYSIS

Figure 7 depicts the location of coal power plants in the EU in 2016. The country level intensity of coal use – measured in coal use per capita – is also shown with darker colours depicting higher coal use intensity. There are clear coal use hotspots, like the Ruhr area and Lusatia in Germany, Upper Silesia in Poland and the Ostrawa region in Czech Republic.

Czech Republic has the highest current coal dependency in per capita terms, followed by Germany, Poland and Bulgaria. France, Sweden and Austria stand out as having comparatively lower coal consumption per capita, with France relying strongly on nuclear power, Austria on hydroelectricity and Sweden on a mixture of both. Belgium, Luxembourg, Malta, Cyprus, Estonia, Lithuania and Latvia have no coal power plants at all.

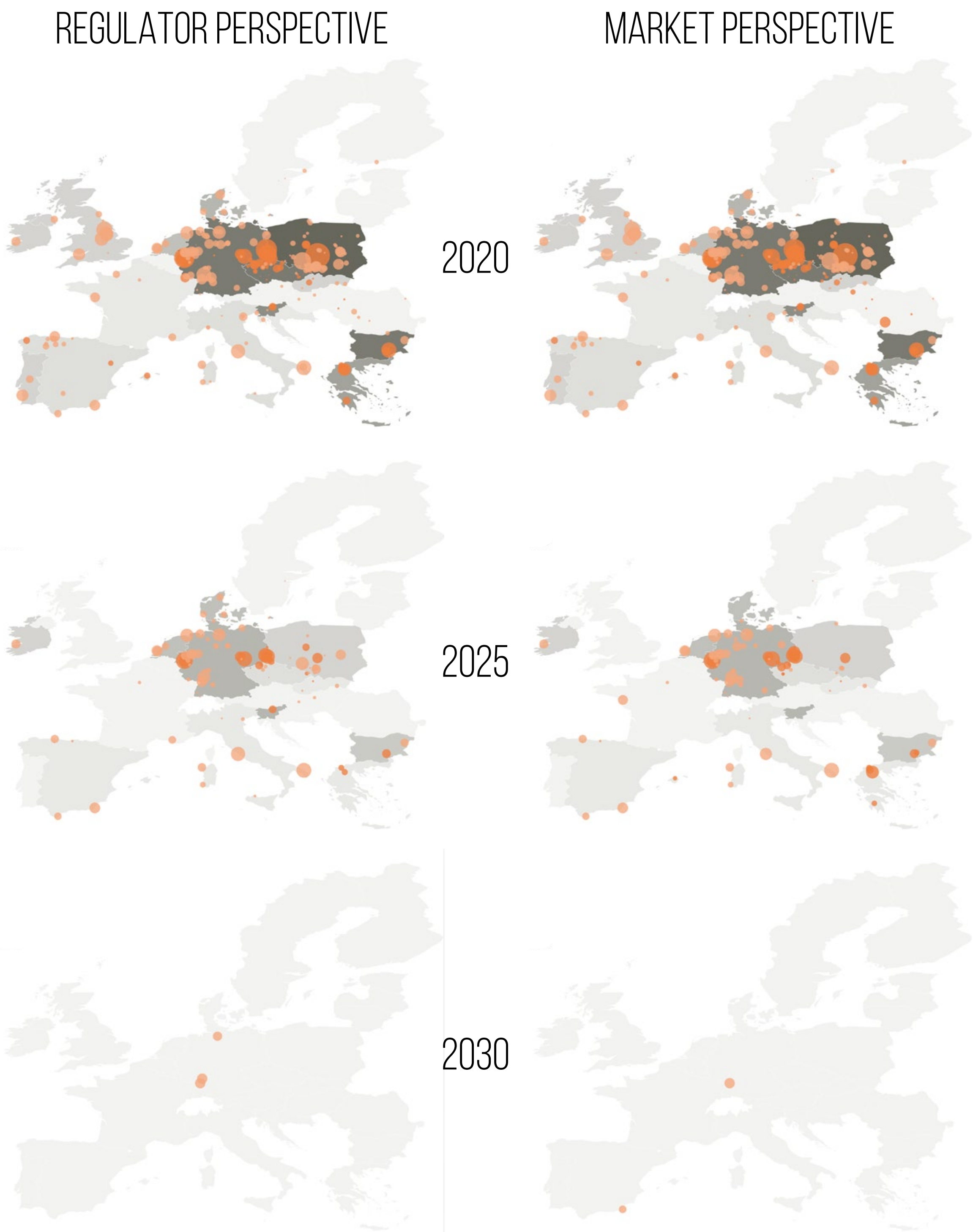

Figure 8: Results for remaining coal power plants and coal used for power plants per capita in 2030. Left panel: Regulator perspective, right panel: Market perspective. Sources: GCPT, CAN Europe, IIASA/Joeri Rogelj, SSP database, own calculations

4.3 REGULATOR VS MARKET PERSPECTIVES

Figure 8 shows how coal power plants are gradually shut down between 2020 and 2030 in line with the Paris Agreement's long-term temperature goal, both for the Regulator (left panel) and the Market perspective (right panel).

Under the Regulator shutdown schedule, only three units located in Germany remain online until 2030. Under the Market perspective, one unit in Germany and one in Spain remain active until 2030. For Poland, the results differ significantly between the two approaches: almost all plants need to be retired already by 2025 under the Market whereas many plants remain under the Regulator perspective. The same pattern is observed for Denmark but, given the much smaller capacity, the earlier shutdown of a single plant unit changes the remaining unit structure significantly.

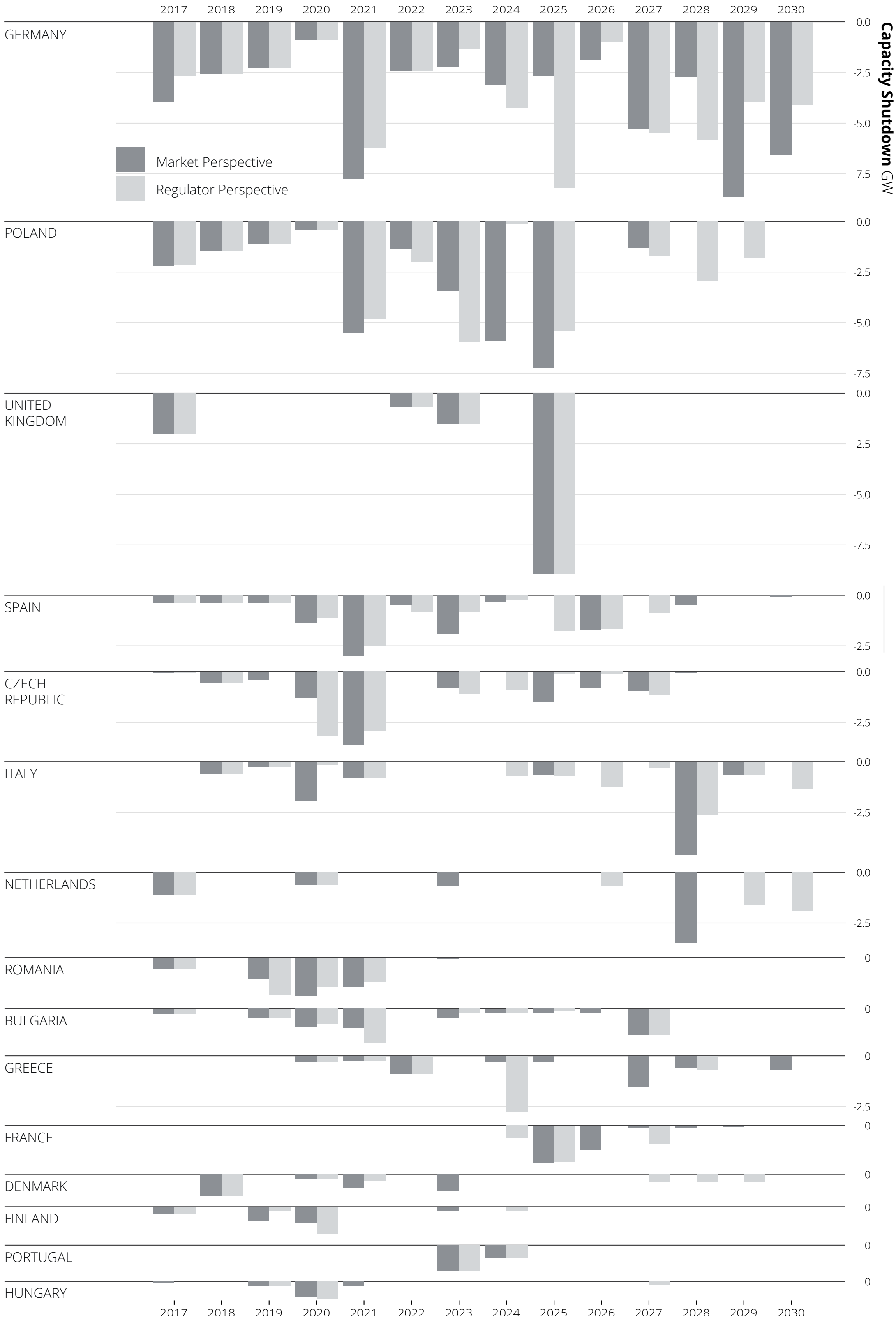

Figure 9: Comparison of Market and Regulator perspective coal power phase-out schedule in line with the Paris Agreement for selected EU member states. Results for remaining countries can be found in Annex I: Additional results. Sources: GCPT, CAN Europe, IIASA/Joeri Rogelj, SSP database, own calculations

For the Czech Republic and Bulgaria, a large share of capacity needs be shut down already before 2020 under the Regulator perspective, showing the high emissions burden of plants in these countries.

Figure 9 compares the Paris Agreement scenario phase out schedules for the countries

Table 4: Phase-out date for largest coal power plants in Europe. The BAU (business-as-usual) column shows the year in which the last unit of the power plant would be shut down based on our expectations of lifetime. The two columns Regulator and Market show the year by which the last unit of each power plant needs to be shut down under the two perspectives

RANK	PLANT	COUNTRY	FUEL	CAPACITY	UNITS	SHUT DOWN YEAR		
				MW		BAU	Regulator	Market
1	Bełchatów**	Poland	Lignite	4 928	12	2055	2027	2027
2	Neurath	Germany	Lignite	4 424	7	2055	2029	2030
3	Kozienice*	Poland	Hard coal	3 915	11	2061	2028	2025
4	Niederaussem	Germany	Lignite	3 676	7	2045	2028	2030
5	Opole*	Poland	Hard coal	3 280	6	2063	2029	2025
6	Jänschwalde	Germany	Lignite	3 210	6	2028	2024	2027
7	Drax***	UK	Hard coal	2 640	4	2025	2025	2025
8	Brindisi Sud	Italy	Hard coal	2 640	4	2044	2028	2028
9	Boxberg	Germany	Lignite	2 427	4	2055	2029	2030
10	Jaworzno 3*	Poland	Hard coal	2 255	7	2063	2028	2025
11	Mannheim	Germany	Hard coal	2 147	4	2058	2031	2030
12	Fiddler's Ferry	UK	Hard coal	2 000	4	2017	2017	2017
13	Cottam	UK	Hard coal	2 000	4	2025	2025	2025
14	Ratcliffe	UK	Hard coal	2 000	4	2025	2025	2025
15	Torrevaldaliga Nord	Italy	Hard coal	1 980	3	2061	2030	2029
16	Weisweiler	Germany	Lignite	1 958	4	2021	2021	2021
17	West Burton	UK	Hard coal	1 924	4	2025	2025	2025
18	Lippendorf	Germany	Lignite	1 866	2	2043	2027	2029
19	Turów*	Poland	Lignite	1 765	7	2063	2028	2024
20	Moorburg	Germany	Hard coal	1 730	2	2058	2031	2029

* Capacity includes units that are under construction and will be online in the next 1-3 years.

** Bełchatów has a total capacity of 5 400 MW (with 12 older units of 360-390 MW capacity and a newer unit of 858 MW). One unit was scheduled to be be retired in 2016 and the data above and our analysis reflects this. However there is uncertainty surrounding the future of this unit.

*** Drax has 6 units of 660 MW and a total nameplate capacity of 3 960 MW but as of 2015, two units have been modified to be fired by biomass (potentially a mix of biomass and coal) leaving the effective coal capacity of the remaining 4 units at 2 640 MW. Conversion of a 3rd unit was scheduled for 2016.

Note that the above plant capacity values are derived from the Global Coal Plant Tracker database as of July 2016. While every effort to ensure accuracy has been made, we cannot guarantee there are no errors, especially with the ever shifting nature of individual units being commissioned, decommissioned, refurbished or modified to use different fuels.

with the largest coal power capacity at present for the Market and Regulator perspectives.

The similarities between the two approaches, combined with the steep emissions reduction required to stay within the Paris Agreement budget result in around 98% of the units being retired with a five or less years of difference between the two approaches. While the two shutdown schedules are overall quite similar in terms of retired capacity, there are some interesting differences between two approaches.

The abrupt shut down of all remaining capacity in the United Kingdom in 2025 is due to the recently introduced regulation banning coal-fired power plants after that date.

In the case of Germany, the Market perspective favours longer operation of some remaining capacity than the Regulator's perspective. This is reversed for Poland, where shutdown is considerably faster under the Market perspective. For most other countries, the results are not very different under the two perspectives. The differences for Czech Republic, for instance, lie in the numeric range of single power plant units.

These differences reflect the granularity of coal-fired power supply capacity. Which specific plants go offline by when differs between the two approaches, with different potential impacts in various regions in each country. This level of detail can be seen in the online graphic visualisation on the accompanying webpage.

There is not one common ruling factor determining the final order of the coal power plants in the retirement priority list but rather a combination of different factors that affect all units simultaneously. An early shut down under a Market perspective in Poland, for example, does not mean that in general these coal power plants are relatively less profitable than in other European countries; in fact, they are not. This is rather due to different factors that affect particular units, changing their relative position in the retirement priority list under each of the approaches.

One such factor is future decrease in electricity prices in some member states, which puts some newer, more efficient plants at a disadvantage compared to similar but older generation units, which have already recovered most of the investment costs. Another factor could be, for instance, the historically low observed utilisation rates of more efficient plants compared to similar, less efficient units in some countries. Follow up research could provide a more detailed analysis of the factors determining the probable retirement date of each of the units, which goes beyond the scope of the current analysis.

Table 4 shows the 20 largest coal power plants in the EU and provides a year for their shut down according to the different schedules (Regulator vs Market). These power plants have a combined capacity of around 53 GW, which corresponds to about 32% of the EU's coal-fired capacity currently in operation and under construction. Eight of these plants are fired with lignite, with the remainder using hard coal. Roughly 21.5 GW of this capacity is located in Germany, approximately 16 GW in Poland and the rest in the United Kingdom and Italy.

Each of these large plants comprises of several units. The largest of these, also the largest in Europe – the Bełchatów power plant in Poland – has multiple units with a combined capacity of around 5 GW. One interesting pattern that emerges is that in general, the Market perspective favours a later complete shutdown for a majority of the large lignite plants, showing the higher relative profitability of lignite power plants compared to hard coal. One important fact to remember is that the shutdown of such large plants is a gradual rather than a sudden process.

4.4 THE SPECIAL CASES OF GERMANY AND POLAND

Germany and Poland are jointly responsible for 51% of the installed capacity and about 54% of the emissions from the coal-fired power plants in the EU (Table 1). Action in these two countries is decisive for an efficient and timely coal phase-out compatible with the Paris Agreement. In addition, due to their influence on policy-making at the European level, governments of these two countries will also be decisive in designing how and when coal phase-out takes place. This role is especially important because the negative consequences of coal phase-out will strongly impact Poland and Germany but at the same time the benefits for both countries will be significant. The following two sections describe the peculiarities of these two countries in terms of their coal sectors.

4.4.1 GERMANY AND LIGNITE

Germany is known for its Energy Transition: a decision to phase out nuclear energy and reducing energy-related GHG emissions by significantly increasing the role of renewables and improving energy efficiency (Bundesregierung, 2016a). Between 2000 and 2015, the share of renewables in gross power production increased from 6.5% to 29%. In the same period the share of power from nuclear power plants decreased by 15% and from hard coal by almost 7%. The share of power from the most carbon-intensive fuel, lignite, remained relatively stable at around 25%, with the absolute electricity production from lignite-fired power plants even increasing by 4.5% (AG-Energiebilanzen, 2016).

This had repercussions for the emissions from the power sector, which decreased by less than 4% between 2000 and 2015 – much less than could be expected from Europe's energy transition leader. The failure of the EU ETS to deliver incentives for fuel switching away from coal, combined with decreasing price of hard coal, has led to an increase in power production, in turn leading to higher electricity exports.

An increase in the share of renewables has also to some degree been counterbalanced by the nuclear phase out. Much higher power supply combined with a small decrease in the overall emissions led to only modest decrease in the carbon intensity of the German power mix: from 562 g/kWh in 2000 to 484 g/kWh in 2015 (Agora Energiewende, 2016a). The major obstacle to a deeper and more rapid decarbonisation of the German power sector is the significant share of lignite. In 2015 over 178 million tonnes of lignite were extracted in Germany, 90% of which was burned in coal-fired power plants (Euracoal, 2016).

Between 2000 and 2015, the extraction of lignite in Germany increased by over 6% - from 169 to 178 million tonnes. Lignite remains the cheapest fossil fuel for electricity generation in Germany but only because external costs such as climate change, air pollution and those related to open pit mining are not internalised in its price. The low price of emissions allowances in the EU ETS does not reflect these costs accordingly. Apart from the initial period, when the price reached 30 €/tCO_2 (Bredin, 2010), the allowances traded significantly below the expected price and in December 2016 cost around 4€/tCO_2 (EEX, 2016).

To remedy this situation and facilitate the decarbonisation of the power sector, in early 2015 the Minister of Economy, Sigmar Gabriel, suggested introducing a mechanism that would increase the costs of power production from the most inefficient power plants. The fee (*Klimabeitrag)* would have to be paid by fossil fuel power plants older than 20 years, regardless of fuel type. It would only apply to emissions above a certain threshold, which was initially set at 7 Mt CO_2/GW.

This threshold was to sink annually until it reaches 3 Mt CO_2. The power plants that exceed the emissions intensity threshold would have to purchase *additional* allowances in the value between 1€ initially and 18-20€ in 2020 for each tonne of CO_2 above the threshold (Matthes et al., 2015). This mechanism would have influenced the merit order of the German power sector by increasing the utilisation of cleaner power plants and decreasing the competitiveness of the most carbon-intensive units.

In July 2015, after strong protests from the coal lobby, the German government decided not to introduce the coal fee. Instead, operators of lignite power plants were to move generation units with combined capacity of 2.7 GW to "Capacity Reserve" for four years. After this period these power plants are to be closed. The companies will be paid compensation of EUR 230 million annually for seven years. This measure should reduce emissions by 11-12.5 $MtCO_2$ annually (Leaders of CDU, CSU and SPD 2016). The respective law has been implemented in November 2015 (BMWi, 2015).

While the discussion in Germany focuses on decreasing power generation from existing coal-fired power plants, the oversupply and resulting decrease of electricity prices makes new projects uncompetitive. Already in 2007, a study of the planned Moorburg power plant in Hamburg pointed to its unprofitability (BUND, 2007). Decreasing wholesale electricity prices and increasing competitiveness of renewables over the last decade has further worsened the profitability perspectives of coal-fired power plants. Even before the new power plant went online, its book value decreased, creating a loss of around 1 billion EUR (Vattenfall, 2015).

Nonetheless, some new plants are still planned or under construction. One example is the 1100 MW Datteln power plant in western Germany, initially meant to go online in 2011. Should it go online, it would be one of the biggest in the country, and the largest one built as a single unit. Its final completion has been delayed due to numerous complaints and court proceedings against the investment (Der Westen, 2011). Even though the construction was restarted in 2016, no final date for the plant's opening is currently known (Uniper, 2016). According to Uniper's manager of external communications, Georg Oppermann, Uniper is still optimistic about the plant going online by 2018, which we also assume in our analysis.

4.4.2 POLAND'S COAL DEPENDENCY

Poland is the EU's largest hard coal producer, extracting almost 72% of the region's hard coal (Euracoal, 2016). This share is set to increase even more, as Germany plans to phase out hard coal mining in 2018, and the only hard coal producer in Czech Republic, OKD, is filing for insolvency. This will happen despite the fact that Poland's mining sector remains uncompetitive with extraction costs above the international coal prices. The survival of the coal industry is thus only possible due to the significant direct and indirect state aid provided to the mining industry (Dziennik Zachodni, 2016). The government is unwilling to close the most unprofitable coalmines for political reasons, which makes it difficult to focus resources and modernise those coalmines in which coal extraction could still be profitable.

Almost 85% of Poland's electricity comes from coal-fired power plants (Rynek energii elektrycznej, 2016). However, the energy companies operating these installations are increasingly affected by the growing market penetration of renewables, with near-zero running costs, which has led to a market power price decrease from about 182PLN (43 EUR) per MWh in 2013 to 169.99 PLN (41 EUR) in 2015 (URE, 2016). New grid connections with countries where electricity prices are even lower will further decrease the electricity price in Poland and endanger the profitability of new coal-fired power plants.

Nonetheless, in June 2016, Energy Minister, Krzysztof Tchórzewski pointed out that replacing existing power plants would translate to constructing 20-24 new units with combined capacity of 12-15 GW (WNP, 2016c). Currently 9.2 GW of new coal capacity is planned, with about 4.4 GW under construction (Global Coal Plant Tracker, 2016).

The largest projects are units 5 and 6 of the Opole power plant, with combined capacity of 1.8 GW. The investment is at an advanced stage and supposed be completed in late 2018 (unit 5) and early 2019 (unit 6). The projected annual coal consumption of these new units is estimated at 4.1 million tonnes (PGE, 2016). Even though analysts project these new investments will lead to a decrease in emissions in the short term, as it will replace a number of older, low-efficiency power plants, it will lock Poland's power sector into high carbon dependency for decades to come. At the same time, due to its higher conversion efficiency compared to the older plants, it will worsen the problem that the government is trying to solve: the oversupply of domestic coal.

To improve the situation of energy companies and to finance construction of new projects, the government plans to introduce a capacity market that would ensure profitability of new power plants even in times when they do not generate power (WNP, 2016c). This proposed instrument should function in a similar way to the capacity market already introduced in the United Kingdom. However, it is not compatible with the EU's goal of decarbonising its economy because it lacks measures that ensure a decreasing role of fossil fuels in Poland's power sector, and as such may not be accepted by the European Commission (WNP, 2016a).

The main reason for the government's continued support for coal is the perception of this fuel as domestic, especially compared with alternatives such as natural gas, which is mostly imported from Russia. The significant coal resources and the desire to remain independent were the main drivers for the construction of coal-fired power plants, especially in the 1960s and the 1970s. The situation has changed since then and the heavy reliance on coal has become a burden.

Not only does it lead to significant air pollution and almost 5300 deaths every year (Greenpeace, 2016) but it actually weakens Poland's energy security rather than strengthening it. In August 2015, for instance, energy prices skyrocketed because drought had forced some thermal coal power plants to switch off due to the lack of cooling water, which is sourced from rivers. To avoid a major black-out, the government ordered 1600 largest power consumers to significantly restrict their electricity demand, with significant negative economic impacts (Polskie Radio, 2015). The neighbouring countries, especially Czech Republic and Germany, are in a position to avoid similar problems due to the availability of photovoltaic capacity.

Another factor which will have negative consequences for Poland's energy security is that Polish coal reserves will run out by the 2060s at current exhaustion rate (BP, 2016). Extraction costs will increase significantly before that date – the costs of hard coal in Poland are already much higher than the price of imported coal. Should this trend continue, Poland's dependency on imported coal would increase, with negative consequences for Poland's energy security.

The major challenge in phasing out coal is, however, the concentration of the coal-mining in one region, Upper Silesia, which employs most of Poland's 85 000 coal miners. However, Upper Silesia is also a highly industrialised region with other well-developed industry branches, such as automotive and steel manufacturing. This would help to lessen the social impacts of the coal phase-out in this region.

In addition to strong dependency on hard coal, Poland also generates further 30% of power from lignite (PSE, 2016). This country is also home to one of the largest lignite power plants in Europe – the Bełchatów power station with 5 GW installed capacity. For a number of reasons the government prioritises hard coal over this energy source. First of all, far fewer people are employed in this sector. In 2015, there were fewer than 10 000 coal-miners working in lignite mining (Pietraszewski, 2015). What's more, unlike hard coal, lignite mines are owned by energy companies rather than directly by the state. Finally, the economic situation of the lignite industry is much better than that of the hard coal sector, which decreases the need for direct state intervention.

Another decisive factor in power production from lignite will be the exhaustion of existing fields. If no new fields are opened up, in the 2030s the capacity of the power plants will have to decrease from currently around 9 000 MW to around a third of that level due to fuel scarcity (CIRE, 2008). But strong social protests against new open pit mines (WNP, 2016d) and decreasing competitiveness of this source of energy, further worsened by the potential for an increase in the carbon prices in the coming decades, makes investments in new fields improbable.

5 ALTERNATIVES TO COAL

A steep reduction of lignite and hard-coal based power generation is inevitable in the EU, given the emissions reduction targets established at the national, regional and global levels, which require the complete decarbonisation of the electricity sector by the second half of the century. Compared to other sectors like transport and industry, the electricity sector offers the possibility of rapid mitigation of GHG emissions at a lower cost, given the multiple low-cost alternatives available for replacing fossil fuels.

In 2014, more than a quarter of electricity generated in the EU came from coal-fired power plants. With some countries planning or already implementing nuclear phase-out, removing coal from the power mix will be challenging – especially in countries where over 50% of electricity comes from coal such as Poland, Greece or Czech Republic (Eurostat, 2016b).

Our results show that in order to meet the Paris Agreement long-term temperature goal, coal will need to be phased out in the EU by the early 2030s. While an almost complete removal of coal from the electricity mix within slightly more than a decade seems to be an ambitious undertaking, a significant share of the EU's existing coal-fired power plants has already been underutilised. Alternative clean energy sources such as wind and solar are rapidly gaining in importance in the EU and offer a low-cost alternative to meet the energy requirements of the region. In this section, we investigate how a transition to renewables can replace the retired coal capacity and contribute to decarbonisation of the power sector.

5.1 FACILITATING THE GROWTH OF RENEWABLES

Renewable sources of energy have experienced a rapid growth in the EU over the last decade – especially in the power sector. In 2004, renewables accounted for only 14.4% of electricity generation but by the end of 2014 their share has almost doubled and reached 27.5%. In Denmark and Portugal the share of renewables increased the fastest. In both countries close to a quarter of energy came from renewables in 2004 but a decade later every second kilowatt-hour was produced using wind, solar, biomass or hydro energy.

Also Germany, Spain, Italy and the UK have registered a significant growth in the share of renewables, whereas the growth in France, Finland and Slovakia was slower (Eurostat, 2017b). Currently, renewables account for over 40% of the total installed generation capacity of the EU, and despite concerns about grid integration, nearly a third of total electricity production in 2015 was attributed to renewable sources (European Network of Transmission System Operators, 2016). The share renewables in the power mix is set to further increase.

Growth in renewables is closely connected with the existence of support mechanisms for these new sources of energy. Renewable energy sources profited from support mechanisms for a rapid market uptake. This is especially important due to the inefficiencies of the mechanisms aimed at the internalisation of the external costs of fossil fuels, such as the EU ETS. Concerns about energy security and environmental degradation motivated frontrunner countries like Denmark and Germany to implement support policies for renewables already in the 1980s and 1990s. As technology developed and improved, these mechanisms have led to massive market penetration.

However, bad design of the support mechanism in some countries, e.g. Czech Republic and Spain, which guaranteed an overly generous and thus unsustainable level of support had a boom-and-bust effect. Retroactive changes to the support mechanism and moratoria on renewables development introduced in some countries increased the insecurity of investors and led to a slowdown in renewables development (EREF, 2013). As a result, contrary to global trends, investment in renewables in the EU in recent years slowed down from over USD 120 billion in 2011 to below USD 50 billion in 2015 (Bloomberg, 2016).

A massive acceleration in the renewable energy development is crucial to a successful, rapid coal phase-out. Such transition is only possible if effective and predictable policy is accompanied with financing for renewables. An increase in the costs of carbon allowances by a sensible redesign of the EU-ETS would provide the necessary financial resources for renewables development while simultaneously decreasing the competitiveness of fossil fuels in the power sector.

5.2 ACHIEVING TRANSFORMATION OF THE POWER SECTOR

There is no doubt that the energy sector of the future will look very different from what it is now. The main three differences will be (i) higher reliance on weather-dependent sources of energy, (ii) high upfront investments and almost zero running costs, and (iii) mostly decentralised character. Combined, these differences mean a major transition in the power sector, which is already underway in some EU countries. Coal phase-out will be key in driving this transition.

Managing power grids with a much higher share of intermittent sources of energy, like wind and solar, will be more challenging than currently. However, numerous solutions already exist to cope with this challenge. Grid extension allows to benefit from different weather conditions in different regions. The North Seas Countries' Offshore Initiative, for example, is aimed mainly at reducing the costs of connecting offshore wind farms to the power grid but these will also decrease the volatility of power supply (NSCOGI, 2016). Better-developed grids will also allow more efficient utilisation of large and small-scale storage capacities in different countries.

A case in point are energy exports to Norway with its huge potential for storing energy in hydropower plants at times of high power production from wind and solar power plants and power imports when the conditions worsen.

The spread of e-mobility and thus large number of batteries, can increase the storage potential (Tomorrow, 2017). Finally, demand management and a more efficient utilisation of dispatchable renewables, such as hydropower and biogas, offers a large potential to balance the grid. Introducing policies that would facilitate a more effective utilisation of these opportunities is an important component of coal phase-out.

With the exception of bioenergy, the other significant difference between the current and future power market is the high upfront investment of low-carbon energy sources and the lack of fuel cost for all energy sources except biomass. This increases the role of interest rates in the assessment of the overall investment. The level of the interest rates is strongly influenced by the perceived security of the return on investment: the higher the risk, the higher the interest rates (Grau, Neuhoff, & Tisdale, 2015). That is why the feed-in tariff support mechanism, with guaranteed tariff for electricity from renewables, was so successful in fostering the growth of renewables.

There is a clear trend among the EU countries of moving away from feed-in tariffs towards auctioning, resulting for instance from the European Commission's preference for "market-based approach to renewables" and Europeanisation of the support mechanisms for renewables (European Commission, 2016b). Nonetheless, the investment risk, and thus the costs of renewables could be significantly decreased if the EU member states set themselves clear and ambitious renewable energy targets.

This will not only facilitate development of renewable energy installations, but will also encourage renewable energy companies to invest in production facilities in countries with the largest potential growth. Introducing guarantees for investors to secure their investments in case of unpredicted national policy changes would result in an additional decrease in the


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capital costs of investments. According to some estimates, this would lead to costs reduction amounting to at least EUR 34 billion between 2020 and 2030 (Agora Energiewende, 2016b).

The issue of high upfront investment costs for renewables is to some degree mitigated by their scalability. Unlike fossil fuels installations, renewable energy projects can be realised in stages, with the revenue from the initial stages contributing to financing the subsequent stages. Even more importantly, the small scale of renewables significantly increases the number of participants in the energy transition. Decreasing costs per unit makes renewable energy installations affordable to average citizens leading to democratisation of the energy sector (Szulecki, Ancygier, & Szwed, 2015). This increases the acceptance for energy transformation in the society.

Like any major transformation, replacing coal by renewables also has important social repercussions. Coal phase-out from the European power sector will have especially significant repercussions for coal mining.

In 2014, over 177 000 people worked in coal mining, more than half of them in Poland (Eurostat, 2017a). Of that number 40 000 jobs are in lignite mining, which are closely linked to power generation but a great majority is in hard coal mining, which is much more labour intensive.

Employment in hard coal mining has been falling constantly due to the decreasing competitiveness of European coal compared with imported coal and consequential closure of coal-mines in many EU member states, and will likely continue to decrease regardless of EU coal policy. In Poland employment in hard coal mining fell from 415 000 in 1989 to 340 000 only 3 years later (Czerwińska, 2002). At the end of 2016, employment in hard coal mining in Poland fell to 85 000 (WNP, 2016b). This decreasing trend is set to continue even without coal phase-out. According to some estimates, employment in Polish coal will have to decrease by a further 50% by 2020 to make it competitive (Bukowski, Maśnicki, Śniegocki, & Trzeciakowski, n.d.).

At the same time increasing demand for alternatives to coal will create jobs significantly exceeding the number of jobs in the coal sector. Already in 2014, over 1.1 million people in the European Union were employed in renewable energy sector. More than a third of that number worked in wind and PV sectors – jobs largely non-existent two decades ago (EurObserv'ER, 2015). Due to much higher employment intensity of renewable sources of energy compared with coal – especially keeping in mind the increasing share of imported coal – their development will provide many more jobs then what will be lost as a result of coal phase-out (Schaeffer et al., 2016). The distributed character of renewables will also facilitate much more balanced development of different regions.

6 EU CURRENT POLICIES AND COAL PHASE-OUT

Many EU countries have already announced their intention to phase out coal in the electricity sector in the next decades (CAN EUROPE, 2015): the United Kingdom and Austria aim at phasing out coal by 2025, France has announced the shut down of its last coal-fired power plant by no later than 2023, Finland and Portugal in the 2020s, and Sweden has announced fossil fuels phase-out in the next decade. Even though the German Climate Action Plan 2050 does not include any deadline for coal phase-out, it includes a target of close to halving emissions from the power sector between 2014 and 2030 (Bundesregierung, 2016b). This can only be achieved with the closure or decreased utilisation of a number of coal-fired power plants. In fact, the EU has seen a massive retirement of coal-based power generation units the in the last years, with Germany and United Kingdom advancing particularly fast. In the last decade, a total of 272 coal-based power generation units with a combined capacity of around 52 GW were retired in the EU.

Most countries with a phase-out plan in place (e.g. France, the UK) require little if any effort beyond current measures to implement the least-cost retirement schedule. Countries heavily reliant on coal, however, need additional regional and national measures to achieve the steep decline in coal generation that is required in the next decades.

Below, we discuss how currently implemented EU-level policies can contribute to enabling coal phase-out compatible with the target of the Paris Agreement.

EU-ETS

A number of factors have contributed to the much slower than necessary decrease in coal related CO_2 emissions in the electricity sector in most EU. From an economic perspective, the most relevant factor has been the low price of carbon observed in recent years in the EU Emissions Trading Scheme (EU-ETS).

The EU-ETS, introduced in 2005, is one of the flagship instruments of European climate policy. However, its effectiveness has been far lower than expected when it was initially introduced (Pew Center on Global Climate Change, n.d.). The main reason for the failure to achieve a substantial impact on the European power mix was the fall in the price of emissions allowances, from over 30 €/tCO_2 in 2008 to below 5 €/tCO_2 at the end of 2016 (EEX Homepage, 2016). One clear example of this failure is the situation in Germany, where the utilisation rate of gas-fired power plants has decreased and the role of lignite – the most carbon-intensive source of energy – has increased slightly in the decade following the introduction of the EU ETS (Jones & Gutmann, 2015).

There have been several attempts to alleviate the problem of a too low price for emissions allowances and to make the EU-ETS more effective. In December 2016, the European Parliament's Environmental Committee proposed a number of amendments for the EU ETS functioning post-2020. These include increasing the Linear Reduction Factor - LRF from 2.2% to 2.4%, and doubling the intake rate of the Market Stability Reserve to 24% in the first three years of Phase 4 (European Parliament, 2016). These changes still need to be adopted by the European Parliament's assembly and the Council of Ministers.

One key concern regarding the EU-ETS and its current design is on how to ensure that ambitious national policies in one member state do not result in other countries doing comparatively less. A coal phase-out consistent with the Paris Agreement's temperature limit would further increase the oversupply of the allowances and thus decrease their price. Even without any additional measures, it can be expected that the plans of some EU member states to switch off all coal-fired power plants within the next decade will significantly decrease demand and thus also the price of the allowances. That will increase the competitiveness of coal-fired power plants in countries without any plans to phase out coal and thus undermine the coal phase-out plan.

An alternative would be introducing a carbon price floor or a price corridor to decrease this competitiveness of coal in comparison with other sources of energy with lower carbon intensity (Knopf & Edenhofer, 2014). However, carbon pricing alone is no enough to lead to the removal of coal from the energy system – at least not at the rate required by the Paris Agreement. Unless national carbon intensity targets for the electricity sector are put in place and used to monitor the impact and effectiveness of other mitigation policies to achieve the decarbonisation of the power sector, the effectiveness of the EU-ETS in contributing to a strategy to phase out coal in the EU remains at this point highly uncertain.

PHASE-OUT BY REGULATION

Considering the current ineffectiveness of the EU-ETS and keeping in mind the opposition of some EU countries to the necessary significant changes to the EU ETS, relying solely on market forces to achieve the coal phase-out may be too risky, Furthermore, the lack of consideration for social and economic externalities affecting some regions, like sudden increase in unemployment and significant decrease in tax revenues, may hinder social acceptance not only for the coal phase-out but for climate action altogether. Another risk is the potential threat for the power sector in countries and regions with no backup for coal.

In this context, a phase-out of coal by regulation becomes an effective government tool to achieve emissions reduction targets at a lower cost, while providing stakeholders with certainty to ensure a smooth transition to alternative power sources in regions where coal currently plays an important role. In addition, phase-out regulation would discourage investors to undertake new investments in coal, reducing the risk of stranded assets and re-directing energy sector investments to alternative energy sources.

Many European countries have in fact already moved in this direction, either by announcing phase-out dates or creating specific national regulations to achieve this goal. Some of the most outstanding coal phase-out regulation examples in the EU are the Portuguese National Programme for Climate Change, which commits to a phase-out of coal in the electricity sector by 2030 at the latest (CAN EUROPE, 2015), and the United Kingdom's strategy for the phase-out of coal by 2025 (Department for Business Energy & Industrial Strategy, 2016).

One example of a planned phase-out of a major technology is the agreement between the German government and the operators of nuclear power plants from 2000 to switch off all nuclear power plants by 2022. In this case, the schedule for their closure was determined by their age, with some exceptions (Deutsche Bundesregierung, 2000). A phase-out plan for coal-fired power plants could be determined by a number of additional factors, such as carbon intensity of the produced electricity as studied in this report, the availability of replacement options or the social and economic impact of plant and coal mine closures (which were not evaluated here).

Coal phase-out plans would create an environment of certainty for energy sector investors and allow better national planning to avoid strong economic shocks (mostly in terms of regional tax revenue and employment) created by the spontaneous closure of coal power plants due to market forces. This means that by creating coal phase-out plans, the EU or its member states could not only have a significant impact on reducing national and regional GHG emissions, but also set precedent at the international level for the measures needed to achieve the decarbonisation of the power sector (Jones & Gutmann, 2015).

In July 2015, the German government adopted a plan to move some of the oldest and most carbon-intensive power plants to capacity reserve resulting in a combined capacity of 2.7 GW to be moved to capacity reserve for four years and subsequently switched off. Their operators will be paid compensation (Ministry of Economy and Industry, 2016). Such approach may however turn out too expensive if a country was to phase out all of its power plants within just one decade: to switch off around 13% of Germany's installed capacity, plant operators will receive a compensation of EUR 1.6 billion (Bundestag, 2016).

Capacity reserves and capacity markets turned out to be increasingly often used not only to provide the necessary back-up power for weather-dependent renewables, but also to support economically crippled coal-fired power plants or even finance the construction of new installations. This is especially the case for Poland, which plans to spend over EUR 20 billion to finance the creation of a capacity market (ClientEarth, 2016), with some members of the government openly discussing which coal-fired power plants would be financed by this mechanism (Wysokie Napiecie, 2016).

The European Commission's Proposal for a Regulation on the internal market for electricity presented in November 2016 has done away with this possibility: according to it, new installations emitting more than 550 g CO_2/kWh should not be allowed to participate in the capacity market (European Commission, 2016c). Should this proposal enter into force, it will severely limit the possibilities for supporting coal-fired power plants by the EU member states and may lead to their faster phase-out for economic reasons.

STRENGTHENING ENVIRONMENTAL POLICY

Apart from being the most carbon-intensive fuel, coal also has a number of negative social and environmental impacts. According to some estimates, emissions of air pollutants from coal-fired power plants leads to almost 23 000 fatalities annually in the EU (EEB, Sandbag, CAN Europe, HEAL, 2016). Strengthening regulations not related to climate change and improving sustainability of the national energy systems has already been one of the decisive factors influencing energy policy in the EU and beyond. As the negative impacts of air pollution resulting from coal-fired power plants become clear, the call for stricter emissions standards becomes stronger. Even though some installations could be modernised to fulfil the new requirements, in many cases it is too expensive leading to a decrease in the competitiveness of the installation (Department for Business Energy & Industrial Strategy, 2016). As a result energy companies decide to close their power plants rather than retrofitting them (The Guardian, 2014).

Air pollution has been one of the first areas regulated by European legislation. Already in 1988 the Council of European Communities issued a directive with national ceilings for pollutants such as sulphur dioxide and nitrous oxides. Even though most member states had to decrease their emissions of these pollutants between 1980 and 1998, some states - Greece, Portugal and Ireland – actually increased those by between 94 and 157%. The Council also introduced emissions limits for dust per MW of installed capacity (Council of the European Communities, 1988).

In 2001, this directive has been replaced by the Large Combustion Plants Directive, which slightly reduced the national emissions limits for sulphur dioxide and nitrogen oxides. The standards for dust from large combustion plants were left at previous levels. Power plants exceeding these limits were allowed to stay online until 2015 but had to limit their time of operation to maximum 20 000 hours in total between 1 January 2008 and 31 December 2015 (European Council, 2001). This meant reducing their average utilisation rate to around 28%. This directive was complemented by the Integrated Pollution Prevention and Control Directive (IPPC Directive), which made the issuance of operation permits for industrial activities dependent on the utilisation of the best available techniques (BAT). For this purpose the Commission would periodically issue BAT reference documents, so called BREFs (European Council, 2008).

The Industrial Emissions Directive (IED Directive), adopted in 2010, replaced both the LCP and the IPPC directives, This new directive has also replaced a number of other directives dealing with air pollution from different sources, significantly broadening the list of pollutants. Power plants unable to meet the new standards cannot operate for more than 17 500 hours in the period between 1 January

2016 and 31 December 2023. This reduces the average utilisation rate to below 25%. The practice of making the operation permit dependent on the utilisation of the best available techniques determined by the Commission in Best available technologies Reference documents (BREFs) has been taken over from the IPPC directive (European Council, 2010).

The impact of these standards on the coal phase-out remains unclear; especially as GHG emissions reduction was not the subject of these directives. The IED clearly stated that "[w]here emissions of a greenhouse gas from an installation are specified in Annex I to Directive 2003/87/EC [introducing the EU ETS] in relation to an activity carried out in that installation, the permit shall not include an emissions limit value for direct emissions of that gas, unless necessary to ensure that no significant local pollution is caused." But these air quality regulations and emissions performance standards forced many coal power plants to install additional equipment to meet tight NO_x emissions limits, which implies an additional cost to the plant operation. Exceptions and time extensions to comply with the standards allowed delayed compliance, which decreased the effectiveness of air quality requirements to reduce CO_2 emissions.

This situation may change due to the adoption of the new BREFs referred to in the IED Directive. The document lists the best available techniques for combustion plants, which need to be implemented by power plants within four years after the document has been adopted in the early 2017. Otherwise the respective national authorities will not be allowed to issue or extend their operation permits (Joint Research Institute, 2016). According to a recent report, the implementation of these new requirements would reduce the number of premature deaths in the EU caused by air pollution from coal-fired power plants from 22 900 to 2 600 annually (EEB, Sandbag, CAN Europe, HEAL, 2016).

Furthermore, on 31 December 2016 the National Emission Ceilings Directive (NEC Directive) has entered into force. It strengthens the air quality standards adopted earlier for the period after 2020 for five major pollutants (SO_2, NO_X, NMVOC, NH_3 and $PM_{2.5}$). As a result the *average* emissions in any year between 2020 and 2029 should decrease in comparison to 2005 by 59% for SO_2, 42% for NO_x, and 22% for $PM_{2.5}$ (European Council, 2016). Whereas a significant share of these emissions comes from transport and heating, increased air quality standards will also force operators of coal-fired power plants to retrofit and thus worsen their economic competitiveness.

None of the above measures requires the closure of the coal-fired power plants or reduction of their utilisation rate as long as they stay below the limits adopted. In fact, there are numerous ways to fulfil the standards, or be granted a limited life time derogation from the BREFs (EPPSA, 2016). The air quality standards included in the NEC Directive may also be improved by a significant reduction in emissions pollutants in other sectors, e.g. transport or households. However, the evolution of European air quality policy shows a clear tendency towards more stringent and broader requirements imposed on the operators of coal-fired power plants. Even if these requirements can be fulfilled in the short- to mid-term, the threat of more stringent standards in the long-term increases the risk premium for new investments or upgrade of new coal-fired power plants. As a result, their competitiveness in comparison with other sources of energy decreases.

While air quality measures cannot replace policies directly related to coal, like the EU ETS and phase-out regulations, they can contribute in many ways to increase their effectiveness. They can for instance ensure that plants with higher externalities are retired first and that market failures, like fuel switching from gas to coal, are minimised. Strengthening of air quality requirements is thus a necessary condition for making sure that the national coal phase-out strategy maximises the social welfare and thus increases the social acceptance of coal phase-out.

7 CONCLUSIONS

The closure of most coal-fired power plants in the EU in less than 15 years is a fundamental transformative challenge. But such a transformation is crucial to meet the commitments made in the Paris Agreement. Furthermore, an energy transition away from coal will avoid large environmental and health costs, such as air pollution or – in the case of hard coal and some EU member states (e.g. Germany) – increasing reliance on energy imports.

In recent years, coal power plant shut down has been made cheaper by the significant, rapid decrease in renewable energy costs. Even though wind and solar energy come with their own challenges, mainly related to weather dependency, a number of options, like storage, grid development or dispatchable renewables, exist to cope with these issues. At the same time renewables come with the benefits of being inexhaustible and scalable thus allowing completely new business models and leading to job creation, including in areas which will be affected by coal phase-out.

The role of coal has already been decreasing in almost all EU member countries and this trend is set to continue, independently from any attempts at coal phase-out. With the increasing market penetration of renewables and resulting decrease in their price, investors in coal-fired power plants are facing difficult times ahead. Furthermore, they have to deal with the challenge of stricter air quality standards and rising opposition of people affected by the new open pit mining. The impact of these measures is clearly visible in the decreasing number of planned investments.

To remain compatible with the Paris Agreement's long-term temperature goal, the coal phase-out needs to happen much faster. While policy measures already in place, like the EU ETS or support for renewables, could play an important role driving the EU's transformation away from coal if strengthened or scaled up, a coal phase-out needs to be effectively complemented by additional regulations that would increase its predictability and decrease the economic, social and environmental costs of this transformation. Making further investments in this sector would in effect be throwing good money after bad.

Open pit coal mining Cottbus Nord in Lower Lusatia, Brandenburg, Germany in 2011.
Photo © Vladimir Wrangel / Shutterstock, Inc.

REFERENCES

AG-Energiebilanzen. (2016). Bruttostromerzeugung in Deutschland ab 1990 nach Energieträger. Retrieved from http://www.ag-energiebilanzen.de/

Agora Energiewende. (2016a). *Die Energiewende im Stromsektor: Stand der Dinge 2015*. Retrieved from www.agora-energiewende.de

Agora Energiewende. (2016b). Reducing the cost of financing renewables in Europe. A proposal for an EU Renewable Energy Cost Reduction Facility ("RES-CRF").

Bloomberg. (2016). Europe Is Losing Its Reputation as a Renewable Energy Leader.

BMWi. (2015). Verordnung zur Regelung des Verfahrens der Beschaffung, des Einsatzes und der Abrechnung einer Kapazitätsreserve.

BP. (2016). *BP Statistical Review of World Energy*. Retrieved from http://www.bp.com/content/dam/bp/pdf/energy-economics/statistical-review-2016/bp-statistical-review-of-world-energy-2016-full-report.pdf

Bredin, D. (2010). *An Analysis of the EU Emission Trading Scheme*.

Bukowski, M., Maśnicki, J., Śniegocki, A., & Trzeciakowski, R. (n.d.). Polski węgiel>Quo Vadis. Perspektywy rozwoju górnictwa węgla kamiennego w Polsce.

BUND. (2007). Hamburg-Moorburg – das Aus für den Klimaschutz? Retrieved from http://bund-hamburg.bund.net/fileadmin/bundgruppen/bcmslvhamburg/Proj1_Klima_Energie/Energiegewinnung/moorburg-V2.pdf

Bundesregierung. (2016a). Energiewende im Überblick. Retrieved December 31, 2016, from https://www.bundesregierung.de/Content/DE/StatischeSeiten/Breg/Energiekonzept/0-Buehne/maßnahmen-im-ueberblick.html;jsessionid=F3F6980FB6955106CE87310872317764.s4t2

Bundesregierung. (2016b). Klimaschutzplan 2050. Retrieved from http://www.bmub.bund.de/fileadmin/Daten_BMU/Download_PDF/Klimaschutz/klimaschutzplan_2050_bf.pdf

Bundestag. Gesetz zur Weiterentwicklung des Strommarktes (Strommarktgesetz) (2016).

CAN Europe. (2016). European Coal Map.

CAN EUROPE. (2015). *Coal briefing: Government policies on the phasing-out of coal*.

Carbon Tracker Initiative. (2013). Unburnable Carbon 2013: Wasted capital and stranded assets. *Carbon Tracker & The Grantham Research Institute, LSE*, 1–40. http://doi.org/10.1108/meq.2013.08324eaa.003

CIRE. (2008). Węgiel brunatny - Rynek energii elektrycznej. Retrieved December 30, 2016, from http://www.rynek-energii-elektrycznej.cire.pl/st,33,257,tr,72,0,0,0,0,0,wegiel-brunatny.html

ClientEarth. (2016). Poland's support for coal through capacity market will hit household bills | ClientEarth. Retrieved from http://www.clientearth.org/poland-pledges-support-for-coal-power-by-capacity-market/

Council of the European Communities. (1988). Council Directive of 24 November 1988 on the limitation of emissions of certain pollutants into the air from large combustion plants, *49*(336), 11–20.

Czerwińska, E. (2002). Restrukturyzacja górnictwa węgla kamiennego w Polsce. Retrieved from http://biurose.sejm.gov.pl/teksty_pdf/i-891.pdf

Department for Business Energy & Industrial Strategy. (2016). COAL GENERATION IN GREAT BRITAIN. Retrieved from https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/567056/With_SIG_Unabated_coal_closure_consultation_FINAL__v6.0_.pdf

Der Westen. (2011). Eon-Kraftwerk Datteln ist nicht zu retten - Wirtschaft - derwesten.de. Retrieved from http://www.derwesten.de/wirtschaft/eon-kraftwerk-datteln-ist-nicht-zu-retten-id4158000.html

Deutsche Bundesregierung. Vereinbarung zwischen der Bundesregierung und den Energieversorgungsunternehmen vom 14. Juni 2000 (2000). Retrieved from http://www.energie-fakten.de/pdf/kernenergie-konsens.pdf

Dziennik Zachodni. (2016). Trzy spółki idą na ratunek Kompanii. Energa na giełdzie leci w dół - Dziennikzachodni.pl. Retrieved from http://www.dziennikzachodni.pl/strefa-biznesu/wiadomosci/a/trzy-spolki-ida-na-ratunek-kompanii-energa-na-gieldzie-leci-w-dol,10149548/

EEA. (2016). Overview of electricity production and use in Europe. Retrieved January 19, 2017, from Overview of electricity production and use in Europe

EEB, Sandbag, CAN Europe, HEAL, W. (2016). Lifting Europe's Dark Cloud. How Cutting Coal Saves Lives. Retrieved from http://www.eeb.org/index.cfm?LinkServID=E3882544-5056-B741-DBB3E8DE57F619F6

EEX. (2016). European Emission Allowances (EUA). Retrieved from https://www.eex.com/en/market-data/environmental-markets/auction-market/european-emission-allowances-auction#!/2016/12/05

EEX Homepage. (2016). European Emission Allowances Auction (EUA) | Global Environmental Exchange. Retrieved from https://www.eex.com/en/market-data/environmental-markets/auction-market/european-emission-allowances-auction#!/2016/11/25

EPPSA. (2016). Implications of the new LCP-BREF/BAT conclusions. Retrieved from http://www.eppsa.eu/tl_files/eppsa-files/0. Members Only/Info for members/2016 09 22_Implications_of_BREF-LCP_-_BAT_conclusions_Tigges_Final presentation.pdf

EREF. (2013). Policy paper on retrospective changes to RES legislations and national moratoria.

Euracoal. (2016). *Market Report 2016 no.2*. Retrieved from https://euracoal.eu/library/coal-market-reports/

Eurelectric. (2016). *EU ETS Reform - EURELECTRIC recommendations on proposals to strengthen the EU ETS A EURELECTRIC position paper*.

EurObserv'ER. (2015). The State of Renewable Energies in Europe. Edition 2015.

European Commission. 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 (2014).

European Commission. (2016a). aProposal for a Directive of the European Parliament and of the Council amending Directive 2012/27/EU on energy efficiency. Retrieved from http://ec.europa.eu/energy/sites/ener/files/documents/1_en_act_part1_v16.pdf

European Commission. (2016b). Proposal for a directive of the European Parliament and of the Council on the promotion of the use of energy from renewable sources (recast). Retrieved from http://ec.europa.eu/

energy/sites/ener/files/documents/1_en_act_part1_v7_1.pdf

European Commission. (2016c). Proposal for a Regulation of the European Parliament and of the Council on the internal market for electricity.

European Council. (2001). 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. *Official Journal of the European Union*, (309), 1–21. http://doi.org/10.1039/ap9842100196

European Council. (2008). Directive 2008/1/EC of the European Parliament and of the Council of 15 January 2008 concerning integrated pollution prevention and control.

European Council. Presidency Conclusions (2009). Retrieved from https://www.consilium.europa.eu/uedocs/cms_data/docs/pressdata/en/ec/110889.pdf

European Council. Presidency Conclusions (2009).

European Council. (2010). Directive 2010/75/EU of the European Parliament and of the Council of 24 November 2010 on industrial emissions. *Official Journal of the European Union*, *L334*, 17–119. http://doi.org/10.3000/17252555.L_2010.334.eng

European Council. Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency, amending Directives 2009/125/EC and 2010/30/EU and repealing Directives 2004/8/EC and 2006/32/EC (2012).

European Council. European Council (23 and 24 October 2014) Conclusions on 2030 Climate and Energy Policy Framework (2014). Retrieved from http://www.consilium.europa.eu/uedocs/cms_data/docs/pressdata/en/ec/145356.pdf

European Council. (2016). Directive of the European Parliament and of the Council of 14 December 2016 on the reduction of national emissions of certain atmospheric pollutants, amending Directive 2003/35/EC and repealing Directive 2001/81/EC, *2016*(1386).

European Environment Agency. (2016). *Transforming the EU power sector: avoiding a carbon lock-in*. Copenhagen.

European Parliament. (2016). Amendments on the proposal for a directive of the European Parliament and of the Council amending Directive 2003/87/EC to enhance cost-effective emission reductions and low-carbon investments, *148*(2015).

European Union. EUR-Lex - 32009L0028 - EN - EUR-Lex (2009). Retrieved from http://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:32009L0028

European Union. (2015a). 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), 1–5. http://doi.org/10.1007/s13398-014-0173-7.2

European Union. (2015b). Intended Nationally Determined Contribution of the EU and its Member States. Retrieved from http://www4.unfccc.int/submissions/INDC/PublishedDocuments/Latvia/1/LV-03-06-EU INDC.pdf

Eurostat. (2016a). Coal consumption statistics - Statistics Explained.

Eurostat. (2016b). Gross electricity production by fuel. Retrieved January 2, 2017, from http://ec.europa.eu/eurostat/statistics-explained/index.php/File:Gross-electricity-production-by-fuel-GWh-EU28-2014-TABLE.png

Eurostat. (2017a). Annual detailed enterprise statistics for industry - Mining of coal and lignite.

Eurostat. (2017b). Share of energy from renewable sources.

Global Coal Plant Tracker. (2016). Global Coal Plant Trakker. Retrieved June 9, 2016, from http://endcoal.org/global-coal-plant-tracker/

Grau, T., Neuhoff, K., & Tisdale, M. (2015). Mandatory direct marketing of wind power increases financing costs.

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

Greenpeace. (2016). *Poland: Europe's most polluted country in trouble with the EU but still won't clean up coal - Energydesk*. Retrieved from http://energydesk.greenpeace.org/2015/06/25/polands-smog-crisis-europes-most-polluted-country-in-trouble-with-the-eu-but-wont-cut-coal-emissions/

Huscher, J., Smith, D., Holland, M., & Jensen, G. (2013). THE UNPAID HEALTH BILL How coal power plants make us sick A report from the Health and Environment Alliance. *Health and Environment Alliance*.

I4CE & Enerdata. (2015). *Exploring the EU ETS beyond 2020: A first assessment of the EU commission's proposal for Phase IV of the EU ETS (2021-2030)*. Retrieved from http://www.i4ce.org/wp-core/wp-content/uploads/2015/11/15-11-30-COPEC-FULL-REPORT.pdf

IEA. (2015). *World Energy Outlook*. http://doi.org/10.1787/weo-2014-en

IEA. (2016). World Energy Outlook 2016. http://doi.org/10.1787/weo-2016-en

IIASA. (2016). MESSAGE. Retrieved from http://www.iiasa.ac.at/web/home/research/modelsData/MESSAGE/MESSAGE.en.html

International Energy Agency (IEA). (2016). Energy and Air Pollution - World Energy Outlook 2016 Special Report.

IPCC. (2014a). *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report if the Intergovernmental Panel on Climate Change*.

IPCC. (2014b). Summary for Policymakers. In Stocker & V. B. and P. M. M. (eds T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia (Eds.), *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

IRENA. (2016). Roadmap for a Renewable Energy Future.

Joint Research Institute. (2016). Best Available Techniques (BAT) Reference Document for Large Combustion Plants - draft.

Jones, D., & Gutmann, K. (2015). *End of an Era: Why every European country needs a coal phase-out plan*. Retrieved from https://www.greenpeace.de/sites/www.greenpeace.de/files/publications/end-of-era-coal-phase-out-plan-20151204.pdf

Knopf, B., & Edenhofer, O. (2014). Save the EU Emissions Trading Scheme : set a price band. *Energy Post*, 1–5. Retrieved from http://energypost.eu/eu-emissions-trading-scheme-can-saved-price-band/

Leaders of CDU, C. and S. (2016). Eckpunkte für eine erfolgreiche Umsetzung der Energiewende.

Massachusetts Institute of Technology. (2007). *The Future of Coal*.

Matthes, F., Loreck, C., Hermann, H., Peter, F., Wünsch, M., & Ziegenhagen, I. (2015). *Das CO_2 -Instrument für den Stromsektor: Modellbasierte Hintergrundanalysen*.

Retrieved from http://www.bmwi.de/BMWi/Redaktion/PDF/S-T/strommarkt-praesentation-das-CO2-instrument-fuer-den-stromsektor,property=pdf,bereich=bmwi2012,sprache=de,rwb=true.pdf

Ministry of Economy and Industry. (2016). Beginn der Sicherheitsbereitschaft. Retrieved from http://www.bmwi.de/DE/Presse/pressemitteilungen,did=781730.html

NSCOGI. (2016). Political Declaration on energy cooperation between the North Seas Countries.

Pew Center on Global Climate Change. (n.d.). *The European Union Emissions Trading Scheme (EU-ETS) Insights And Opportunities Synopsis*.

PGE. (2016). Parametry Techniczne. Retrieved from http://www.blok5i6.pl/parametry-techniczne/

Pietraszewski, A. (2015). Podsumowanie wyników produkcyjnych uzyskanych w sektorze wydobywczym węgla brunatnego za I półrocze 2015 roku. *Węgiel Brunatny*, *91*(2). Retrieved from http://www.ppwb.org.pl/Static/upload/File/wegiel_91_2_2015.pdf

Pollitt, H., Alexandri, E., Gonzalez-Martinez, A., Wuester, H., Press, E., Oksanen, S., … Gherboudj, I. (2016). Renewable Energy Benefits: Measuring the Economics.

Polskie Radio. (2015). Brakuje prądu. Są ograniczenia do 30 sierpnia dostaw dla firm. Odbiorcy indywidualni bezpieczni - Gospodarka - polskieradio.pl. Retrieved from http://www.polskieradio.pl/42/273/Artykul/1486937,Brakuje-pradu-Sa-ograniczenia-do-30-sierpnia-dostaw-dla-firm-Odbiorcy-indywidualni-bezpieczni

PSE. (2016). Miesięczne raporty z funkcjonowania Krajowego Systemu Elektroenergetycznego i Rynku Bilansującego. Retrieved from http://www.pse.pl/index.php?modul=8&y=2013&m=12&id_rap=212

Rocha, M., Parra, P., Roming, N., Ural, U., Ancygier, A., Cantzler, J., … Hare, B. (2016). *Implications of the Paris Agreement for coal use in the power sector*.

Rogelj, J., Luderer, G., Pietzcker, R. C., Kriegler, E., Schaeffer, M., Krey, V., & Riahi, K. (2015). Energy system transformations for limiting end-of-century warming to below 1.5 °C. *Nature Climate Change*, *5*(6), 519–527. http://doi.org/10.1038/nclimate2572

Rynek energii elektrycznej. (2016). Podstawowe dane. Retrieved from http://www.rynek-energii-elektrycznej.cire.pl/st,33,207,tr,75,0,0,0,0,0,podstawowe-dane.html

Sandbag. (2016a). *2015 EU ETS Emissions analysis*.

Sandbag. (2016b). *Last chance saloon for the EU ETS*. Retrieved from http://libweb.ben.edu/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=nfh&AN=200709081063400898&site=ehost-live

Schaeffer, M., Rocha, M., Hare, B., Schleußner, C.-F., Baarsch, F., Granadillos, J., … Zavala, P. (2016). *Low Carbon Monitor 2016. Pursuing the 1.5C limit. Benefits and Opportunities*.

Schleussner, C.-F., Rogelj, J., Schaeffer, M., Lissner, T., Licker, R., Fischer, E. M., … Hare, W. (2016). Science and policy characteristics of the Paris Agreement temperature goal. *Nature Climate Change*. http://doi.org/10.1038/nclimate3096

Shearer, C., Ghio, N., Myllyvirta, L., & Nace, T. (2015). Boom and Bust?: Traking the Global Coal Plant Pipeline, 86.

Szulecki, K., Ancygier, A., & Szwed, D. (2015). Energy democratization? Societal aspects of de-carbonization in the German and Polish energy sectors.

The Guardian. (2014). E.ON runs down power stations despite blackout warning | Business | The Guardian. Retrieved from https://www.theguardian.com/business/2014/jan/22/eon-close-power-stations-blackout

The Intergovernmental Panel on Climate Change (IPCC). (2014). *Climate Change 2014: Mitigation of Climate Change*. *Working Group III Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. http://doi.org/10.1017/CBO9781107415416

Tomorrow. (2017). Electricity Map. Live CO_2 emissions of the European electricity production. Retrieved January 3, 2017, from http://electricitymap.tmrow.co/

UNEP. (2014). *The Emissions Gap Report 2014*. *Unep*. Retrieved from http://www.unep.org/pdf/SEI.pdf

UNEP. (2016). *The Emissions Gap Report 2016*. http://doi.org/ISBN978-92-807-3617-5

UNFCCC. (2015). Paris Agreement, 1–16.

Uniper. (2016). Kraftwerk Datteln 4. Retrieved from https://www.uniper.energy/de/unser-geschaeft/unsere-standorte/datteln-4.html

URE. (2016). Średnia cena sprzedaży energii elektrycznej na rynku konkurencyjnym za 2015 rok - Aktualności - Urząd Regulacji Energetyki. Retrieved from https://www.ure.gov.pl/pl/urzad/informacje-ogolne/aktualnosci/6471,Srednia-cena-sprzedazy-energii-elektrycznej-na-rynku-konkurencyjnym-za-2015-rok.html

Vattenfall. (2015). Hohe Abschreibungen und weiterhin niedrige Strompreise - Vattenfall. Retrieved December 31, 2016, from https://corporate.vattenfall.de/newsroom/pressemeldungen/2015/hohe-abschreibungen-und-weiterhin-niedrige-strompreise-ander-borse-beeinflussen-quartalsergebnis-von-vattenfall/

Whitmore, A., & Lagadinov, B. (2016). *Getting in touch with reality: Rebasing the EU ETS Phase 4 cap*. *Sandbag*. Retrieved from https://sandbag.org.uk/site_media/pdfs/reports/Sandbag_Realiging_EUETS_Ph4_cap.pdf

WNP. (2016a). Ekspert: może być trudno o zgodę KE na polski model rynku mocy - Wiadomości. Retrieved from http://www.wnp.pl/wiadomosci/282278.html

WNP. (2016b). Energia głównie z węgla. Retrieved January 3, 2017, from http://gornictwo.wnp.pl/energia-glownie-z-wegla,289012_1_0_0.html

WNP. (2016c). Tchórzewski: Polsce potrzeba 24 nowych bloków energetycznych - Energetyka. Retrieved from http://energetyka.wnp.pl/tchorzewski-polsce-potrzeba-24-nowych-blokow-energetycznych,276786_1_0_0.html

WNP. (2016d). ZE PAK odpiera zarzuty protestujących przeciwko odkrywce węgla - Energetyka. Retrieved December 30, 2016, from http://energetyka.wnp.pl/ze-pak-odpiera-zarzuty-protestujacych-przeciwko-odkrywce-wegla,273277_1_0_0.html

Wysokie Napiecie. (2016). Bruksela przemodelowuje rynek energii cz.3. Rynki mocy nie dla węgla? Retrieved from http://wysokienapiecie.pl/rynek/1935-bruksela-przemodelowuje-rynek-energii-cz-3-rynki-mocy-nie-dla-wegla

The Melnik Power Station in the Czech Republic. The 1050 MW four unit plant is fueled by lignite from mines in North and West Bohemia.
Photo © BESTWEB

ANNEX I: ADDITIONAL RESULTS

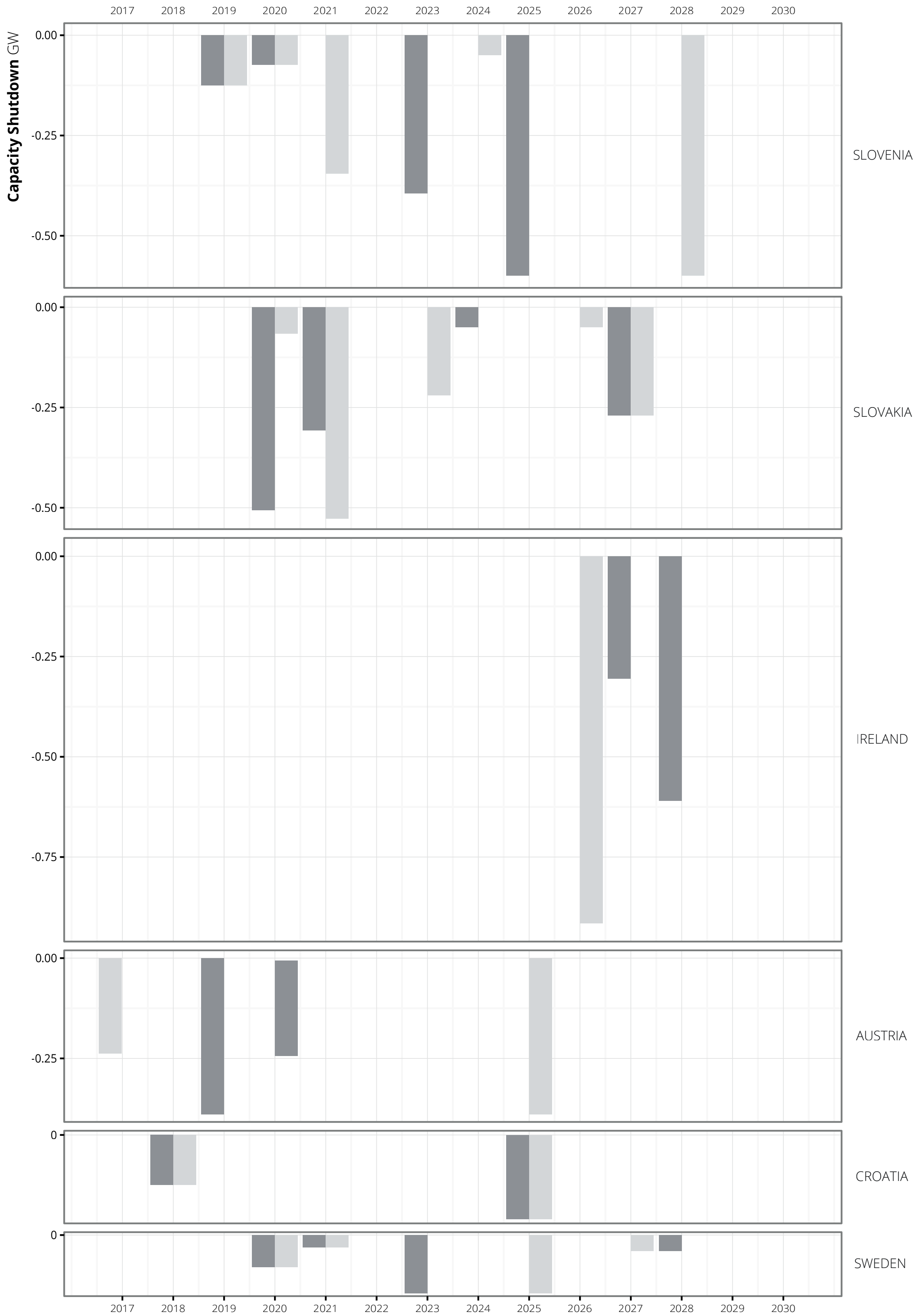

Figure 10: Comparison of Market and Regulator perspective coal power phase-out schedule in line with the Paris Agreement for smaller (below 5GW capacity) EU member states. Source: Own calculations

ANNEX II: ADVANTAGES AND LIMITATIONS OF IAMS

One of the main advantages of Integrated Assessment Models (IAMs) is that they explicitly take into account trade-offs between the deployment of different energy supply technologies (for example, due to differences in investment and fuel costs related to resource stocks) and many other economic relationships. All IAMs come to the same conclusion: the earlier strong climate action is initiated and implemented, the lower the combined global cost of meeting a temperature limit over the whole of the century.

IAMs also have limitations, for example related to their underlying driving assumptions. For instance, the MESSAGE scenarios used in this report are based on high energy efficiency improvements (low primary energy demand) and full technology availability. The latter means that certain debated and at present uncertain technologies are assumed to be available for mitigation. These include nuclear power, fossil fuel power generation with CCS and carbon-dioxide removal or negative CO_2 emissions technologies, all of which may have important sustainability-related and other implications.

Particularly for 1.5°C scenarios (such as the Paris Agreement's 1.5°C scenario), but also for 2°C scenarios (such as the Cancun Agreements 2°C scenario), some degree of negative CO_2 emissions are essential to stay in line with the warming limit. Even after taking into account the assumed potential for carbon sequestration in forests and soils, a need for industrial scale negative CO_2 emissions remains. Negative CO_2 emissions have not always been a necessity, but have become one due to limited emissions reductions over the past couple of decades. IAMs most often use biomass in combination with carbon capture and storage (BECCS) in order to achieve negative CO_2 emissions at scale.

In practice, there may be indirect economic constraints placed upon technologies. For example, policy makers may restrict CO_2 storage to only the geologically most secure repositories. This might lead to a lower storage potential than assumed in IAMs and higher costs. There may also be sustainability constraints placed upon the deployment of biomass energy systems, due to land use and other environmental considerations. Concerns with nuclear power in many jurisdictions are well known and may limit future deployment at least in some regions.

IPCC AR5 and subsequent literature shows clearly that delaying mitigation action not only increases the overall mitigation costs and undermines the probability of limiting warming to the agreed level **but also increases reliance on negative CO_2 emissions**. For illustration, *Figure 11* shows the relationship between 2030 emissions levels (as a % of 2010 emissions levels) and cumulative negative CO_2 emissions from BECCS. This relationship is not perfectly linear, since 2°C probability levels are also affected by non-CO_2 forcing that varies across scenarios. However, these scenarios do indicate that deeper pre-2030 mitigation lowers the need for later compensation by negative CO_2 emissions.

It must be noted that this is only a small set of scenarios that merely illustrates the issue. Further research is needed, especially towards the assessment of the influence of potential carbon sequestration in the land use, land use change and forestry (LULUCF) sector and measures to reduce non-CO_2 emissions. Research is ongoing in many of these areas, including in relation to limitations of use and deployment of certain technologies for sustainability, or other considerations in order to succeed in remaining below global warming limits. These issues are not covered in this report, but remain important to any real-world deployment of options described here.

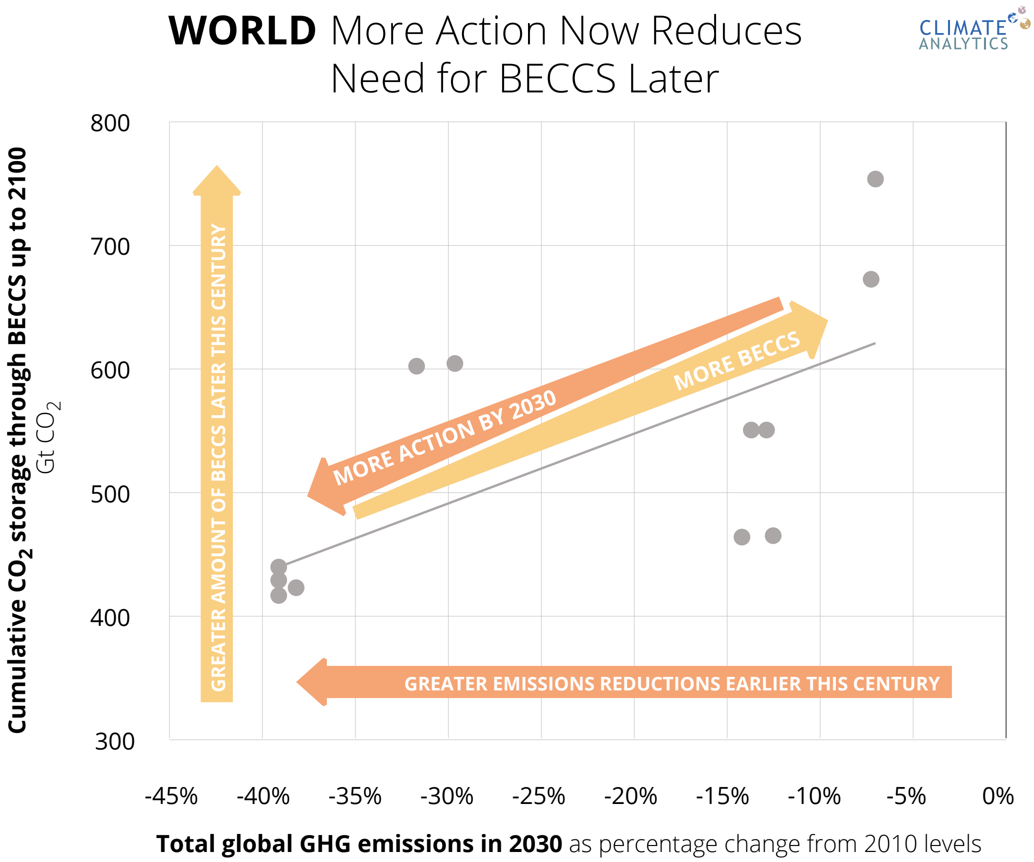

Figure 11. GHG Emissions levels in 2030 in percentage from 2010 levels and cumulative negative emissions from BECCS under a selection of 2°C scenarios (about 70% likely warming below 2°C by 2100) that in 2020 approximate global total GHG emissions levels estimated from Copenhagen pledges. Source: own calculations based on IPCC AR5 database.

ANNEX III: INTEGRATED ASSESSMENT MODEL SCENARIOS SELECTION

To obtain illustrative 1.5°C and 2°C consistent scenarios from all MESSAGE scenarios at our disposal, we selected scenarios based on their maximum exceedance probability temperature targets during the 21st century and their exceedance probabilities in 2100. These exceedance probabilities are computed with the reduced form carbon-cycle and climate model MAGICC (Meinshausen, Raper, & Wigley, 2011). From these scenarios, we choose those that limit global mean temperature increase to 1.5°C or less in 2100 with a probability of at least 50%. We only select scenarios in which climate policy starts after 2020, since these are deemed more in line with historical evolution of global climate policies. This led to the selection of three MESSAGE scenarios:

- The **No Policy** scenario is the baseline scenario assuming no further climate action after 2020 but a low energy intensity/high energy efficiency.

- The **Cancun Agreements (CA)** and **Paris Agreement (PA)** scenarios are compatible with 2°C and 1.5°C, respectively.

It must be noted that all scenarios used in this study assume availabiltiy of the full mitigation technology portfolio, i.e. all technologies present in the model are allowed to be deployed at rates determined by the model under respective constraints – e.g. fossil fuel resources or renewable energy potentials.

To date, all published 1.5°C consistent scenarios overshoot 1.5°C of global mean warming above pre-industrial during the 21st century by about 0.1 to 0.2°C, before returning to 1.5°C or below in 2100 with a 50% likelihood (median warming in 2100 of 1.4°C). There is a range of new scenarios under consideration and in preparation by different research groups which limit warming to 1.5°C with a higher probability and with a corresponding peak warming somewhat lower than indicated above. These are not yet published and therefore cannot be used at this point.

In this report, we opt for a class of scenarios often called **"delayed action" scenarios**, as opposed to those termed "immediate action" scenarios. Delayed action scenarios usually assume that countries will meet their Cancun Agreements pledges for 2020, before beginning deeper action to meet the 2°C or 1.5°C long-term temperature goal, as opposed to immediate action scenarios, which assume strong global concerted climate action starting in 2010. In effect, using *immediate action* scenarios would imply that full global climate action to meet the 2°C (or any other limit) started more than 5 years ago and that emissions levels in 2020 would be much lower than presently projected. Such scenarios, while useful for analytical purposes, are of limit use to the analysis conducted here. It is important to note, however, that if climate action would be ramped up in the pre-2020 period, this would relieve pressure on post-2020 targets.

ANNEX IV: SIAMESE

The **S**implified **I**ntegrated **A**ssessment **M**odel with **E**nergy **S**ystem **E**mulator (SIAMESE) seeks to address most of the present-day IAMs' complexity by creating a simple emulation of the IAMs energy system. SIAMESE was developed to emulate the energy-system characteristics of a particular IAM to reproduce its specific energy and emissions scenarios, and extend the field of application by applying this particular IAM's effective behaviour to different sub-regions or countries.

In order to downscale MESSAGE's regional output to the EU, the results of the MESSAGE model for the regions Western Europe (WEU) and Eastern Europe (EEU) are inputted to the SIAMESE model, in terms of GDP and primary energy consumption. At the base year (2010), the model is calibrated to replicate observed energy consumption for the respective sub-region[1] or country of interest. In a way, this calibration process takes into account the countries' or sub-regions' preferences regarding the primary energy mix composition. More precisely, SIAMESE allocates energy consumption in the regions by equalising the marginal utility of energy, under a welfare maximisation approach. Energy prices are endogenous in the model[2] and coincide with the marginal utility of energy.

Coal without CCS can be used as primary energy for the supply of electricity and as final energy (mainly in industry for the production of steel and cement). The available MESSAGE model output did not contain data on how much coal (in energy units [EJ]) is used without CCS ($PE_{t,r}^{Coal|Elec}$) for electricity supply, which is the quantity of interest for the purpose of this report. However, this number can be computed as the difference between total primary coal without CCS ($PE_{t,r}^{Coal}$) and final energy ($FE_{t,r}$) as there is no CCS for coal as a final energy type. This is depicted by the equation below with t and r being indices for time and region, respectively:

$$PE_{t,r}^{Coal|noCCS|Elec} = PE_{\mathrm{t},r}^{Coal|noCCS} \text{-} FE_{t,r}$$

This energy amount can now be converted to emissions using an average emissions factor that basically reflects the average carbon content of coal.

$$Em_{t,r}^{Coal|noCCS|Elec} = PE_{t,r}^{Coal|noCCS|Elec} * em^{Coal}$$

As the SIAMESE downscaler does only deliver data on primary energy demand for the six different "fuel" types coal, oil, gas, nuclear, biomass and non-biomass renewables, further calculations are necessary to compute cost optimal emissions pathways for coal use in the electricity supply sector. In a first step, the amount of coal used without CCS is computed according to the share in the respective MESSAGE base region. Then again, the amount of this coal that is used in power plants is computed according to the share of coal that is used in power plants without CCS in the respective MESSAGE base region. SIAMESE outputs are in energy units, we converted them into emissions using the implicit conversion factor from the MESSAGE model, which equals 25.8 tC/TJ *44/12.

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1 MESSAGE delivers results for 11 world regions. The 28 member states of the EU are contained in the two regions WEU (Western Europe) and EEU (Eastern Europe), respectively. Each of these regions is then split up into two sub-regions containing all EU and non-EU states, respectively. The MESSAGE energy supply for 2010 results are then split up between according to weights derived from 2010 historical primary energy demand figures, future split is endogenous to SIAMESE taking into account GDP and population projections from the Shared-Socioeconomic pathways and the constraint that the sum of energy demand for each source (coal, oil, renewables, etc.) from both sub-regions must equal the MESSAGE pathway for the base region.

2 SIAMESE determines the energy prices for each fuel, based on energy consumption levels from the MESSAGE model.

Regarding its equations, SIAMESE mimics the structure of IAMs. Similar to other IAMs, the economic output (GDP) is a function of capital, labour and energy consumption and TFP (total factor productivity), by using a CES (Constant Elasticity of Substitution) production function. The basic idea behind the CES production function is that it would be possible, to some extent (and at increasing cost), to replace one factor of production with another (e.g. capital with energy). Therefore, GDP is an endogenous variable. In order to provide comparable results, we harmonise the GDP with external projections by adjusting the TFP assumptions until a good fit is reached. The TFP is exogenous and it can be interpreted as a proxy of technological progress.

SIAMESE results are the outcome of numerical simulations. At times, adjustments are required to make these simulations directly useful for present day policy making. For example, in SIAMESE, coal emissions for Europe already deviate quite significantly in 2016 (15%) from the actual historical emissions, and this for both 2°C and 1.5°C pathways. We therefore adjust the historical emissions in SIAMESE based on GCPT results in 2016. Then we assume a common pathway for both 2°C and 1.5°C until the early 2020s, which ensures consistency with real-world policy developments and pledges. Only after 2022, the 1.5°C and 2°C SIAMESE pathways start to diverge significantly. Due to numerical reasons, emissions from coal always stay (just) above zero in SIAMESE. Therefore we assume that a "complete" phase out of coal power plants occurs whenever emissions are reduced by more than 95% compared to 2010 levels. During these adjustments, it is made sure that the resulting emissions budget is the same as for the unadjusted pathway.

These changes are necessary to adjust modelled pathways to the most recent real-world data. At the same time, we make sure that those pathways are fully consistent with the original SIAMESE results: first we ensure that pathways after adjustment have the same carbon budgets for the period 2010-2100 (for 1.5°C and 2°C pathways respectively). Second, after 2022 we make sure that pathways do not deviate more than 5% (of 2010 emissions levels) compared to the original pathways from SIAMESE after adjustment.

ANNEX V: ESTIMATING CO_2 EMISSIONS FROM COAL PLANTS

To estimate emissions from coal power plants in the European Union, we combine the information from Global Coal Plant Tracker (GCPT) database -version of June 2016- and the Climate Action Network (CAN) EU coal-fired power plants database -version of September 2016-. The GCPT database contains all known power plant units in the world, including those used as part of industrial installations to provide heat and power. The CAN database only contains coal power plants in the European Union that are used to supply electricity (and heat) for the market. We combine the two databases by matching the information for units contained in both sources. This approach has multiple benefits:

- By comparing the data – especially the capacity – we can spot differences between the two datasets that might be explained by the development stage of both datasets. When important differences have been detected, we have conducted unit level research and chosen the respective source we found more plausible using expert judgement.
- The main advantage of the GCPT database is that it includes units used in industrial installations, which are very relevant for our analysis given that our focus is on actual emissions to the atmosphere. If those units were not included in the analysis, a significant amount of emissions that actually occur would not be taken into account.
- The main advantage of the CAN database on the other hand is that it contains actual plant level fuel input data for 2013, which was derived from the data raised according to the Large Combustion Plants Directive.[1] By using this data and the knowledge of which plant units were actually online in 2013 (some might have been retired prior to or commissioned after 2013), we were able to compute the average 2013 capacity factor for most plants, which we furthermore assume to be applicable to all respective subunits for all periods.

The combined data used in this report comprises detailed information per unit concerning its location, status, capacity, capacity factor, status and efficiency and coal type, which allows estimating CO_2 emissions from these plants, using the following formula:

$$Annual\ CO_2 = capacity \times capacity\ factor \times \frac{1}{efficiency} \times emission\ factor \times \Phi$$

- The **capacity** describes the maximum amount of power a plant can produce and is measured in Megawatt (MW). The **capacity factor** gives the share of the year that the plant is actually running at this maximum capacity. It is influenced by electricity demand fluctuations, the position of the plant in the merit order and downtimes due to planned and unplanned maintenance. The observed values for 2013 range between 0.28 and 0.88 (10-90 percent quantile) with a median of 0.59. Where possible, we used plant level capacity factors. Units for which no plant level capacity factors could be computed were assigned the respective country averages capacity factor.
- The **efficiency** describes how well a plant unit is at converting energy from coal into electricity and it is usually expressed as the amount of energy output over the primary energy input. This rate is derived by comparing the quantity of energy contained in coal as it enters the plant site to the quantity of energy contained in the electricity that exits the plant side into the grid. The efficiency in our data varies only slightly between 38 and 41 percent depending on factors like

1 http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32001L0080

the type of combustion technology, the type of coal and the size of the plant (Sargent & Lundy, 2009)

- The **emissions factor** refers to the average amount of CO_2 emissions resulting of burning coal to produce a certain quantity of energy. The actual carbon content varies across coal types, which results in different emissions per unit of primary energy released from different coal types. We use the emissions factors given in IPCC (2006) for Anthracite, Sub-Bituminous Coal, (Other) Bituminous Coal and Lignite and unweighed averages for unit that use more than one coal type as fuel (see Table 5).
- For Waste/Bituminous, we assume the same emissions factor as for Bituminous coal, which very likely overstates the actual emissions factor as waste has a lower carbon content as any type of coal. This, however, is only a problem for a very small installed capacity – 40 MW.

Based on the formula above, we calculated the emissions on a per unit basis, which were then aggregated country and region level and distinguished by the unit status, taking into account the plants that are either operating, under construction, announced, permitted or pre-permitted.

Table 5: Emissions factors for different coal types. Source: IPCC (2006), own calculations

COAL TYPE	EMISSIONS FACTOR, LOWER CALORIC VALUE	CURRENTLY (2016) OPERATING CAPACITY IN EU
	kg/TJ	MW
Anthracite	98 300	7 044
Bituminous [a]	94 600	92 519
Sub-Bituminous	96 100	7 125
Lignite	101 000	48 795
Anthracite/Bituminous	96 450	5 034
Bituminous/Sub-Bituminous	95 350	600
Lignite/Bituminous	97 800	2 948
Waste/Bituminous	94 600	40

[a] The same emissions factor as for bituminous coal is also used for plants burning waste and bituminous coal.

In addition, due to some missing information in our database regarding retirement date, type of fuel, and other relevant variables, we had to make assumptions for some power units. The main following assumptions made were the following:

- Where information about the capacity of the plant was missing, we made a case-by-case research to include the capacity of the unit. Where our research yielded no results (only six units in the whole EU), we decided to not make an assumption on this variable and instead we excluded those power plants in our calculations.
- For the 1100 MW unit Datteln IV in Germany, which is nearly completed but whose actual opening is part of an ongoing court process, we assumed an opening date of 2018.
- For power plants that are currently operating, already beyond their planned retirement date, we assume they will be online for another 5 years but not beyond that.
- For power plants that did not have a planned retirement date, we assumed they will have the average lifetime of plants that have been already retired in the given country.

ANNEX VI: CALCULATING THE NET PRESENT VALUE OF COAL POWER PLANTS

The Net Present Value (NPV) is a financial computation that allows estimating an approximation of the profitability of an investment project by converting its anticipated future cash flows to the present cash values making use of a discount rate. The standard formula to calculate the net present value is the following:

$$NPV(i, N) = \sum_{t=0}^{N} \frac{Rt}{(1+i)^t}$$

Where Rt represents the net cash inflow (inflow-outflow) at time t, N represents the number of time periods and i is the discount date. For a coal-based power plant outflows include the initial investment, and fixed and variable operational costs (including fuel and carbon cost), while inflows can be approximated as the incomes coming from actual electricity output of the plant times the national energy price. The following illustration shows the cash flow for a coal power plant during its lifetime:

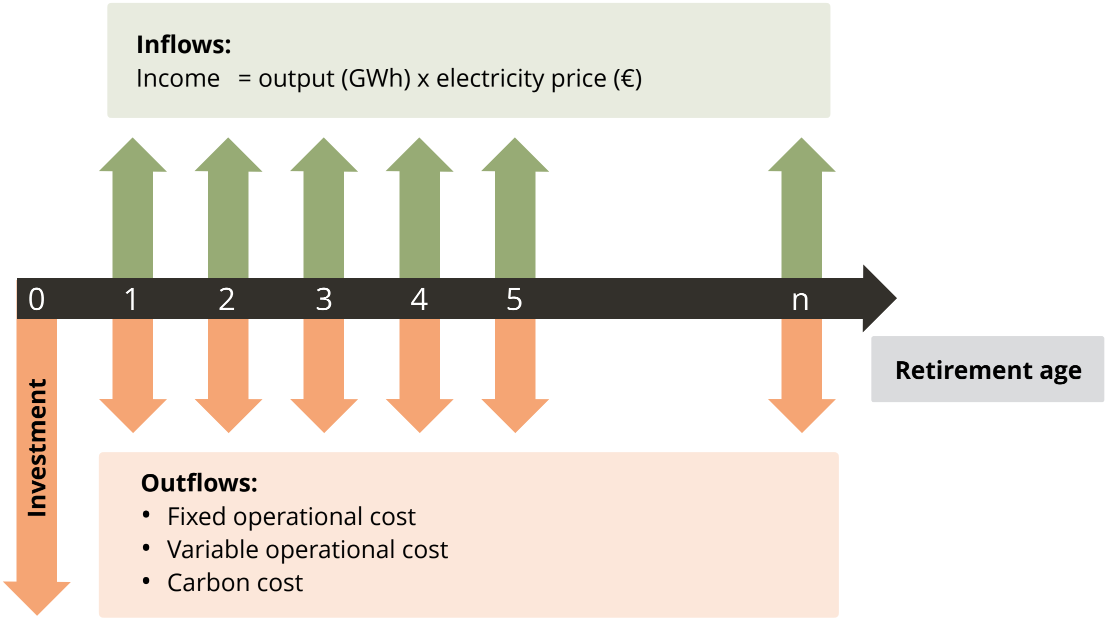

Figure 12: Cash flow diagram of an average coal-based power generation unit.

Taking into account the large number of coal-based generation units in the EU, it would be a major challenge to estimate individual parameters for each of the variables included in the cash flow calculations. In consequence, we have created approximated cash flows for each of the units using standard cost estimates per combustion technology, type of fuel and capacity and national level electricity prices.

For investment and operational costs we use the mean values of the ranges compiled by the Deutsches Institut für Wirtschaftsforschung (DIW) in 2013 to estimate the future cost of electricity generation until 2050 (Schröder et.al., 2013); which collect information from multiple technical studies dealing with cost estimation of power generation units. For simplicity reasons and acknowledging the difficulties of estimating projected values for each of the cost parameters we assume constant parameters for the full projection period. The values used for our approximated cash flows are summarised in the table below.

Table 6: Cost parameters for coal-based power plants by technology.

COAL TYPE	CAPITAL COST €/KW			FIXED OPERATING COST €/KWa			VARIABLE OPERATING COST €/MWh		
	min	central	max	min	central	max	min	central	max
Coal – IGCC w/o CCTS	1418	1800	1870	63	63	63	6	8	9
Coal – PC w/o CCTS	1020	2000	2346	24	42	47	3	4	6
Coal – PC w/o CCTS	998	1300	1425	24	26	43	2	6	6
Coal – PC w/o CCTS (Subcritical)	960	1263	1862	30	25	20	2	6	10
Lignite – Advanced (BoA) w/o CCTS	998	1769	2336	27	32	37	3	7	11
Lignite – Old	998	1769	2336	31	34	37	3	7	11

Note: Min and max values are taken directly from the compilation by DIW, the central values correspond to the median of all studies presented in the DIW analysis.

Our approach to include the capital or investment cost into the NPV calculations relies on a straight-line depreciation method, consistent with the International Financial Reporting Standards, according to which the total cost of the fixed asset is depreciated on the basis that best reflects the consumption of the economic benefits of the asset: generally time-based for a power station (PWC, 2011). Taking into account that large coal-fired generating units are usually designed to operate with a minimum of modification for around 25 years (IEA Coal Research. Clean Coal Centre., 2005) we assume a 5% yearly depreciation rate for all power generation units, which means that we distribute the outflow correspondent to the investment cost during approximately the technical lifetime of the power plant. Fixed and variable operational costs on the other hand are calculated for all periods where the unit is operational and vary depending only on technology and size (capacity and estimated electricity output).

Another important operational cost that does not relate directly to the combustion technology is the fuel cost that the generation units incur to produce electricity. For this parameter we distinguish only between two types of fuel: hard coal and lignite. Taking into account fossil fuel price fluctuations, it is important to include a dynamic price estimate for this cost. For this purpose we have obtained historic prices series for both fuels from the EIA (U.S. Energy Information Agency, 2012). Hard coal price forecasts until 2040 are based on a recent United Kingdom governmental study about fossil fuels prices (Department of Energy and Climate Change U.K., 2015) while for lignite price forecasts, in absence of external projections, we assume prices until 2040 will follow the global trend observed in the last 25 years. For the period after 2040 we assume a constant price for both fuel types given the lack of reliable projections for this period. The former means that our fuel cost estimates are conservative for power plants still on operation after 2040, which constitute only a small fraction of all plants in the EU. The chart below shows our fuel price assumptions for the cash flows.

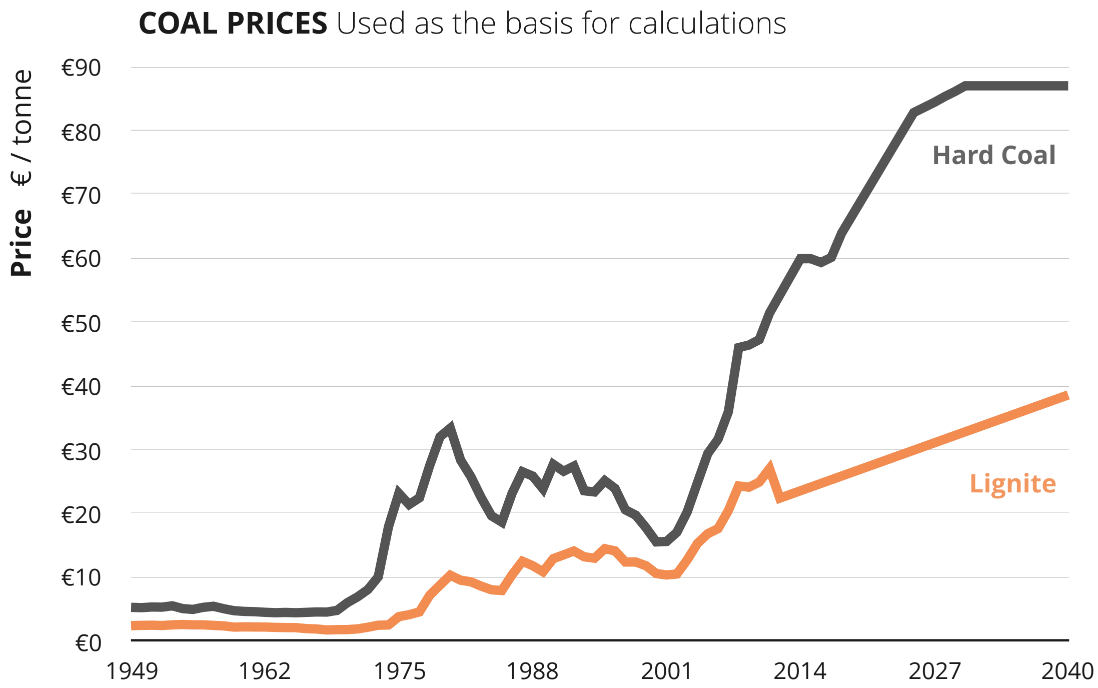

Figure 13: Cash flow diagram of an average coal-based power generation unit.

Note: Historical values were originally obtained in current USD and converted to EUR making use of the average exchange rate between the currencies for each of the yearsz.

Additionally, given that we are dealing with coal power generation units operating in the European Union, the carbon price must be included in the operational cost of the power plants. For this variable we use historical price series for the EU-ETS emissions trading scheme and projected price evolution until 2030 from a recent study by Carbon Tracker (Carbon Tracker, 2015), which assume the carbon price will go from around to 5 €/t in 2014 to 27 €/t in 2030. For the period after 2030 we apply the average price yearly growth rate of the period 2008-2014 to the value projected by Carbon Tracker in 2030. For all units we have applied the carbon price to the estimated emissions generated yearly; which we have calculated using the assumptions described in detail in Annex V: Estimating CO_2 emissions from coal plants.

The European carbon price evolution we assume for our calculations is shown in the figure below together with the global carbon price assumption the MESSAGE model makes for a two degrees scenario pathway until 2050. Both price levels are very similar after 2030 but differ significantly in the first two decades in the absence of a global carbon price for this period.

Finally, in order to estimate the inflows that a power generation unit would create for the investor we have taken the assumed electricity yearly output of each unit (calculated with the same assumptions we have done under the emissions calculations) and multiplied it by the national average electricity price excluding levies and taxes. Given that consistent historic data is only available at the country level for the European Union for the period 2008-2015 (“Eurostat - Data Explorer,” 2016) we have applied historical trends to estimate the country-level prices for the period before 2008 and for the period until 2030. The ample range of historic prices observed in the different countries was our main reason to use a differentiated country-level price instead of the EU average.

As the next step the net present value was calculated for each of the units by converting future net cash flows to present values using a discount rate. Discount rates reflect the capital cost and expected rate of return of investments and allow a conversion of future cash flows to present value. They are directly linked to the interest rate on the capital market as they reflect the opportunity cost of capital to finance an investment opportunity. The discount rate used for the central estimate is 4%, which is the rate recommended by the European Commission in it guide to Cost-Benefit Analysis of Investment Projects (European Commission, 2014b) and broadly corresponds to the average real yield on longer-term government debt in the EU over a period since the early 1980s (European Commission, 2009). A sensitivity analysis was done with higher and lower discount rates, namely a 3% rate for the minimal estimate and 5% rate for the maximal estimate.

It must be noted that larger units usually have higher NPV as they can generate more electricity. In consequence our sorting criteria that reflect the profitability of each unit more accurately is the Net Present Value per MW of capacity.

While the results presented in the main text of this report take into account only the central estimate of the NPV/MW as a sorting criterion for phase-out schedule of generation units we consider necessary to highlight the large uncertainty associated to the calculation of future cash flows of investment project using standard income and cost assumptions instead of unit-specific data. In order to give an idea of the possible uncertainty range associated to our NPV estimates we have done a sensitivity analysis of our results by calculating a minimal and a maximal NPV and cash flow estimate for the units.

Figure 14 shows the aggregated results for all power plants in the EU under the sensitivity analysis scenarios. For the minimal cash flow we have used the minimal income estimates (lower generation due to smaller load factor) against the maximal cost estimates for a duration equivalent to the lower lifetime estimate, and for the maximal cash flows we have done the opposite (max. income, min cost and max. lifetime). Additionally, as described above, a lower and higher discount rate was applied to the minimal and maximal cash flows respectively to convert future flows to present values. Central estimates in contrast use central estimates for all the income and cost parameters.

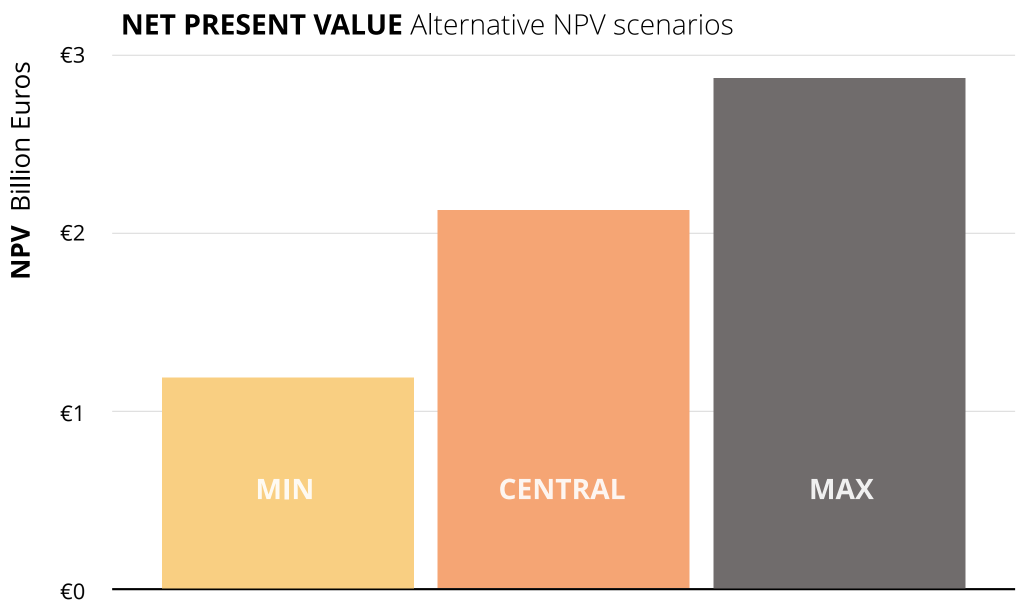

Figure 14: Alternative Net Present Value scenarios for EU coal-based power generation capacity

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