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SCIENCE BASED COAL PHASE-OUT PATHWAY FOR GERMANY IN LINE WITH THE PARIS AGREEMENT 1.5°C WARMING LIMIT

OPPORTUNITIES AND BENEFITS OF AN ACCELERATED ENERGY TRANSITION

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Open pit coal mining Cottbus Nord in
Lower Lusatia, Brandenburg, Germany
in 2011.
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Introduction

Germany, the largest contributor to greenhouse gas emissions in the European Union, has identified the need to phase out coal in order to achieve its climate targets[1]. Coal, including both domestic lignite and imported hard coal, contributes to around 37% to German gross power production, and 22% to primary energy consumption (Bundesministerium für Wirtschaft und Energie - BMWi, 2018). Reducing emissions from coal power generation plays a key role in closing the gap for the national 2020 emissions reduction target and achieving the 2030 emissions target agreed for the energy sector in the Climate Action Plan 2050.

In this context, the coalition agreement between Christian Democrats (CDU/CSU) and Social Democrats (SPD) for the first time includes a process for the Government to agree to a coal phase-out plan, including a phase-out date, through mandating a commission representing a wide range of interest groups and experts. This commission is tasked with making a recommendation for a phase-out plan by the end of 2018[2].

The Commission on Growth, Structural Change and Employment (hereafter referred to as the Coal Commission) was installed in June 2018 (BMU, 2018). The composition of the commission, which is more or less balanced between opponents and advocates of a coal phase-out, consists of four board members, 24 other members including representatives of industries, unions, science, environmental organisations and the affected regions, and three members of the German parliament without voting rights. The Coal Commission has the mandate to propose, for final decision by the German Government:

- A pathway for a structured coal phase-out with an end date for coal-based electricity generation in Germany.
- Measures to achieve the emissions reduction target for the energy sector for 2030 (61-62 % GHG below 1990 levels).
- Contribution of the energy sector to close the remaining gap to Germanys 2020 emission reduction target (40 % GHG reduction compared to 1990).
- Additional concrete measures to jointly address economic development and the social acceptability of coal phase-out in the affected regions.

The process outlined in the coalition agreement builds on the Climate Action Plan 2050[3] that was agreed by the previous government (same coalition partners) and submitted as Long Term Strategy to the UNFCCC in November 2016 (BMUB, 2016). This Plan and its implementation is fully endorsed by the new coalition, including all its targets and measures. In addition, the coalition agreed to legislate the 2030 sectoral targets to ensure they are met.

The Climate Action Plan 2050 was developed in the light of the adoption of the Paris Agreement, recognising the need for more ambition. It includes a strengthened national 2050 overall GHG target ("almost GHG neutrality"), and a recognition of the need to scale up the 2030 targets, including a review process aligned with the ratcheting up timeline under the Paris Agreement. It refers explicitly

1 Overview of Germany's emissions profile and climate targets in English available here.

2 Summary of Energy and Climate agreements in the coalition's treaty in English available here.

3 Summary of Germany's Climate Action Plan 2050 in English available here. Submission to UNFCCC here

to the need for enhanced Nationally Determined Contributions (NDCs) by 2020 – including for the EU, and therefore an enhanced 2030 target for Germany.

With the Coal Commission, Germany has turned from discussing the need to phase out coal to discussing how to structure it. This study aims to contribute to this discussion by:

- Providing a science-based Paris Agreement compatible coal phase-out pathway for consideration by the commission.
- Proposing a coal phase-out schedule at the unit level for Germany, which is compatible with the Paris Agreement and national mitigation targets, based on the most recently available data on coal power plants operating in Germany, building on the methodology developed by Climate Analytics for its 2017 EU coal phase-out study (Climate Analytics, 2017).
- Examining other proposals put forward for a structured coal phase-out and evaluating them according to their compatibility with the Paris Agreement requirements in terms of GHG emissions reductions.
- Providing estimates of the benefits of a Paris Agreement-compatible coal phase-out.

A science-based coal phase-out pathway for Germany

Context: Germany's targets and projections

In order to determine a timeframe for a coal phase-out in Germany, it is necessary to understand what emissions reductions from coal are needed in the power sector and the size of the current emissions gap. For this, it is essential to unpack the national, EU-level and international targets, to which Germany has committed, to understand the implications of these targets for the power sector.

In 2007, the German government set an overall national (domestic) GHG emissions reduction target of 40% below 1990 levels by 2020, in line with the recommendation for industrialised nations in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4). In November 2016, the German government adopted the Climate Action Plan 2050, which confirms and specifies the climate targets agreed to earlier (2010/2011) in the context of the Energy Transition (Energiewende), largely based on the findings of the IPCC's AR4 for emissions pathways for developed countries. These targets are summarised in Table 1.

Table 1 – Greenhouse gas emission reduction targets for Germany.

Target	2020	2030	2040	2050
Greenhouse gas emissions (base year 1990)	−40%	At least −55%	At least −70%	−80 to −95% Extensively greenhouse gas neutral

Note: In 2014, emissions were 27% below 1990.

The medium-term target is to cut GHG emissions in Germany by at least 55% below 1990 levels by 2030. Germany's long-term reduction target range (80 to 95% reduction by 2050) has been qualified and strengthened with the Climate Action Plan 2050 with the new objective to become extensively greenhouse gas-neutral by 2050 (BMUB, 2016). This is based on the Paris Agreement objective of achieving global GHG neutrality in the second half of the century and the recognition of the need to revisit the 80-95% reduction range in the light of the Paris Agreement temperature goal, which is more stringent than the earlier 2°C target agreed in Cancun and previously within the EU.

The Climate Action Plan also lays down 2030 targets for individual sectors, describes the necessary development pathways for them, lists initial strategic measures for implementation and establishes a process for developing specific policies and measures, as well as monitoring and updating policies and measures.

Table 2 – Sector targets for greenhouse gas emission reductions for 2030 (MtCO_2e.)

Sector	1990	2014	2030	Reduction (2030 relative to 1990)
Energy	466	358	175–183	61–62%
Buildings	209	119	70–72	66–67%
Transport	163	160	95–98	40–42%
Industry	283	181	140–143	49–51%
Agriculture	88	72	58–61	31–34%
Other	39	12	5	87%
Total	**1248**	**902**	**543–562**	**55–56%**

Note: The Buildings Sector includes both private households and small- and medium size enterprises.

As shown in Table 2, for the energy sector (which mainly includes distributed electricity generation and heat) the GHG target for 2030 is 175–183 MtCO_2e (equivalent to a reduction of 61–62% relative to 1990). In addition, the Plan clarifies that the energy supply must be "almost completely decarbonised" by 2050, with renewables as its main source. For the electricity sector, "in the long-term, electricity generation must be based almost entirely on renewable energies" and "the share of wind and solar power in total electricity production will rise significantly" (Bundesregierung, 2016).

The plan also states that "the climate targets can only be reached if coal-fired power generation is reduced step-by-step" (Bundesregierung, 2016). Determining the date for this phase-out is part of the Coal Commission’s mandate.

The Commission will make additional recommendations measures in the energy sector by 2020 to close as far as possible the remaining gap to Germany´s 2020 emission reduction target. The latest monitoring report focusing on closing the 2020 gap, adopted by the government (Klimaschutzbericht 2017, adopted on 13 June 2018) estimates this gap to be up to 100 Mt CO_2e. The report projects a reduction by only 32%, taking into account recent trends in economic and population growth (BMU, 2017) compared to an earlier estimate in the April 2017 Climate Projection Report, of 35% by 2030 compared to 1990 based on existing policies (Bundesregierung, 2017a).

Paris Agreement 1.5°C compatible pathway for coal in the power sector

In 2016, Climate Analytics concluded that, to be consistent with the Paris Agreement temperature goal, emissions of unabated coal (i.e. coal-fired power plants without carbon capture and storage), would need to be phased out[4] globally by 2050, by 2040 in China, and by 2030 in the OECD and EU (Climate Analytics, 2016a). The study was based on evaluation of Integrated Assessment Model (IAMs) scenarios with cost-optimal emissions pathways available at that point in time. On this basis, Climate Analytics also developed unit-by-unit phase out schedules for the EU (Climate Analytics, 2017).

Scenario studies published in 2017 and 2018 confirmed the main findings of the Climate Analytics 2016 report (Rogelj et al., 2018a; Steckel et al., 2017). More recently the much larger number and variety of 1.5°C compatible scenarios assessed in the now published IPCC 1.5°C Special Report (SR1.5) extend the scientific basis for the findings on the coal phaseout needed to limit warming to 1.5°C (IPCC, 2018).

The SR1.5 assessed 42 different pathways, from a broad range of energy-economic models, that are 1.5°C compatible – defined to mean that they hold warming at or below 1.5°C, or do so with a limited and temporary overshoot of at most 0.1°C. The online IPCC database of SR1.5 scenarios[5] provides data on coal use in the electricity sector for 21 of those pathways[6] at a regional level including in aggregate for the OECD plus non-OECD EU countries. An important issue that acts as a filter on the selection of pathways relate to concerns about feasibility and hence limitations on the sustainability of the large-scale deployment of bioenergy with carbon capture and storage (BECCS) and hence the scale of negative CO_2 emissions assumed in the scenarios. The IPCC SR1.5 provides some guidance on this in its Summary for Policy Makers (SPM) (paragraph C3.2) that specified BECCS potential of up to 5GtCO_2/yr by 2050 at that level (IPCC, 2018). Pathways with higher BECCS are excluded from consideration here.

The IPCC database does not, however, provide data at the level of the EU separately, let alone for Germany. Given the extensive computational time needed to downscale these pathways to the EU and Germany we believe the IEA ETP Beyond 2°C scenario (B2DS)[7] provides a close analogue to a 1.5°C compatible pathway for the EU and Germany that fits in key respects within the coal pathways from the IPCC SR1.5 scenario set. The B2DS pathway is drawn from the International Energy Agency's (IEA) report Energy Technology Perspectives (ETP) (IEA, 2017). The B2DS scenario contains energy-system data not only at OECD level, but at EU level as well. The B2DS pathway does not however match the Paris Agreement long-term temperature goal and 1.5°C limit, as it has a peak global warming of 1.75°C above pre-industrial with a 50% likelihood.

We have applied the same climate model evaluation of warming levels as was applied in the IPCC SR1.5 and earlier IPCC AR5 to the B2DS scenario to check as an analogue to a 1.5°C compatible pathway, and it reaches a warming of 1.6°C. Global warming through 2100 for the B2DS scenario is projected using the carbon-cycle/climate model MAGICC (Meinshausen, Raper, & Wigley, 2011) in the same configuration used for IPCC's Fifth Assessment Report (IPCC, 2014) and in the IPCC SR1.5. In

4 In this study, consistent with the IPCC approach, we assume that a phase-out of coal-fired power plants is achieved whenever emissions are reduced by more than 90% below 2010 levels.

5 https://data.ene.iiasa.ac.at/iamc-1.5c-explorer.

6 To reflect the characteristics of the Paris Agreement we only include pathways that are consistent with warming below 1.5°C or low overshoot scenarios, with less than 5GtCO_2e yearly negative CO_2 emissions from BECCS in the second half of the century.

7 The IEA report includes two additional scenarios that are not relevant here: the Reference Technology Scenario (RTS) or baseline scenario, assuming the implementation of present day climate change mitigation commitments (NDCs and other); and the 2°C scenario (2DS) that includes assumptions on additional mitigation action that would result in a 50% chance of keeping anthropogenic global warming below 2°C above pre-industrial levels by 2100.

these projections global warming reaches a peak of 1.6°C by 2060 and stays around that level afterwards. In contrast to 1.5°C compatible pathways in the IPCC SR1.5, warming does not drop to below 1.5°C after the peak due to IEA's predefined assumption of that there would not global negative CO_2 from the energy sector (IEA, 2017)[9]. If net negative CO_2 from the energy sector were assumed as in other 1.5°C compatible pathways warming would drop to below 1.5°C after the peak at 1.6°C. Therefore with both the energy-related CO_2 emissions in the B2DS scenario up to 2060, and its peak warming at 1.6°C around 2060, comparable to low-overshoot 1.5°C scenarios, the B2DS scenario until 2060 is confirmed to be a suitable analogue to 1.5°C compatible pathways for the period to 2030.

For the OECD the B2DS scenario has a coal phase out date in the power sector at the 90% level some 5 years later (2035) than the median of the IPCC SR1.5 scenarios (2030). As can be seen in Figure 1, the IEA B2DS OECD trajectory of coal use in electricity (without CCS) lies above the median of 1.5°C pathways assessed in SR1.5.

Within the B2DS, the energy modelling by IEA leads to coal being phased out in the power sector across the EU by 2030 to a 99% level which is a few years faster than for the OECD in the B2DS scenario, and is more in line with the 1.5°C pathways for the OECD as a whole (Figure 1). Given this context the 2030 phase out date for coal in the power sector in the EU in the B2DS scenario appears to be a conservative estimate for a 1.5°C consistent pathway for this region, and could even be sooner.

For Germany then, we derived a cost-optimal pathway from the ETP B2DS scenario for electricity generation from unabated coal plants in line with the Paris Agreement's temperature limit, by making use of Climate Analytics' SIAMESE (Simplified Integrated Assessment Model with Energy System Emulator) model (Sferra, Krapp, et al., 2018), consistent with other reports looking at national implications of global and regional energy models (Climate Analytics, 2016b, 2017, 2018). SIAMESE is able to downscale the results of aggregated regions. In this report, we employ SIAMESE to downscale the results for the European Union region from the ETP/B2DS to Germany, consistent with previous publications looking at individual Member States for the EU28 (Sferra, Schaeffer, & Torres, 2018). SIAMESE determines the optimal electricity mix and emission pathways at the country level by using a welfare maximisation approach. At the same time, we add in current policies in place at the country level, including nuclear phase out policies and renewables targets for Germany. For more details on the downscaling methodology and model assumptions see Annex I: SIAMESE.

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9 IEA provides only energy-related CO_2 emissions. For a full climate-model simulation one needs to assume pathways for non-CO_2 emissions and air pollutants. This information is available most extensively for "likely below 2°C" scenarios in the public database of IPCC SSP-RCP2.6 scenarios (https://tntcat.iiasa.ac.at/SspDb). Rogelj et al (2015; 2018) showed that the key difference between 1.5ºC compatible pathways and "likely below 2°C" scenarios is in CO_2 emissions, because the potential to reduce non-CO_2 emissions is seen as essentially the same as "likely below 2°C" scenarios. Consequently, we used non-CO_2 emissions as the average of RCP2.6 scenarios (SSP2 representing middle-of-the-road socio-economic and technical developments). In addition, we assumed CO_2 emissions from the land sector also follow the average of these scenarios, reaching largest amounts of annual removals of about -2 $GtCO_2$/yr around 2060, within the sustainable potential estimated by IPCC SR1.5 at around -3.6 $GtCO_2$/yr by 2050.

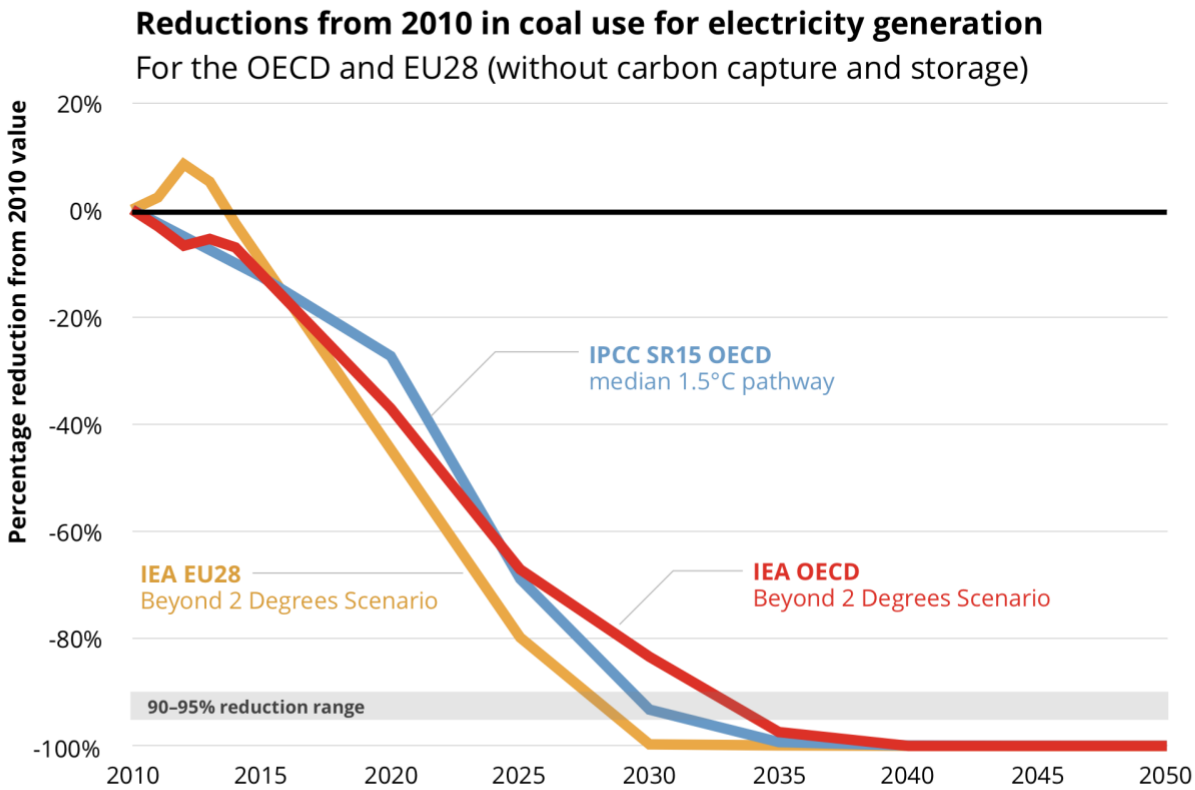

Figure 1 – Reductions below 2010 levels in electricity from coal-fired power plants without CCS in IPCC SR1.5 for 1.5°C compatible pathways (blue line: OECD median) and from the ETP B2DS scenario (EU orange and OECD red line). Sources: IEA (2017); IEA Energy Statistics and Balances 2016 (https://www.iea.org/statistics. Accessed 18 October 2018); SR1.5 scenario database (https://data.ene.iiasa.ac.at/iamc-1.5c-explorer. Accessed 15 October, 2018). We have used data from 21 pathways from the SR1.5 database, excluding pathways that have more than 5 $GtCO_2$/yr removals via BECCS by 2050. This limitation on BECCS is consistent with SR1.5 Summary for Policy Makers (SPM) paragraph C3.2 that specified BECCS potential by 2050 at that level, and not higher in the context of concerns about feasibility and sustainability of the large-scale deployment of bioenergy with carbon capture and storage (BECCS).

To reflect accurately the most recent emissions trends for coal-fired electricity generation we made two adjustments to the downscaled pathway from the SIAMESE model.

- First, we harmonise the pathway to observed emissions in the starting year (2014) and derive a Paris Agreement compatible budget for coal-based power generation (cumulative emissions 2016 to 2050) based on this pathway which leads to a phase out in 2030[10].
- Second, given that observed and expected emissions in Germany for the years 2015-2018 are higher than the levels that would result if Germany had followed the Paris Agreement consistent pathway from 2016 (the year of the adoption of the Climate Action Plan in the light of the Paris Agreement), we modify the emission trajectory between 2018 and 2025 so that the total emissions budget derived from the original pathway is not exceeded as a consequence of higher emissions in the first years. Keeping in mind the importance of closing the 2020 emissions gap, we assume emissions level in 2020 that are consistent with what has been estimated to be the contribution of coal power generation to the closure of this gap (Fraunhofer IEE, 2018a) and assume a linear trajectory between this level and the emissions levels in 2025 resulting from the downscaled pathway.

10 The IEA and SIAMESE models have 2014 as a starting date and provide results for 2025 and 2030. Values between the starting point and these data points are linearly interpolated.

The coal fired electricity generation CO_2 emissions pathway for the European Union from the ETP/B2DS, as well as the resulting downscaled pathway for Germany are shown in Figure 2.

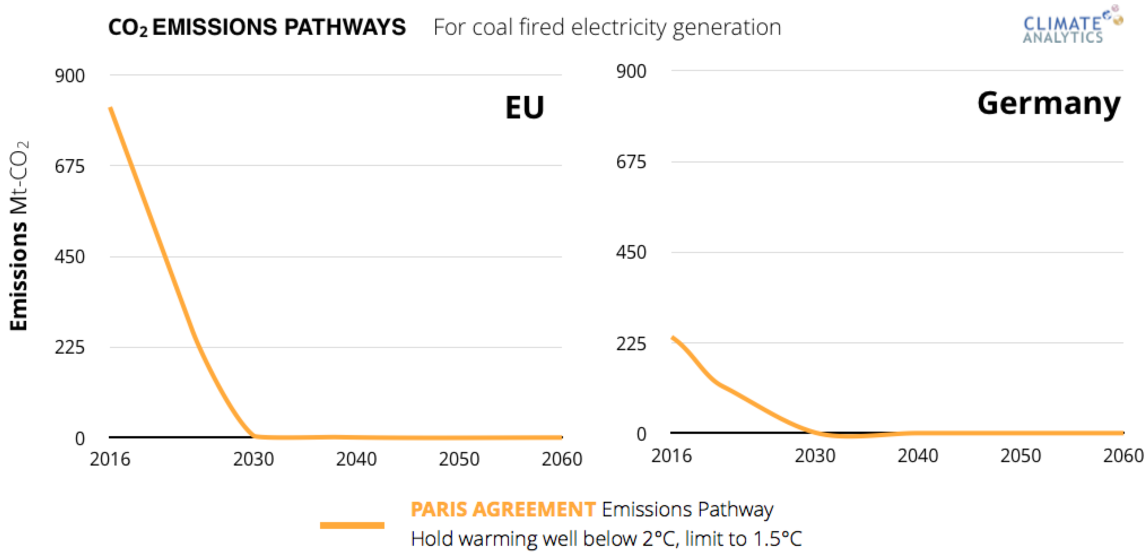

Figure 2 – emissions from coal power plants for the EU and Germany. Source: EU pathway is an output from the ETP B2DS scenario. Pathway for Germany is a result of the downscaling of the EU pathway with the SIAMESE model and adjusting to historical/expected emissions, keeping the same cumulative emissions and closing the 2020 mitigation gap.

Consistently with our previous findings, the cost-optimal emissions pathway derived using the SIAMESE model to downscale the European Union coal emissions pathway from the ETP B2DS for Germany, shows that coal power plant emissions need to decrease steeply in the coming years and be phased out by 2030. The delay in action until 2018 means steeper reductions have to be achieved by 2020 to keep within the limit of cumulative emissions in line with the Paris Agreement and at the same time close the 2020 mitigation gap.

In the Paris Agreement compatible pathway, emissions from coal in the power sector should be reduced 42% below 2017 levels by 2020 (equivalent to 60% below 1990 levels) and 100% by 2030. This is much faster than the benchmarks the Coal Commission discussed so far. The Federal Minister of Economics Peter Altmaier (CDU) has referred to only halving of coal emissions from current levels by 2030 (Finanzen.net, 2018), equivalent to around 110 $MtCO_2$ in 2030, and other governmental officials have stated that coal emissions should be 84-92 Mt CO_2 in 2030 (Energate, 2018).

Based on the methodology described in detail in ANNEX II – Estimating CO_2 emissions from coal plants, we estimate CO_2 emissions from currently operating and planned coal capacity in Germany. Our key assumptions to estimate emissions refer to lifetime and utilisation rate: We have assumed a coal plant lifetime of 55 years, which is consistent with the "with measures scenario"(MMS) from the latest official projections - (Bundesregierung, 2017b) – but substantially above the global average coal plant retirement age (40 years) that has been assumed in previous reports by Climate Analytics. There is large uncertainty about the future utilisation rate in Germany; for our scenario we assume an average utilisation factor of 60%, which is equal to the average calculated emissions factor for all coal power plants throughout the projection period in the latest government projections[11]. Finally,

11 Unlike lifetime, the utilisation rate is an endogenous parameter in the model behind the latest official emissions projections. Based on the outputs reported (capacity and net power supply) we estimate an approximate utilisation rate for all coal power plants (without distinguishing lignite from hard coal) for the reported years, which goes from 60% in 2014 to 61% in 2030 and going down to 58% in 2035. For our baseline emissions scenario we use the average estimated utilisation rate during the whole projection period (60%).

emissions intensities are estimated based on standard reported values per combustion technology and coal type.

Some plants are close to reaching their economic lifetime and are already officially scheduled for retirement (Table 3). We take this into account in the calculation of the baseline emissions pathway from the German coal power plant fleet, as well as information on power plants that are transferred into the so-called security readiness (see Table 4).

Table 3 – Planned decommissioning

Unit Name	Coal type	Capacity (MW)	Planned closure
Gemeinschaftskraftwerk Kiel	Hard Coal	323	2018
Kraftwerk Werdohl-Elverlingsen	Hard Coal	310	2018
HKW Elberfeld 2	Hard Coal	85	2019
HKW I - Duisburg-Mitte 1	Hard Coal	95	2018
Kraftwerk Ensdorf 1 & 3	Hard Coal	389	2017-2019
Reuter C	Hard Coal	124	2019
Lünen 1 & 6	Hard Coal	473	2019
Gersteinwerk K	Hard Coal	614	2019
Total		**2 413**	

Source: Bundesnetzagentur. Status as of April 27, 2018.

In the current security readiness scheme ("Sicherheitsreserve"), some coal power plants are not used, but kept operational. The plant operators are compensated for the related cost. These plants can be reactivated only if other plants cannot provide enough power, e.g. limited wind and solar energy outputs on cloudy, still winter days ("Dunkelflaute"). After four years on standby, the power plant is finally retired. A total of eight lignite power plant units have been gradually introduced into the safety reserve since 2016, as decided in the Action Programme 2020 in 2014. The table below shows the plants to be included in security readiness until 2020.

Table 4 - Planned transitions into security readiness

Unit Name	Coal type	Capacity (MW)	Planned closure
Niederaußem F	Lignite	299	2018
Niederaußem E	Lignite	295	2018
KW Jänschwalde F	Lignite	465	2018
KW Jänschwalde E	Lignite	465	2019
Neurath C	Lignite	292	2019
Total		**1 816**	

Source: Bundesnetzagentur. Status as of April 27, 2018.

If we consider only emissions, there is no difference between a plant in security reserve and one that is decommissioned as long as the given plant is not working. For this reason, we assume as retirement year the year where the plant enters into the security reserve.

Our analysis shows that even with no new coal power plants coming online, and some units planned to be retired or transitioning into the so-called security readiness, cumulative CO_2 emissions from current coal-based electricity generation capacity would exceed the Paris Agreement compatible cost-optimal emissions budget for the remainder of the century. In order to achieve the Paris Agreement long-term temperature goal, our results show that Germany will need to implement early retirement of operating power plants and/or to reduce dramatically their utilisation rate.

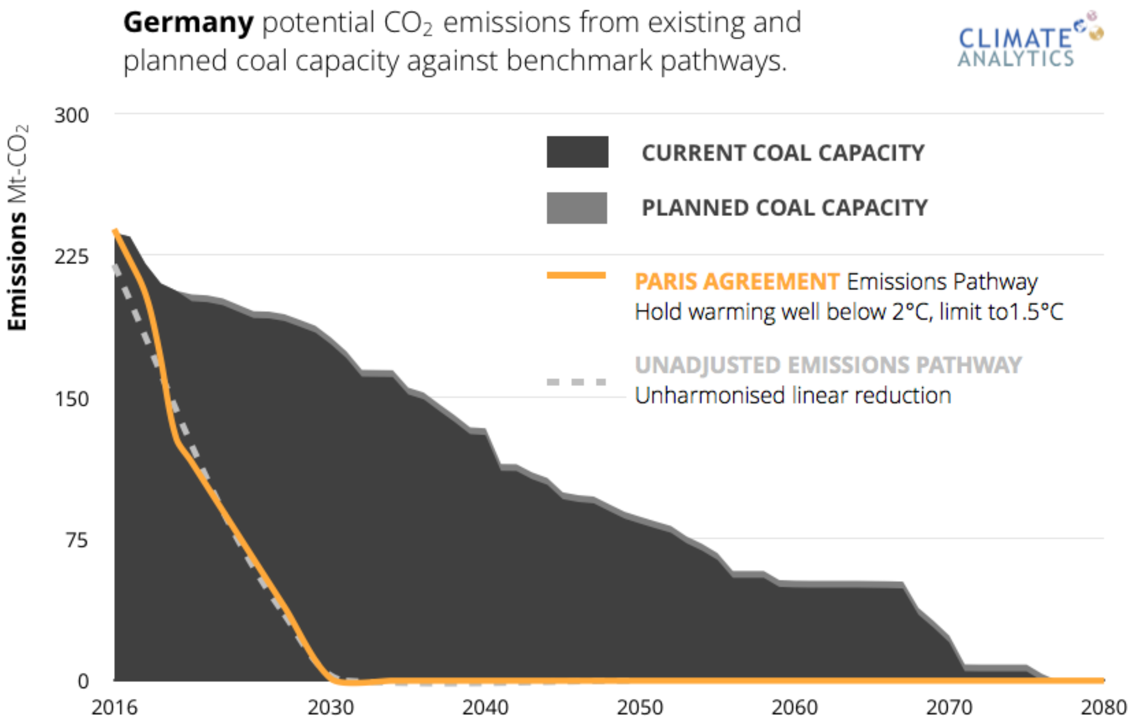

Figure 3 – Emissions from existing and planned coal-fired power plants compared with the coal emissions pathway according to the Paris Agreement temperature goal. Source: own calculations based on downscaled emissions pathways from the ETP/B2DS (harmonised to historical data until 2017) and unit level information for coal power generators from the Platts database[15]. Potential emissions from coal fleet are calculated using a lifetime of 55 years and an average utilisation rate of 60%, consistent with underlying assumptions from the most recent government projections for current policies ("MMS"). According to the Platts database, just one 800 MW unit is currently still planned in Stade in Northern Germany[16] – with the unit –(Niederaussem L recently announced to be cancelled[17]. For the large (1050 MW) unit Datteln IV, which is nearly finished, we assumed an opening in 2020.

Coal-related CO_2 emissions are projected to fall in the following decades even without additional policies in Germany due to ageing of the coal fleet and profitability and policy prospects that make refurbishment or opening of new plants unfeasible. However, if the speed of coal retirements continues at its currently planned slow pace, operating capacity would emit much more than what would be in line with the Paris Agreement. According to our modelling results, current cumulative emissions will exceed the cumulative emissions in line with the Paris Agreement for Germany (see Figure 3) five times until 2050 and six times until 2100.

A more detailed analysis of the difference between the Paris Agreement compatible emissions pathway and the expected emissions from Business as Usual operation of current coal power shows a growing emissions gap, from around 76 $MtCO_2$ in 2020 to more than 180 $MtCO_2$ in 2030.

15 https://www.spglobal.com/platts/en/products-services/electric-power/world-electric-power-plants-database

16 https://www.ndr.de/nachrichten/niedersachsen/lueneburg_heide_unterelbe/Kohlekraftwerk-in-Stade-darf-gebaut-werden,stade718.html

17 https://www.montelnews.com/en/story/11-gw-lignite-plant-project-to-be-cancelled--rwe-official/933638

Coal phase-out schedule at the unit level for Germany

Based on the emissions pathway presented in the previous section, we propose two alternative phase-out schedules for Germany's coal power plants, with suggested retirement dates at the unit level, which relies on the methodology developed by Climate Analytics to determine a phase out schedule for the European Union (Climate Analytics, 2017). In the following section, as well as in the supplementary data accompanying this report, we compare our results with other alternative phase-out schedules put forward by different actors. We hope a clear comparison of closure dates at the unit level under different approaches can inform the Coal Commission discussions of the specific order of retirement of power plants and its implications at the national and regional level.

The critical question is which criteria should determine the sequence in which the different coal plants will need to be switched off.

Power plants owners and holding operators will aim to maximise the revenue that they can generate from their assets. Therefore, they would prioritise the maintenance of those units that generate the highest net revenue for as long as possible, regardless of their polluting potential. Local policy makers may aim to shut down any plant that is not located in their area and keep local plants online as long as possible. This is especially the case for some regions – like the lignite mining areas in the Rhine area and in Lusatia. From the perspective of a national regulator the focus should be on finding the common denominator considering environmental and economic issues on the national level and also Germany's responsibility within the EU and internationally.

Taking all these views into account, we consider two approaches to determine the phase-out schedule:

- **"Regulator" perspective:** it adopts an environmental integrity approach and prioritises the shutdown of the most emissions intensive units, while also considering the maximisation of the revenue they can generate. For this perspective, the phase-out date is primarily determined by carbon intensity (amount of CO_2 emitted per unit of electricity generated), and secondarily by economic value (calculated as net present value).
- **"Owner" or "market" perspective**: it aims to reduce the overall national cost (regardless of region) of the shut down for investors and owners by keeping units with higher economic value online as long as possible. For this perspective, the shut-down date is primarily determined by economic value, and secondarily by carbon intensity.

For further details on the unit-by-unit phase-out approaches see Annex III: Regulator and Owner approaches.

Figure 4 shows the total capacity to be retired under these two perspectives. In addition to 4.2 GW that are already planned to be retired between 2018-2020. shutting down additional 16 GW capacity until 2020 would put Germany on a Paris Agreement compatible pathway for coal-fired power generation[18].

18 Under our scenarios approximately 1.4 GW (4-5 units) are retired in 2018 in addition to the planned retirements for this year to close the emissions gap between the Paris Agreement compatible pathway and the Business as Usual emissions trajectory. Given the decisions by the Coal Commission will only likely be implemented starting in 2019, closure of additional plants in 2018 is unlikely. This means that these emissions reductions will need to be shifted to the future via faster retirements (our scenario assumes for simplicity all plants shut-down at the end of the year) or reduction in utilisation rates (not assessed here).

As shown in Figure 4, the main difference between the two approaches is that the Regulator perspective prefers, in the short term, to shut down lignite power plants (11.5 GW lignite by 2020, and 9.3 GW of hard coal) whereas the Owner prefers, in the short term, to shut hard coal power plants (9.6 GW of lignite and 11 GW of hard coal). This clearly reflects the higher economic value (to owners) of operating power plants fuelled by comparatively cheap local lignite compared to those fuelled with imported hard coal, but also the higher carbon intensity of lignite compared to hard coal.

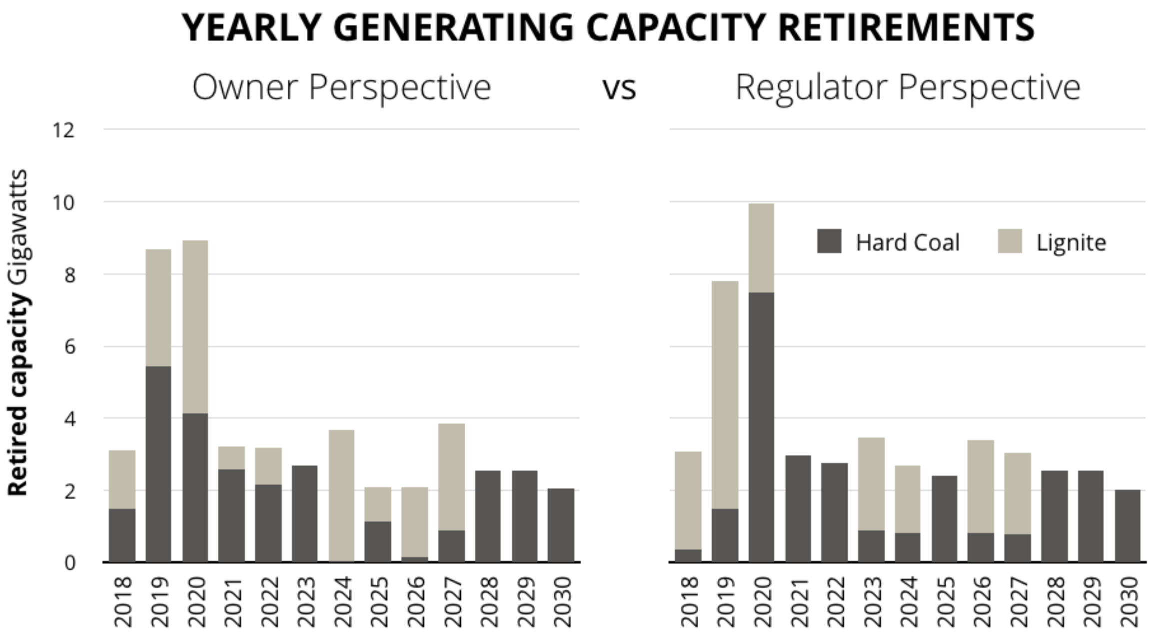

Figure 4 – Yearly capacity retirements regulator and owner perspectives. This includes planned retirements (and units entering in security readiness) until 2020.

An analysis at the unit level reveals that for 84% of the units in Germany, the difference between the retirement date under the owner and market perspective is maximum three years (with 34% of the units being retired the same year under both perspectives). Detailed results at the unit level are provided in the excel accompanying this report.

Table 5 – Comparison retirement dates market and regulator perspectives

Differences market and regulator (years)	total units	share of total
0 to 3	160	84%
4 to 6	23	12%
more than 6	7	4%

The proposed schedule is at the unit level, which means that full shut-down of large plants comprised of several such units, in general, would be a gradual and not a sudden process. This concerns especially those plants that comprise several subunits. It is sometimes argued that lignite opencast mines and associated power plants are economic entities and shutting down units might lead to the whole mine and remaining plants becoming unprofitable. Most opencast mines and power plants in the Rhine area and Lusatia are interconnected with dedicated railroads so that individual plants can be supplied with lignite from different mining sites (DIW, 2018; Matthes et al., 2015). This allows some mines to be shut down – thereby protecting settlements and ecosystems – while others continue to operate and supply remaining coal power plant units in the area with fuel.

While our scenario assumes a full decommissioning by the suggested date under each perspective, in reality there are multiple ways to reduce or eliminate emissions from power plants, including reducing its utilisation factor or stopping operations without full decommissioning. Other studies focusing on coal phase-out for Germany have proposed alternative measures to full decommissioning, which are not assessed directly in our scenarios. In particular, some proposals (for example by the Umweltbundesamt (UBA) (2018), or Agora Energiewende (2017b)) have suggested a combination of decommissioning older (lignite) power plants and limiting the operation hours of remaining coal power plants to avoid potential legal requirements for compensation payments.

Most coal power plants have difficulties to operate at low utilisation rates. While there are some examples of plants that are capable of operating at low outputs and with higher flexibility after multiple physical (hardware) and operational practice modifications; the replicability of the operating conditions of these plant in other contexts and countries is very low (Cochran, Lew, & Kumar, 2013) and would imply substantial investments in currently operating power plants, which are unlikely under current market conditions in Germany.

Given that the profitability of the coal plants would be significantly impacted (likely leading to an eventual closure of the plant) under a scenario of very limited utilisation rates, a progressive reduction of operation hours limits, as suggested by German Environment Agency (UBA), could be one policy to rid the power sector of coal.

The feasibility of this measure, as well as its financial implications and the emission reductions potential, depend largely on the limits imposed on the plants and other market conditions affecting the profitability of the plants (e.g. commodity, electricity and carbon prices). This measure creates less predictability around coal plan closure dates for key stakeholders (e.g. owners, employees, local governments) than a planned decommissioning. However, these limits could be useful to predict the output from coal power plants and planning the integration of their replacements in the electricity mix. In the current security readiness scheme (“Sicherheitsreserve”) plant operators are compensated for the related cost, meaning that ultimately tax payers bear the cost.

Overview of proposals and studies on coal phase-out for Germany

A science-based analysis of the Paris Agreement compatible coal phase-out date for Germany shows that coal should be eliminated from the electricity mix by 2030 at the latest. As illustrated by the market and regulator's perspective, there are different ways to organise a phase-out that is consistent with the Paris Agreement. Multiple organisations have put forward alternative proposals for closure of coal power plants in Germany. In this section we examine these proposals, and whenever possible (if enough information is provided) we evaluate them according to their compatibility with the objectives of the Paris Agreement in terms of GHG emissions reductions.

Only a few recent publications have proposed phase-out deadlines and pathways consistent with the Paris Agreement for Germany. The 2030 phase-out consistent with the Paris Agreement (Climate Analytics (2017a) has been endorsed by the Powering Past Coal Alliance in its Declaration with an explicit reference to the study by Climate Analytics (2016). This phase-out date has been proposed by (BUND, 2018) and Greenpeace (Energy Brainpool, 2017; Kopiske & Gerhardt, 2018).

The comparison in Table 6 shows that the retirement schedules outlined in this study are broadly consistent with proposals that focus on a phaseout by 2030 and on closing the 2020 mitigation gap pathway. Some of these (Energy Brainpool, 2017; Fraunhofer IEE, 2018b, 2018a) have explicitly analysed an alternative pathway to demonstrate energy security and affordability can be secured mainly through additional renewable energy capacity, and in case of (Energy Brainpool, 2017) some additional gas power plant capacity.

A study prepared for Greenpeace (Fraunhofer IEE, 2018a) proposes a coal phase out by 2030 in order to achieve a reduction of energy sector emissions to zero by 2035. In addition shows how Germany could make sure it achieves its 2020 climate target of 40% reduction in GHGs compared to 1990, closing the gap of 100 $MtCO_2e$ identified recently by the government through retiring 6.1 to 7.4 GW lignite capacity and keeping all hard coal power plants running. The remaining 11-12 GW of lignite capacity would be limited to 6000 full load hours/year in 2020, compared to an average of 7000 hours/year in 2016 and 2017 (Fraunhofer IEE, 2018a). By combining further load hour reductions and complete shutdown of coal power plants over the 2020s, and an accelerated increase in renewable energy capacity, the scenario achieves a complete coal phase out by 2030.

WWF had proposed a 2035 coal phase out based on (Öko-Institut & Prognos, 2017), and the German Advisory Council on Environment (Sachverständigenrat für Umweltfragen, 2017) proposed a 2040 deadline. Both WWF and SRU take into account global mitigation requirements but these studies are not consistent with the Paris Agreement's long term temperature goal (LTTG) as they aim to limit warming to 2°C with 66% probability. The Paris Agreement LTTG is to hold warming below 2°C and pursue efforts to limit warming to 1.5°C (Schleussner et al., 2016), a limit whose importance has been reinforced by the IPCC SR1.5. The study commissioned by WWF also includes a scenario for a phase out by 2025, which would lie within a 1.5°C compatible pathway.

Other studies do no refer to any specific global benchmark scenario or budget to derive the phase-out year for coal power plants. They rather focus on how to close the 2020 mitigation gap and how to achieve the current 2030 reduction target for the energy sector. These generally do not lead to a phase out in 2030.

UBA proposes a 2030 deadline for plants 30 years or older, DIW sets a 2030 date for lignite phase out (2018); Agora Energiewende (2016) proposes a 2040 deadline; and DIW (together with Wuppertal Institute and Ecologic) suggest a 60-85% reduction by 2030 and a 2040-2050 deadline for full coal phase-out.

An important conclusion is that the 2030 reduction target for the energy sector is not consistent with the Paris Agreement as it would allow for too much coal still being used for power generation.

Agora Energiewende (2017a) proposes a reduction of coal use by only 50% in 2030 compared to 2015 (shutting down 3 GW per year) to achieve 60% energy-related GHG emissions reduction in 2030 compared to 1990 – consistent with the current 2030 reduction target, but not consistent with the Paris Agreement. Agora Energiewende (2017b) focuses on closing the 2020 mitigation gap and analyses a scenario of shutting down the 20 oldest lignite plants (8.4 GW) by 2020, in addition to already planned decommissioning, which would reduce emissions by additional 50 Mt without a risk to energy security and halving German electricity exports.

Similarly, the German Environment Agency (UBA) (2018) recommends to close at least 5 GW of the oldest/most inefficient lignite power plants in addition to the currently planned closures, and to limit coal-fired power generation to 4,000 full-load hours per year for hard coal and lignite plants that are at least 20 years old by 2020. After 2020, the Agency recommends to combine limitations to full-load hours with the closures between 2020 and 2030, reducing the coal capacity to 19 GW after the nuclear phase-out in 2022. This is combined with limiting the operation of coal plants older than 20 years to 4000 hours per year in order to achieve the existing 2030 sectoral target.

The German energy company Uniper has proposed a much more conservative contribution of coal power plants closures to close the 2020 gap: Uniper's CEO Klaus Schäfer, suggested that a closure of 3-4 GW of installed capacity by 2020 was "conceivable and tangible" and would abate 20 MtCO_2 covering one third of a 60 MtCO_2 2020 emissions gap[20] (Handelsblatt, 2018).

DIW (2018) has a scenario that achieves a lignite phase-out by 2030 in its most ambitious scenario, but some hard coal fired capacity remains. In a more recent and very comprehensive study, DIW (together with Wuppertal Institute and Ecologic, provide an overview of the issue of how coal should be phased-out of the energy system on a global and domestic level. (DIW, Wuppertal Institute, & Ecologic, 2018) review scenarios that achieve the upper end of the German 2050 greenhouse gas reduction target (95% overall emissions reduction by 2050 compared to 1990). These scenarios lead to a phase out of coal fired power generation between 2040 and 2050 and a reduction by 72 – 84% by 2030 from 2017 levels. However, the consistency of the reviewed scenarios with the Paris Agreement has not been assessed.

Finally, some of these reports look at coal phase-out scenarios at the plant level in Germany, with significant differences in the approaches and suggestions for shutting down specific units.

A study commissioned by Greenpeace (Energy Brainpool, 2017) provides a specific phase-out year for each plant by first taking into account already communicated decommissioning. The remainder of the coal phase-out is accomplished following what the authors call an ecological merit order, with efficiency as criterion for selection:

- Phase out plants with an efficiency of less than 36.5% or age above 40 years, respectively until 2020, least efficient/oldest first.
- Further shutdown according to efficiency.
- If several plants have the same efficiency, phasing out the older ones first.

WWF (2017) explores a whole space of possible future developments in the German power sector by varying assumptions on maximum allowed coal power plant lifetime and the speed of renewables

20 Note that this does not take into account the more recent government estimate of the emission gap of 100MtCO_2e.

build-up. The rapid phase-out and the transformation scenario, which are highlighted in Table 6, are the scenarios that are elaborated in WWF (2017) in more detail. This scenario set shows that even limiting coal power plants to a maximum lifetime of 20 years will not result in a complete phase-out of coal by 2030, but only in or shortly before 2040. Longer lifetimes would lead to an even later phase-out in the 2040s.

A more recent study by WWF Germany (2018) suggests retiring about 20 GW by 2020 and thereby closing most of the domestic mitigation gap until 2020. Alternatively, they suggest to only retire 7 GW of lignite in Germany by 2020 and introduce a price floor of 25€/t CO_2 in Germany, Denmark, France, Austria, Belgium, the Netherlands and Luxembourg, which might lead to a very similar mitigation in Germany and additional mitigation in the other countries subjected to the price floor.

A more detailed comparison, at the unit level, can be found in the supplementary material accompanying this report.

Table 6 – Comparison of phased out coal power plant capacities for different studies. Some studies propose, in addition to retirement of units, a limitiation of utilisation of some of the remaining capacity (lignite)

Source	Scenario characteristics		Coal type	Capacity at start of analysis (GW) (Year)	Total retired/remaining capacity (GW) by		
	General	Specific			2020	2030	2040
This study	Least cost downscaling of IEA B2DS pathway for the EU	Regulator – highest emissions intensity first	Lignite	21 (2018)	12/9	21/0	
			Hard coal	28 (2018)	7.6/20.4	28/0	
		Owner – lowest value first	Lignite	21 (2018)	9/12	21/0	
			Hard coal	28 (2018)	9.6/18.4	28/0	
BUND (2018)	Coal phase out by 2030		Lignite	20 (2017)	10/20	20/0	
			Hard coal	22.7 (2017)	10/12.7	22.7/0	
Energy Brainpool (2017), commissioned by Greenpeace	Coal phase out and 80 % renewables in the power sector by 2030, ensuring energy security and affordability through addional capacity of wind, solar and gas.		Lignite	21.4 (2017)[a]	17.8/28.8	46.6/0[b]	
			Hard coal	25.2 (2017)			
Fraunhofer IEE (2018), commissioned by Greenpeace	Reduc energy sector emissions to zero by 2035, coal phase out by 2030, expansion of Renewable energy, replacing coal cogeneration with gas cogeneration, increased carbon price	**with** additional renewables according to coalition treaty	Lignite Hard coal		6.1/12.1	18.2/0	
		medium (2040)	Lignite		0/21.8	21.8/0	
		without additional renewables according to coalition treaty			7.4/10.8	18.2/0	
Öko-Institut & Prognos (2017) commissioned by WWF	Comparison of a rapid phase-out scenario (as fast as technically possible) with variants of a scenario similar to nuclear phase out with limited lifetimes of CPPs, transformation scenario is central to ES	• **rapid phase-out (before 2025)**	**Lignite**	**21 (2015)**	**14/7**	**21/0 (<2025)**	-
		• **very ambitious renewables expansion**	**Hard coal**	**29 (2015)**	**22/7**	**29/0 (<2025)**	-
		• coal plant lifetime 20 years	Lignite	21 (2015)	15/6	18/3	21/ß (<2035)
		• EEG 2017 renewables expansion	Hard coal	29 (2015)	21/8	22/7	29/0
		• coal plant lifetime 25 years	Lignite	21 (2015)	12/9	18/3	21/0
		• EEG 2017 renewables expansion	Hard coal	29 (2015)	21/8	21/8	24/5
		• coal plant lifetime 30 years	Lignite	21 (2015)	12/9	15/6	18/3
		• EEG 2017 renewables expansion	Hard coal	29 (2015)	18/11	21/8	22/7
		• coal plant lifetime 20 years	Lignite	21 (2015)	15/6	18/3	21/0 (<2035)
		• ambitious renewables expansion	Hard coal	29 (2015)	21/8	22/7	29/0
		• coal plant lifetime 25 years	Lignite	21 (2015)	12/9	18/3	21/0
		• ambitious renewables expansion	Hard coal	29 (2015)	21/8	21/8	25/4
		• coal plant lifetime 30 years	Lignite	21 (2015)	12/9	15/6	18/21
		• ambitious renewables expansion	Hard coal	29 (2015)	18/11	21/8	22/7
		• **transformation scenario**	**Lignite**	**21 (2015)**	**12/9**	**15/6**	**21/0**
		• **ambitious renewables expansion**	**Hard coal**	**29 (2015)**	**18/11**	**21/8**	**29/0**

DIW (2018)		Reference	Lignite	21 (2015)	3/18	11/10	
			Hard coal	25 (2015)	6/19	8/17	
		Medium phase out,	Lignite	21 (2015)	6/15	20/1	
			Hard coal	25 (2015)	6/19	8/17	
		Fast phase out	Lignite	21 (2015)	10/11	21/0	
			Hard coal	25 (2015)	6/19	16/9	
WWF Germany (2018)		domestic coal phase-out to close 2020 mitigation gap	Lignite		8.4		
			Hard coal		11.4		
		price floor of 25€/t CO_2 in the EU-ETS	Lignite		7		
			Hard coal				
Agora Energiewende (2017)	50% less coal by 2030						
Agora Energiewende (2016)		slow (2045)		< 50 (2015)	<9/41	<29/21.2	<39/11
		medium (2040)			<12/38	<31/19	50
		fast (2035)			<13/37	<39/11	50 (2035)

Notes: Numbers in red represent scenarios in which coal phase-out is achieved. Capacity values are rounded to the nearest GW.

a) The capacity numbers the analysis is using are not fully consistent. On page 8, the numbers given in the table are mentioned. On page 41, the text mentions 46.6 GW (the sum of above numbers). Table 1, however, list capacities of 22.3 GW and 29.2 GW for lignite and hard coal, respectively. Figure 1 starts out in 2017 again with different capacities, adding up to around 42.5 GW. Since the retired capacity by 2020 is given 17.8 GW, this uncertainty results in uncertainty about the capacity retired until 2030, which was calculated as the difference between initial capacity and capacity retired in 2020.

b) last hard coal plant retires by 2029, last lignite plant by 2028

Managing the transition to renewable energy and reaping opportunities

Phasing out coal has several implications that go beyond carbon emission reductions. Some of these have been discussed as challenges that need to be overcome, others present opportunities and clear benefits. We summarise the main findings from the literature and provide own estimates of benefits in terms of air pollutant emissions, related health impacts and costs that can be avoided by a Paris Agreement compatible coal phase-out.

Transition to renewable energy - ensuring reliable and affordable electricity supply

Various studies find that **energy security** and **reliability of electricity supply** is not expected to be a major concern and will be manageable for a planned and structured coal phase out. A substantial coal capacity from lignite could be phased out in the very short term without causing shortages in electricity supply, mainly due to current large excess capacities and reactivated available gas power capacities in Europe (BUND, 2018; Energy Brainpool, 2017; Klima Allianz Deutschland, 2017). Further capacity can be replaced through increased investment in renewable energy capacity and, to a smaller extent, gas fired power plants (Fraunhofer IEE, 2018, Energy Brainpool, 2017).

Importantly, decarbonising electricity is a **crucial prerequisite of successfully decarbonising other sectors** that will need to transition towards a stronger use of electricity, such as transport or heating. A planned coal phase-out will support the transition towards renewable energy, laying the basis for a successful decarbonisation of the coupled sectors, also generating local employment opportunities. Delaying a coal exit beyond 2030 would require much stronger climate action in the future which could make it even harder for the affected regions to adapt. A structured phase-out plan accompanied by adequate regulatory measures, in contrast, may incentivise innovation to develop technical solutions to address e.g. increases in peak demand due to sectoral coupling and exploit demand side flexibilities (DIW, 2018).

Phasing out coal is expected to lead to reduced export of electricity from Germany to neighbouring countries. Concerns have been raised that this could lead to an increase in use of nuclear energy or dirtier coal power plants in neighbouring countries. However, studies provide evidence that this concern is unfounded, because these plants mostly already run at their capacity limits. It is therefore more likely that some of the efficient gas power plants could increase their power generation (DIW, 2018; DIW et al., 2018; Sachverständigenrat für Umweltfragen, 2017). Moreover, coal phase-out in Germany would be a **decarbonisation driver** in Europe because additional incentives for renewable energy and technological innovation arise when importing cheap electricity from German coal power plants is no longer an option (DIW, 2018; DIW et al., 2018).

Several technologies already exist that can be applied in a mix and will need to be developed further to deliver electricity system services such as maintenance of frequency and voltage (Sachverständigenrat für Umweltfragen, 2017) in a system based on renewable energy and storage facilities and in a transition phase, gas-fired power plants (DIW et al. (2018). Moreover, the higher flexibility of gas power plants enables and supports a better integration of the fluctuating renewable energy technologies (Sachverständigenrat für Umweltfragen, 2017), contributing to grid stability and power reliability. In contrast, the relatively high technical inflexibility of coal power plants hampers adjustments in power generation to RE-electricity changes, increasing the load on the power grid and causing additional system costs (DIW et al., 2018). Moreover, Germany has comprehensive regulation measures in place to avoid supply gaps, such as the Federal Network Agency (BNetzA) examining the effect ahead of power plant shut downs (DIW et al., 2018).

It is often argued that an accelerated coal phase out would lead to higher **electricity prices** for consumers and industry. Most studies reviewed here conclude that increases in wholesale market prices for electricity due to a structured German coal phase-out are expected to remain rather moderate, mostly due to available excess power generation capacities and the expansion of renewable energy (enervis, 2016; Öko-Institut, 2017a; Sachverständigenrat für Umweltfragen, 2017; Wehnert et al., 2017, DIW et al., 2018). Additionally, the increase in the wholesale market price for electricity would again lead to a decrease in the EEG[21] levy ("EEG-Umlage") as the cost difference between the trading price of electricity and the agreed renewable energy prices would decrease DIW et al., 2018). This would lessen the burden on consumers and firms that are not exempted from paying the EEG levy by around half (DIW et al., 2018).

Just transition: managing economic restructuring in affected coal regions

Economic impacts and **job losses** due to an accelerated coal phase out are a major concern in the affected coal regions. However, actively supporting the necessary structural change in these regions, which has been ongoing for decades already, can contribute to establishing economic options with better future prospects also for younger generations. Financial support and retraining affected employees while providing alternative employment options can buffer the negative social impacts of a coal phase-out.

While managing the economic restructuring and job losses of a coal phase-out will be more challenging in less economically diversified regions, the absolute number and share of affected jobs is relatively low: RWI calculates that the direct employment in the German lignite industry in 2016 was around 19 800, with almost 8 300 in Lusatia (Lausitz), almost 9 000 in the Rhein region (Rheinisches Revier), about 2 400 in central Germany (Mitteldeutsches Revier) and close to 200 in the Helmstedt area (Helmstedter Revier) (RWI - Leibnitz-Institut für Wirtschaftsforschung, 2018).

These numbers represent less than 1% (0.88%) of the total number of employees[22] in these regions, with the highest share of 2% in the Lausitz region. This accounts for only 0.06% of employees in all of Germany (RWI - Leibnitz-Institut für Wirtschaftsforschung, 2018). What's more, two thirds of employees in the lignite industry will be older than 60 in 2030 (enervis, 2016; Sachverständigenrat für Umweltfragen, 2017; Umweltbundesamt (UBA), 2017b). This means that a **large proportion of current employees in German coal power plants will retire or be close to retirement in 2030**, reducing the number of employees affected by a coal phase out significantly (DIW et al., 2018).

The number of affected indirect jobs in the coal industry is more difficult to determine. Some studies suggest that the number could be twice as high as of direct jobs (Sachverständigenrat für Umweltfragen, 2017). However, it is very unclear whether all these jobs would be lost due to a coal phase-out, as the market will adjust and new business ideas will create new employment opportunities (DIW et al., 2018).

In the past, Germany has already successfully managed larger structural changes, such as in the textile and steel industry, where several hundred thousand jobs were affected in Germany (Sachverständigenrat für Umweltfragen, 2017b).

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21 Renewable Energy Sources Act ('Erneuerbare Energien Gesetz' EEG)

22 Employees here referring to "sozialversicherungspflichtig Beschäftigte", i.e. subject to social insurance contributions, not total jobs which would also include self-employed.

Phasing out coal also creates **new employment opportunities in the renewable energy sector (RE).** In 2016, gross employment in the German renewable energy sector was estimated at 338 500 jobs, with around 18 600 in Brandenburg, 15 100 in Saxony and almost 45 600 in North Rhine-Westphalia (Ulrich & Lehr, 2018). These estimates by far outnumber the estimated 20 100 - 24 500 jobs in the hard coal and lignite industries[23] projected for 2019 (Sachverständigenrat für Umweltfragen, 2017).

Assessing the total employment effects is very challenging but estimates from the literature suggest the net employment effect of the German energy transition "Energiewende" is positive (Dehnen, Mattes, & Traber, 2015). The study arrives at this conclusion using macro-economic modelling and taking RE-related job creation as well as negative and positive job impacts in other sectors into account. For the regions and people nevertheless negatively affected, infrastructure development, social plans, financial support and retraining for affected employees while providing alternative employment options in the regions can dampen negative social impacts of a coal phase out.

Most studies conclude that a swift coal phase-out is unavoidable and that the consequences for the affected regions **can be managed in a socially just way** (DIW, 2018; enervis, 2016; Sachverständigenrat für Umweltfragen, 2017; Umweltbundesamt (UBA), 2017b; Ver.di, 2016). Beyond the discussed challenges and related opportunities, many additional benefits can be expected from a coal phase out.

Benefits for air quality and health

Several positive impacts (often referred to as **'co-benefits'** as they add to the benefits from reducing greenhouse gas emissions) result directly from phasing out coal. Coal-fired power plants emit a substantial amount of **health-damaging air pollutants and heavy metals**. In 2014, Germany's ten largest lignite power plants were responsible for more than half of the total German emissions of mercury, more than one quarter of sulphur oxides (SO_x) and about 10% of all nitrogen oxides (NO_x) (Öko-Institut, 2017b). Within the power sector, coal-fired power plants have been responsible for more than 80% of sulphur dioxide (SO_2), cadmium, arsenic and lead emissions from electricity generation (Umweltbundesamt (UBA), 2017, Abb. 10).

To provide some indication of the **magnitude of air pollutant emissions that could be avoided by ridding Germany of coal by 2030**, we estimated avoided emissions for the coal phase-out scenarios developed in this study. We estimated emissions for sulphur oxides (SO_x), nitrogen oxides (NO_x), primary particulate matter (PM_{10})[24] and mercury for each German power plant, based on reported emissions in the European Pollutant Release and Transfer Register (EPRTR) and the observed relation of the air pollutant emissions to reported CO_2 emissions.

Based on this observed relation, we project the air pollutant emissions for each power plant unit for the modelled coal phase-out scenarios (for a detailed description of the methodology see Appendix V: Methodology for estimating phase out implications for air pollution emissions of this report). We then calculate total expected air pollutant emissions for each pollutant and year for the "business as usual" scenario[25] as well as the two phase-out schedules outlined in this study - the regulator perspective scenario and the owners' perspective scenario.

23 Covering power plants, mining and refinement ("Veredelung").

24 Primary PM_{10} refers to fine particles (defined as having diameter of 10 μm or less) that are emitted directly to the atmosphere. Additionally, emitted precursor gases can form secondary particulate matter in the atmosphere. Important precursor gases are particularly sulfur dioxide, nitrogen oxides, ammonia, and volatile organic compounds.

25 In the baseline ("business as usual") scenario, we assume that coal power plants remain online until they reach the end of their lifetime of 55 years. See Appendix III for more information on the underlying scenario assumptions on the coal phase-out scenarios.

Figures 5 to 8 show that substantial air pollutant emissions can be avoided compared to the baseline scenario. Aggregating the respective air pollutant emissions of all German coal power plants from 2018 to 2030 shows that cumulative emissions for NO_x, SO_x and PM_{10} would be 53-54% lower for both coal phase-out scenarios compared to the baseline, with small differences between the two perspectives. The difference in cumulative mercury emissions between the regulator and the owner scenario is most pronounced, with almost 54% less than business as usual in the regulator scenario compared to 52% in the owner scenario, mainly due to an earlier phase-out of specific lignite plants in the regulator scenario.

Shutting down coal capacities at the end of 2020 according to the Paris Agreement compatible phase out scenarios would result in 38-41% lower NO_x, 34-37% lower SO_x, 39-41% lower PM_{10} and 33-37% lower Mercury emissions compared to the baseline emissions expected in the year 2021. This means that in the regulator perspective scenario emissions of over 51 000 tonnes of NO_x, more than 31 000 tonnes of SO_x, almost 1 400 tonnes of primary PM_{10} and over 1 400 kg of Mercury would be avoided in the year 2021 only. In the owner perspective scenario over 48 000 tonnes of NO_x, around 29 000 tonnes of SO_x, over 1 300 tonnes of primary PM_{10} and almost 1 300 kg of Mercury would be avoided in 2021 alone.

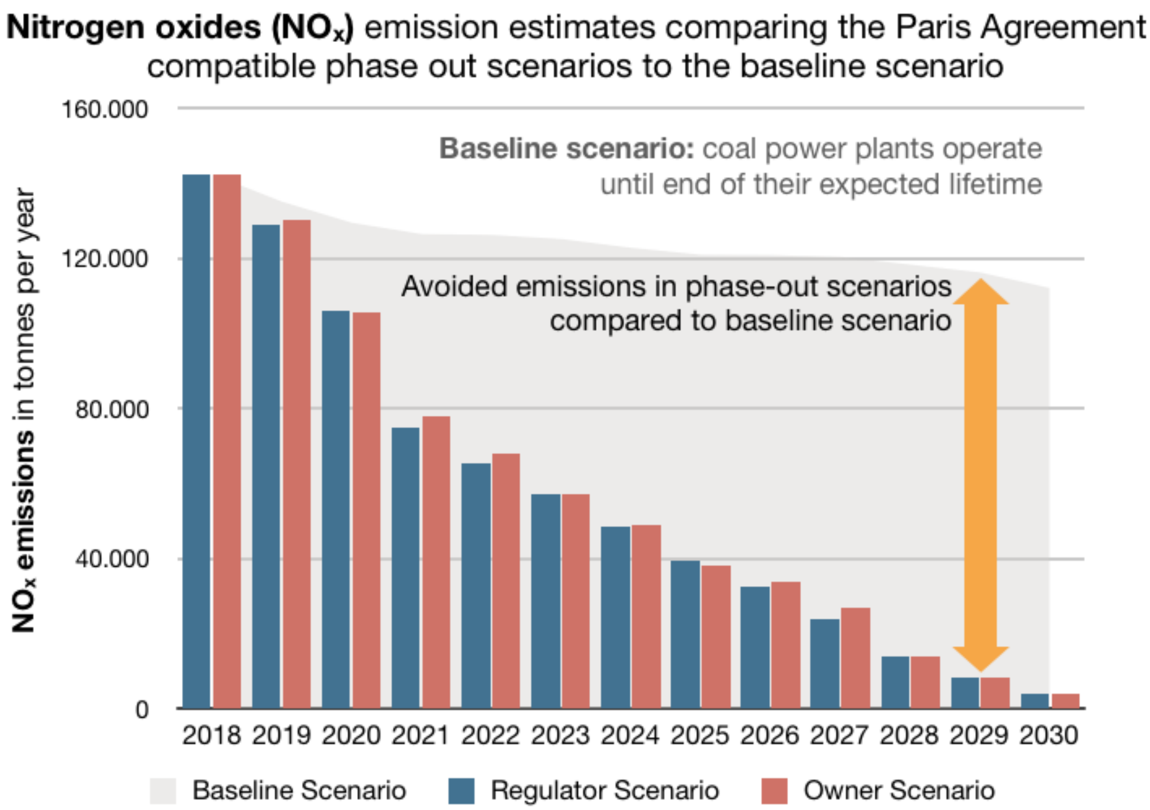

Figure 5 –Estimated nitrogen oxides (NOx) emissions from German coal power plants comparing the Paris Agreement compatible phase out scenarios to baseline scenario emissions (in tonnes). Source: Own calculation based on EPRTR data.

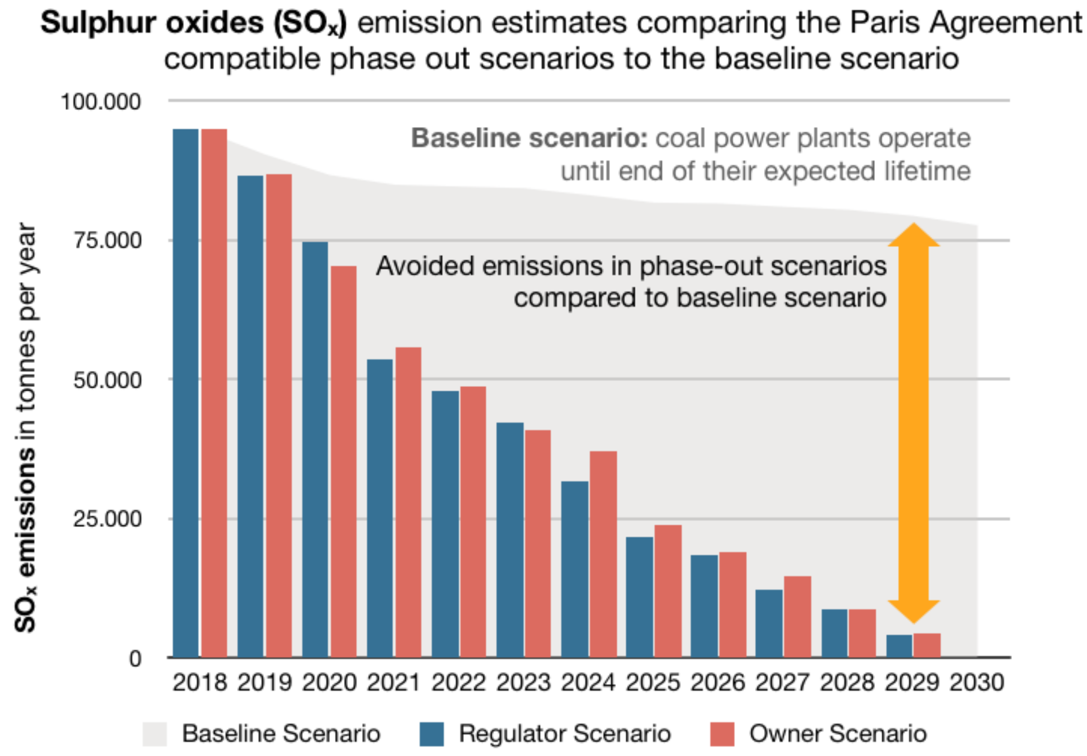

Figure 6 – Estimated sulphur oxides (SOx) emissions from German coal power plants comparing the Paris Agreement compatible phase out scenarios to baseline scenario emissions (in tonnes). Source: Own calculation based on EPRTR data.

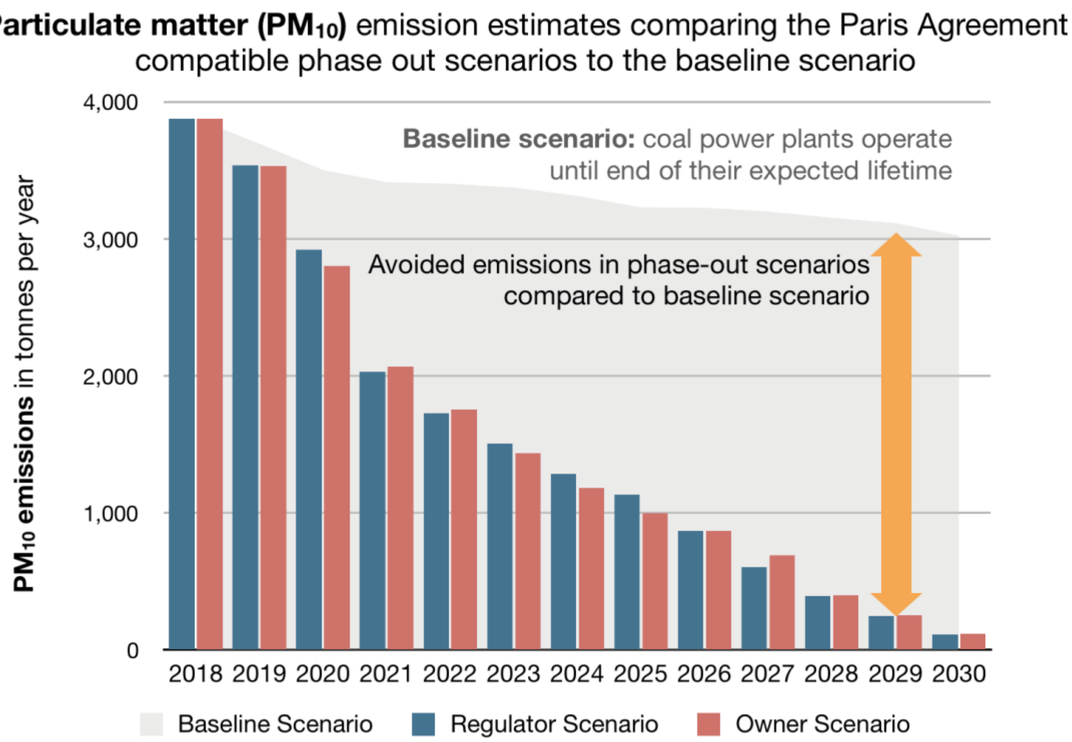

Figure 7 – Estimated primary particulate matter (PM10) emissions from German coal power plants comparing the Paris Agreement compatible phase out scenarios to baseline scenario emissions (in tonnes). Source: Own calculation based on EPRTR data.

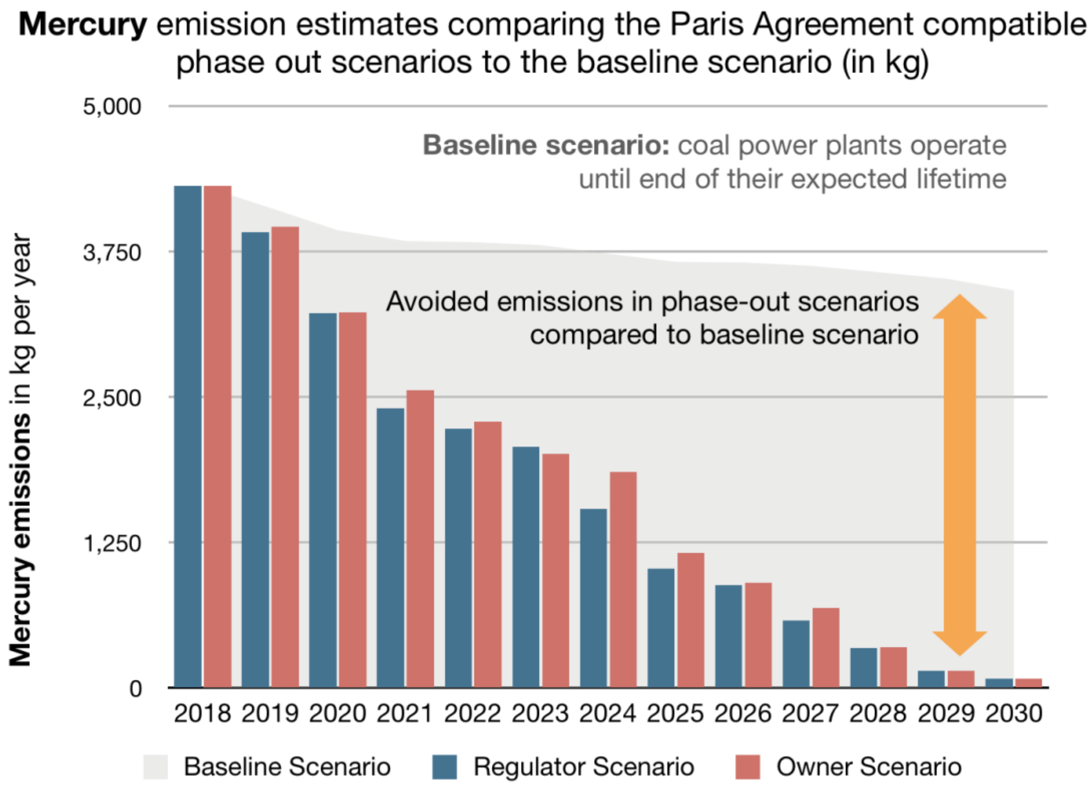

Figure 8 – Estimated mercury emissions from German coal power plants comparing the Paris Agreement compatible phase out scenarios to baseline scenario emissions (in kg). Source: Own calculation based on EPRTR data.

A recent report by Europe Beyond Coal estimates that in 2015 air pollution emissions from German coal power plants have been responsible for around 3850 premature deaths, as well as 1800 cases of adult chronic bronchitis, about 1800 hospital admissions, 79 000 asthma attacks in children and over 1.2 million working days lost (Europe Beyond Coal, 2017). The **related health costs** are estimated at 5.5 - 10.5 billion Euro (Europe Beyond Coal, 2017).

The same report notes German coal power plants have caused more premature deaths in Europe than non-German EU plants have caused in Germany through air transport of pollution from smoke-stack emissions (Europe Beyond Coal, 2017). In the study's ranking of the most health-damaging coal power plants in Europe, six in the top 30 are in Germany (see Table 7).[26] Though modelling uncertainty should be considered, the estimates indicate the severity of the health impacts and related costs caused by coal power plants in Germany.

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[26] Europe Beyond Coal estimates the number of deaths for each power plant based on atmospheric modelling (EMEP/MSC-W chemical transport model) and methodologies to assess health implications recommended by the WHO (see https://beyond-coal.eu/data/).

Table 7 – Germany's coal power plants in the list of the 30 most health-damaging coal power plants in Europe

2015 Ranking	Power plant name	2015 modelled premature deaths	2015 modelled health costs
Rank 6	Niederaussem	390	1076 Mio Euro
Rank 8	Neurath	390	1049 Mio Euro
Rank 9	Jaenschwalde	380	1052 Mio Euro
Rank 12	Boxberg	280	774 Mio Euro
Rank 17	Weisweiler	230	615 Mio Euro
Rank 24	Lippendorf	190	530 Mio Euro

Source: Adopted from Europe Beyond Coal (Europe Beyond Coal, 2017)

Based on the Europe Beyond Coal[27] estimates of health impacts from individual coal power plants in Germany, we calculated the **implications for health** for the three scenarios, following a similar methodological approach as for the air pollutant estimates above (for details on the underlying methodology see Appendix V: Methodology for estimating phase out implications for air pollution emissions).

The resulting estimates do not intend to accurately project the number of cases of premature deaths, but to give an indication of the order of magnitude of avoided health impacts that could be achieved through the proposed coal phase-out timeline.

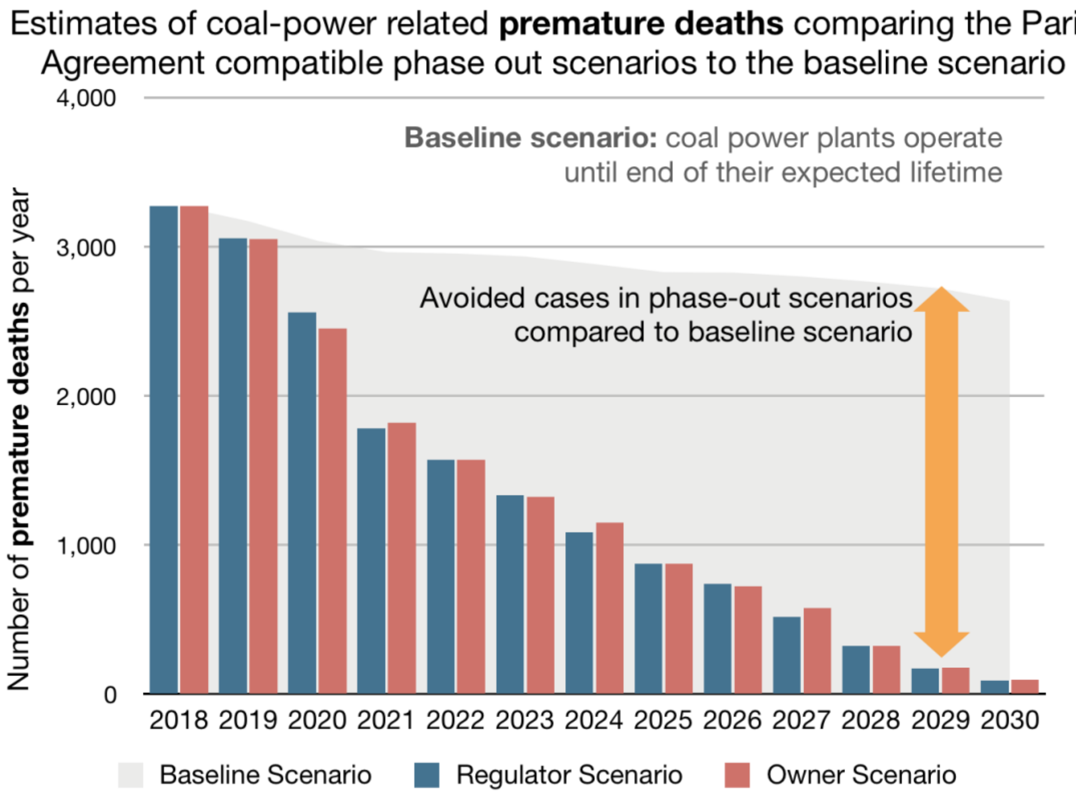

Figure 9 – Estimates of the number of premature deaths (within Germany and beyond its borders) attributed to German coal power plants comparing the Paris Agreement compatible phase out scenarios with the baseline scenario. Source: Own calculation based on data from Europe Beyond Coal (Europe Beyond Coal: European Coal Plant Database, 22 Jun 2018).

27 Europe Beyond Coal: European Coal Plant Database, Version of 22 June 2018.

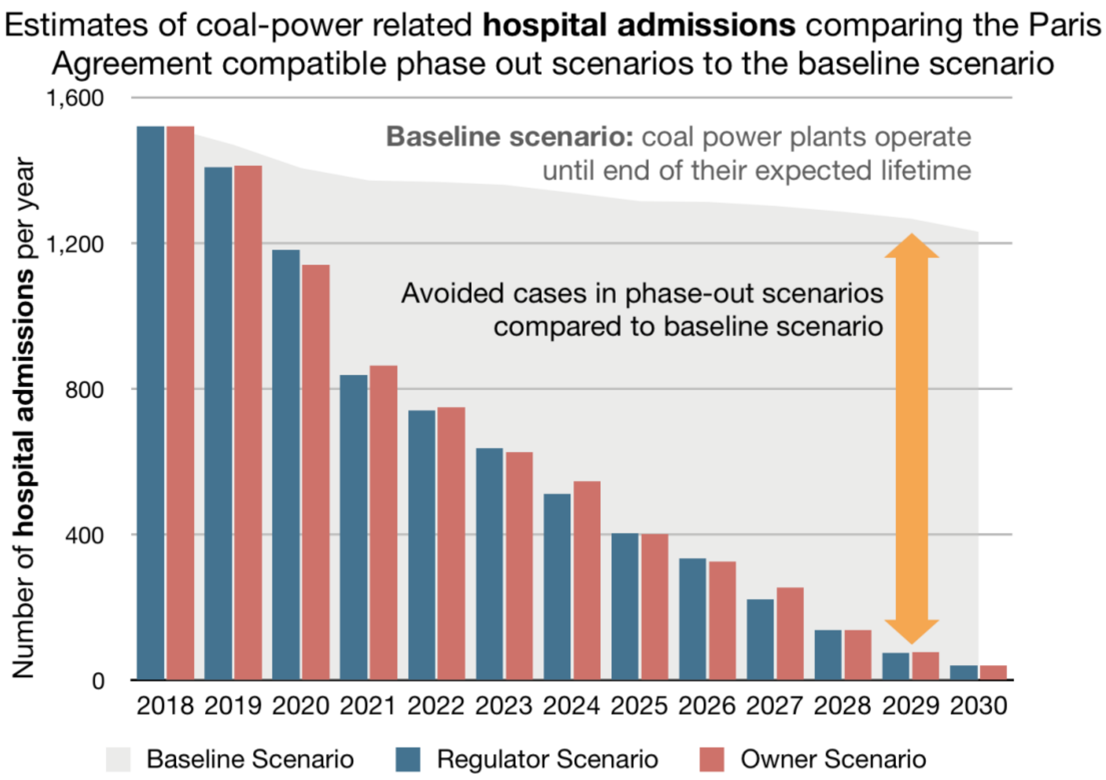

Figure 10 – Estimates of the number of hospital admissions (within Germany and beyond its borders) attributed to German coal power plants comparing the Paris Agreement compatible phase out scenarios with the baseline scenario. Source: Own calculation based on data from Europe Beyond Coal (Europe Beyond Coal: European Coal Plant Database, 22 Jun 2018).

Figure 9 to 12 show that premature deaths, asthma attacks in children, hospital admissions and lost working days caused by German coal-fired power plant emissions[28] could be considerably reduced if Germany phases out coal power by 2030 in line with the Paris Agreement.

All health impacts analysed here would be around 54% lower in both 2030 coal phase-out scenarios compared to business as usual aggregating impacts from 2018 to 2030. Under the baseline scenario, there would be almost 38 000 premature deaths, over 17 500 hospital admissions, over 780 000 asthma attacks in children and over 12 million working days. The two Paris Agreement consistent phase-out scenarios avoid more than 20 000 premature deaths, over 9 400 hospital admissions, over 420 000 asthma attacks in children and around 6.7 million lost working days. In line with findings about the air pollutant emissions, the benefits in terms of avoided health impacts would be slightly higher for the regulator scenario than for the owner scenario mainly due to an earlier phase-out of lignite plants.

28 The estimates refer to health impacts within Germany as well as beyond German borders due to air pollution from German coal power plants.

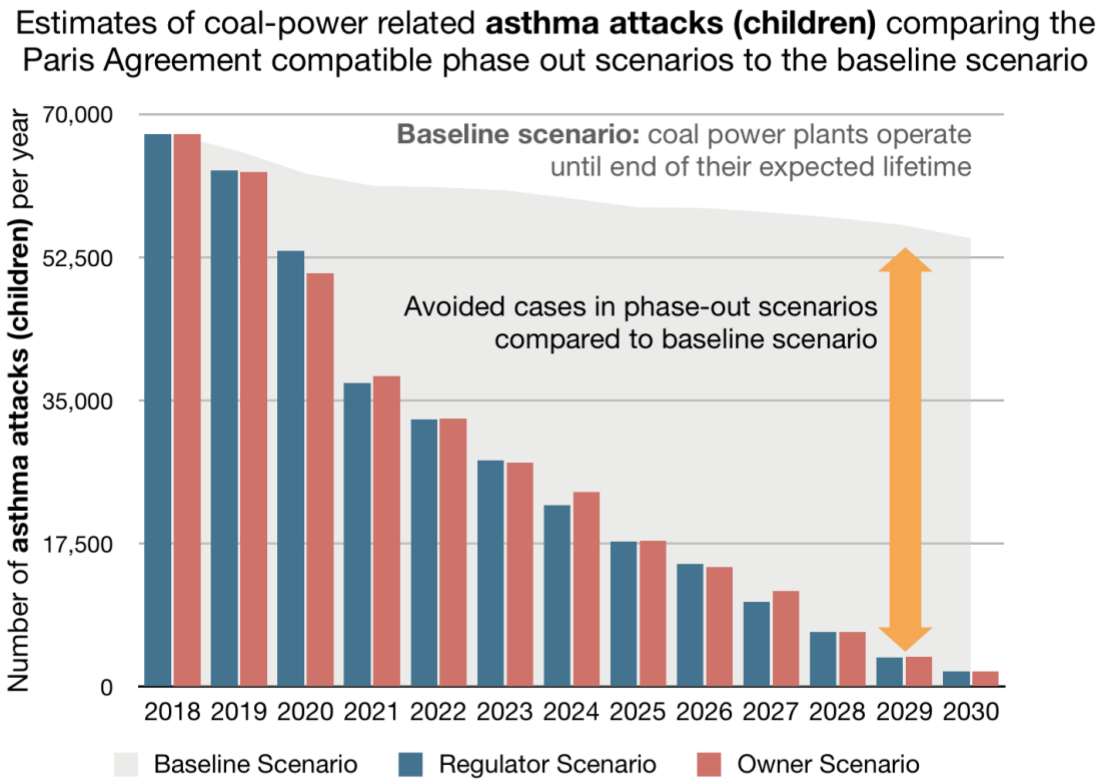

Figure 11 – Estimates of the number of asthma attacks affecting children (within Germany and beyond its borders) attributed to German coal power plants comparing the Paris Agreement compatible phase out scenarios to the baseline scenario. Source: Own calculation based on data from Europe Beyond Coal (Europe Beyond Coal: European Coal Plant Database, 22 Jun 2018).

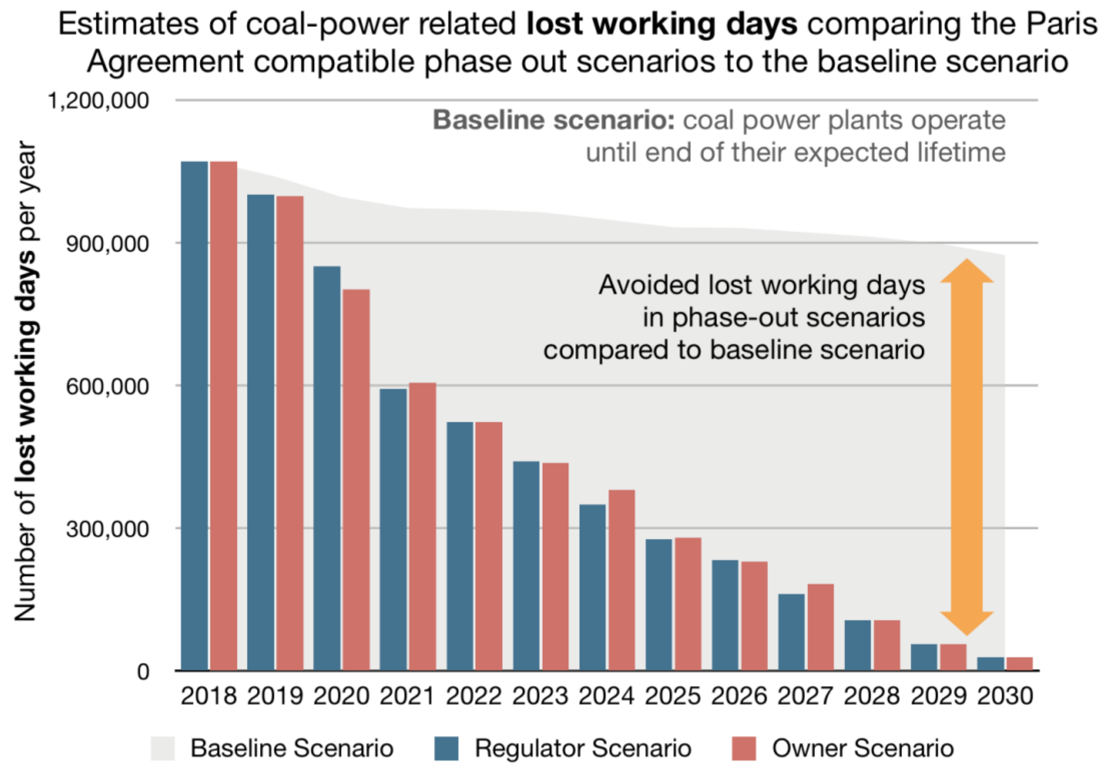

Figure 12 – Estimates of the number of working days lost (within Germany and beyond its borders) attributed to German coal power plants comparing the Paris Agreement compatible phase out scenarios to the baseline scenario. Source: Own calculation based on data from Europe Beyond Coal (Europe Beyond Coal: European Coal Plant Database, 22 Jun 2018).

To obtain a rough estimate of the **avoided health damage costs**, i.e. the economic costs that could be avoided by a rapid coal phase-out, we apply damage cost estimates for Germany per tonne of air pollutant emitted provided by the European Environment Agency (EEA) (European Environment Agency, 2014) (for more details on the methodology see Appendix V). The damage cost estimates of the EEA account for a broad set of mortality and morbidity impacts as well as crop losses and damages to buildings attributed to the respective air pollutant, and are not specific to the power sector.

Translating health damages into monetary terms is contentious as it involves an economic valuation of life and wellbeing and is sensitive to the underlying assumptions. EEA provides damage cost estimates following two different underlying approaches that are both commonly used in the scientific literature: The Value of a Life Year (VOLY) approach represents a lower estimate compared to the Value of Statistical Life (VSL) approach.[29] We follow this example and provide a cost range for these two approaches. Table 8 shows the avoided health damage costs for the two rapid phase-out scenarios compared to business as usual for selected pollutants (total avoided damage costs from 2018-2030). The results show potential savings between 18 and 53 billion Euro[30] in the regulator scenario, and around 18 to 52 billion Euro in the owner's scenario, thanks to reducing NO_x, SO_x and PM_{10} only.[31]

These saving estimates mainly reflect reduced health costs and do not account for the avoided damages from other harmful pollutants emitted by coal power plants nor damages from CO_2 emissions. Table 10 in the Appendix indicates that accounting for the damage cost from other pollutants not considered here, such as fine particulate matter ($PM_{2.5}$) and ammonia, would considerably increase the cost savings of phasing out coal. On the other hand, damage costs per tonne of pollutant emitted are expected to change over time. Given the simplifying assumption of constant damage costs and the limited coverage of pollutants, the provided estimates on savings in damage cost are only meant to illustrate potential cost savings of a rapid coal phase-out.

Table 8 – Estimates of damage costs that could be avoided by a rapid coal phase out compared to the baseline scenario damage costs (total costs for 2018-2030 for each pollutant in billion Euro (2005 Euros), estimates based on EEA damage costs estimates for Germany). Value of Statistical Life (VSL) and Value of Life Year (VOLY).

	Regulator scenario compared to baseline		**Owner scenario** compared to baseline	
	VOLY	VSL	VOLY	VSL
NOx	5.9 billion €	16.6 billion €	5.9 billion €	16.4 billion €
SOx	11.2 billion €	34.1 billion €	11.1 billion €	33.6 billion €
PM10	0.7 billion €	2.2 billion €	0.7 billion €	2.3 billion €
Sum	**17.9 billion €**	**52.9 billion €**	**17.7 billion €**	**52.2 billion €**

The reviewed literature as well as our own estimates indicate that phasing out coal would substantially **reduce air pollution from coal power plants** - proven to be harmful to human health and the environment – and would save many lives in Germany and beyond German borders. The savings in health-related costs would also be considerable. Reducing the need for lignite mining

29 The VSL and VOLY approaches are described in more detail in Appendix V. One important difference between the two approaches is that VOLY puts a higher weight on younger age groups (WHO Regional Office for Europe & OECD, 2015).

30 EEA damage cost estimates refer to 2005 Euros.

31 Damage cost estimates for mercury were not available in the EEA report used.

could also bring additional environmental and health benefits not considered here, such as reduced water pollution.

Managed and planned transition – avoiding stranded assets

Beyond air pollution co-benefits, a clearly defined strategy for an accelerated coal phase-out would **increase planning security** for affected regions and industries and would help to cushion the negative impacts by active planning and supporting measures. Moreover, an accelerated coal phase out plan would help to avoid that investments continue to flow into unsustainable assets and new coal-related infrastructure, leading to **carbon intensive lock-in effects and stranded assets**. A fast coal phase out could also help to **avoid relocation of towns** for new lignite mining (as e.g. planned for the extension of Garzweiler II) and **forest clearing** (e.g. the Hambach forest) (DIW, 2018; Umweltbundesamt (UBA), 2017c, DIW et al., 2018). Transforming open cast mining sites into lakes and recreation sites has already successfully happened in the past and bears potential for former coal regions to **attract tourism as an alternative source of income and economic development** as well as increasing the quality of life of the local population. Regions can build on this as part of their economic diversification.

In contrast, **delaying coal phase out would result in much more drastic and potentially more disruptive coal plant closures in order to be back on track for the 2030 targets**, not to mention the need to strengthen ambitions to achieve the 1.5°C target, which Germany agreed to by signing the Paris Agreement. Defining a plan for a structured accelerated coal phase-out and thereby bridging the emissions gap for its 2020 target will put Germany not only in a much better position to achieve its 2030 targets, it will also send a **positive and very important reassuring signal to other EU countries and the international community** that Germany is serious about tackling the climate change problem. This could help to reconcile the contradiction of being the pioneer of "Energiewende" while widely missing own 2020 emission reduction targets, which again might **re-establish Germany's role as a leader on climate change mitigation** and **motivate other countries to strengthen their climate ambitions**.

Conclusion

Coal use for electricity generation will need to be phased out by 2030 in Germany in order to achieve a rapid decarbonisation that is consistent with the Paris Agreement. Emissions from coal for electricity generation need to be reduced by 42% below 2017 levels by 2020 (equivalent to 60% below 1990 levels) and 100% by 2030.

This phase out pathway will lead to considerable health benefits. We estimate that more than half of the air pollution from coal fired power generation can be avoided, with substantial benefits for health and avoided health costs.

The 2030 phase out timeframe is much faster than the benchmarks that have been discussed so far in order to achieve Germanys existing 2030 sectoral target.

There is increasing recognition for the need of this phase out date both internationally (e.g. by the Powering Past Coal Alliance) and nationally by an increasing number of recent studies and position papers. Such a phase out timeframe would allow Germany to ratchet up its 2030 mitigation target and support a scaled up EU target for 2030 in line with the Paris Agreement.

Even with no new coal power plants coming online, to be consistent with global efforts to meet the Paris Agreement long-term temperature goal, Germany will need to implement early retirement of operating power plants and/or to reduce dramatically their utilisation rate.

Large retirements of existing capacity and reduced utilisation in the short term enable Germany to achieve its 2020 emissions reduction target and can be managed without risk to energy security and reliability of supply due to existing overcapacity.

A number of studies have shown pathways for an accelerated investment in renewable energy in line with a coal phase out by 2030, while ensuring reliability and affordability of electricity, and with large benefits for health and employment opportunities that can help manage the economic restructuring of Germanys lignite mining regions.

In addition, a clearly defined strategy for an accelerated coal phase out would

- Provide stakeholders with certainty to facilitate a transition out of coal in regions where coal plays an important role.
- Increase planning security for affected regions and industries.
- Help to cushion the negative impacts by active planning and supporting measures as well as job creation in other more sustainable sectors.
- Help to avoid that investments continue to flow into unsustainable assets and new coal-related infrastructure, leading to carbon intensive lock-in effects and stranded assets.
- Help to avoid relocation of towns for new lignite mining (as e.g. planned for the extension of Garzweiler II) and forest clearing (e.g. the Hambach forest).
- Save many lives by reducing health-damaging air pollution as well as related health costs.
- Create an environmentally *and* economically more sustainable future for the affected regions and Germany as whole.

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ANNEX

Annex I: SIAMESE

The **S**implified **I**ntegrated **A**ssessment **M**odel with **E**nergy **S**ystem **E**mulator (SIAMESE) is able to downscale the energy-system characteristics of a particular energy model at the country level, by providing cost-effective scenario in line with a global temperature target. At the same time, SIAMESE can take into account specific policy in place and expected energy trends (e.g. nuclear phase-out dates) at the country level. Therefore, it can provide insights to policy makers on how to realistically improve current policies and pledges in line with the Paris Agreement long term target.

In this study we downscale the European Union energy consumption results of the ETP/B2D model to Germany. At the base year (2014), the model is calibrated based on observed energy consumption, GDP and population data. In a way, this calibration process sets some preferences regarding the 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[32] and coincide with the marginal utility of energy.

In terms of the equations, SIAMESE mimics the structure of Integrated Assessment Modesl, where the economic output (GDP) is a function of capital, labour and energy consumption by using a CES (Constant Elasticity of Substitution) production function.

This version of SIAMESE focuses on downscaling electricity generation from the European Union region of the IEA's ETP model. In terms of gases, SIAMESE focuses on CO_2 emissions only (excluding LULUCF) and on while it does not cover other GHG such (e.g. CH_4, N_2O etc.).

Given that the outputs of the B2D scenario are only available for the year 2025, 2040, and 2060, it is only possible to downscale the results to Germany for those years. In order to estimate a policy-relevant emissions pathway, we make the following adjustments during our downscaling process:

- Include the following constraints to the results for Germany:
  - Nuclear phase out by 2022
  - Renewables (incl. biomass):
    - At least 40% in the power mix by 2025
    - At least 65% in the power mix by 2030

- For emissions between historical data and target years downscaled, we assume a linear emissions reduction (constant emissions reduction between target years).
- To reflect historical development in CO_2 emissions in Germany, we harmonise the downscaled pathway to the reported CO_2 emissions from coal power plant until the last reported year (2017)

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

ANNEX II - Estimating CO_2 emissions from coal plants

To estimate emissions resulting from currently operating and planned coal power plants in Germany we used the Platts' World Electric Power Plants Data Base (WEPP). This is a global inventory of electric power generating units, which provides information on every known coal-fired power generation unit, including its location, status, investor, capacity, combustion technology33 and fuel, year of opening and retirement date for officially retired plants. For this analysis we use the information provided in the March 2018 version of the WEPP.

The WEPP data used in this report comprise of detailed information per plant concerning the country, its capacity, status and combustion technology, which allows to estimate CO_2 from these plants, using the following formula:

Yearly emissions:

$$Emi_{it} = Cap_i * \frac{1}{eff_i} * lf_{it} * ef_i * \boldsymbol{\phi}$$

with:

$\boldsymbol{Emi_it}$ are the yearly emissions of plant unit *i* in $MtCO_2$ in a particular year *t*

$\boldsymbol{Cap_i}$ is the Capacity of plant unit *i* in MWel. MWel describes the electrical output of a power plant (unit). About two thirds (actual value depending on the combustion technology) of the energy contained in a coal power plant's fuel is lost while converting it into electricity. The thermal energy released during the conversion is usually not used anymore but gotten rid of via cooling towers or rivers.

$\boldsymbol{eff_i}$ is the conversion efficiency of a power plant unit: How much of the energy contained in the fuel (coal) is converted to electricity. In general, this is higher for modern plants. In the case of Germany, it ranges between 38.2 and 40.5 percent, with an average of 38.5 percent.

$\boldsymbol{lf_{it}}$ is the load factor of the power plant in a particular year t. The load factor is the ratio of the actual power plant output over its theoretical maximum output and is usually calculated over the course of a year. The theoretical maximum output can be calculated by assuming that a power plant runs at its nameplate capacity 24 hours a day, 365 days a year. I.e. a power plant unit with a capacity of 100 MW has a theoretical maximum output of

$$100 \text{ MW}_{\text{el}} * 24 \frac{\text{hours}}{\text{day}} * 365 \frac{\text{days}}{\text{year}} = 876.000 \text{ MWh}.$$

Actual output over a given year is lower since the plant will not always operate at full output – e.g. due to demand and renewable power fluctuations – and has to be taken offline completely for planned maintenance or due to technical restrictions and forced outages. There is large uncertainty about the future utilisation rates of coal power plants in Germany, for our scenario we assume an average utilisation factor of 60%, which is equal to the average calculated emissions factor for all coal power plants throughout the projection period in the latest government projections for currently implemented policies (MMS)[34].

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33 The database distinguishes between different combustion technologies in the following categories: subcritical, supercritical and ultra-supercritical, ranking from least to most efficient respectively. We do not consider coal fired power plants retrofitted with CCS technology further in our analysis.

34 Unlike lifetime, the utilisation rate is an endogenous parameter in the model behind the latest official emissions projections. Based on the outputs reported for the "with measures" scenario (MMS) (capacity and net power supply) we estimate an approximate utilisation rate for all coal power plants (without distinguishing lignite from hard coal) for the reported years, which goes from 60% in

$\boldsymbol{ef_i}$ is the emissions factor, which contains information on how much CO_2 is released for a given amount of coal burned. Unit is kg CO_2/TJ. Higher grade coal contains a higher share of carbon, which is converted to CO_2 during combustion. We use emission factors from (IPCC, 2006). Since this source contains only emission factors for pure types of coal, we assumed a 50/50 share for plants that use two different coal grades, e.g. bituminous and sub-bituminous coal.

$\boldsymbol{\phi}$ is a conversion factor to end up with the correct units (Mt CO_2/yr).

Calculating lifetime emissions:

$$Lifetime\ Emi = \sum_{2017}^{\mathrm{T}} \mathrm{Emi}_{\mathrm{it}}$$

with T being the last year the plant unit is in operation, i.e. expected retirement date.

For simplicity, we assume that the shutdown of a given unit happens on 31 December of the respective year. T is calculated for operating power plants or the plants which are planned or under construction as $\mathrm{Opening\ year} + \mathrm{lifetime}$. The decisive assumption here is the lifetime. To align our scenario as much as possible[35] with the latest emissions projections from the government we have assumed a lifetime of 55 years, which is consistent with the "with measures scenario"(MMS) from the latest official projections - (Bundesregierung, 2017b) – but substantially above the global average coal plant retirement age (40 years) that has been assumed in previous reports by Climate Analytics.

In total, 59 units with a total capacity of 2.3 GW are registered as officially retired in the database without any retirement date reported. For those plants we also calculated the potential retirement date as $\mathrm{Opening\ year} + \mathrm{lifetime}$, taking the 55 lifetime assumed. If this causes inconsistency by putting the already retired plants in the operating mode, we fixed the calculated retirement date to the current year (2018). For the future power plants (only two in Germany), we assume plants under construction (Datteln 4) will start operation in 2018 and planned ones (Stade Energy) will start operation in 2021. It is important to note that our assumptions regarding the operation year for planned plants do not affect the cumulative emissions estimated presented (used to compare with Paris Agreement carbon budget).

2014 to 61% in 2030 and going down to 58% in 2035. For our baseline emissions scenario we use the average estimated utilisation rate during the whole projection period (60%).

35 Given that assumptions and parameters at the unit level of the modelling exercise behind the last emissions projections are not publicly available, in particular for the utilisation rates, it is impossible for us to replicate the exact emissions resulting from this exercise. Additionally, only total GHG are reported in the projections report, while in the figures presented in this report refer only to CO_2 emissions, which account for the vast majority of GHG emissions from power plants.

Annex III: Regulator and Owners approaches

In this study we consider two approaches to determine the phase-out schedule at the unit level:

- **"Regulator" perspective:** it adopts an environmental integrity approach and prioritises the shutdown of the least efficient units, while also taking into account the maximisation of the revenue they can generate. For this perspective, we assume generation 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 second 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 cash value of the anticipated future cash flows of each unit during its remaining lifetime, after controlling for the units' size. For detailed information on the approach followed to calculate the NPV refer to Annex IV: Calculating the Net Present Value of coal power plants

- **"Owner" or "market" perspective**: it aims to reduce the overall national cost (regardless of region) of the shut down for investors and owners by keeping units with higher economic value online as long as possible. Similarly to the Regulators 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 worst carbon intensity, understood as emissions per unit of energy they generate. Including efficiency considerations in the Owners 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 than more efficient units from the investors' perspective.

The shutdown is performed at a stepwise manner. For each year in which the sum of emissions from the coal plants are above target emissions pathway, plants need to be shut down until the emissions are below this level. Coal power units are sorted as explained above and those units with highest priority will be shut down in a certain year, as depicted in Figure 13

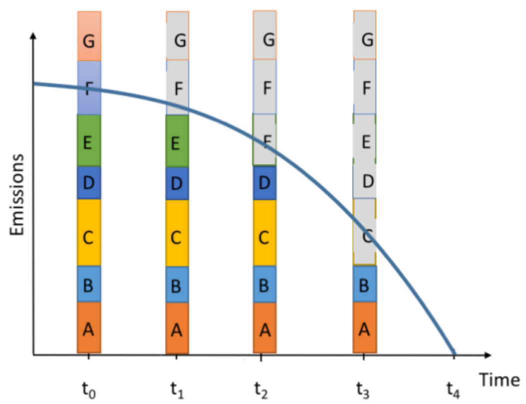

Figure 13 – Schematic overview of methodology. Each of the boxes labelled A to G shows emissions from a power unit. The blue line indicates cost-optimal coal emissions pathways in line with the Paris Agreement long-term temperature goal, and t_0 through t_4 depict the time steps (years). If we assume that our shutdown regime starts in t_1, this means that plants G and F need to shut down – as indicated by the grey colour. In t_2 plant E needs to be shut down under a least-cost strategy and in t_3 only plants A and B may remain in operation. In t_4 all remaining plants need to be shut down, as emissions need to reach zero.

Annex IV: 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:

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

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 the electricity output of the plant times the national energy price. The following illustration shows a graphic representation of the cash flow for a coal power plant during its lifetime:

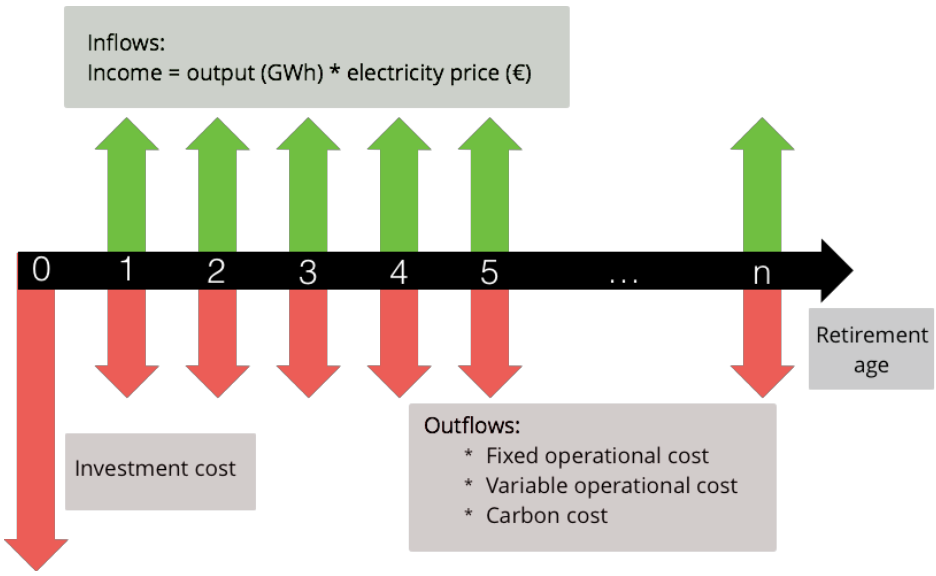

Figure 14 – Cash flow diagram of an average coal-based power generation unit.

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

For the 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 summarized in the table below.

Table 9 – Cost parameters for coal-based power plants by technology.

Technology	Capital Cost €/kW			Fixed Oper. Cost €/kWa			Variable Oper. Cost €/MWh		
	min	central	max	min	central	max	min	central	max
Coal – IGCC w/o CCTS	1.418	1800	1.870	63	63	63	6	8	9
Coal – PC w/o CCTS	1.020	2000	2.346	24	42	47	3	4	6
Coal – PC w/o CCTS	998	1300	1.425	24	26	43	2	6	6
Coal – PC w/o CCTS (Subcritical)	960	1263	1.862	30	25	20	2	6	10
Lignite – Advanced (BoA) w/o CCTS	998	1769	2.336	27	32	37	3	7	11
Lignite – Old	998	1769	2.336	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 incurs to produce electricity. For this parameter we distinguish only between two types of fuel: hard coal and lignite. Taking into account the fluctuations in fossil fuels prices 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 from 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.

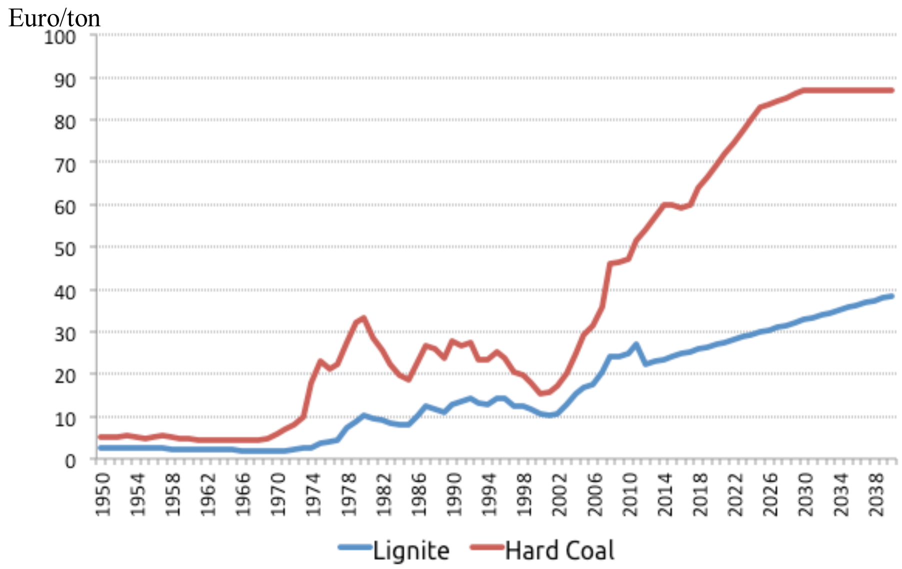

Figure 15 – Underlying price of hard coal and lignite used for calculations.

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 years.

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 the PRIMES Reference Scenario , which assume the carbon price will go from around to 5,5 €/t in 2014 to 40 €/t in 2030, reaching 107 €/t in 2050. For all units we have applied the carbon price to the estimated emissions generated yearly.

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. We use Eurostat price data for the European Union for the period 2008-2017 ("Eurostat - Data Explorer," 2018) and apply historical trends to estimate the prices for Germany for the period before 2008 and for the period until 2030. Moreover given the large uncertainly regarding the evolution of electricity prices in the following decades, for the period after 2030 we keep electricity prices constant.

On a 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, 2014) 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 bigger units usually have bigger 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 big uncertainty associated to the calculation of future cash flows of investment project using standard income and cost assumptions instead of unit-specific data.

Appendix V: Methodology for estimating phase out implications for air pollution emissions

Methodology for estimating avoided air pollutant emissions

To provide insights on the air pollution co-benefits potential, we estimate the avoided emissions in terms of health damaging air pollution emissions from coal power plants using the methodology described in the following.

Data on plant-specific air pollutant emissions for Sulphur Oxides (SO_x), Nitrogen Oxides (NO_x), (primary) particulate matter (PM_{10}) and Mercury (Hg) for the analysed scenarios are derived based on reported air pollutant emissions using the European Pollutant Release and Transfer Register (EPRTR)[36] of the European Environment Agency (EEA). For this, we calculated a ratio of the reported emissions of the respective air pollutant and the reported CO_2 emission in EPRTR in 2016[37] for each plant, indicating how much SO_x, NO_x, PM_{10} and Mercury was reportedly emitted per ton of CO_2 emitted. The individual power plants in EPRTR are then matched with German power plants in the Platts database using on plant-specific information such as postal code, facility name and city or village names. The matching allows to combine the plant specific information on air pollution emissions from EPRTR with more information on the individual plant and unit characteristics available in Platts, such as technology, fuel type and construction date. Moreover, the matching allows to obtain a more comprehensive list of coal power plants in Germany, as not all plants are required to report their emissions to EPRTR (Annex I of the EPRTR regulations defines a reporting threshold for thermal power installations and other combustion installations with a heat input of 50 MW (European Parliament and Council, 2006)). As EPRTR data does not allow to differentiate between individual units of a power plant, the calculated plant-specific air pollutant to CO_2 ratio are assumed to be valid for all units of a plant.

The data exhibits missing values for reported air pollutant emissions from EPRTR. These missing values either occur if a plant falls below the general reporting threshold in terms of capacity of 50 MW and is therefore not covered in EPRTR, or for plants covered but exhibiting pollutant specific missing values, the respective plant might have stayed below the threshold values defined in Annex II of the EPRTR regulations (SO_x/SO_2: 150 000 kg/year, NO_x/NO_2: 100 000 kg/year, PM_{10}: 50,000 kg/year, Mercury: 10 kg/year) (European Parliament and Council, 2006). For all missing values in air pollutant emissions, the respective air pollutant to CO_2 ratios are imputed by the average ratio value of all power plants with reported EPRTR data that have the same technology type and fuel type. Due to a larger number of missing values in EPRTR for reported PM_{10} and mercury emissions, no average air pollutant to CO_2 ratios for plants with the combination of having a combustion technology “SUBCR” (subcritical) and the coal type “SUB” (sub-bituminous coal) could be calculated as this combination was not observed in non-missing EPRTR data. For these plants, the average air pollutant to CO_2 ratio for SUBCR-LIG (subcritical lignite) plants has been used.

36 http://prtr.eea.europa.eu/#/home

37 In case data for 2016 was missing in EPRTR, data from 2015 or 2014 was used.

To obtain estimates on the unit-specific air pollution emissions for the analysed scenarios, the respective air pollutant to CO_2 ratios are multiplied with the CO_2 emission projections for the coal phase out scenarios. If these calculated air pollutant emissions for imputed pollutant specific missing values exceed the threshold values defined in Annex II of the EPRTR regulation (European Parliament and Council, 2006), the estimated air pollutant emissions are set to the threshold value to avoid overestimation of air pollution emissions.

Based on the projected air pollutant emissions three different scenarios are analysed:

1) A reference scenario, assuming that coal power plants remain active until they reach the end of an expected lifetime of 55 years. This scenario can be interpreted as a "no policy" scenario.
2) A regulator-perspective scenario, assuming unit specific phase-out dates as described in Annex III of this report.
3) An owner-perspective scenario, assuming unit specific phase-out dates as described in Annex III of this report.

For this, we assume that a power plant unit emits the projected amount of air pollutants for all years that it remains online for the respective scenario. The projected air pollutant emissions then fall to zero the year after the plant unit is phased out, i.e. assuming that the plant unit is shut down at the end of the phase-out year.

To assess the co-benefits in terms of avoided air pollutant emissions, we sum the projected air pollutant emissions for all power plants remaining online for each year and for each scenario and compare the aggregated emissions for each air pollutant for each year until 2030 across scenarios.

Note that:

- all scenario calculations end in 2030, also the reference scenario, although assuming an expected lifetime of 55 years would mean that many power plants would remain online long after 2030 and would continue to emit health damaging air pollutants as well as CO_2 beyond 2030.
- these estimates should only be interpreted as "first order" estimates to give an indication of the difference in emitted air pollution between phase out pathways and not as absolute values.
- these estimates refer to implications in terms of emitted air pollution, not to changes in concentration levels of the respective pollutants nor do we account for how many people are exposed to this air pollution. How emitted air pollution translates to changes in concentration levels depends on several factors such as meteorology, geography, height of the smokestack as well as the level of precursor gases emitted by other sources, that can e.g. form secondary particulate matter, therefore requiring more complex air quality modeling techniques.

Methodology for estimating avoided health impacts

To provide a first order estimate of the co-benefits in terms of avoided health impacts, we built on estimates from Europe Beyond Coal[38] that have assessed plant specific health impacts based on EPRTR air pollutant emissions data among other data sources using air quality modelling. The assessment of Europe Beyond Coal contains estimates on health impacts in terms of mortality and

38 Europe Beyond Coal: European Coal Plant Database, 22 Jun 2018

morbidity (modelled number of premature deaths, chronic bronchitis (adults), hospital admissions, lost working days, asthma attacks in children) for each plant covered by EPRTR. The modelled estimates have been obtained by Europe Beyond Coal based on a methodology used in the report "Europe's dark cloud – how coal burning countries are making their neighbours sick" (CAN, HEAL, Sandbag, & WWF, 2016). As air pollution does not stop at country borders, the health impacts estimated by Europe Beyond Coal refer to health impacts within and outside of Germany caused by power plants located in Germany.

To estimate health implications for our phase out scenarios, we follow a similar approach as described above for air pollutant emissions. We merge our data on plant-specific emissions from EPRTR and plant characteristics from Platts with the plant-specific estimates from Europe Beyond Coal using EPRTR plant IDs. We then calculate the ratios of the respective estimates for several health aspects from Europe Beyond Coal to the reported EPRTR-CO_2 emissions and multiply the projected CO_2 emissions for each power plant and scenario with this ratio to obtain projections of the unit-specific health impacts. As above, missing values for plants not in EPRTR are imputed based on average ratios for plants with the same combustion technology and coal type combination. Based on these ratios, the projected unit specific health impacts are calculated by multiplying the ratios with the respective projections for CO_2. Note, that due to complex interrelations and non-linearities in air quality models, these estimates should only be interpreted as "first order" estimates to give an indication of the difference in health impacts between phase out pathways and not as absolute values.

Damage cost estimates

The EEA provides country-specific damage cost estimates per ton emitted for various pollutants (see table below), covering costs from mortality and morbidity impacts and also estimates of damage to buildings and crops (European Environment Agency (2014), see Table A2.1 for impacts covered in the estimates and Table A2.7 to A2.9 for the country- and pollutant-specific damage cost estimates). Damage cost estimates are country-and pollutant specific, but are independent of the source of pollution covering a range of sectors.

To provide a rough indication on the co-benefits in terms of avoided economic costs, we apply the damage cost estimates of the EEA to our estimates of air pollution emissions from coal power plants for NO_x, SO_x and PM_{10}. The economic valuation of health impacts is a contentious question. To indicate the range cost estimates resulting from different approaches of translating health impacts into monetary terms, the EEA provides damage cost estimates following two different underlying approaches that are both commonly used in the literature: The Value of a Life Year (VOLY) approach represents a lower estimate compared to the Value of Statistical Life (VSL) approach.
The EEA describes the value of statistical life (VLS) as "an estimate of damage costs based on how much on how much people are willing to pay for a reduction in their risk of dying from adverse health conditions" (European Environment Agency, 2014, p. 23) and the value of a life year (VOLY) as "an estimate of damage costs based upon the loss of life expectancy (expressed as potential years of life lost, or YOLLs). This measure takes into account the age at which deaths occur by giving greater weight to deaths at younger age and lower weight to deaths at older age" (European Environment Agency, 2014, p. 23). Historically, the VSL has been used as the standard method and is still used by most governments on OECD countries. More recently, some governments as well as the European Commission have also calculated VOLY (additional to VSL) to obtain a cost range (WHO Regional Office for Europe & OECD, 2015).

Note that for our estimates we need to make the simplifying assumption of constant damage costs, however, damage costs would need to change (WHO Regional Office for Europe & OECD, 2015) over time as the damage per ton of pollutant is affected by a range of factors such as baseline mortality rates, the level of other health damaging impacts and precursor gases. Moreover, the damage cost estimates provided by EEA do not specifically refer to air pollutant emissions from coal power plants but cover a wide range of sector. Therefore, the damage costs provided estimates provided in this study should be interpreted as first order estimates indicating the order of magnitude and not as absolute values.

Table 10 – EEA damage cost estimates for selected pollutants for Germany (in 2005 Euros per ton emitted)

Germany (€/ton, 2005 prices)		Value of Life Years (VOLY)	Value of Statistical Life (VSL)
Ammonia	NH_3	13,617	41,798
Nitrogen Oxides	NOx	6,817	19,059
Fine particulate matter	$PM_{2.5}$	47,310	147,553
(coarse) Particulate matter	PM_{10}	30,721	95,814
Non-methane volatile organic compounds	NMVOC	1,891	4,772
Sulphur Oxides	SO_2	18,956	57,524

Note: The range provided corresponds to applying two different but complementary approaches of valuating health damages; The Value of a Life Year (VOLY) approach represents a lower estimate compared to the Value of Statistical Life (VSL) approach.

Source: EEA Technical report No 20/2014, Appendix Table A2.7-2.9 (European Environment Agency, 2014)

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