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Stranded Asset Risk and Political Uncertainty: The Impact of the Coal Phase-out on the German Coal Industry

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Abstract

We assess the value of stranded coal-fired power plants in Germany due to the critical phase-out by 2038. Within a Monte Carlo simulation, the scenarios under consideration (a slow decommissioning at the end of the technical lifetime in 2061, the highly probable phase-out by 2038, and an accelerated phase-out by 2030) are additionally assigned distributions to display the uncertainty of future developments. The results show an overall stranded asset value of €0.4 billion given the phase-out by 2038 and additional €14.3 billion if the phase-out is brought forward by eight years. This study also depicts the impacts of carbon pricing and the feed-in from renewable energy sources on the merit order and eventually the deterioration in economic conditions for hard coal and lignite power plants. Lastly, we illustrate immediate concerns for share prices of affected companies and contributes to closing the research gap between stranded physical and financial assets.

Keywords: Coal Phase-out; Energy transition; Germany; Stranded Assets

JEL classification: C53, L13, L94, Q38

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1 Introduction

Under the 2015 Paris Agreement, the global community committed itself to keeping global warming well below 2.0°C (UNFCCC, 2015). In its 2018 report, the Intergovernmental Panel on Climate Change (IPCC) also raised alarms regarding the potential impacts of global warming greater than 1.5°C above pre-industrial levels. It endorses the obligations set within the Paris Agreement to keep the global warming below 2.0°C and, at best, limit it to 1.5°C (IPCC, 2018). One of the crucial steps towards mitigating climate change is thus phasing out coal-fired power generation (Zhao and Alexandroff, 2019). This is especially important for Germany because on the one hand it is failing to fulfill its voluntarily set obligations, most notably its greenhouse gas emissions target for 2020 (Heinrichs et al., 2017) and on the other hand coal is the largest source of CO_2 emissions of the German energy sector (Umweltbundesamt, 2019).[1]

In order to achieve the national climate targets the German government has appointed the German Commission on Growth, Structural Change and Employment, commonly referred to as Coal Commission, to develop a national emission reduction initiative. It presented its final report in early 2019 and the future of the coal industry in Germany is a major part. Within this final report, the coal commission, that included representatives of all major stakeholders, suggested to phase-out coal-fired generation by 2038. This phase-out design is, however, in conflict with the phase-out requirements by 2030, in order to meet the 2.0°C target established during the 2015 Paris Climate Agreement (Climate Analytics, 2018). While insisting on the national phase-out of coal power generation in 2038, the commission's recommendation contradicts German voters' preferences of an early coal phase-out. Across all political parties, German voters' favor an accelerated phase-out of coal within the next five to ten years, even if additional payments amounting to €8.5 billion arise (Rinscheid and Wüstenhagen, 2019).

These current political developments raise the question how the coal-phase-out will impact the German coal industry valuation. Thereby, arising costs adversely impacting the commitment to phase-out coal can be specified as stranded assets (Jewell et al., 2019), which refer, in this

[1] Germany's reliance on coal was politically driven in the past, despite the liberalization of the electricity markets. Coal-fired power generation proved to be well received by the broad political spectrum merely ten years ago (Pahle, 2010). The country has then been prone to the so-called 'carbon lock-in effect', the inability to facilitate the shift towards low-carbon technologies due to its coordinated energy market and historically strong political and institutional interest in coal-fired electricity generation (Rentier et al., 2019). Since 2007, however, power generation from fossils started to decrease and at the same time generation from renewable energy sources increased benefitting from continuous feed-in tariffs. Currently, Germany enters the next phase of its energy transition, where climate change urgency requires an advanced transition towards low-carbon technologies as well as the accelerated decline of electricity generation from fossil fuels (Markard, 2018). Thus, the phase-out of coal-fired power generation is in the light of discussion.

context, to the decrease in valuation of the coal power generation industry in Germany. The decrease in valuation can be a basis for possible compensation payments that have been proposed by the coal commission to alleviate the financial impact of the coal phase out for the coal industry (Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, 2019). On the one hand, some studies argue that compensation is inevitable due to the size of the industry, which can be seen as "too big to fail" (Sen and von Schickfus, 2018). On the other hand, recent studies conclude that the coal phase-out is in line with the constitution and compensation payments are legally controversial (German Bundestag, 2018; Institute for Climate Protection, Energy and Mobility, 2018). While the industry is expecting considerable payments and is therefore against the coal phase-out,[2] especially the lawyers of environmental organizations assume that no compensation will be due (Client Earth, 2019; Leipprand and Flachsland, 2018). If no compensation payments are made to reimburse energy suppliers, the potential decrease in valuation is transferred onto financial assets. Accordingly, this study also highlights the impacts of stranded asset risk on the financial sector as well as estimates compensation payments resulting from the stranded asset value.[3]

In this study, we contribute to the related literature on stranded assets valuation by quantifying the economic, financial, and industrial impacts of the coal phase-out in Germany due to the growing concern over stranded assets. This issue is of paramount importance because the coal phase-out uncertainty would significantly affect the national energy transition policy and cost-benefit analysis of coal-related industries. To the extent that the likelihood and severity of assets stranding are strongly driven by economic (e.g. fuel and carbon prices) and political developments, a scenario analysis is proposed to examine the potential impact of the unanticipated early phase-out by 2030 (Enforcing Paris Agreement Scenario) and the scheduled phase-out of German coal-fired power plants by 2038 (Maintaining Climate Action Scenario). Our analysis also considers a reference scenario in which current hard coal and lignite power plants operate until the end of their technical lifetimes (Delaying Climate Action Scenario). For all three regulatory scenarios the valuation of the German coal industry is estimated by the overall net present value derived from the cash flows of the coal power industry.

[2] Expecting claims for compensation, the Coal Commission recommends negotiations with energy utilities intending an orientation towards payments for reserve power around €0.6 billion per GW (Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, 2019). In January 2020, the Minister of Finance announced that utilities will receive compensation payments of €4.35 billion over the next years (German Government, 2020).
[3] According to applicable law, the German government can change regulatory policies and decommission certain power plants. However, the shareholders are entitled to compensation in the amount of the lost profits.

Under the assumption of moderate carbon and fuel prices, we find evidence that an accelerated coal phase-out by 2030 would lead to the lowest valuation of coal and lignite power plants, with an absolute stranded asset value (defined as the loss difference between the Delaying Climate Action and the Enforcing Paris Agreement Scenarios), reaching €14.72. Moreover, the stranded asset value for the scheduled phase-out by 2038 only amounts to €0.4 billion, which is however significantly below the approximated values by the Coal Commission and industry. In addition, we also point out that, if no compensation is paid, stranded asset risks affect share prices of listed companies in the utilities sector and, thus spill-over to the financial sector (Dietz et al., 2016). Finally, higher carbon and fuel prices as well as feed-in from renewable energy sources are found to be important factors that decrease the valuation for both hard coal and lignite.

The remainder of this paper is organized as follows. Section 2 briefly reviews the literature related to the financial assessment of stranded assets. Section 3 presents the underlying scenarios as well as methodology of the Monte Carlo simulation employed to conduct the scenario analysis. Section 4 reports the empirical findings and discusses their implications. Section 5 concludes this work and gives an outlook to policy implications. The Supplementary Material to our study provides further technical details, data, assumptions, and additional robustness checks.

2 Literature Review on Stranded Assets Assessment

Stranded assets generally describe economic losses resulting from assets becoming devalued or no longer earning economic return. Since political decisions on the phase-out will terminate and impair the running business with coal to differing extents, these devalued or stranded assets bear an uncertain risk for energy suppliers. Stranded assets eventually translate into a decrease in firm valuation (Carbon Tracker Initiative, 2011). The subject of stranded assets is associated with environmental risks, which was first brought up and publicly discussed by Meinshausen et al. (2009) published in *Nature*. The authors investigate the remaining carbon emissions and therefore possible energy resources that could be burned between 2000 and 2050 to not exceed the 2.0°C global warming carbon budget. They document that carbon reserves may not be fully exhausted. In this regard, the Carbon Tracker Initiative (2011) coins the terms of 'unburnable carbon' and the 'carbon bubble' therewith making stranded assets a subject of discussion.[4]

Stranded asset risk has, over the last decade, gained increased attention with growing topicality of climate change emergency, climate policy uncertainty, and financial implications through environmental hazards (Bloomberg New Energy Finance, 2013; Breitenstein et al., 2019; Caldecott, 2017). Beyond this, companies faced with the risk of valueless assets draw attention towards financial assets that will be directly affected.[5] For instance, Atanasova and Schwartz (2019) examine the North American oil industry and conclude that adverse effects between firm value and proved oil reserves exist. Thus, the higher the firm's oil reserves the higher their exposure to climate policy risk. Van der Ploeg and Rezai (2019)find that immediate climate action, e.g. a carbon tax, reduces the societal cost in terms of CO_2 emissions and increase the value of stranded assets for exposed firms.

Current research on stranded asset is mainly driven by academic and non-academic research initiatives including, among others, the Stranded Assets Programme at the University of Oxford's Smith School of Enterprise and the Environment (introduced by the Carbon Tracker Initiative), the World Resources Institute and the United Nations Environment Programme Finance Initiative, the International Renewable Energy Agency, and the Economist Intelligence Unit. The branches of institutional investment and investment consulting (e.g. HSBC, Bloomberg, and Mercer Consulting) are also concerned by assets becoming stranded and have addressed the financial assessment of stranded assets. However, the overall quantitative results show that financial assessment research, especially academic research, except for contributions published by the Oxford's Smith School, remains quite rare. The relevant literature on this subject is aggregated through the previously identified research institutions, proceeding snowball literature research and selected scientific journals instead of a comprehensive systematic literature research, as common databases depict only few scientific research concerning practices and tools of assessment.

[4] It is to be noted that the concept of stranded assets originates in the late 1980s. Krause et al. (1989) firstly outlined the relationship between unburnable carbon, fossil fuel assets and the adverse financial impacts to financial markets. Michaels (1994) also discussed possibilities of stranding assets for the utilities sector. These ideas, however, did not receive enough attention due to the common perception of climate change as neglectable at the time. A comprehensive recap of this study can be found in Caldecott (2017).

[5] The Bank of England has announced stranded assets to be a material risk to financial stability given the exposure of the financial sector to the vast risk of assets becoming stranded following climate change (Carney, 2015). In his speech, the Bank of England's Governor, Mark Carney, outlined that 19% of the Financial Times Stock Exchange 100 Index value are invested in natural resource and extraction sectors of oil, gas, and coal; and 11% are invested in power utilities or other industrial sectors that depend on these natural resources (Carney, 2015). The IPCC (2015) have also voiced concerns about future impacts of stranded asset risk for the financial sector and advocated emissions to the G7 finance ministers in the group.

Table 1 provides main features of the relevant literature that recently assesses and estimates the financial impact of stranded assets. Most studies featured are case studies with the exception of Ansar et al. (2013), Silver (2017), and World Resources Institute and UNEP Finance Initiative (2016) who provide theoretical frameworks on the financial assessment. The remaining are mostly motivated by climate change and its impacts on high-carbon commodities and sectors. The analyses were conducted on different levels: the financial portfolio level or the industry/company/asset level. First, the financial portfolio level includes Integrated Assessment Models (IAM) such as the macroeconomic Dynamic Integrated Climate–Economy (DICE) or E3ME-FTT-GENIE models. A quarter of the studies assesses cumulated losses for financial assets with exposure to carbon-intensive industries. There is interestingly the large amount of case studies employing the Discounted Cash Flow (DCF) method in order to assess the stranded asset value on the industry, company or asset levels. Noteworthily, most studies estimate valuation impacts through the Net Present Value (NPV) of cash flows and the primary fossil fuel industries form the core of the sectors considered within the analyses.

All case studies are scenario analyses in order to estimate the potential value of prospective stranding assets, over the short- to medium-terms, with respect to impending policy, technology, and physical climate change hazards. For most studies, however, the recognition of assets stranding is poorly pronounced and not directly considered in the construction of the different scenarios. Instead, the macroeconomic models do not allow for the disaggregation of financial assets or industry-specific impacts of stranded assets (The Economist Intelligence Unit, 2015). Moreover, the focus on cross-industrial and global estimates induces simplification and insignificance for specific industries. Finally, research considering financial impairment along the stranding of physical assets is rare.

Our study, while focusing on stranded asset risks for the German coal industry, argues that the estimation of the extent of negative implications for the valuation of industry-specific financial assets is a necessary step to further advance research on stranded assets. Doing so, thus stress on the necessity of institutional investors, asset manager, and asset owners to incorporate climate risks into their overall governance and risk management frameworks (Breitenstein et al., 2019; Ernst & Young, 2016).

Author	Type	Model	Outcome Metrics	Sector	Geographic Coverage
HSBC Global Research (2012)	Lobby group report	DCF	NPV (of industry cash flows)	Coal mining	United Kingdom
Ansar et al. (2013)	Academic publication	DCF	NPV (intrinsic value of stock)	-	-
Bloomberg New Energy Finance (2013)	Lobby group report	DCF	NPV, shareholder value	Oil	Global
HSBC Global Research (2013)	Lobby group report	DCF	VaR	Oil	Europe
Caldecott et al. (2013)	Academic publication	-	VaR	Agriculture	Global
Kepler Cheuvreux (2014)	Lobby group report	DCF	NPV (of revenues)	Oil, gas, coal	Global
Mercer Investment Consulting (2015)	Lobby group report	IAM (FUND, DICE)	10-year asset return impacts	Utilities, coal, oil	Global
The Economist Intelligence Unit (2015)	Non-academic publication	IAM	NPV of global financial asset losses	All sectors	Global
Dietz et al. (2016)	Academic publication	IAM (DICE)	NPV of global financial asset losses, 'climate VaR'	All sectors	Global
UBS (2016)	Lobby group report	DCF	NPV (of Industry/peer group cash flows) / EV	Oil, gas	Global, focus U.S. and Canada
World Resources Institute and UNEP Finance Initiative (2016)	Non-academic publication	DCF, IRR, break-even price	NPV (of cashflows)	-	-
Caldecott et al. (2017)	Academic publication	DCF	NPV (total coal stranded plant value)	Coal	China
International Renewable Energy Agency (2017)	Non-academic publication	-	Undiscounted stranded plant value	All sectors	Global
Silver (2017)	Academic publication	DCF	NPV, shareholder value	-	-
Byrd and Cooperman (2018)	Academic publication	CAPM-based return model	Shareholder value in response to stranded asset risk news	Coal	Global
Mercure et al. (2018)	Academic publication	IAM (E3ME-FTT-GENIE)	NPV of global financial asset losses, GDP	Oil, gas, coal	Global
Atanasova and Schwartz (2019)	Academic publication	Panel regression model	Tobin's Q (firm value)	Oil	U.S. and Canada
Van der Ploeg and Rezai (2019)	Academic publication	Pyndick's canonical model	NPV (market valuation)	Oil, gas	Global

The models are Discounted Cash Flow (DCF), Integrated Assessment Models (IAM) such as the Dynamic Integrated Climate–Economy (DICE) and Framework for Uncertainty, Negotiation and Distribution (FUND), and E3ME-FTT-GENIE models, Internal Rate of Return (IRR), and Capital Asset Pricing Model (CAPM). The outcome metrics are the Net Present Value (NPV), also in relation to the Enterprice Value (EV), the Gross Domestic Product (GDP), or the Value-at-Risk (VaR).

Table 1: Overview of case and theoretical studies on financial assessment.

3 Methodology

Generally, risks initially concerned with climate change are uncertain and driven by policy and market developments. Therefore, historical or parametric data do not provide sufficient use cases and, as mentioned in Section 2, scenario analyses are more suitable (World Resources Institute and UNEP Finance Initiative, 2016). Hence, our study relies on a scenario analysis which is conducted on the industry level or, more specifically, for the hard coal and lignite power generation industry in Germany.

3.1 Scenario Description

Three scenarios are set out in order to for the assessment of different levels of stranded assets. Throughout the years 2019 to 2061, different estimates of future input data are included to match the scenarios constructed along the World Energy Outlook published by the International Energy Agency (2018). Thereby, the coal business includes mining, power plants and the supply chain, including sales, to the consumer. The scenario analysis focuses on hard coal and lignite power plants in Germany that belong to energy utilities, municipal energy utilities and mining companies. This limitation is mainly driven by the inaccessibility of relevant data on the costs of the sales processes in utility and mining companies. The power plants considered within the analysis also do not account for revenues from heat cogeneration.

3.1.1 Delaying Climate Action: “Back to Normality”

The Delaying Climate Action Scenario (hereafter, DCAS) serves as the benchmark for the assessment of the stranded asset value. For this purpose, the scenario depicts the hypothetical valuation of the coal industry knowing it would be possible to keep coal and lignite power generation in operation past 2038. The DCAS represents the status quo with no additional policies to change current emission levels and consequently an electricity production from coal that decreases depending on the lifetime-determined decommissioning of all power plants. Furthermore, the DCAS does not include retro fits and new power plants starting operation. Addressing the key factors, the scenario is driven by socio-economic and economic key factors such as the expectation that fossil fuels are needed to sustain the increasing energy demand.

This scenario presumes that short-term physical climate change hazards are not as evident and threatening. Consequently, society and policy makers feel no urgency to further mitigate and adapt to climate change. Therefore, the scenario at hand includes no further policy action in response to climate change and is, instead, the reversal of the commission's proposal on the German coal phase-out in 2038. However, the pan-European policy instrument Emissions Trading System (ETS) is not abolished which implies a moderate increase in carbon prices.

Due to current public discussions about climate change brought up by the Fridays for Future movement in society (Institut für Protest- und Bewegungsforschung, 2019) and new political developments like the European "New Green Deal" (European Commission, 2018), this scenario is highly improbable. Nonetheless, it is of great relevance to the later assessment of valuation impacts of the coal-fired power generation industry.

3.1.2 Maintaining Climate Action Scenario: Current Pathway

Our second scenario, the Maintaining Climate Action Scenario (MCAS), relies on the announcements of the Commission on Growth, Structural Change, and Employment that Germany will decrease its installed capacities of coal electricity production to 8 GW for hard coal and 9 GW for lignite (Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, 2019). Even though the proposal has not yet been legally decided on by the German parliament, it is most likely to present the current pathway of the coal phase-out.[6] A key driving force, again, is found in the policy perspective. The current policy for Germany is included in the MCAS, but no further climate action on limiting greenhouse gas emissions. However, certificate prices are expected to increase due to the additional deletion of certificates. The expansion of renewable energy increases moderately according to the planned reductions in energy from coal. Other key driving forces are a moderate urgency of climate change to society and politics and an increase in climate change related physical events.

This scenario resembles the Current Policies Scenario from the World Energy Outlook by the International Energy Agency (2018). It is constructed along the planned decommissioning published by the Bundesnetzagentur (2019). Overall the MCAS has a low degree of uncertainty. However, the pathway does not follow the Paris Agreement and, therefore further actions are

[6] As of January 2020, a possible pathway to lignite coal phase-out is presented, but not yet confirmed. The MCAS is slightly more progressive than the announced possible decommission plan, i.e. while we assume an almost straightly linear decommission, the plan by the Coal Commission is slower in the early years and accelerates in the years after 2030.

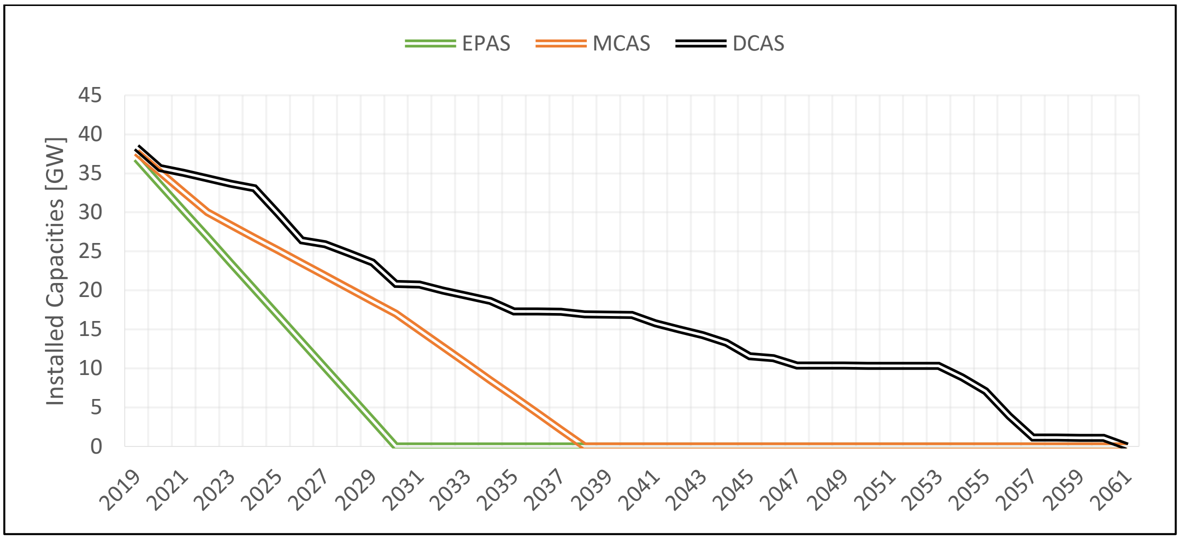
required to meet the international climate goals. The MCAS reflects the current policy framework in place.

3.1.3 Enforcing the Paris Agreement: Limiting Global Warming to 2.0°C

The last scenario, the Enforcing Paris Agreement Scenario (hereafter, EPAS), is consistent with the 2015 Paris Agreement on limiting the average global increase in temperature to below 2.0°C by decreasing the concentration of greenhouse gases in the atmosphere to around 450 parts per million of CO_2 equivalent. It includes a 42% decrease of CO_2 emissions from coal in the power sector by 2020 and a 100% decrease by 2030 in comparison to 2017 levels (Climate Analytics, 2018). Since there have been no adequate reductions in installed capacity of coal-fired power plants, under the EPAS, Germany must reduce installed capacity from around 97% in 2018 to zero in 11 years. Hence, the construction of the scenario to speed up coal phase-out until 2030 is designed along the Paris Agreement self-set goals. Key drivers in this envisioned scenario are short-term physical climate change hazards that are evident and threatening to society, economy, and policymakers.

The EPAS provides strong climate change mitigation action and resembles the Sustainable Development Scenario built by International Energy Agency (2018). Moreover, the scenario is in line with preferences of German voters as well as a wider public who favor the early coal phase-out within the next 10 years (Rinscheid and Wüstenhagen, 2019). In comparison to the MCAS, the phase-out by 2030 is not scheduled within the proposal by the Coal Commission. Given voters' preferences and current debates, it is moderately predictable and exposes a high level of policy action in respond to an impeding climate change magnitude.

The respective annual development in terms of installed capacities of hard coal and lignite for each scenario is illustrated in Figure 1.



Source: Own presentation based on Bundesnetzagentur (2019), Climate Analytics (2018), and Federal Ministry for the Environment, Nature Conservation and Nuclear Safety(2019).

Figure 1: Development of installed capacities of hard coal and lignite combined.

3.2 Monte Carlo Analysis

The analysis at hand covers a long time span from 2019 until 2061 and therefore uncertainty places a substantial role. As previous studies such as Barnett et al. (2019) and Cai et al. (2017) note, climate-change-related uncertainties largely impact the to be obtained output parameters of macroeconomic models. To some extent, uncertainty in this study is covered by the scenario approach, but even within the scenarios, input parameters could vary greatly. Thus, a Monte Carlo simulation for each scenario is carried out. It allows to assign specific input parameters with uncertainty and a distribution of the uncertainty.

The outcomes of the analysis exhibit an impact on future cash flows since cash flows resulting from the coal power generation business are then reduced by lost profits. For this purpose, the EBIT is calculated as the differential between revenues from the clearing price and operation costs and depreciation. The cost variables consist of fuel, carbon, variable, and fixed costs described and determined for all years of the scenarios within the Supplementary Material. Revenues are the output variable of a further complex modelling itself. It is assumed that power plants operators hedge positions and therefore receive either the prices for base or peak load. The prices for base and peak load are determined by applying a simplified merit-order. Figure 2 depicts the modelling procedure of estimating the revenues for all scenarios.

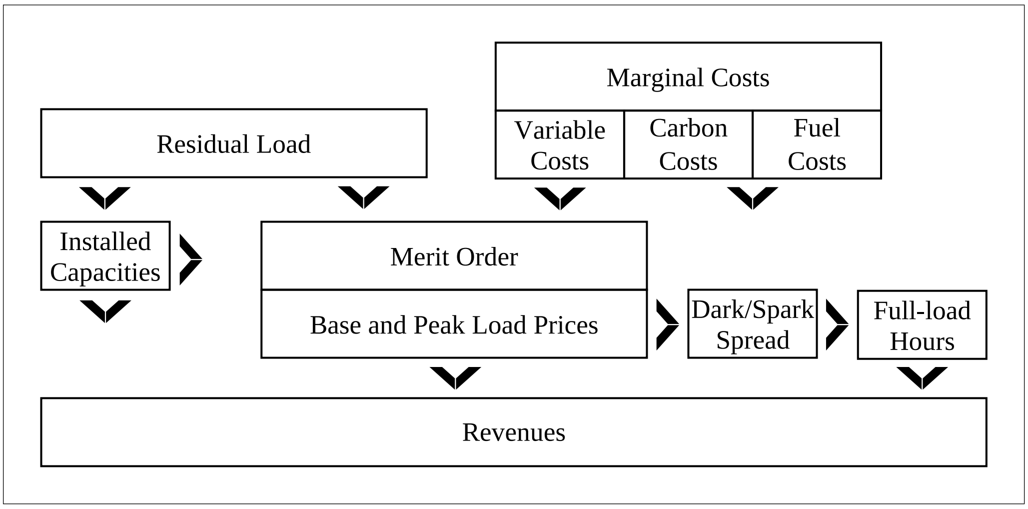


Figure 2: Modelling procedure of the determination of revenues.

In order to calculate the cash flows, we, first, asses the amount of taxes (via EBIT). Secondly, we subtract taxes and other cash-effective expenditures from EBITDA to yield the yearly free cash flows, which are the relevant data for the DCF model. We use the Weighted Average Cost of Capital (WACC) to discount the yearly free cash flows and derive the NPVs.

As seen in Section 2, the DCF model is widely used for the physical asset level, operator level, and financial asset level because it includes a prospective perspective on valuation. Different NPVs allow for the comparison of hypothetical and potential prospective industry valuations across the chosen scenarios.

Due to the increasing installation of and feed-in from fluctuating renewable energy sources, the German residual load composition will experience major changes. Base, mid, and peak load become less distinct and the base load may decrease highlighting the need of flexible power plants to replace continuously running base load power plants (Brunner et al., 2019). As the assumed base load depends heavily on the expectation of future renewable energy installations, the Monte Carlo analysis is conducted four times. Thereby, the upper limit of the base load serves as the baseline analysis. In order to assess the sensitivity of the upper limit base load assumption, the Monte Carlo analysis is repeated by setting the base load to its lower limit, its mean, or by assuming an underlying stochastic triangular distribution based on the given lower, mean, and upper limits. The upper limit depicts the current base load of 44.5 GW, the lower limit amounts to 30 GW for DCAS, 20 GW for the MCAS, and 10 GW for EPAS. The mean base load thus varies for each scenario as well. The determined and randomly sampled base load remains constant for all years of each scenario.[7]

Data, assumptions, and detailed descriptions concerning the Monte Carlo simulation are presented in Supplementary Material appendix to our study.

4 Valuation of the Lignite and Hard Coal Power Generation in Germany

The results for valuation for lignite and hard coal are presented in Table 2 which shows the NPV distributions and their respective summary statistics. Overall in all scenarios lignite has a much higher valuation as hard coal even though both industries are comparable in size. The difference is caused by lignite's lower variable costs and higher full load hours which increase the profitability of lignite. In the following the results for lignite and hard coal are separately presented and analyzed.

Parameter	**DCAS**		**MCAS**		**EPAS**	
	Hard Coal	**Lignite**	**Hard Coal**	**Lignite**	**Hard Coal**	**Lignite**
Minimum	-4.52	11.59	-1.70	8.83	-4.78	-2.13
Maximum	-3.12	16.41	-0.52	12.97	-3.39	1.03
Mean	-3.79	13.97	-1.12	10.90	-4.11	-0.48
Range	1.40	4.83	1.17	4.14	1.39	3.17
VaR (α=0.05)	-4.06	12.68	-1.34	9.79	-4.32	-1.24
VaR (α=0.01)	-4.17	12.32	-1.44	9.44	-4.41	-1.51
STDEV	0.1641	0.7760	0.1370	0.6554	0.1324	0.4549
Rel. STDEV	0.0434	0.0555	0.1225	0.0601	0.0322	0.9466

We refer to the different scenarios by Delaying Climate Action Scenario (DCAS), Maintaining Climate Action Scenario (MCAS), and Enforcing Paris Agreement Scenario (EPAS). We denote VaR as the Value-at-Risk and STDEV as standard deviation. Numbers with the exception of the relative STDEV are in billion €.

Table 2: Summary statistics of hard coal and lignite using the upper base load assumption.

4.1 Results of the Valuation of Lignite and Hard Coal Power Plants

4.1.1 Lignite Power Plants

As presented in Table 2, the valuations for lignite range between the scenarios from €-2.13 to €16.41 billion (from minimum EPAS to maximum DCAS). Across the scenarios, the mean NPV decreases gradually from €13.97 billion in the DCAS to €-0.48 billion € in the EPAS,

[7] In addition to the sensitivity analysis of the base load (Section 4.1.3), further robustness is checked by a sensitivity analysis on the WACC. While a higher (lower) WACC leads to lower (higher) NPVs in each scenario, the differences between the scenarios and, thus, the stranded assets value remains almost the same. The results are presented in the Supplementary Material.

which results in a loss in valuation of 104%. It is worth noting an absolute decrease of €3.07 billion between the DCAS and MCAS in comparison to the absolute decrease of €11.38 billion between the MCAS and EPAS as evident also in Figure 3. On the one hand, this suggests less profitable conditions for lignite past 2038. On the other hand, the strong valuation impacts resulting from high carbon and fuel prices combined with the strong decline in installed capacity in the EPAS.

Within the DCAS, lignite profits from the substantially higher marginal costs of the price-setting power plant technology. Due to low fuel and carbon prices, the current merit order remains unchanged and lignite receives revenues based upon the marginal costs of hard coal and with decreasing installed capacities from combined cycle gas turbines. Therefore, a scenario with no further regulatory measures and decommissioning after a plant's technical lifetime hypothetically presents the highest valuation of the lignite industry. Nonetheless, the profitability after 2038 diminishes and cash flows decrease to and even out at zero. This results in close NPVs for lignite within the DCAS and MCAS and therefore no changes in the merit order.

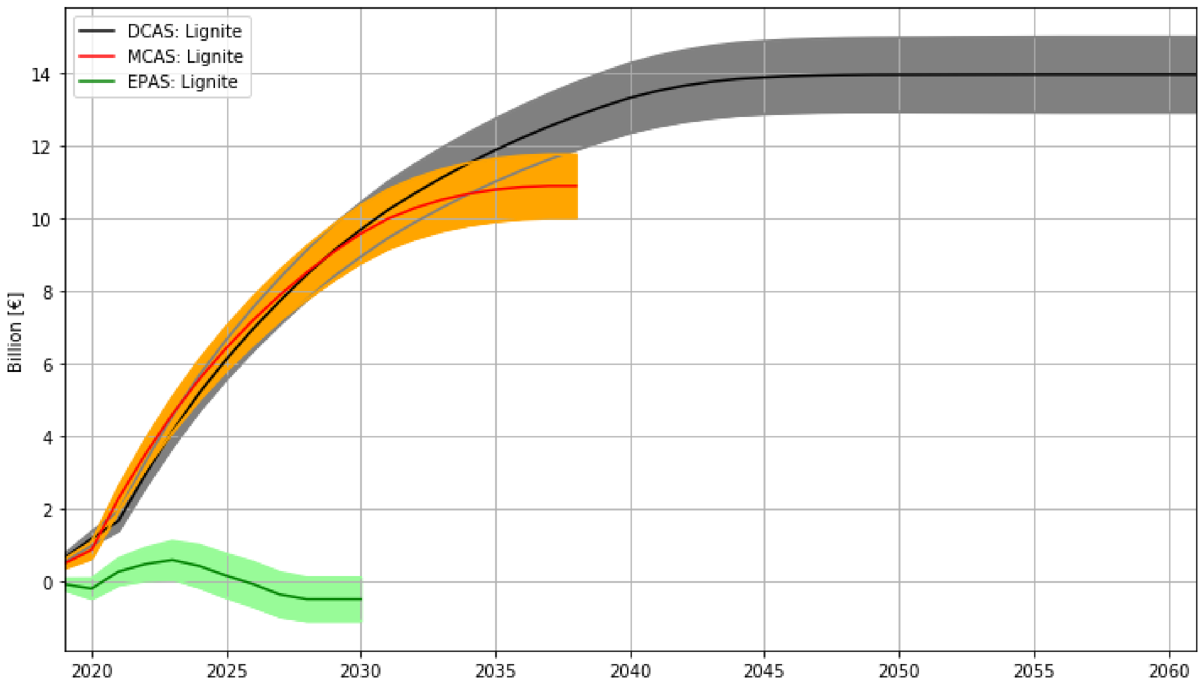


Figure 3: Evolvement of the Net Present Value of the Lignite industry under each scenario with 80% confidence intervals around the mean values.

In the EPAS, a higher carbon price is assumed and leads to the assimilation of the marginal costs of all technologies and in the end to a change in the merit-order where gas replaces lignite at the front. Therefore, lignite provides mostly peak load which reduces the full load hours.

Additionally, the installed capacity of combined cycle gas turbines increases over time so that it also covers the averaged peak load. Thus, the large profits of lignite are cut and result in lower mean NPVs previously outlined. However, the change within the merit order also raises the question whether it is technically feasible for lignite to operate in the peak load. This could eventually result in lignite power plants becoming uncompetitive by 2024 or 2025.

Furthermore, the risk measure Value-at-Risk (VaR) is estimated to determine the downside risk of the distribution. The VaRs at the 5% and 1% quantiles depict the severe decrease from the MCAS to the EPAS reducing by 113% and 116%, respectively. The mean NPV and the VaRs turn negative in the EPAS indicating that, by a probability of 99%, the lignite NPV does not fall short of €-1.51 billion. The standard deviation (STDEV) of the empirical NPV distributions for each technology varies within the three scenarios depicting differences in the risk-return profiles. As the standard deviation is compared to the mean of the NPV distribution, the relative standard deviation refines the comparability between the scenarios and the technologies themselves. In the DCAS, the relative standard deviation remains moderate at 0.0555 and increases only slightly to 0.0601 in the MCAS. In the EPAS, with risky fuel and carbon prices, the relative standard deviation of 0.9466 shows a strong increase of relative variance and is highly exposed to the downside variation of the mean NPV.

Overall, the value of the lignite industry decreases due to the coal phase out. Figure 3 depicts the evolvement of the mean NPVs under scenario. We see that a phase-out by 2038 limits the loss in valuation to about €3 billion while an earlier phase out leads to further losses in the valuation of about €11 billion. Hence the coal phase-out possesses a risk for stranded assets in the lignite industry.

4.1.2 Hard Coal Power Plants

The NPVs of the hard coal power generation industry range between €-4.78 billion and €-0.52 billion (from minimum EPAS to maximum MCAS). This generally perceptible pattern of negative NPVs is caused by the alignment of the marginal costs of hard coal with the ones of combined cycle gas turbines. Depending on the rapidity of decommissioning and the merit order, hard coal is the price-determining power plant later being replaced by combined cycle gas turbines. However, given the low positive spreads throughout most of the scenarios, hard coal power plants are not able to fully cover their fixed costs with the predetermined low number of full-load hours of 3,387.5 hours/year. Nevertheless, the MCAS reveals the highest valuation in comparison to the almost equally negative NPVs in the DCAS and EPAS (see also Figure 4). In order to generate positive cash flows a clean dark spread of at least 16 €/MWh is required. This can indicate that assumed fixed costs are too high. Nonetheless, the economic profitability remains compromised, as marginal power plants in an energy only market cannot cover their fixed costs due to the missing money problem.

Although the results of the DCAS and EPAS are almost the same the reasons for that are quite contrary. In the EPAS, high carbon prices increase variable costs of hard coal over those of gas and therefore these technologies switch their position by 2024 or 2025 in the merit order. Hence, earnings as well as full load hours decrease, since they act as peak load power plants, which leads to lower NPV compared to MCAS. On the other side in the DCAS as well as in the MCAS the cash flows are negative, which leads to lower NPVs because of the longer running time of the hard coal. Again, the technical feasibility of hard coal's peak load capability remains a further point of attention.

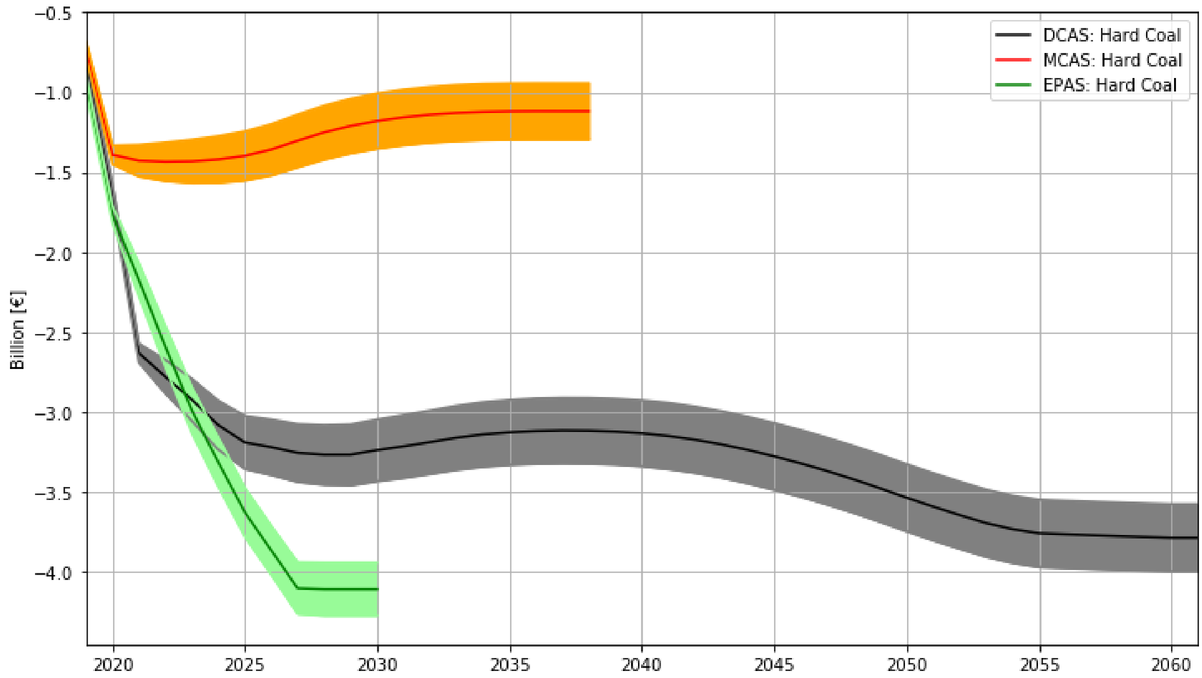


Figure 4: Evolvement of the Net Present Value of the Hard Coal industry under each scenario with 80% confidence intervals around the mean values.

This is further corroborated by the VaRs which display similar values in the DCAS and EPAS of €-4.17 and €-4.41 billion at the 1% quantile, respectively. A strong incline of the VaRs, however, is visible in the MCAS. The MCAS suggests that, by a probability of 99%, the NPV does not fall below €-1.44 billion economizing around €2.7 billion in losses in comparison to the DCAS. The MCAS has the highest relative standard deviation of 0.1225. In comparison, the relative standard deviations of DCAS and EPAS are 0.0434 and 0.0322, respectively.

Summarizing, a coal phase-out increases the valuation of hard coal (from €-3.79 to €-1.12 billion) due to a shorter period of negative cash flows. Although, in reality when companies expect future negative cash flows they would decommission their assets to minimize their losses. However, the coal phase-out does not create a risk for stranded assets from the hard coal industry.

4.1.3 Sensitivity Analysis of the Base Load

Base load constitutes a crucial input factor and can have a great impact on the profitability and thus on the NPVs of the two technologies. In this study, base load is to be understood as the minimum residual load for 7,000 hours per year. Hence, lowering the residual load accounts for the impact of a further expansion of renewable energies. Therefore, we repeat our Monte Carlo analysis to test for the sensitivity of the base load level. In our previous calculations, we assumed the current residual load (2019) to which we refer as 'upper limit'. The further analysis employs a lower limit, a mean, and a stochastic load level. For the latter, we employ a triangular distribution for the base load (from lower limit to mean to upper limit).[8]

The results for the different base load assumptions are presented in Table 3. Overall, the structure of the previous results remains the same, i.e. lignite has its highest valuation in the DCAS which decreases over the MCAS to the EPAS. Furthermore, the valuation for lignite follows the intuitive logic that the valuation decreases when base load is lower. In contrast, for hard coal, the valuation does not necessarily decrease with the load, thus its lowest valuation is derived for the mean base load assumption. This is due to the fact that hard coal can generate comparatively good cash flows in case of low base load in the first years.

Base Load	**DCAS**		**MCAS**		**EPAS**	
	Hard Coal	**Lignite**	**Hard Coal**	**Lignite**	**Hard Coal**	**Lignite**
Upper	-3.79	13.97	-1.12	10.90	-4.11	-0.48
Mean	-5.18	11.00	-2.03	4.00	-3.64	-2.33
Lower	-4.59	6.66	-0.59	2.52	-3.31	-1.28
Stochastic	-4.74	11.27	-1.67	5.92	-3.62	-1.68

We refer to the different scenarios by Delaying Climate Action Scenario (DCAS), Maintaining Climate Action Scenario (MCAS), and Enforcing Paris Agreement Scenario (EPAS). Numbers are in billion €.

Table 3: Mean NPVs of the simulation employing different base load assumptions.

Furthermore, the absolute differences in the valuation between the different base load assumptions are much smaller for hard coal than for lignite. This result is explained by the fact, that hard coal has already negative cash flows with high base load assumptions and with the

[8] For technical details, we refer to the Supplementary Material to this study.

decreasing base load level more capacity is decommissioned earlier, which limits the loss in valuation. In contrast, with less load, lignite accrues fewer positive cash flows which lowers its valuation.

Summarizing, the level of the base load has a great impact on the valuation, especially for lignite. The impact for hard coal is much smaller. Furthermore, a reduction of base load, for instance due to the expansion of renewable energies, reduces the valuation of lignite and therefore possesses the risk of stranded assets.

4.1.4 Contrasting the Results for Lignite and Hard Coal Power Plants

The results for the valuation of lignite and hard coal differ quite significantly not only in the absolute value but also in their structure. The fact that lignite has a generally higher valuation when both industries are comparable in size is to be expected, since lignite has lower variable costs. This leads to a better position in the merit order and therefore to higher earnings. The lower variable costs come at the price of higher investments, which are neglected in this study since only existing power plants are considered.

More interesting is the difference in the structure of the results: Lignite has the highest valuation in the DCAS while hard coals valuation is almost as low as in the EPAS. Due to its low variable costs lignite is able to constantly generate positive cash flows, which decrease over time due to increasing carbon prices. In contrast, hard coal struggles in most years to pay off its fixed costs, since it often sets the market clearing price. When setting the market clearing price, fix costs cannot be covered and therefore hard coal accumulates negative cash flows over a long period of time leading to the lowest NPV.

In summary, the different variable costs of lignite and hard coal are the reason for the large differences of their respective valuation. While for lignite the coal phase-out possesses a risk, it does not for hard coal. In contrast, both technologies EPAS. The main reason is the feed-in from renewable energy sources and moreover high carbon prices, which cut profits and valuation compared to the MCAS for both, hard coal and lignite.

4.2 Economic and Political Implications

4.2.1 Compensation Payments

The decrease in valuation, shown in Section 4.1, depicts severe consequences for the profitability of affected utilities and companies. These potential developments could follow the very similar political events of the nuclear phase-out in Germany resolved after the Fukushima nuclear disaster in 2011. Due to missing revenues, the early nuclear phase-out resulted in losses of billions of euros on behalf of German energy suppliers. In consequence, they sued the government for their claims of damage compensation in the amount of €19.7 billion before the Federal Constitutional Court and the International Centre for Settlement of Investment Disputes (ICSID). The Federal Constitutional Court ruled that the government is responsible for adequately compensating utilities indicating the government's accountability also for the closely linked losses in consequence of the coal phase-out (Bos and Gupta, 2018).

Due to the interdependencies between politics and the energy industry, compensation payments remain highly critical to policymakers (Bos and Gupta, 2019). In this regard, compensation payments for stranded assets could present a practical tool to achieve a reduction in coal capacity. In the past, the German government has indicated its willingness to compensate the energy industry by offering compensation payments to energy suppliers. In return for shutting down 2.7 GW of installed capacity from lignite power plants, energy suppliers received €1.6 billion from, ultimately, German taxpayers (Zhao and Alexandroff, 2019). This equals €0.6 billion per GW of installed capacity. The Coal Commission conforms with this payment in its final report, claiming that potential compensation payments for operating and yet to operate power plants may orientate towards payments for security reserves. These statements imply overall payments of €24.0 billion for the current amount of installed capacities of hard coal and lignite, estimated at 40.3 GW. According to the Coal Commission, overall €1.6 billion are already to be paid to lignite power plants in the security reserve mode (Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, 2019). On the other hand, highly exposed energy supplier RWE raises a claim for the compensation of decommissioning coal power plants estimated at a range of €1.2 to €1.5 billion per GW of installed capacity (Steitz and Eckert, 2019). On that basis, payments could amount up to €60.0 billion. In January 2020, the Minister of Finance announced that the government plans to pay €4.35 billion in compensation to operators of lignite power plants over the next years.

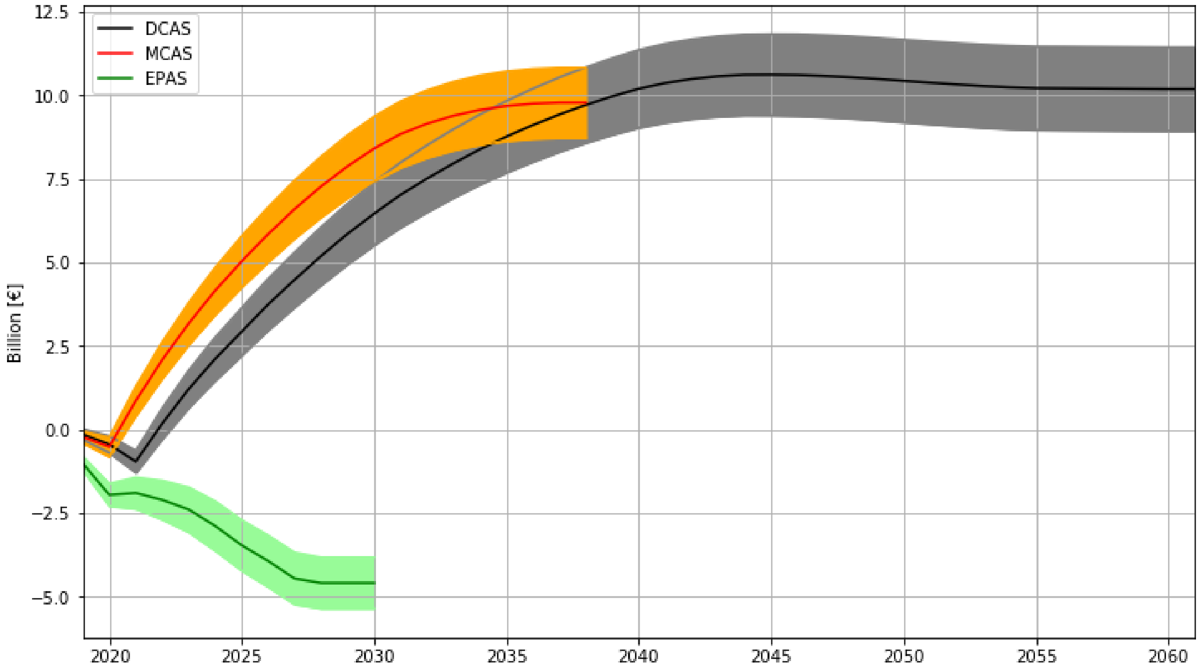


Figure 5: Evolvement of the Net Present Value of the Coal Industry under each Scenario with 80% confidence intervals around the mean values.

Based on our results, we calculate a total stranded asset value of €0.4 billion for a phase-out by 2038 instead which is also depicted in the difference between the respective end points of DCAS and MCAS in Figure 5. Even if only lignite power plants are taken into consideration, the total amount would only sum up to €3.07 billion. Thus, our estimates are considerably lower than the demanded compensation.

Since energy utilities argue with their current running capacity, it might also be of interest to know which amount of power generation is actually to be compensated. Our calculations show that in the DCAS only 9.07 GW are still running by the end of 2038. Multiplied with the previously paid €0.6 billion per GW results in €5.44 billion, which is still significantly lower than the amount demanded by the energy suppliers.

On another note, an even earlier phase-out would be more costly, but still below the raised claims. Rinscheid and Wüstenhagen (2019) show that German voters would accept additional costs of €8.5 billion for a phase-out by 2025 or €3.2 billion by 2030 compared to the scheduled 2038 phase-out. Our calculations for a phase-out in 2030 instead of 2038 lead to an additional stranded asset value of about €14.32 billion (€11.38 billion) for both technologies (lignite only). The large difference between the phase-out dates is depicted in Figure 5. Thus, the total strand asset value for a phase-out in accordance with the Paris Agreement would sum up to €14.72 billion (€14.45 billion lignite only).

In addition to the far lower decrease in valuation for an early phase-out, our study evidences that the phase-out of coal-fired electricity generation by 2030 does not require an accelerated decommissioning. Instead, the introduction of carbon prices on adequate levels present economic conditions where hard coal and lignite power plants cannot remain competitive. More specifically, high carbon prices can disrupt the merit order to an extent that leads to the phase-out of lignite and hard coal simply based upon economic conditions. This outcome confirms Michaels (1994) who argues that stranded investment compensation solely designate lost revenues of companies that were not to be reclaimed in a competitive market. However, this requires prices of at least 35 €/t by 2020 quickly increasing to 180 €/t, as they were provided by the Forum Ökologisch-Soziale Marktwirtschaft (2019) on behalf of the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety. However, as of January 2020 the settlement price for CO2 emission allowances futures is about 25€/t.

4.2.2 Carbon Dioxide Emissions

The yearly and overall CO_2 emissions have been calculated for the baseline scenario, as well, to give a brief overview on Germany's political ambitions on mitigating climate change impacts. Figure 6 depicts the cumulated CO_2 emissions based on the mean values of the distribution. This reduction in CO_2 emissions is in line with Jewell et al. (2019), who estimate the avoided emissions at a range of 0.6 and 1.6 Gt depending on the actual phase-out date. If the phase-out for Germany remains in 2038, 1.32 Gt of CO_2 emissions are avoided compared to a phase-out in 2061. The early phase-out by 2030 scenario (EPAS) even has the potential to save up to 2.15 Gt of emissions. In comparison to the current phase-out by 2038, the accelerated phase-out of hard coal and lignite is able to cut CO_2 emitted by 48%. The comparison to the hypothetical emissions approximates the extent of emissions that results only from coal-fired power generation.

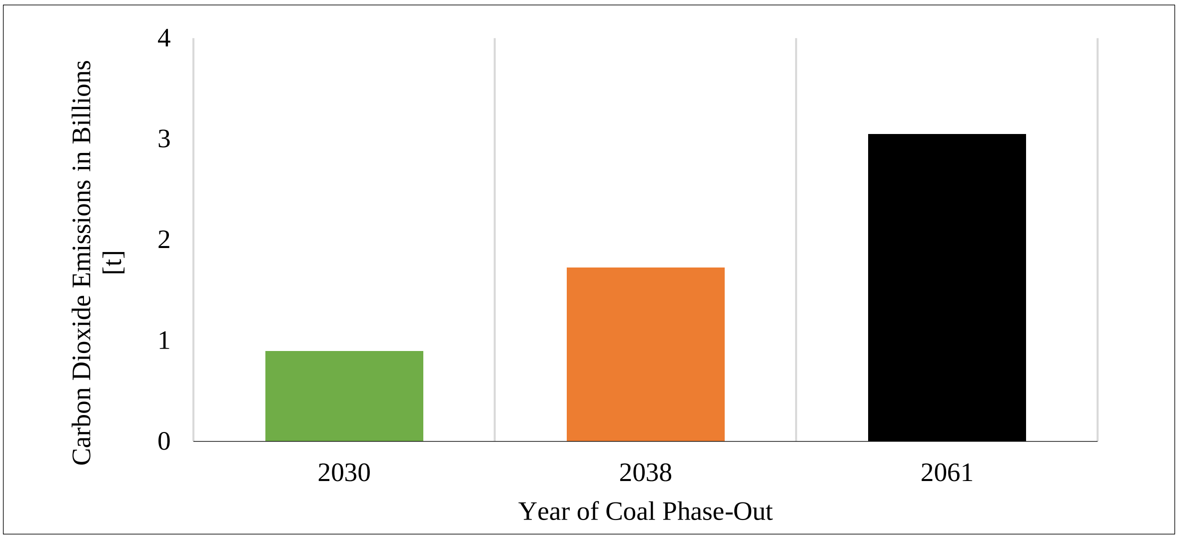


Figure 6: Required carbon budget depending on the timeframe of hard coal and lignite decommissioning.

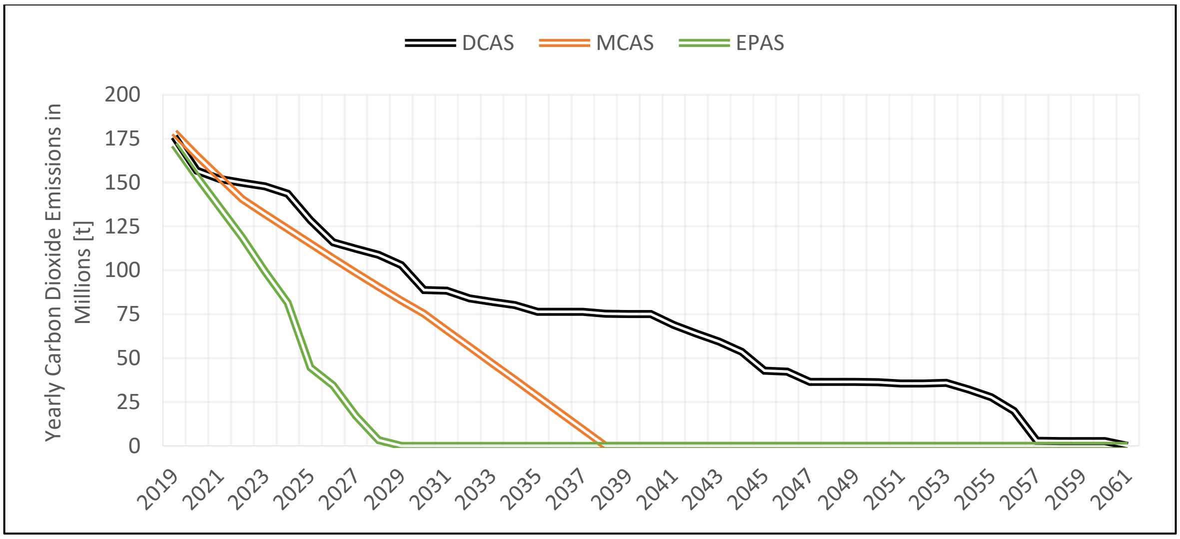


Figure 7: Development of CO_2 emissions for each scenario.

Figure 7 illustrates the mean of the yearly emissions from coal-fired power generation resulting from the three scenarios. Without additional policy measures, emissions decrease slowly due to the ageing of the coal fleet without retro fits and new power plants starting operation. However, accelerating the phase-out of hard coal and lignite up to 2030 presents the only possibility to keep up with the already moderate 2030 goals of reducing greenhouse gas emissions set in the 2015 Paris Agreement. A study by Climate Analytics (2018) demonstrates that only a continuous reduction in coal-related CO_2 emissions down to zero by 2030 ensures the compliance with the defined goals. Thus, Germany is not able to meet its reduction goals set in the Paris Agreement in 2015 given the timeframe of 2038 as proposed by the Coal Commission. In the meanwhile, this data does not address the substitution of coal by natural gas and therewith related emissions.

4.2.3 Financial Market Implications

Our Monte Carlo analysis depicts the extent of assets stranding in the coal power generation industry. The lignite and hard coal industry both suffer losses in valuation between a scenario with current energy and climate policy objectives (MCAS) and a scenario with ambitious objectives to reduce greenhouse gas emissions (EPAS). The valuation impacts of the power generation industry in Germany affect shareholder valuation, if no compensation payments are made. For instance, Sen and von Schickfus (2018) show that current climate policy is already reflected in the share prices of German power utilities. However, the authors also show that while investors care about stranded asset risk, they also expect compensation.

For further assessment, the MCAS displays the valuation of the hard coal and lignite power generation industry that are considered in the current share prices of utility and power generation companies. Using the results from our baseline Monte Carlo analysis, the changes in mean NPVs between the three scenarios are presented in Table 4.

Parameter	**DCAS**		**MCAS**		**EPAS**	
	Hard Coal	**Lignite**	**Hard Coal**	**Lignite**	**Hard Coal**	**Lignite**
Mean NPV	-3.79	13.97	-1.12	10.90	-4.11	-0.48
Absolute Change	-2.67	3.07	-	-	-2.99	-11.38
Relative Change	-239%	28%	-	-	-267%	-104%

We refer to the different scenarios by Delaying Climate Action Scenario (DCAS), Maintaining Climate Action Scenario (MCAS), and Enforcing Paris Agreement Scenario (EPAS). Numbers with the exception of the percentage change are in billion €.

Table 4: Value impacts of the hard coal and lignite power generation between the scenarios.

Since the coal phase-out by 2030 is in the focus of current debates, Table 4, again, underlines the decrease of valuation between the MCAS and EPAS. In order to estimate the potential adverse impacts that shares of exposed companies may experience in the case of the EPAS, this decrease must be transferred onto the shareholder value. We approach the individual stock devaluation by decomposing each company's stock price to the fraction concerned with the coal fired power generation.

In this study, the absolute decrease between the two scenarios is broken down to the affected hard coal and lignite fleets. Neglecting municipal utilities, the companies EnBW, LEAG, RWE, and Uniper account for 96% of the lignite installed capacity in 2019. For hard coal, 74% of installed capacity belongs to EnBW, ENGIE, LEAG, RWE, STEAG, Uniper, and Vattenfall. Table 10 in the appendix visualizes the proportions of the hard coal and lignite capacities, respectively. It is shown that EnBW, RWE, Uniper, and Vattenfall equally account for the largest capacities of hard coal power plants. Lignite power plants are, in contrast, predominantly owned by LEAG and RWE. However, only the shares of ENGIE, RWE, and Uniper are publicly traded and the reduction in valuation is assessed within the shareholder value. In doing so, the percentage of capacity is used to calculate the absolute loss between the MCAS and EPAS. The absolute loss, thus the stranded asset value, for lignite amounts to €11.38 billion and for hard coal to €2.99 billion. Next, this absolute loss is divided by the shares issued by the company. Table 5 presents the shareholder value outcome for each company.

Company	Absolute Loss [billion €]	Loss per Share [€/share]	
		Equity Ratio = 1.0	Equity Ratio = 0.4
Lignite			
RWE AG	5.58	9.07	3.63
LEAG AG	4.29	-	-
Uniper AG	0.54	1.48	0.59
EnBW AG	0.53	-	-
Others	0.45	-	-
Hard Coal			
EnBW AG	0.43	-	-
Uniper AG	0.41	1.11	0.44
RWE AG	0.40	0.66	0.26
Vattenfall GmbH	0.40	-	-
STEAG GmbH	0.27	-	-
ENGIE AG	0.22	0.09	0.04
LEAG AG	0.10	-	-
Others	0.76	-	-

Table 5: Absolute loss and loss per share of listed companies.

Table 5 displays different extents of vulnerability of the investigated shares. Presupposing that equity capital also covers for losses of debt, the cumulated losses for RWE’s stock amount to 9.73 €/share indicating that RWE with its large coal fleet is greatly affected by the coal-phase out prior to 2038. It is followed by Uniper’s share that suffers losses of 2.59 €/share. ENGIE has a lower exposure to hard coal power plants and accounts for losses of 0.09 €/share. Given an autonomous financing, losses for equity only occur for the share of equity in a power plant. Assuming a 60% debt-to-capital ratio (Fraunhofer Institute for Solar Energy Systems, 2018), the loss per share for RWE is 3.89 €/share. Uniper and ENGIE each account for losses of 1.03 €/share and 0.04 €/share, respectively. Given this range of financing structure, the financial analysis highlights the potential, yet immediate impact of regulatory changes to coal assets. The—currently unanticipated—phase-out of coal by 2030 not only has visible valuation impacts but directly impairs shareholder values of affected companies, especially RWE and Uniper.

In summary, this study puts stranded assets in direct relationship to equity prices, exemplary conducted for the stranded asset risk of coal-fired power generation in Germany. It therefore comprehensively addresses not only the operators' exposure but also the financial asset risk of coal assets stranding. This finding corroborates theoretical studies aiming at the potential impairment of bonds and equity in the financial sector, as discussed in Section 2. Furthermore, the coal phase-out impact on financial assets depicts a material risk in the near-term future in contrary to perception of the long-term nature of stranded carbon assets (Griffin et al., 2015). On that note, financing decisions typically of short-term time horizons should factor in the stranded asset risk linked to the coal phase-out in Germany (World Resources Institute and UNEP Finance Initiative, 2016). Nonetheless, this approach is limited, as it does not provide the distribution of losses with a temporal adjustment. The reduction in cash flows is not equally allocated across the years just like the installed capacities. However, this assessment presents an approximation to the extent of adverse impacts on stock prices.

5 Conclusion and Policy Implications

This research addresses the highly topical issue of a coal phase-out driven by the current discussion on the transition to a low-carbon economy in Germany. Employing a Monte Carlo based scenario analysis, we estimate a stranded asset value of the German coal-fired power plants in consequence of the approaching phase-out of coal. The underlying scenarios present three pathways including different phase-out schedules as well as regulatory and economic measures. A two-stage model is constructed that first replicates the merit order and thus determines the peak and base market clearing prices. Second, the model determines the annual cash flows for the NPV estimation. Within this framework, the prospective cash flows for hard coal and lignite power plants are estimated until the final decommissioning to assess the NPV. Additionally, input parameters are assigned distributions in order to display the uncertainty of policy and economic developments. Methodologically, this study further attempts to bridge the gap between the stranding physical and financial assets.

The results from our scenario analysis proves a decrease in valuation for lignite, if the installed capacities phase out until 2038 and moderate carbon and fuel prices are assumed. Unlike lignite, the NPV of hard coal increases by assuming the phase-out by 2038. This difference is mainly due to the substantially lower marginal costs of lignite ensuring a profitable position in the merit order. Looking at the phase-out scenario by 2030, we find evidence of a huge decrease in the valuation of lignite and a moderate decrease in the valuation of hard coal, compared to the phase-out scenario by 2038.

Taken together, the timeframe of coal-phase out by 2038 as proposed by the Coal Commission would help German hard coal and lignite industries to save €14.32 billion, but Germany will not be able to meet its reduction goals set in the Paris Climate Agreement in 2015. Apart from this, the scenario analysis demonstrates that the feed-in from renewable energy sources (and thus a decline in the residual base load) and higher carbon prices would lower the hard coal and lignite industry valuations.

Our study also shows two important implications of stranded assets: Firstly, physical assets become stranded through losses in revenues, as outlined within the exemplary study on the coal phase-out in Germany. This contributes to a broader understanding of stranded assets that is shifted from unanticipated write-downs to rather cash-effective valuation impacts. Secondly, we highlight the interconnection between physical assets and financial assets, which are adversely affected by carbon-intensive sectors. The decrease in valuation of the examined shares poses a significant financial risk to companies, financial institutions, and investors. Given the political uncertainty of the pathways and in progressive policy measures, our findings ultimately call for the incorporation of these climate-related risks into the investment decision-making process.

Concerning the state of research, this study draws further attention to the risks of climate change as well as the understanding of stranding physical assets and implications for the financial sector. Research has yet to proceed on the quantitative assessment of stranded assets related to climate change in order to grasp the complexity of this issue. Additional research is needed to determine the relationship between the stranding of physical and financial assets. For example, our study only investigates the limited case of a coal phase-out in Germany, while other country- or technology-specific cases might also be of interest for academics and policy makers. Hitherto, most studies are using DCF models to assess the value of stranded assets due to climate-related risk. However, Balint et al. (2017) and Monasterolo et al. (2019) call for more sophisticated models considering the complexity of our economic and financial eco-system.

References

Ansar, A., Caldecott, B., Tilbury, J., 2013. Stranded Assets and the Fossil Fuel Divestment Campaign: What Does Divestment Mean for the Valuation of Fossil Fuel Assets? University of Oxford’s Smith School Stranded Assets Programme.

Atanasova, C., Schwartz, E.S., 2019. Stranded Fossil Fuel Reserves and Firm Value (Working Paper No. 26497). National Bureau of Economic Research. https://doi.org/10.3386/w26497
Balint, T., Lamperti, F., Mandel, A., Napoletano, M., Roventini, A., Sapio, A., 2017. Complexity and the Economics of Climate Change: A Survey and a Look Forward. Ecological Economics 138, 252–265.
Barnett, M., Brock, W.A., Hansen, L.P., 2019. Pricing Uncertainty Induced by Climate Change. SSRN Journal 46. https://doi.org/10.2139/ssrn.3440301
Bloomberg, 2019. Stock Quotes Database [WWW Document]. Bloomberg.com. URL https://www.bloomberg.com/markets/stocks (accessed 9.30.19).
Bloomberg New Energy Finance, 2013. Carbon Risk Valuation Tool. White Paper.
Bos, K., Gupta, J., 2019. Stranded Assets and Stranded Resources: Implications for Climate Change Mitigation and Global Sustainable Development. Energy Research & Social Science 56, 101–215. https://doi.org/10.1016/j.erss.2019.05.025
Bos, K., Gupta, J., 2018. Climate Change: The Risks of Stranded Fossil Fuel Assets and Resources to the Developing World. Third World Quarterly 39, 436–453. https://doi.org/10.1080/01436597.2017.1387477
Breitenstein, M., Nguyen, D.K., Walther, T., 2019. Environmental Hazards and Risk Management in the Financial Sector: A Systematic Literature Review (SSRN Scholarly Paper No. ID 3428953).
Brunner, C., Deac, G., Braun, S., Zöphel, C., 2019. The future need for flexibility and the impact of fluctuating renewable power generation. Renewable Energy. https://doi.org/10.1016/j.renene.2019.10.128
Bundesnetzagentur, 2019. Power Plant List for Germany [WWW Document]. URL https://www.bundesnetzagentur.de/DE/Sachgebiete/ElektrizitaetundGas/Unternehmen_Institutionen/Versorgungssicherheit/Erzeugungskapazitaeten/Kraftwerksliste/kraftwerksliste-node.html (accessed 7.10.19).
Byrd, J., Cooperman, E.S., 2018. Investors and Stranded Asset Risk: Evidence from Shareholder Responses to Carbon Capture and Sequestration (CCS) Events. Journal of Sustainable Finance & Investment 8, 185–202. https://doi.org/10.1080/20430795.2017.1418063
Cai, Y., Judd, K.L., Lontzek, T.S., 2017. The Social Cost of Carbon with Economic and Climate Risk. Hoover Institution Economics Working Paper.
Caldecott, B., 2017. Introduction to Special Issue: Stranded Assets and the Environment. Journal of Sustainable Finance & Investment 7, 1–13. https://doi.org/10.1080/20430795.2016.1266748
Caldecott, B., Dericks, G., Tulloch, D.J., Liao, X., Kruitwagen, L., Bouveret, G., Mitchell, J., 2017. Stranded Assets and Thermal Coal in China: An Analysis of Environment-Related Risk Exposure. University of Oxford's Smith School Stranded Assets Programme.
Caldecott, B., Howarth, N., McSharry, P., 2013. Stranded Assets in Agriculture: Protecting Value from Environment-Related Risks. University of Oxford's Smith School Stranded Assets Programme.
Carbon Tracker Initiative, 2011. Unburnable Carbon - Are the World's Financial Markets Carrying a Carbon Bubble?
Carney, M., 2015. Breaking the Tragedy of the Horizon - Climate Change and Financial Stability. Speech by Mr. Mark Carney, Governor of the Bank of England and Chairman of the Financial Stability Board, at Lloyd's of London on 29 September 2015.
Client Earth, 2019. Kein Geld für alte Braunkohlekraftwerke.
Climate Analytics, 2018. Science Based Coal Phase-Out Pathway for Germany in Line With the Paris Agreement 1.5°C Warming Limit.
Dietz, S., Bowen, A., Dixon, C., Gradwell, P., 2016. 'Climate Value at Risk' of Global Financial Assets. Nature Clim Change 6, 676–679. https://doi.org/10.1038/nclimate2972
Ernst & Young, 2016. Climate change: The Investment Perspective.
European Commission, 2018. A Clean Planet for All: A European Long-Term Strategic Vision for a Prosperous, Modern, Competitive and Climate-Neutral Economy.
Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, 2019. Kommission Wachstum, Strukturwandel und Beschäftigung: Abschlussbericht. Berlin.
Forum Ökologisch-Soziale Marktwirtschaft, 2019. Lenkungs- und Verteilungswirkungen einer klimaschutzorientierten Reform der Energiesteuern, on behalf of the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety.
Fraunhofer Institute for Solar Energy Systems, 2018. Stromgestehungskosten Erneuerbare Energien.
German Bundestag, 2018. Ausarbeitung: Stilllegung von Kohlekraftwerken.
German Government, 2020. Bundesregierung | Aktuelles | Bund und Länder einigen sich auf Stilllegungspfad zum Kohleausstieg [WWW Document]. URL https://www.bundesregierung.de/breg-de/aktuelles/einigung-zum-kohleausstieg-1712888 (accessed 1.27.20).
Griffin, P.A., Jaffe, A.M., Lont, D.H., Dominguez-Faus, R., 2015. Science and the Stock Market: Investors' Recognition of Unburnable Carbon. Energy Economics 52, 1–12. https://doi.org/10.1016/j.eneco.2015.08.028

Heinrichs, H.U., Schumann, D., Vögele, S., Biß, K.H., Shamon, H., Markewitz, P., Többen, J., Gillessen, B., Gotzens, F., Ernst, A., 2017. Integrated Assessment of a Phase-Out of Coal-Fired Power Plants in Germany. Energy 126, 285–305. https://doi.org/10.1016/j.energy.2017.03.017
HSBC Global Research, 2013. Oil & Carbon Revisited: Value at Risk from 'Unburnable' Reserves.
HSBC Global Research, 2012. Coal and Carbon-Stranded Assets: Assessing the Risk.
Institut für Protest- und Bewegungsforschung, 2019. Fridays for Future: Profil, Entstehung und Perspektiven der Protestbewegung in Deutschland.
Institute for Climate Protection, Energy and Mobility, 2018. Stellungnahme zum Gutachten der Kanzlei „Redeker Sellner Dahs" für den Deutschen BraunkohlenIndustrieverein (Debriv).
Institutional Investors Group on Climate Change, 2015. Open Letter to Finance Ministers in the Group of Seven (G7).
International Energy Agency, 2018. World Energy Outlook 2018. Paris.
International Renewable Energy Agency, 2017. Stranded Assets and Renewables - How the Energy Transition Affects the Value of Energy Reserves, Buildings and Capital Stock.
IPCC, 2018. Special Report: Global Warming of 1.5°.
Jewell, J., Vinichenko, V., Nacke, L., Cherp, A., 2019. Prospects for Powering Past Coal. Nat. Clim. Chang. 9, 592–597. https://doi.org/10.1038/s41558-019-0509-6
Kepler Cheuvreux, 2014. Stranded Assets, Fossilised Revenues.
Krause, F., Bach, W., Koomey, J., 1989. Energy Policy in the Greenhouse. International Project for Sustainable Energy Paths.
Leipprand, A., Flachsland, C., 2018. Regime Destabilization in Energy Transitions: The German Debate on the Future of Coal. Energy Research & Social Science 40, 190–204. https://doi.org/10.1016/j.erss.2018.02.004
Markard, J., 2018. The Next Phase of the Energy Transition and its Implications for Research and Policy. Nat Energy 3, 628–633. https://doi.org/10.1038/s41560-018-0171-7
Meinshausen, M., Meinshausen, N., Hare, W., Raper, S.C.B., Frieler, K., Knutti, R., Frame, D.J., Allen, M.R., 2009. Greenhouse Gas Emission Targets for Limiting Global Warming to 2°C. Nature 458, 1158–1162. https://doi.org/10.1038/nature08017
Mercer Investment Consulting, 2015. Investing in a Time of Climate Change.
Mercure, J.-F., Pollitt, H., Viñuales, J.E., Edwards, N.R., Holden, P.B., Chewpreecha, U., Salas, P., Sognnaes, I., Lam, A., Knobloch, F., 2018. Macroeconomic Impact of Stranded Fossil Fuel Assets. Nature Climate Change 8, 588. https://doi.org/10.1038/s41558-018-0182-1
Michaels, R.J., 1994. Unused and Useless: The Strange Economics of Stranded Investment. The Electricity Journal 7, 12–22. https://doi.org/10.1016/1040-6190(94)90054-X
Monasterolo, I., Roventini, A., Foxon, T.J., 2019. Uncertainty of Climate Policies and Implications for Economics and Finance: An Evolutionary Economics Approach. Ecological Economics 163, 177–182. https://doi.org/10.1016/j.ecolecon.2019.05.012
Pahle, M., 2010. Germany's Dash for Coal: Exploring Drivers and Factors. Energy Policy 38, 3431–3442. https://doi.org/10.1016/j.enpol.2010.02.017
Rentier, G., Lelieveldt, H., Kramer, G.J., 2019. Varieties of Coal-Fired Power Phase-Out Across Europe. Energy Policy 132, 620–632. https://doi.org/10.1016/j.enpol.2019.05.042
Rinscheid, A., Wüstenhagen, R., 2019. Germany's Decision to Phase-out Coal by 2038 Lags Behind Citizens' Timing Preferences. Nature Energy 4, 1–8. https://doi.org/10.1038/s41560-019-0460-9
Sen, S., von Schickfus, M.-T., 2018. Climate Policy, Stranded Assets, and Investors' Expectations. Journal of Environmental Economics and Management 102–277. https://doi.org/10.1016/j.jeem.2019.102277
Silver, N., 2017. Blindness to Risk: Why Institutional Investors Ignore the Risk of Stranded Assets. Journal of Sustainable Finance & Investment 7, 99–113. https://doi.org/10.1080/20430795.2016.1207996
Steitz, C., Eckert, V., 2019. Coal Compensation Talks With Government Driven by Facts: RWE CEO [WWW Document]. Reuters. URL https://www.reuters.com/article/us-rwe-results-coal-idUSKCN1V40TT (accessed 9.30.19).
The Economist Intelligence Unit, 2015. The Cost of Inaction: Recognising the Value at Risk from Climate Change.
UBS, 2016. Stranded Assets: What Lies Beneath?
Umweltbundesamt, 2019. Energiebedingte Emissionen [WWW Document]. URL https://www.umweltbundesamt.de/daten/energie/energiebedingte-emissionen (accessed 10.16.19).
UNFCCC, 2015. Summary of the Paris Agreement [WWW Document]. URL https://unfccc.int/resource/bigpicture/ (accessed 6.13.19).
van der Ploeg, F., Rezai, A., 2019. The Risk of Policy Tipping and Stranded Carbon Assets. Journal of Environmental Economics and Management 102–258. https://doi.org/10.1016/j.jeem.2019.102258
World Resources Institute, UNEP Finance Initiative, 2016. Carbon Asset Risk Discussion Framework.
Zhao, S., Alexandroff, A., 2019. Current and Future Struggles to Eliminate Coal. Energy Policy 129, 511–520. https://doi.org/10.1016/j.enpol.2019.02.031

A Appendix

A.1.1 Sensitivity Analysis of the Base Load

Parameter	DCAS Hard Coal	Lignite	MCAS Hard Coal	Lignite	EPAS Hard Coal	Lignite
Minimum	-5.76	8.79	-2.64	2.39	-4.29	-3.32
Maximum	-4.60	13.18	-1.43	5.52	-2.80	-1.28
Mean	-5.18	11.00	-2.03	4.00	-3.64	-2.33
Range	1.16	4.39	1.20	3.13	1.49	2.04
VaR (α=0.05)	-5.41	9.73	-2.25	3.08	-3.88	-2.82
VaR (α=0.01)	-5.50	9.37	-2.35	2.81	-3.99	-2.99
STDEV	0.14	0.76	0.14	0.53	0.15	0.30
Rel. STDEV	0.0263	0.0693	0.0679	0.1320	0.0414	0.1291

We refer to the different scenarios by Delaying Climate Action Scenario (DCAS), Maintaining Climate Action Scenario (MCAS), and Enforcing Paris Agreement Scenario (EPAS). We denote VaR as the Value-at-Risk and STDEV as standard deviation. Numbers are in billion €.

Table 6: Summary statistics of hard coal and lignite using the mean base load assumption.

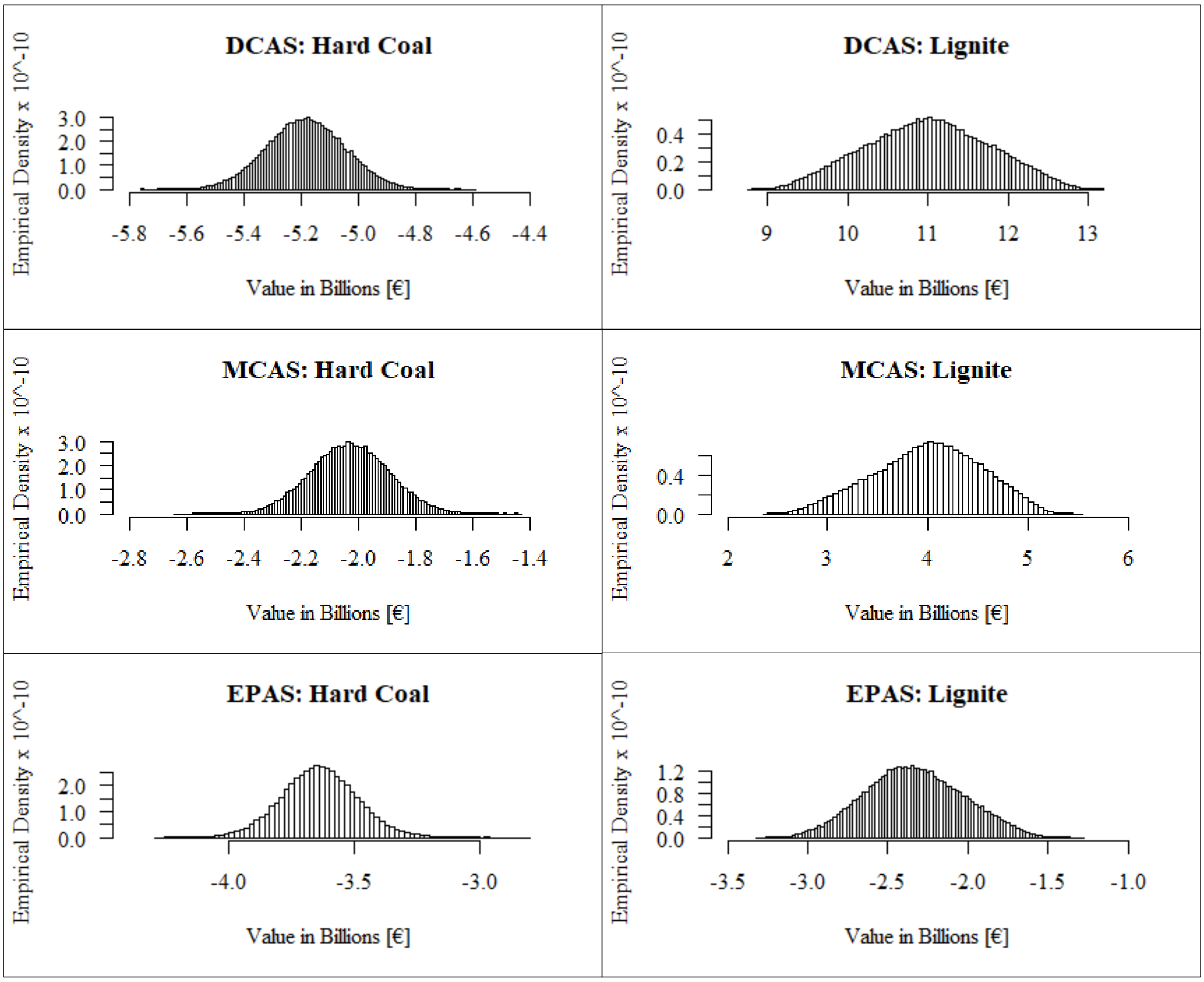


Figure 8: Distributions for each technology in each scenario using the mean base load assumption.

Parameter	DCAS Hard Coal	Lignite	MCAS Hard Coal	Lignite	EPAS Hard Coal	Lignite
Minimum	-5.23	4.76	-1.27	1.11	-4.16	-2.55
Maximum	-3.88	8.50	0.17	3.87	-2.31	-0.05
Mean	-4.59	6.66	-0.59	2.52	-3.31	-1.28
Range	1.35	3.73	1.43	2.76	1.85	2.50
VaR (α=0.05)	-4.85	5.59	-0.86	1.77	-3.59	-1.80
VaR (α=0.01)	-4.96	5.29	-0.97	1.54	-3.71	-1.98
STDEV	0.16	0.64	0.17	0.45	0.17	0.32
Rel. STDEV	0.0354	0.0961	0.2817	0.1794	0.0522	0.2472

We refer to the different scenarios by Delaying Climate Action Scenario (DCAS), Maintaining Climate Action Scenario (MCAS), and Enforcing Paris Agreement Scenario (EPAS). We denote VaR as the Value-at-Risk and STDEV as standard deviation. Numbers are in billion €.

Table 7: Summary statistics of hard coal and lignite using the lower limit base load assumption.

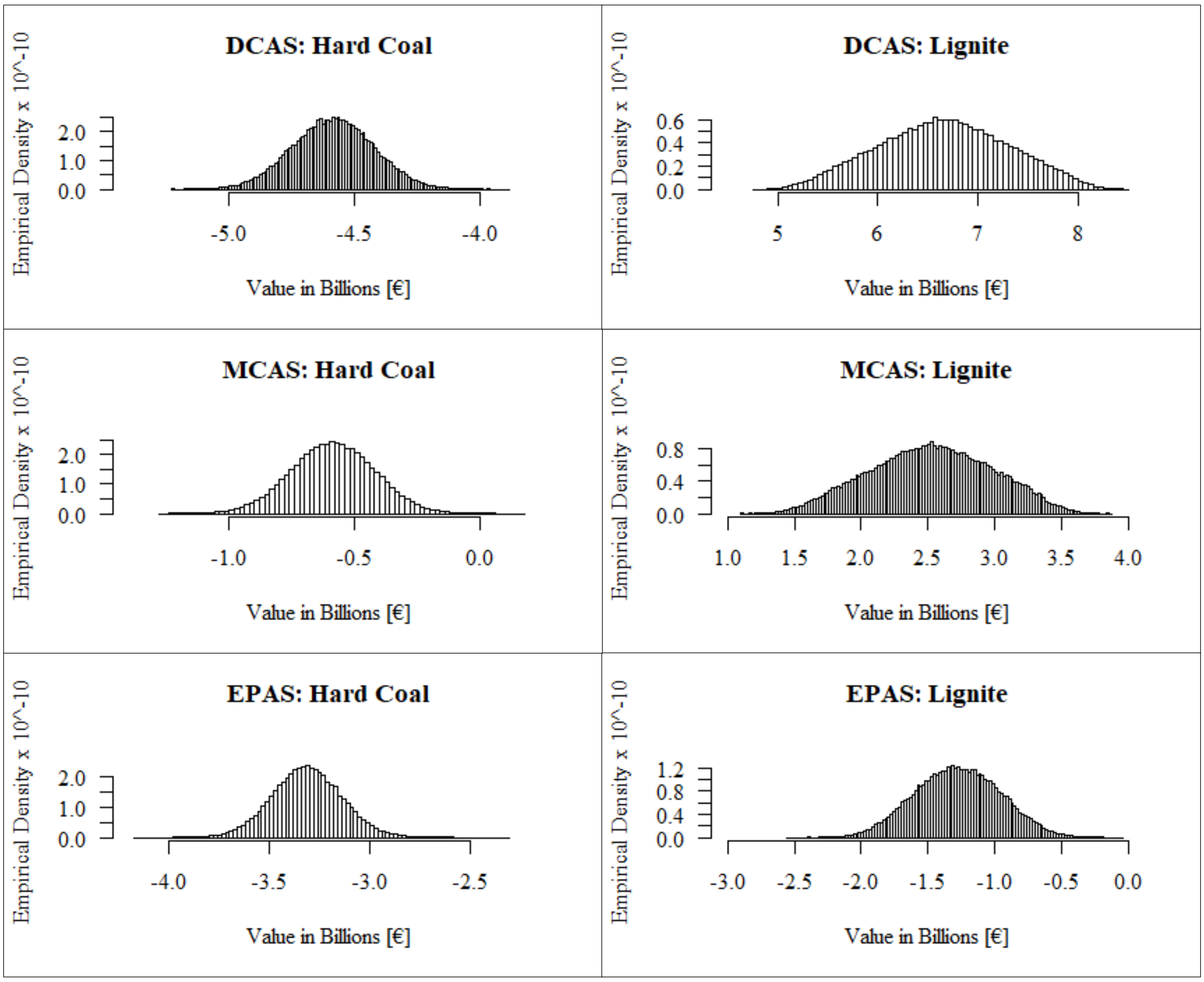


Figure 9: Distributions for each technology in each scenario using the lower limit base load assumption.

Parameter	DCAS Hard Coal	Lignite	MCAS Hard Coal	Lignite	EPAS Hard Coal	Lignite
Minimum	-5.86	5.21	-2.66	1.23	-4.79	-3.86
Maximum	-2.87	16.30	0.10	12.24	-2.45	0.88
Mean	-4.74	11.27	-1.67	5.92	-3.62	-1.68
Range	2.99	11.09	2.76	11.01	2.34	4.74
VaR (α=0.05)	-5.35	8.50	-2.17	2.85	-4.10	-2.91
VaR (α=0.01)	-5.52	7.20	-2.31	2.30	-4.31	-3.23
STDEV	0.45	1.46	0.36	2.53	0.27	0.79
Rel. STDEV	0.0956	0.1291	0.2163	0.4266	0.0754	0.4741

We refer to the different scenarios by Delaying Climate Action Scenario (DCAS), Maintaining Climate Action Scenario (MCAS), and Enforcing Paris Agreement Scenario (EPAS). We denote VaR as the Value-at-Risk and STDEV as standard deviation. Numbers are in billion €.

Table 8: Summary statistics of hard coal and lignite using the stochastic base load assumption.

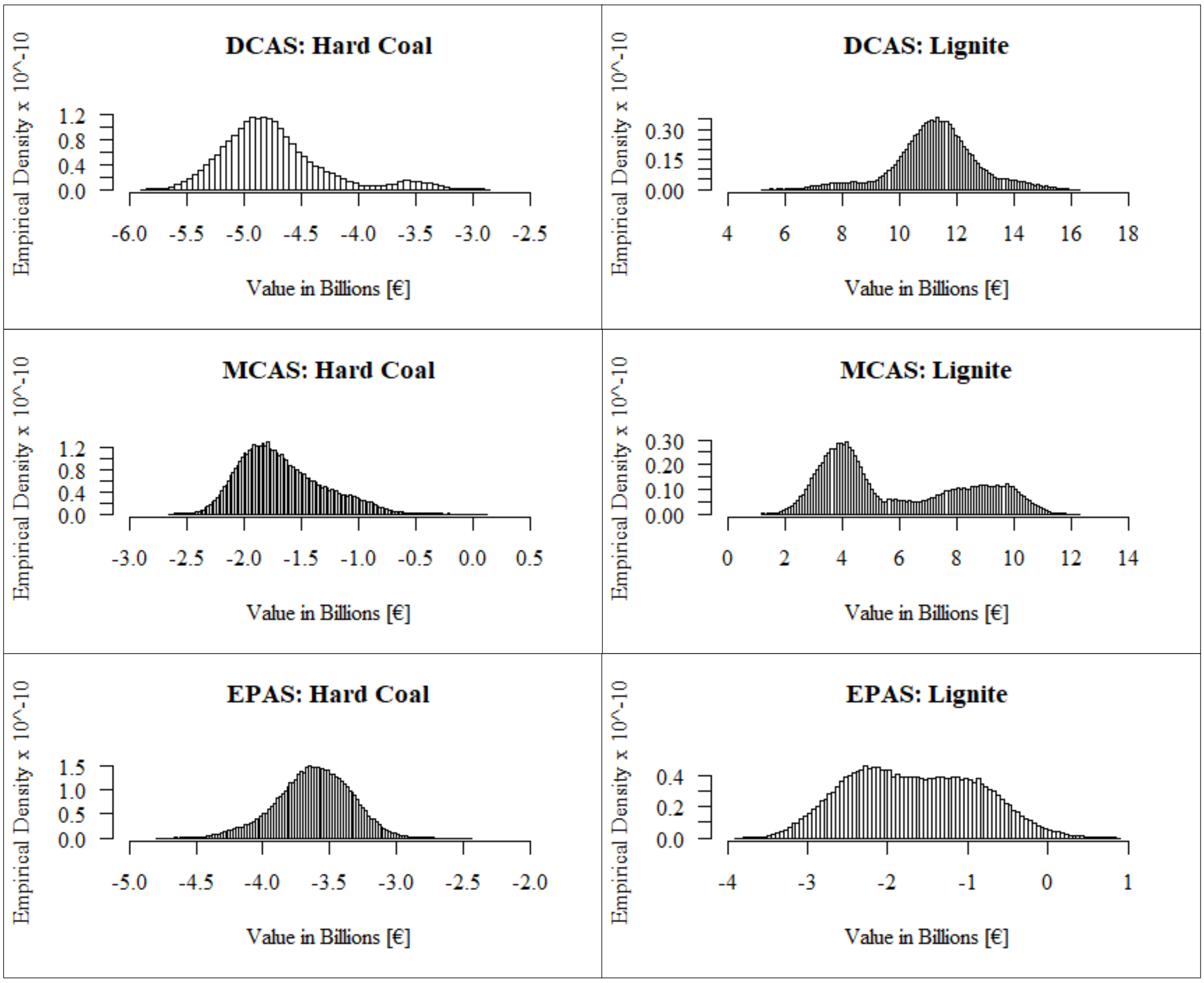


Figure 10: Distributions for each technology in each scenario using the stochastic base load assumption.

Baseload	DCAS	MCAS	EPAS
Stochastic	0.4272	0.4965	0.2196
Lower Limit	0.1046	0.2367	0.4930
Mean	0.1451	0.1182	0.1258
Upper Limit	0.2474	0.2838	0.3219

We refer to the different scenarios by Delaying Climate Action Scenario (DCAS), Maintaining Climate Action Scenario (MCAS), and Enforcing Paris Agreement Scenario (EPAS).

Table 9: Correlation of hard coal and lignite across the used baseload analyses.

A.1.2 Financial Market Implications

Company	Power Plants	Capacity [MW]	Share of Capacity [%]	Shares Outstanding [Mio.]
Lignite				
RWE AG	19	9273.00	49.02	614.75
LEAG AG	12	7127.00	37.67	-
Uniper AG	2	900.00	4.76	365.96
EnBW AG	1	875.00	4.63	-
Others	20	742.52	3.93	-
Hard Coal				
EnBW AG	8	3091.60	14.48	-
Uniper AG	6	2902.00	13.59	365.96
RWE AG	4	2888.70	13.53	614.75
Vattenfall AB	9	2831.00	13.26	-
STEAG GmbH	5	1934.00	9.06	-
ENGIE SA	3	1553.00	7.27	2435.28
LEAG AG	1	690.00	3.23	-
Others	37	5458.89	25.57	-

Capacity values and power plant ownership based on the power plant list as of March 2019.

Source: Own presentation based on Bloomberg (2019) and Bundesnetzagentur (2019).

Table 10: Percentages of hard coal or lignite capacity share.

Supplementary Material

A Determination of Input Parameters and Collection of Data

Within this study, the scenario analysis makes use of prospective input parameters that have impact upon future cash flows and the net present value assessment. The screening of the required input variables is further broken down to the parameters that are assumed and altered for the different scenarios. These input factors are either direct components of the cash flow calculation or serve as preceding parameters for further calculations of parameters that eventually enter the cash flow calculation. The order of the following input variables is approximating a chronological sequence as required for the discounted cash flow model.

A.1 Residual Load Composition

Crucial for the construction of the scenarios, or more precisely of the base and peak load prices model, is the estimation of the residual load with its installed capacities for all relevant energy sources. The residual load describes the electricity demand once fluctuating renewable energy sources from wind, solar, and water power plants are fed-in and must be covered by regulatable power plants (Umweltbundesamt, 2015, p. 38). Biomass is not included within the volatile renewable energy sources due to its good controllability (Umweltbundesamt, 2015, p. 40).

The year 2018, again, is the base year for the constant assumption of the residual base and peak load in Germany. The base load in Germany amounts to around 44.70 GW and is used as a constant throughout the years (European Network of Transmission System Operators for Electricity, 2019). The demand for base load is covered by nuclear and lignite power plants, which – due to technical inflexibility – are designed to continually operate. Further, biomass is considered as a base load power plant technology. Base load power plants run at least 7000 hours per year. The mid load comprises hard coal and gas power plants, which run between 2000 and 7000 hours a year, while the peak load comprises gas, oil, and pump-storage power plants that run less than 2000 hours per year (Büro für Technikfolgenabschaetzung beim Deutschen Bundestag, 2012, pp. 23, 30; Umweltbundesamt, 2015, p. 51). The peak load, more specifically the maximum load, is at 78.8 GW.[2] However, the peak load is seldom demanded and therefore extended by the year-average demand of 61.5 GW of installed capacity. The year-average load is used to approximate the power plant that determines the average peak load price

[2] The estimation of the mid load for the scenarios is negligible due to the remuneration of mid load electricity production with the peak load day-ahead price.

across the scenarios (European Network of Transmission System Operators for Electricity, 2019).

A.2 Installed Capacities

This chapter addresses the installed capacities, which is the fundamental assumption all scenarios are grounded on. The installed capacity concerns firstly, hard coal and lignite power plants, as well as the determination of the installed capacities for biomass, nuclear and gas power plants. All estimates concern the capacity installed at the end of each year.

All scenarios are based on the reconstruction of the 2018 installed capacity reported by the Bundesnetzagentur (2019). The installed capacity of 18.9 GW lignite power plants is achieved by selecting lignite as the primary fuel and the operation mode status as of the end of 2018. Since this scenario analysis only takes power plants into account that are active energy generators, security operation mode, temporary closure, prohibition of decommissioning prescribed by law states are neglected. The installed capacity of 21.4 GW of hard coal power plants is achieved in the same manner. This totals 127 coal power plants in Germany as of the end of 2018.

Within EPAS, emissions from the coal power generation sector must decrease by 100 percent until 2030 compared to 2017 levels (Climate Analytics, 2018, p. 7). These percentage reductions can be transferred to the installed capacity of hard coal and lignite assuming a linear and equally weighted decrease until 2030.

MCAS follows the proposal by the Coal Commission to reduce the installed capacity down to 15 GW for both, hard coal and lignite power plants, by 2022. By 2030, the installed capacity of hard coal power plants amounts to 8 GW and of lignite power plants to 9 GW. The single reduction steps for each year are assumed to be linear.

DCAS relies on the previously described installed capacity of power plants using data by the Bundesnetzagentur (2019). In order to assess the natural phase-out of coal-fired electricity generation, the technical lifetime of hard coal and lignite power plants is required. A study by Marketwitz et al. (2018, p. 15) investigates the lifetime of coal-fired power plants indicating a lifetime between 40 and 45 years for the two technologies. The subsequent annual decrease in installed capacity is thus based on the average lifetime of 41 years for hard coal and 45 years for lignite power plants in Germany (Carbon Brief, 2019; Jewell et al., 2019, p. 595). Power plants' decommissioning dates are assumed to retire before the end of each year so that the end-of-year installed capacity fully considers the decommissioning of those installed capacities. Thus, the last power plant in DCAS eventually decommissions in 2061. A further detailed overview on the reduction of the installed capacities of hard coal and lignite is in Chapter A.2.

Currently, there is one hard coal power plant, Datteln 4, in pre-commissioning status, which eventually starts operation in 2020.[3] The 1.1 GW installed capacity of the power plant is included within all scenarios but is adjusted to the reduction in capacity.

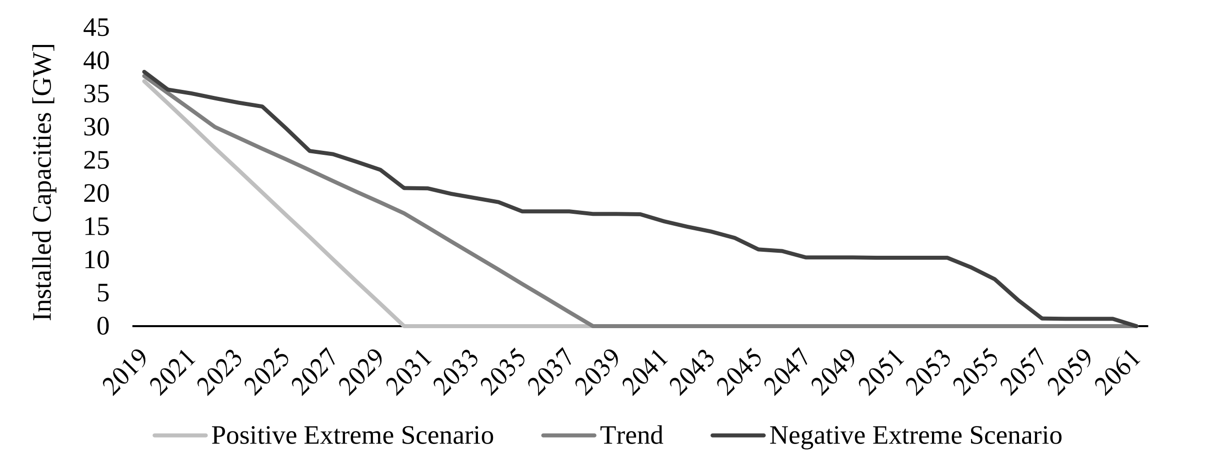


Figure 1: Development of installed capacities of hard coal and lignite combined.

Other installed capacities regarding the electricity production from biomass, nuclear, and gas power plants are furthermore required in order to determine the base load and peak load prices for each year of the developed scenarios. First, biomass shows an installed capacity of 7.7 GW in 2018 (Fraunhofer Institute for Solar Energy Systems, 2018a). This installed capacity is assumed to be constant throughout all years of the scenarios. Nuclear power plants still account for nearly 10 GW of installed capacity and gradual decommissioning of those power plants continues until the end of 2022 (Bundesnetzagentur, 2019; Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, 2019a). Gas turbines cover mid and peak load due to the higher marginal costs. Gas power plants can be further subdivided into high-efficient gas turbines and combined cycle gas turbine. The installed capacity of 6 GW for gas turbines is assumed to be constant throughout the scenario analysis for all scenarios. Concerning the topic of dark doldrums, a time of lacking feed-in of fluctuation renewable energy sources, the future residual load cannot be covered by batteries and therefore requires

[3] However, the current debate in Germany also puts the actual commissioning into question. This study relies on the legal immission protection license issued by the District Government in Muenster and the statements by the plant operator Uniper that the operation is scheduled for 2020 (District Government Muenster, 2017, p. 6; Reuters, 2018).

to be covered by gas power plants (Hauser et al., 2018, p. 446). Since combined cycle gas turbines present the most cost-efficient way of covering dark doldrums, it is determined as the remaining load once nuclear, biomass, hard coal, lignite, and gas turbine capacities are subtracted from the residual peak load (Energiewirtschaftliches Institut an der Universität zu Köln, 2017, p. 8).

These installed capacities of these crucial base load power plants are necessary to identify the price-determining plant technology for the base and peak load prices.

A.3 Marginal Cost Components

In order to determine the merit order of the power plant portfolio and estimate the overall costs, each technology is assigned with its marginal costs. The following formula refers to the calculation by the Forschungsstelle für Energiewirtschaft (2010):

$$c_{Marginal} = \frac{c_{Fuel}}{\eta} + c_{Certificate} \times \frac{ef}{\eta} + c_{Variable} \tag{1}$$

The in Equation (1) presented calculation of marginal costs comprises three components. First, fuel-specific sale costs c_{Fuel} are estimated in €/MWh_{th} for each technology and further divided by the efficiency ratio η to determine the required fuel price in €/MWh_{el}. Second, the certificate costs $c_{Certificate}$ in €/ton are adjusted with the emission factor ef of each technology in ton/MWh_{th} and subsequently divided by the efficiency rate η. The variable costs $c_{Variable}$ are the third component of the marginal costs and are expressed in €/MWh_{el}. The three single cost types added up present the marginal costs for each technology.

These costs are estimated for four power plant types, namely hard coal, lignite, combined cycle gas turbines, and gas turbines. The marginal costs of uranium, non-fluctuating renewable energy sources, and oil power plants are not included in the modeling. Uranium and non-fluctuating renewable energy sources both exhibit lower marginal prices and are therefore listed first within the merit order model. Therefore, they do not set the market clearing price(Association of German Chambers of Commerce and Industry, 2017, p. 10). However, a specific assessment is needed for hard coal and lignite, but also two types of gas power plants, namely combined cycle and gas turbine power plants. This requires fuel and carbon prices but also additional variable costs. Moreover, efficiency ratios and the carbon dioxide emissions of each installed capacity are determined for all scenarios.

A.3.1 Fuel Costs

The choice of hard coal and gas follows the International Energy Agency (2018). The comprehensive study established three different price paths that closely match the chosen scenarios. Thereby, the estimates for DCAS are taken from the Current Policies Scenario, estimates for MCAS from the New Policies Scenario and estimates for EPAS from the Sustainable Development Scenario (International Energy Agency, 2018, p. 602). The data displays that the more the electricity generation depends on fossil energy sources, the higher is the increase in prices of hard coal and lignite resources. The scenarios forecast prices for the years 2025, 2030, 2035, and 2040. In order to prevent abrupt changes, the years in between are adjusted by the Compound Annual Growth Rate (CAGR). The data is provided in 2017 price levels and therefore adjusted for inflation. The data is based on conversion data, which is visualized in Section B.4.2.

Lignite is not included within the study by the International Energy Agency (2018), since there are no fuel prices for lignite. As a result, lignite prices are composed of extraction costs that are not expected to considerably increase in the future (Pahle, 2010, p. 3435). Data is retrieved from the Fraunhofer Institute for Solar Energy Systems (2018b, p. 14). The price for lignite, 1.83 €/MWh, remains constant throughout all years across the different scenarios.[4]

A.3.2 Carbon Costs

The price of European Union (EU) ETS allowances and possibly also taxes on carbon emissions greatly determine the development of the power plant and mining sector imposing pressure on the profitability. The EU ETS is a so-called ‘cap and trade’ system, where industrial emissions must be covered by emissions allowance certificates. The aim of this system is to constantly reduce the number of available allowances and increase the market price of traded ETS allowances (European Environment Agency, 2018, pp. 5–6). Within its third phase, allowances are distributed through an exclusively auction-based system and allowances must be purchased (Hobbie et al., 2019, p. 2). The emission allowances price for 2018 is at an average of 15.80 €/t emitted carbon (European Energy Exchange, 2019). The allowances price has increased from around 5 € in 2017 to over 20 € in 2018 indicating a further increase for the following years, especially within the fourth trading phase (Potsdam Institute for Climate Impact Research, 2018, p. 5). The price of carbon dioxide emission allowances must be adjusted to DCAS and

[4] This value is adjusted by the inflation rate for the year 2019 (Federal Statistical Office, 2019a).

MCAS, even though data on this development is rare due to uncertainty regarding the fourth phase. The fuel prices are estimated exogenously by the Potsdam Institute for Climate Impact Research (2019, p. 3) and assumes prices until 2050. Certificate prices increase sharper for MCAS, up to 87 €/t, than for DCAS, where a price of 80 €/t is reached by 2050.

Carbon taxes are currently employed in several European countries. However, the levels of taxes range from around 5 €/t in Latvia and Estonia to 44.60 €/t in France and over 60 €/t of emitted carbon in Finland. The highest carbon taxes of 139 $/t in the world are found in Sweden (World Bank, 2018, pp. 17, 27). These comparative figures show a wide range of a possible carbon tax for Germany. Within the scenario analysis, DCAS and MCAS do not consider a carbon tax for Germany. EPAS includes the most recent proposal on behalf of the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, which has launched several studies focusing on the implementation of a carbon tax. The carbon tax is supposed to be introduced in 2020 with a price of 35 €/t increasing to 180 €/t by 2030 (Forum Ökologisch-Soziale Marktwirtschaft, 2019, p. 5). The carbon taxation replaces the emissions trading system since a carbon tax is costlier than the developments of the certificates.

The discrete price assumptions are adjusted using CAGR for the years in between.

A.3.3 Other Variable Costs

Material and waste material cost data is retracted from the comprehensive cost assessment employed by Konstantin (2013). Considering the inflated value for 2018, these costs are at 1.39 € per megawatt hour (MWh) for hard coal and 1.76 €/MWh for lignite power plants. As gas turbines and combined cycle gas turbines require additional costs for the gas turbines, the variable costs amount to 3.75 €/MWh for gas turbines and 5.89 €/MWh for combined cycle gas turbine.[5]

A.4 Fixed Costs

As mentioned previously, fixed costs comprise personnel, maintenance, insurance, minor and major inspection costs (Büro für Energiewirtschaft und technische Planung, 2018, p. 21; Oeko-Institut, 2017, p. 104). The fixed costs for German lignite power plants range between 40 and 62.50 € per kilowatt (kW) of installed capacity in 2015. The fixed costs or German hard coal

[5] The inflation rate for the years 2014 through 2019 was at 1.0, 0.5, 0.5, 1.5, 1.8 and 1.56 respectively (Federal Statistical Office, 2019b, 2019a).

power plants range from 40 to 90 €/kW installed capacity for the year 2018 (Büro für Energiewirtschaft und technische Planung, 2018, pp. 25–29).[6]

In order to more precisely display fixed costs within the total number of power plants, the cost ranges for lignite and hard coal power plants are adjusted regarding the age of each power plant unit. For the assessment, hard coal and lignite power plants receive averaged fixed costs depending on whether it is classified as a 'modern' or 'old' power plant unit. For lignite, units built before 1990 report fixed costs of 60 €/kW and more recently built power plant units report average fixed costs of 41 €/kW (base year 2015) (Oeko-Institut, 2017, p. 104).6 This leads to fixed costs of 53.50 €/kW averaged over the installed capacity of each unit in 2019. This finding is similar to data assumed within other studies that assume yearly fixed costs (Energy Brainpool and Greenpeace Nordic, 2015). For hard coal, the procedure is similar, with a fixed cost range for old power plants between 45 and 90 €/kW, and new plants between 40 and 55 €/kW of installed capacity (base year 2018) (Büro für Energiewirtschaft und technische Planung, 2018, pp. 25–29). Assigning each power plant unit with the mean of these ranges the averaged fixed costs for hard coal power plant are at 59.80 €/kW for 2019. Across all scenarios, these fixed costs remain unchanged except for alterations caused by the fleet composition. The more old power plants are decommissioned, the lower are the averaged fixed costs. More detailed information is found in Chapter B.3.

A.5 Full-Load Hours

The determination of the 2018 full-load hours for hard coal and lignite is the result of the electricity production 2018 divided by the installed capacity for 2018 (cf. Chapter A.2). The data on German hard coal and lignite electricity production is provided by the Fraunhofer Institute for Solar Energy Systems (2018c). As there is no average full-load hour estimation for German power plants in 2018, this calculated input parameter remains unchanged for all scenarios to reflect long-term contracting as a hedging instrument of energy suppliers. Hard coal receives full-load hours of 3387.5 hours/year, lignite receives substantially higher full-load hours of 6951.2 hours/year. However, if the clean dark spread turns negative for either hard coal or lignite, the full-load hours decrease linearly to zero, where the clean dark spread is at -15 €/MWh for hard coal or at -30 €/MWh for lignite. If the spread turns negative but does not subsequently fall below this lower limit, it continuously decreases by 50 percent. Further

[6] These values are adjusted by the inflation rate for the years 2016 through 2019 (Federal Statistical Office, 2019b, 2019a).

assuming a change within the merit order, full-load hours are also reduced for lignite to 3000 hours/year, if lignite covers the peak load. The chosen full-load hours comply with the specified mid and peak load hours in Chapter A.1. Section B.5.2 provides further information of the clean dark and spark spreads.

A.6 Capital Expenditures

Capital expenditures exclude maintenance payments, which are already included within the fixed costs as pointe out in Chapter A.4. Since all scenarios do not assume further investments in coal and lignite power plants, capital expenditures are only indirectly required in order to determine the depreciation levels for all years. Therefore, a capital expenditure of 1300 €/kW of installed capacity is assumed for hard coal and 1600 €/kW is assumed for lignite (2018 base year) (Fraunhofer Institute for Solar Energy Systems, 2018b, p. 10). Concerning Datteln 4, the power plant has been under construction for over 10 years and therefore all investment costs lie in the past (Reuters, 2018).

A.7 Depreciation

Depreciation is first based on the assumption of a capital expenditure and second the assumption that hard coal and lignite power plants are depreciated over a period of 20 years (Arrhenius Institut für Energie- und Klimapolitik, 2009, p. 7). Therefore, all power plants put into operation from 2000 onwards, are included in the depreciation assessment. This sums up to 15 hard coal power plants around 8 GW of installed capacity and 10 lignite power plants around 5.6 GW of installed capacity. The procedure of depreciation assessment includes adjustments, if the coal-phase out is scheduled for 2038 or 2030 as supposed within MCAS and EPAS. The depreciation period of 20 years, and therefore operation period, is minimized in order to match the coal-phase out plan. While doing so, the installed capacity of each year according to the capacity reduction must considered carefully, since a shift forward can imply an exceedance of the intended capacity. This assumption is in accordance with the phase-out based on the power plant age structure, which is discussed in Chapter B.3. Specifications on the depreciation data is found in Chapter B.6.

A.8 Taxes

The earnings resulting from the coal power generation business are reduced by corporate and trade taxes (Konstantin, 2013, pp. 161–162). In Germany, the overall corporate tax of 29.80%

is applied to the EBIT (Federal Ministry of Finance, 2019, p. 18). The taxes remain constant for all scenarios. However, if the EBIT turns negative, no taxes are considered.

A.9 Discount Rate

The interest rate is an essential parameter for the subsequent calculation of the NPV. The most recent weighted average cost of capital (WACC) is used to discount future cashflows from both expected returns on equity and debt capital. More specifically, the real WACC is chosen for discounting, because all data is already adjusted for inflation. The Fraunhofer Institute for Solar Energy Systems (2018c) provides an average WACC of 5.6% for both, hard coal and lignite industries.

A.10 Discounted Cash Flow Model

The choice of model employed for estimating he value of the coal power generation industry is the explicit DCF model. The DCF model determines the present value of the future cash flow generated and thereby makes assumptions to substantiate the valuation according to specific perceptions and expectations of an investor. Those assumptions are considered explicitly within the input factors. It therefore allows further highlights differences by assuming explicit factors and is best suited for adjustments made within the different scenarios (French, 2006, pp. 176–179). The DCF model is composed of two steps. First, the unleveraged free cash flows for all years are calculated. Using the weighted average capital costs (WACC) method, those free cash flows are then discounted to estimate the net present value with leverage. Thereby, the WACC already implicitly comprises the tax advantage and interest payments of debt capital by including debt capital in the calculation of the WACC (Berk and DeMarzo, 2019, pp. 636–638, 651).

The calculation of free cash flows is first based on Berk and DeMarzo (2019, p. 260). First, the Earnings Before Interests and Taxes (EBIT) must be estimated for each year beginning in 2019 and ending in 2061. The free cash flow calculation following Berk and DeMarzo (2019) first determines the Earnings Before Interest, Taxes, Depreciation, and Amortization (EBITDA) by reducing the revenues generated by the operating costs. Further, depreciation and amortization lower the earnings and estimate the EBIT (Berk and DeMarzo, 2019, p. 639):

$$\text{EBIT}_t = \text{Revenues}_t - \text{Operating Costs}_t - \text{Depreciation}_t \tag{2}$$

The input factors from Formula (2), operating costs, comprising fuel, carbon, other variable and fixed costs, follow the cost structure presented by Konstantin (2013, p. 310). The cost variables and moreover depreciation are in detail described and determined for all years of the scenarios within the previous Part A. Revenues, however, are the output variable of a further complex modelling itself. As power plants receive the base of peak load clearing price on the spot market for the offer of electricity, it is crucial to identify the base and peak load price-determining power plants with regard to the merit order principle. Lignite and hard coal receive consequently receive either of the prices depending on whether they cover base load, peak load or both partially. The merit order, in turn, illustrates the employment sequence of power plant types according to its marginal costs (Association of German Chambers of Commerce and Industry, 2017, p. 10). Figure 2 depicts the modelling procedure of estimating the revenues for all scenarios.

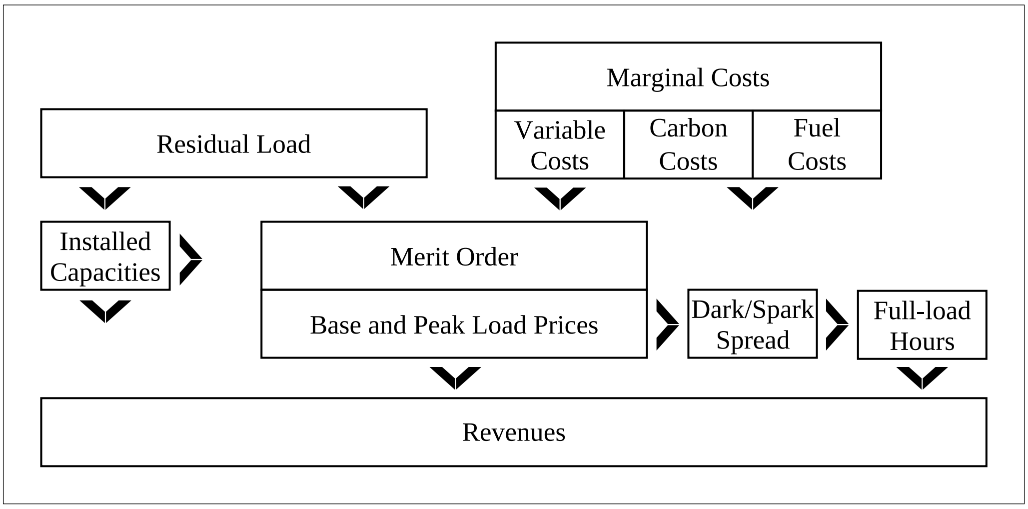


Figure 2: Modelling procedure of the determination of revenues.

The EBIT is then used to assess the amount of taxes as a percentage of the EBIT. Since depreciation is not cash-effective, the EBITDA relies on and is reduced by the cash-effective outflows of taxes and capital expenditures to determine the free cash flow (Berk and DeMarzo, 2019, p. 639):

$$FCF_t = EBITDA_t - Taxes_t - Capital\ Expenditures_t \tag{3}$$

The free cash flows are discounted by the WACC to determine the NPV of the hard coal and lignite industries (Ansar et al., 2013, p. 25):

$$NPV_0\ (T, i_{WACC}) = \sum_{t=1}^{T} \frac{FCF_t}{(1 + i_{WACC})^t} \tag{4}$$

The NPV is the outcome of the DCF model and calculated for all scenarios. An NPV of zero, or even negative numbers, implies that the industry is not or only just able to cover the costs of the lignite and hard coal industry. A positive value indicates profits for the industry within the scenario envisioned (Arnold and Yildiz, 2015, p. 228).

A.11 Monte Carlo Analysis

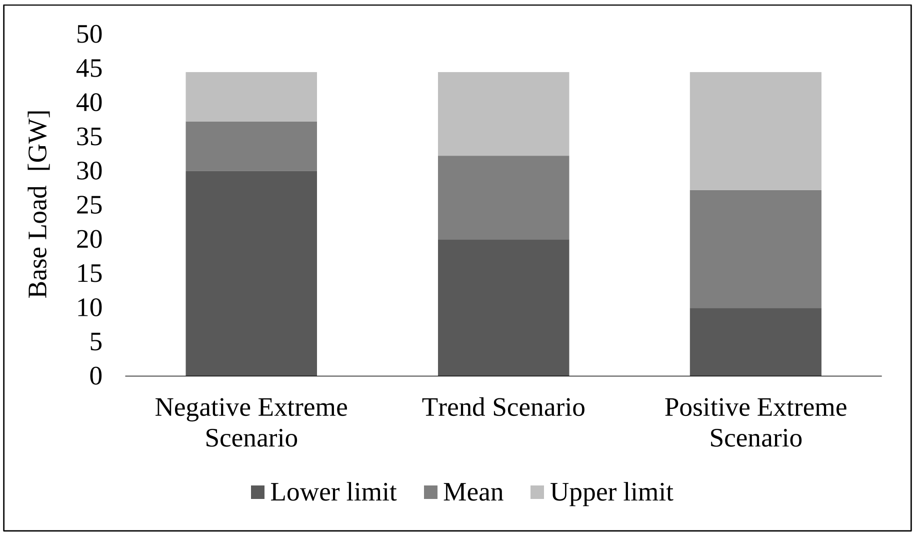
Scenario analyses are grounded upon various assumptions of future developments and, in this case, additionally cover a long-term time horizon. Thus, the scenarios themselves depict a range of potential outcomes or pathways and require further sensitivity and uncertainty analyses to advance the usefulness of the outcomes (World Resources Institute and UNEP Finance Initiative, 2016, p. 38).

The Monte Carlo simulation considers the great uncertainty of variables but also tests the dependent variable for its sensitivity on specific independent variables. The Monte Carlo Simulation is employed after the completion of the scenario analysis. Specific input variables x_i, that are further described in the following, are transferred to a probability density function $\mathrm{pdf}\,(x_i)$ given a specific distribution of the input variable. Hereby, the input variables chosen must be uncorrelated, thus independent, in order to prevent simulation errors. The Monte Carlo simulation then draws a (pseudo-) random number ξ from the interval [0;1] in order to match the interval of the probability density function of the input variable to create a random sample $x_i^\zeta(\xi)$, whereby ζ describes the run number. The random sample is embedded within the already employed deterministic model, which in this case is the DCF model. This procedure applies to several input variables at one and is run various times s with $1 \leq \zeta \leq s$. The deterministic mathematical model calculates the output variable each time and delivers the probability density function $\mathrm{pdf}\,(y_i)$ of the output, therefore dependent, variable y_i (Arnold and Yildiz, 2015, p. 229).

The independent variables are assigned a distribution in order to determine the probability density function $\mathrm{pdf}\,(x_i)$. The assumptions of a distribution are based on literature that demonstrate the uncertainty and ranges of the input variable to be assessed. There are three key uncertainties, which are assessed as part of this Monte Carlo analysis. As the purpose of the Monte Carlo analysis is to more precisely display the regulatory and economic uncertainties within each pathway, the independent variables to be assessed regard future economic and policy assumptions.

A.11.1 Residual Base Load

Due to the increasing installation of and feed-in from fluctuating renewable energy sources, the German residual load composition will experience major changes. Base, mid and peak load become less distinct and the base load may decrease highlighting the need of flexible power plants to replace continuously running base load power plants (Büro für Technikfolgenabschaetzung beim Deutschen Bundestag, 2012, p. 8).



Source: Own presentation based on Umweltbundestamt (2015, p. 56).

Figure 3: Base load assumptions for the Monte Carlo analyses.

Useful literature on this topic is provided by the Umweltbundesamt (2015), who display a forecast of the residual load composition for the year 2030. The previously assumed 44.5 GW of installed base load capacity is to be understood as the upper limit, as increasing installations of volatile renewable energy sources cause a reduction of the residual base load depending on the underlying scenario (Umweltbundesamt, 2015, p. 56). The assumptions of this forecast, which itself is based on the reference scenario by the European Union Commission, are matched with MCAS of this study(European Union Commission, 2013). The base load is assumed to decrease to 20 GW by 2030, which is a constant floor throughout all years. In order to display the implicitly assumed increased feed-in from renewable energy sources within each scenario, EPAS assumed a lower base load floor of 10 GW. Correspondingly, DCAS assumes a floor of 30 GW, thus further closing the gap to the current base load of around 44.5 GW. These upper and lower limits are then used to construct a stochastic, i.e. triangularly distributed, base load in order display the uncertainty. A triangular distribution is selected to amplify the probability of centered values.

As the base load assumed is greatly depend on the expectancy of future renewable energy installations, the Monte Carlo analysis is conducted four times. Thereby, the upper limit serves as the baseline analysis. The base load is then altered using the lower limit, the mean, and the stochastic distribution. The determined base load data or random sample further remains constant for all years of each scenario.

A.11.2 Fuel and Carbon Prices

The carbon prices are determined in Section A.3.2 and follow forecasts that line up with the selected scenarios. However, fuel and carbon prices greatly depend on future economic and regulatory developments, and therefore are sampled from a more complex log-normal distribution. The development of prices is based upon the growth rate between the carbon prices previously determined:

$$P_t = P_{t-1} \times r_t \tag{5}$$

P_t, the price of each fuel or carbon within each year t, is the product of the previous year's fuel price P_{t-1} and the growth rate r_t. For the Monte Carlo analysis, the growth rates are each assigned uncertainty displaying distributions.

The yearly growth rates of the fuel and carbon prices are assigned a normal distribution. The mean value μ is represented by the price paths selected for each scenario. Using daily hard coal and gas future prices from the years 2014 through 2018, the historical growth rates and following, the standard deviation and relative standard deviation are calculated. The futures concern coal and gas historical New York Mercantile Exchange (NYMEX) traded contracts due to its high liquidity and required link to forecasted supranational data from the World Energy Outlook. The relative standard deviation of carbon prices has been determined based on solely the year 2018 to prevent the distortion by statistical outliers due to unbalanced developments caused by phase III of the EU ETS. The relative standard deviation remains constant throughout the scenarios and years so that the standard deviation of the fuel prices rises proportional to the mean prices. The correlations between hard coal and gas fuel prices are also determined, as historic correlations show that the input variables are not independent from one another (Arnold and Yildiz, 2015, p. 229). This estimation reveals a correlation factor of 0.4876, which is applied for DCAS. MCAS receives a correlation factor of 0.2438 and EPAS provides no correlation, as it assumes that the prices are decoupled. Carbon prices are not correlated with fuel prices in this analysis, particularly because they rely on a different underlying data.

As lignite is not publicly traded, it remains constant throughout the years. However, the previously identified lignite price of 1.83 €/MWh receives a stochastic assumption including data published by Osorio et al. (2018, p. 15). Thus, lignite is triangularly distributed between 1.83 €/MWh and 3.65 €/MWh, with 2.74 €/MWh as the mean value.[7]

Data concerning historic distribution parameters as well as correlation of the provided estimations are depicted in Table 13 and Table 14.

B Detailed Scenario Analysis Data

B.1 Inflation

Since inflation is not considered within the scenarios, all data incorporated is on the 2019 prices level. Data prior the year 2019 is adjusted for inflation.

Year	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**
Consumer Price Index	1.1	2.1	2.0	1.4	1.0	0.5	0.5	1.5	1.8	1.56

Numbers are in percent [%]. The 2019 consumer price index is calculated as the average of the months January through July. Source: Federal Statistical Office (2019b, 2019a).

Table 1: Annual inflation for adjustments of future input factors.

B.2 Installed Capacities

Year	**DCAS** Installed Capacity [GW]	[%]	**MCAS** Installed Capacity [GW]	[%]	**EPAS** Installed Capacity [GW]	[%]
2017	46.34	100	46.34	100	46.34	100
2018	40.27	97	40.27	97	40.27	97
2019	38.33	92	37.70	91	36.91	89
2020	35.67	86	35.13	84	33.56	81
2021	35.06	84	32.57	78	30.20	73
2022	34.34	83	30.00	72	26.84	65
2023	33.68	81	28.38	68	23.49	56
2024	33.10	80	26.75	64	20.13	48
2025	29.80	72	25.13	60	16.78	40
2026	26.40	63	23.50	56	13.42	32
2027	25.91	62	21.88	53	10.07	24
2028	24.75	59	20.25	49	6.71	16

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[7] This value is adjusted by the inflation rate for the year 2019 (Federal Statistical Office, 2019a).The inflation rates are attached in **Fehler! Verweisquelle konnte nicht gefunden werden.**.

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2029	23.57	57	18.63	45	3.36	8
2030	20.83	50	17.00	41	0.00	0
2031	20.75	50	14.88	36	0.00	0
2032	19.95	48	12.75	31	0.00	0
2033	19.33	46	10.63	26	0.00	0
2034	18.67	45	8.50	20	0.00	0
2035	17.30	42	6.38	15	0.00	0
2036	17.29	42	4.25	10	0.00	0
2037	17.28	42	2.13	5	0.00	0
2038	16.92	41	0.00	0	0.00	0
2039	16.89	41	0.00	0	0.00	0
2040	16.87	41	0.00	0	0.00	0
2041	15.79	38	0.00	0	0.00	0
2042	15.00	36	0.00	0	0.00	0
2043	14.25	34	0.00	0	0.00	0
2044	13.30	32	0.00	0	0.00	0
2045	11.57	28	0.00	0	0.00	0
2046	11.31	27	0.00	0	0.00	0
2047	10.37	25	0.00	0	0.00	0
2048	10.37	25	0.00	0	0.00	0
2049	10.37	25	0.00	0	0.00	0
2050	10.33	25	0.00	0	0.00	0
2051	10.33	25	0.00	0	0.00	0
2052	10.33	25	0.00	0	0.00	0
2053	10.33	25	0.00	0	0.00	0
2054	8.87	21	0.00	0	0.00	0
2055	7.08	17	0.00	0	0.00	0
2056	3.90	9	0.00	0	0.00	0
2057	1.14	3	0.00	0	0.00	0
2058	1.12	3	0.00	0	0.00	0
2059	1.10	3	0.00	0	0.00	0
2060	1.10	3	0.00	0	0.00	0
2061	0.00	0	0.00	0	0.00	0

Source: Own presentation based on Bundesnetzagentur (2019), Climate Analytics (2018, p. 7), Carbon Brief (2019), and Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (2019b, p. 63).

Table 2: Reduction of installed capacity within each scenario.

B.3 Coal Fleet Structure

Two input variables, fixed costs and the efficiency ratio, display significant differences in level within the age of power plants. As the data on these different amounts of fixed costs and levels of efficiency ratios is available for hard coal and lignite power plants, an adjustment to the age structure increases the accuracy of the actual efficiency ratio and fixed costs of the coal fleet. The available data on current decommissioning dates shows that power plants built before 1990 phase-out before the power plants after 1990 classified as ‘modern’. Therefore, the adjustment of the age structure for the scenarios implies the phase-out according to the age of power plants to approximate the actual phase-out sequence (Oeko-Institut, 2017, p. 104).

Lignite Plant	**Operator**	**Commissioning**	**Scheduled Decommissioning**
Wedel 1	Vattenfall Europe Wärme AG	01.01.1961	2019
G-Kraftwerk	Currenta GmbH & Co. OHG	01.01.1962	2019
Wedel 2	Vattenfall Europe Wärme AG	23.07.1962	2019
Scholven C	Uniper Kraftwerke GmbH	01.01.1968	2019
Reuter C	Vattenfall Wärme Berlin AG	01.01.1969	2019
Scholven B	Uniper Kraftwerke GmbH	01.01.1969	2019
Farge	ENGIE Deutschland AG	01.01.1969	2019
Gemeinschaftskraftwerk Kiel	Gemeinschaftskraftwerk Kiel GmbH	02.10.1970	2019
Kraftwerk N 230	Currenta GmbH & Co. OHG	01.01.1971	2020
Wilhelmshaven	Uniper Kraftwerke GmbH	01.01.1976	2019
KWM	LEAG AG	01.06.1979	2019
KW Hafen	SW Bremen	01.12.1979	2019
Bergkamen	RWE Generation SE	02.07.1981	2019
Modellkraftwerk	STEAG GmbH	15.08.1982	2019
GKM 7	Grosskraftwerk Mannheim AG	01.11.1982	2019
Gersteinwerk	RWE Generation SE	01.06.1984	2020
Zolling	ENGIE Deutschland AG	01.01.1985	2019
Ibbenbüren	RWE Generation SE	19.06.1985	2019
HKW West	Volkswagen AG	01.11.1985	2019
HKW West	Volkswagen AG	01.11.1985	2019
Heizkraftwerk Heilbronn	EnBW Energie Baden-Württemberg AG	01.12.1985	2019
Heyden	Uniper Kraftwerke GmbH	01.01.1987	2019
Reuter West D	Vattenfall Wärme Berlin AG	14.12.1987	2019
KW Walsum 9	STEAG GmbH	01.06.1988	2019
Reuter West E	Vattenfall Wärme Berlin AG	04.08.1988	2019
GKH	enercity AG	26.01.1989	2020
GKH	enercity AG	21.06.1989	2020

KW Herne	STEAG GmbH	25.07.1989	2020
Heizkraftwerk	STEAG GmbH	30.11.1989	2020
Nord 2	SW München	15.12.1991	2022
Staudinger	Uniper Kraftwerke GmbH	01.01.1992	2023
Tiefstack	Vattenfall Hamburg Wärme GmbH	01.03.1993	2024
GKM 8	Grosskraftwerk Mannheim AG	05.04.1993	2024
KNG Kraftwerk Rostock	EnBW Energie Baden-Württemberg AG	01.10.1994	2025
Heizkraftwerk Altbach/Deizisau	EnBW Energie Baden-Württemberg AG	01.01.1997	2028
GKM 6	Grosskraftwerk Mannheim AG	26.12.2005	2036
Trianel Kohlekraftwerk Lünen	Trianel GmbH	01.01.2013	2036
KW Walsum 10	STEAG GmbH	20.12.2013	2036
KW Hastedt	SW Bremen	01.03.2014	2020
Westfalen	RWE Generation SE	02.07.2014	2036
Moorburg B	Vattenfall Heizkraftwerk Moorburg GmbH	28.02.2015	2036
GKM 9	Grosskraftwerk Mannheim AG	02.05.2015	2036
Moorburg A	Vattenfall Heizkraftwerk Moorburg GmbH	31.08.2015	2036
Kraftwerk Wilhelmshaven	ENGIE Deutschland AG	30.10.2015	2036

Source: Bundesnetzagentur (2019).

Table 3: Overview on reported hard coal power plant decommissioning dates.

Hard Coal Plant	Operator	Commissioning	Scheduled Decommissioning
Weisweiler G	RWE Power AG	14.02.1974	2019
Niederaußem G	RWE Power AG	16.09.1974	2019
Niederaußem H	RWE Power AG	23.10.1974	2019
Frechen/Wachtberg	RWE Power AG	01.01.1959	2019
Niederaußem C	RWE Power AG	27.06.1965	2020
Weisweiler D	RWE Power AG	02.12.1965	2019
Weisweiler H	RWE Power AG	18.01.1975	2019
Neurath D	RWE Power AG	24.06.1975	2019
Neurath E	RWE Power AG	22.02.1976	2019
Boxberg	LEAG AG	01.01.1979	2019
Weisweiler F	RWE Power AG	04.09.1967	2019
Niederaußem D	RWE Power AG	31.05.1968	2020
Boxberg	LEAG AG	01.07.1980	2019
KW Jänschwalde A	LEAG AG	01.10.1981	2019
KW Jänschwalde B	LEAG AG	29.11.1982	2019
KW Jänschwalde C	LEAG AG	01.02.1984	2019
Neurath C	RWE Power AG	30.06.1972	2019
Neurath B	RWE Power AG	14.10.1972	2019
Neurath A	RWE Power AG	21.03.1973	2020
KW Jänschwalde D	LEAG AG	06.10.1985	2019
Schkopau A	Uniper Kraftwerke GmbH	01.01.1996	2027
Schkopau B	Uniper Kraftwerke GmbH	01.01.1996	2027
Schwarze Pumpe A	LEAG AG	15.12.1997	2028
Schwarze Pumpe B	LEAG AG	25.05.1998	2029
Braunkohlekraftwerk Lippendorf	EnBW Energie Baden-Württemberg AG	01.12.1999	2030
Lippendorf	LEAG AG	20.06.2000	2031
Boxberg	LEAG AG	01.10.2000	2031
Niederaußem K	RWE Power AG	30.08.2002	2033
BoA 2	RWE Power AG	08.07.2012	2036
BoA 3	RWE Power AG	03.08.2012	2036
Boxberg	LEAG AG	06.11.2012	2036

Source: Bundesnetzagentur (2019).

Table 4: Overview on reported lignite power plant decommissioning dates.

The fleet's scheduled decommissioning highlights that the phase-out is set to be in line with the age of the hard coal and lignite power plants. Since specific input variables exhibit differences depending on the age of the power plants, the efficiency ratio and fixed costs for each year are adjusted to the fleet age composition. The age structure is first based on the installed capacity that is determined in Chapter 0. To display the change within the age structure, old power plants decommission in advance of the most recently build power plants. Thus, the following tables display the percentage distribution according to the three scenarios.

B.3.1 DCAS

Year	**Hard Coal** **Old**	**Modern**	**Lignite** **Old**	**Modern**
2019	56.82	43.18	45.84	54.16
2020	50.79	49.21	37.43	62.57
2021	50.79	49.21	34.75	65.25
2022	49.05	50.95	34.75	65.25
2023	47.31	52.69	34.75	65.25
2024	47.13	52.87	32.30	67.70
2025	40.36	59.64	26.44	73.56
2026	28.15	71.85	23.60	76.40
2027	28.06	71.94	20.52	79.48
2028	21.75	78.25	20.46	79.54
2029	17.27	82.73	17.13	82.87
2030	6.83	93.17	5.70	94.30
2031	6.15	93.85	5.70	94.30
2032	3.22	96.78	0.97	99.03
2033	0.00	100.00	0.36	99.64
2034-2061	0.00	100.00	0.00	100.00

Numbers are in %. Source: Own presentation based on Oeko-Institut (2017, p. 104).

Table 5: Percentage proportions of old and modern power plants within DCAS.

B.3.2 MCAS

Year	Hard Coal Old	Modern	Lignite Old	Modern
2019	53.35	46.65	48.74	51.26
2020	43.22	56.78	45.78	54.22
2021	37.79	62.21	42.46	57.54
2022	31.21	68.79	38.70	61.30
2023	26.95	73.05	35.47	64.53
2024	22.12	77.88	31.89	68.11
2025	16.61	83.39	27.88	72.12
2026	10.27	89.73	23.38	76.62
2027	2.88	97.12	18.27	81.73
2028	0.00	100.00	12.43	87.57
2029	0.00	100.00	5.69	94.31
2030-2038	0.00	100.00	0.00	100.00

Numbers are in %. Source: Own presentation based on Oeko-Institut (2017, p. 104).

Table 6: Percentage proportions of old and modern power plants within MCAS.

B.3.3 EPAS

Year	Hard Coal Old	Modern	Lignite Old	Modern
2019	54.21	45.79	45.20	54.80
2020	43.62	56.38	39.72	60.28
2021	37.36	62.64	33.02	66.98
2022	29.53	70.47	24.65	75.35
2023	19.46	80.54	0.00	100.00
2024-2030	0.00	100.00	0.00	100.00

Numbers are in %. Source: Own presentation based on Oeko-Institut (2017, p. 104).

Table 7: Percentage proportions of old and modern power plants within EPAS.

B.4 Marginal Cost Components

B.4.1 Conversion Factors

Classification	Fuel	Conversion factor
Currency		1 $ = 0.90 € (accessed: 08/02/2019)
Energy units	Natural gas	1 MBtu = 0.293 MWh
	Hard coal	1 t SKE = 8.138 MWh
	Lignite	1 GJ = 0.278 MWh

Source: Own presentation based on Konstantin (2013) and European Central Bank (2019).

Table 8: Fuel prices conversion factors.

B.4.2 Fuel Costs

Year	DCAS	MCAS	EPAS
2019	9.60	9.14	7.89
2025	9.60	9.14	7.89
2030	-	9.49	-
2035	-	9.60	-
2040	11.20	9.71	7.54

Numbers are in €/MWh. Source: Own presentation based on International Energy Agency (2018).

Table 9: Hard coal fuel prices.

Year	DCAS	MCAS	EPAS
2019	25.08	24.76	23.81
2025	25.08	24.76	23.81
2030	-	26.03	-
2035	-	27.30	-
2040	29.84	28.57	24.45

Numbers are in €/MWh. Source: Own presentation based on International Energy Agency (2018).

Table 10: Gas fuel prices.

B.4.3 Carbon Costs

Year	DCAS	MCAS	EPAS
2019	18	20	35
2020	18	20	35
2025	23	25	-
2030	30	32	180
2035	38	41	-
2040	49	53	-
2045	63	68	-
2050	80	87	-

Numbers are in €/t. Source: Own presentation based on Potsdam Institue for Climate Impact Research (2019) and Forum Ökologisch-Soziale Marktwirtschaft (2019).

Table 11: Carbon certificate and tax prices.

B.4.4 Efficiency Ratio

The efficiency ratios are required in order to estimate the price of fuel and carbon within the scenario analysis. Hard coal and lignite efficiency ratios are derived from Umweltbundesamt (2018) and range between 34% and 43% for lignite and 36% and 46% for hard coal depending on the age of the power plant. These hard coal and lignite efficiency ratios are adjusted to the structure of power plants, as presented in Chapter B.3. The ratios for gas turbines and combined cycle gas turbines are set at 40% and 56%, respectively (Gülen, 2019, p. 25; Probstein and Hicks, 2013, p. 243).

B.4.5 Emission Factors

Carbon dioxide emission factors are considered to estimate the tons (t) emitted per MWh of electricity generated from each energy source. Using this ratio, the carbon certificate or tax costs are calculated The Federal Office of Economics and Export Control (2019) provides the official carbon emission factors for hard coal, 0.337 t/MWh, lignite, 0.381 t/MWh, and natural gas, 0.202 t/MWh.

B.5 Revenue Assessment

Utility companies and power plant operators receive revenues from the sale of electricity for their power plants reflecting a share of the overall remuneration for electricity generation from coal. The contribution margins arise from electricity sales on the spot market or, more specifically, the day-ahead spot market for base and peak load (Energy Brainpool and Greenpeace Nordic, 2015). It is to add that these revenues only consider the compensation for electricity, but not heat (cogeneration and thermal plants), and only covers the contribution margin for the power generation business leaving out the profit from the sale of electricity.

The revenues for hard coal and lignite are the product of the installed capacity, the full-load hours and the base or peak market clearing prices. The base and peak market clearing prices, however, are determined through the merit order principle, which is further described in the following section.

B.5.1 Base and Peak Market Clearing Prices

The market clearing prices for the base and peak loads depend on a variety of estimated input variables and are therefore modelled for each year of each scenario.

In order to determine base and peak load prices and following the revenues for hard coal and lignite power generation, the merit order of the German power plant park is crucially important. The merit order depicts the power generation sequence of the different types of power plants. It is compiled based upon the marginal costs of the power plant park and the installed capacities of the power plant technologies, sorted in an ascending order (Association of German Chambers of Commerce and Industry, 2017, p. 10).

Therefore, the marginal costs, the sum of fuel, carbon, and other variable costs, is calculated to determine the sequence power plants. This sequence is then matched with the installed capacities of each power plant type that have been estimated beforehand also depending on the residual load and its composition. The residual load composition, as described in Chapter A.1, is required in order to identify the price-setting power plant at the demand of the base load at 40 GW of installed capacity and of the peak load at around 58 GW of installed capacity. The base load and peak load prices are the output of the marginal costs' calculation of the price-determining power plant type. The procedure is visualized in Figure 4.

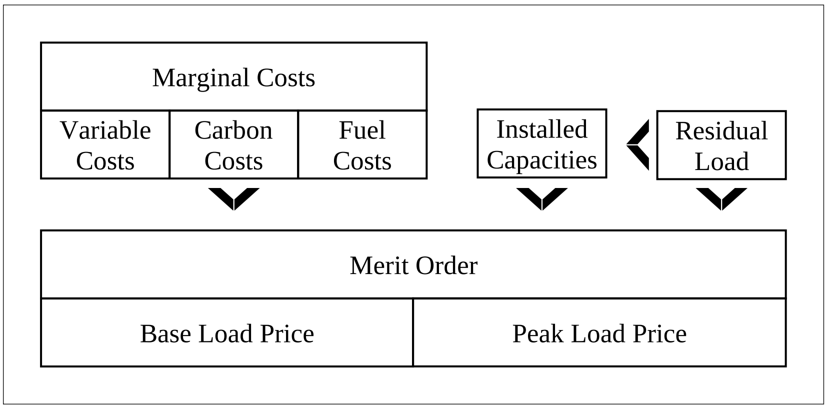

Figure 4: Modelling procedure of the merit order and base and peak load prices.

B.5.2 Clean Dark and Spark Spreads

The dark and spark spreads define the difference between the peak or base load price depending on which compensation is received and fuel and carbon costs of the technology (Spodniak, 2017, p. 1). Including carbon costs within the differential leads to the clean spark and dark spreads. The spark spread is used for gas-fired power plants, whereas the dark spread specifies coal-fired generation technologies. The spread is estimated according to the following formula:

$$\begin{aligned} & Clean\ Dark/Spark\ Spread_t \\ & = Peak\ Load\ Price_t \vee Base\ Load\ Price_t - Fuel\ Costs_t \\ & -\ Carbon\ Costs_t \end{aligned} \tag{6}$$

If the spreads are positive, the power plants run in operation mode. For this study, an approximating procedure is selected. The dark and spark spread are required in order to adjust the full-load hours. The full-load hours decrease linearly to zero, if the spread turns negative until it falls below -15 €/MWh for hard coal or -30 €/MWh for lignite.

B.6 Depreciation

Year	DCAS Hard Coal	Lignite	MCAS Hard Coal	Lignite	EPAS Hard Coal	Lignite
2019	464.35	452.73	464.35	452.73	747.51	485.47
2020	528.84	312.01	537.34	312.01	884.62	344.75
2021	528.84	312.01	537.34	312.01	884.62	344.75
2022	528.84	235.31	537.34	235.31	884.62	268.06

2023	528.84	235.31	537.34	235.31	884.62	268.06
2024	528.84	235.31	537.34	235.31	884.62	268.06
2025	512.01	233.89	520.51	233.89	867.79	266.64
2026	512.01	233.89	520.51	233.89	748.46	266.64
2027	512.01	233.89	520.51	233.89	566.46	266.64
2028	512.01	233.89	520.51	233.89	383.63	266.64
2029	510.52	233.89	519.02	233.89	209.57	138.47
2030	510.52	227.77	519.02	227.77	0.00	0.00
2031	491.84	227.77	500.34	227.77	0.00	0.00
2032	491.84	3.54	500.34	3.54	0.00	0.00
2033	395.46	1.65	403.96	1.65	0.00	0.00
2034	282.14	0.00	290.64	0.00	0.00	0.00
2035	72.61	0.00	81.11	0.00	0.00	0.00
2036	72.61	0.00	81.11	0.00	0.00	0.00
2037	72.61	0.00	73.35	0.00	0.00	0.00
2038	72.61	0.00	0.00	0.00	0.00	0.00
2039	72.61	0.00	0.00	0.00	0.00	0.00
2040	0.00	0.00	0.00	0.00	0.00	0.00

Numbers are in million €.

Table 12: Yearly depreciation based on installed capacities.

B.7 Monte Carlo Analysis

For the Monte Carlo Analysis, we used @Risk version 7.6, with a seed number of 31416 for the pseudo random number generator.

B.7.1 Simulation Data

Parameter	Historic Mean	Growth Rate STDEV	Growth Rate Rel. STDEV
Hard coal	54.22 $/t	0.014	0.014
Gas	3.11 $/MBtu	0.028	0.028
Carbon costs	15.82 $/t	0.031	0.032

Source: Calculation based on data extracted from Chicago Mercantile Exchange (2019), European Energy Exchange (2019), and U.S. Energy Information Agency (2019).

Table 13: Parameters of lognormal price distributions of hard coal and gas from 2014 through 2018.

Correlation Coefficient	DCAS	MCAS	EPAS
Hard Coal/Gas	0.488	0.244	0.000

Source: Calculation based on data extracted from Chicago Mercantile Exchange (2019) and U.S. Energy Information Agency (2019).

Table 14: Correlation of hard coal and gas prices.

B.7.2 Sensitivity Analysis

Scenarios are also tested for sensitivity towards the weighted average cost of capital (WACC). For this purpose, the WACC is decreased and increased by each 1% to 4.6% and 6.6%.Table 15 illustrates the summary statistics employing the upper limit of the base load assumption. In contrary to the selected WACC of 5.6%, the lower 4.6% WACC exhibits generally higher absolute NPVs implying a fewer reduction of already negative cash flows and an increase of positive cash flows, as seen for lignite. Replacing the WACC of 5.6% by 6.6%, on the other hand, reduces cash flows so that negative mean NPVs increase and positive mean NPVs decrease. For hard coal in the Positive Scenario, this pattern does not apply indicating that the WACC’s two-fold impact on positive and negative cash flows is dominated by one.

Parameter	DCAS Hard Coal	Lignite	MCAS Hard Coal	Lignite	EPAS Hard Coal	Lignite
Minimum	-4.84	12.64	-1.70	9.40	-4.92	-2.24
Maximum	-3.31	17.91	-0.48	13.73	-3.47	1.03
Mean	-4.04	15.25	-1.10	11.57	-4.22	-0.54
Range	1.54	5.27	1.23	4.33	1.45	3.26
VaR (α=0.05)	-4.33	13.84	-1.33	10.40	-4.44	-1.32
VaR (α=0.01)	-4.45	13.44	-1.43	10.04	-4.54	-1.59
STDEV	0.1763	0.8448	0.1431	0.6876	0.1374	0.4651
Rel. STDEV	0.0436	0.0554	0.1306	0.0595	0.0326	0.8677

We denote VaR as the Value-at-Risk and STDEV as standard deviation. Numbers are in billion €.

Table 15: Distribution statistics employing the upper base load assumption and a WACC of 4.6%.

Parameter	DCAS Hard Coal	Lignite	MCAS Hard Coal	Lignite	EPAS Hard Coal	Lignite
Minimum	-4.25	10.65	-1.69	8.31	-4.64	-2.04
Maximum	-2.98	15.11	-0.57	12.27	-3.31	1.04
Mean	-3.59	12.86	-1.14	10.30	-4.00	-0.43
Range	1.27	4.46	1.13	3.96	1.34	3.08
VaR (α=0.05)	-3.84	11.67	-1.35	9.24	-4.21	-1.18
VaR (α=0.01)	-3.94	11.33	-1.44	8.90	-4.29	-1.44
STDEV	0.1560	0.7174	0.1314	0.6260	0.1278	0.4452
Rel. STDEV	0.0435	0.0558	0.1155	0.0608	0.0319	1.0356

We denote VaR as the Value-at-Risk and STDEV as standard deviation. Numbers are in billion €.

Table 16: Distribution statistics employing the upper base load assumption and a WACC of 6.6%.

C References

Ansar, A., Caldecott, B., Tilbury, J., 2013. Stranded Assets and the Fossil Fuel Divestment Campaign: What Does Divestment Mean for the Valuation of Fossil Fuel Assets? University of Oxford’s Smith School Stranded Assets Programme.

Arnold, U., Yildiz, Ö., 2015. Economic Risk Analysis of Decentralized Renewable Energy Infrastructures – a Monte Carlo Simulation Approach. Renewable Energy 77, 227–239. https://doi.org/10.1016/j.renene.2014.11.059

Arrhenius Institut für Energie- und Klimapolitik, 2009. Discussion Paper 2: Anreize für Investitionen in konventionelle Kraftwerke – Reformbedarf im liberalisierten Strommarkt.

Association of German Chambers of Commerce and Industry, 2017. Faktenpapier: Strompreise in Deutschland.

Berk, J.B., DeMarzo, P.M., 2019. Grundlagen der Finanzwirtschaft. Hauptband: Analyse, Entscheidung und Umsetzung, 4., updated edition. ed. Pearson, Hallbergmoos.

Bundesnetzagentur, 2019. Power Plant List for Germany [WWW Document]. URL https://www.bundesnetzagentur.de/DE/Sachgebiete/ElektrizitaetundGas/Unternehmen_Institutionen/Ve

rsorgungssicherheit/Erzeugungskapazitaeten/Kraftwerksliste/kraftwerksliste-node.html (accessed 7.10.19).
Büro für Energiewirtschaft und technische Planung, 2018. Kurzstudie: Entwicklung der energiewirtschaftlichen Rahmenbedingungen für Steinkohle- und Kernkraftwerke.
Büro für Technikfolgenabschaetzung beim Deutschen Bundestag, 2012. Regenerative Energieträger zur Sicherung der Grundlast in der Stromversorgung.
Carbon Brief, 2019. How Far Would Germany's 2038 Coal Phaseout Breach Paris Climate Goals? [WWW Document]. Carbon Brief. URL https://www.carbonbrief.org/analysis-how-far-would-germanys-2038-coal-phaseout-breach-paris-climate-goals (accessed 7.10.19).
Chicago Mercantile Exchange, 2019. Coal Historical Future Prices on NYMEX [WWW Document]. URL https://www.cmegroup.com/trading/energy/coal-futures-options.html (accessed 9.12.19).
Climate Analytics, 2018. Science Based Coal Phase-Out Pathway for Germany in Line With the Paris Agreement 1.5°C Warming Limit.
District Government Muenster, 2017. Legal Immission Protection License.
Energy Brainpool, Greenpeace Nordic, 2015. Economic Analysis of Vattenfall's Lignite Power Plants Offered for Sale.
European Central Bank, 2019. ECB Euro Reference Exchange Rate: US Dollar (USD) [WWW Document]. URL https://www.ecb.europa.eu/stats/policy_and_exchange_rates/euro_reference_exchange_rates/html/eurofxref-graph-usd.en.html (accessed 8.2.19).
European Energy Exchange, 2019. EUA Spot Prices [WWW Document]. URL (accessed 10.2.19).
European Environment Agency, 2018. Trends and Projections in the EU ETS in 2018: The EU Emissions Trading System in Numbers.
European Network of Transmission System Operators for Electricity, 2019. Installed Capacity per Production Type [WWW Document]. URL https://transparency.entsoe.eu/generation/r2/installedGenerationCapacityAggregation/show (accessed 8.29.19).
European Union Commission, 2013. EU Energy, Transport and GHG Emissions: Trends to 2050. Publications Office of the European Union, Luxembourg.
Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, 2019a. Kernkraftwerke in Deutschland [WWW Document]. URL https://www.bmu.de/themen/atomenergie-strahlenschutz/nukleare-sicherheit/aufsicht-ueber-kernkraftwerke/kernkraftwerke-in-deutschland/ (accessed 8.27.19).
Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, 2019b. Kommission Wachstum, Strukturwandel und Beschäftigung: Abschlussbericht. Berlin.
Federal Ministry of Finance, 2019. Die wichtigsten Steuern im internationalen Vergleich 20158.
Federal Office of Economics and Export Control, 2019. Merkblatt zu den CO2-Faktoren.
Federal Statistical Office, 2019a. Verbraucherpreisindex: Gesamtindex 2019 [WWW Document]. URL https://www.destatis.de/DE/Themen/Wirtschaft/Preise/Verbraucherpreisindex/Tabellen/Verbraucherpreise-12Kategorien.html (accessed 9.5.19).
Federal Statistical Office, 2019b. Verbraucherpreisindex (inkl. Veränderungsraten): Deutschland, Jahre [WWW Document]. URL https://www-genesis.destatis.de/genesis/online/logon?language=de&sequenz=tabelleErgebnis&selectionname=61111-0001&startjahr=1991 (accessed 8.21.19).
Forschungsstelle für Energiewirtschaft, 2010. Merit Order des Kraftwerksparks.
Forum Ökologisch-Soziale Marktwirtschaft, 2019. Lenkungs- und Verteilungswirkungen einer klimaschutzorientierten Reform der Energiesteuern, on behalf of the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety.
Fraunhofer Institute for Solar Energy Systems, 2018a. Energy Charts: Net Installed Capacity in Germany [WWW Document]. URL https://www.energy-charts.de/power_inst_de.htm?year=2018&period=annual&type=power_inst (accessed 8.14.19).
Fraunhofer Institute for Solar Energy Systems, 2018b. Stromgestehungskosten Erneuerbare Energien.
Fraunhofer Institute for Solar Energy Systems, 2018c. Energy Charts: Net Electricity Production in Germany [WWW Document]. URL https://www.energy-charts.de/energy_pie_de.htm?year=2018&month=4 (accessed 8.13.19).
French, N., 2006. Value and Worth: Scenario Analysis. J of Property Inv & Finance 24, 176–179. https://doi.org/10.1108/14635780610655111
Gülen, S.C., 2019. Gas Turbines for Electric Power Generation. Cambridge University Press.
Hauser, P., Heinrichs, H.U., Gillessen, B., Müller, T., 2018. Implications of Diversification Strategies in the European Natural Gas Market for the German Energy System. Energy 151, 442–454. https://doi.org/10.1016/j.energy.2018.03.065
Hobbie, H., Schmidt, M., Möst, D., 2019. Windfall Profits in the Power Sector During Phase III of the EU ETS: Interplay and Effects of Renewables and Carbon Prices. Journal of Cleaner Production.

Institute of Energy Economics, 2017. Energiemarkt 2030 und 2050 – Der Beitrag von Gas- und Wärmeinfrastruktur zu einer effizienten CO2-Minderung.
International Energy Agency, 2018. World Energy Outlook 2018. Paris.
Jewell, J., Vinichenko, V., Nacke, L., Cherp, A., 2019. Prospects for Powering Past Coal. Nat. Clim. Chang. 9, 592–597. https://doi.org/10.1038/s41558-019-0509-6
Konstantin, P., 2013. Praxisbuch Energiewirtschaft: Energieumwandlung, -transport und -beschaffung im liberalisierten Markt, 3. ed, VDI. Springer Vieweg, Berlin.
Markewitz, P., Robinius, M., Stolten, D., 2018. The Future of Fossil Fired Power Plants in Germany - a Lifetime Analysis. Energies 11, 1616–1636. https://doi.org/10.3390/en11061616
Oeko-Institut, 2017. Die deutsche Braunkohlenwirtschaft: Historische Entwicklungen, Ressourcen, Technik, wirtschaftliche Strukturen und Umweltauswirkungen, on behalf of Agora Energiewende and European Climate Foundation.
Osorio, S., Nahmmacher, P., Schmid, E., Knopf, B., 2018. Documentation of LIMES-EU - a Long-Term Electricity System Model for Europe. Potsdam Institute for Climate Impact Research.
Pahle, M., 2010. Germany’s Dash for Coal: Exploring Drivers and Factors. Energy Policy 38, 3431–3442. https://doi.org/10.1016/j.enpol.2010.02.017
Potsdam Institute for Climate Impact Research, 2019. Die unterschätzten Risiken des Kohleausstiegs.
Potsdam Institute for Climate Impact Research, 2018. Eckpunkte einer CO2-Preisreform für Deutschland.
Probstein, R.F., Hicks, R.E., 2013. Synthetic Fuels. Courier Corporation.
Reuters, 2018. Uniper will Kraftwerk Datteln nicht für Kohleausstieg stilllegen [WWW Document]. URL https://de.reuters.com/article/deutschland-energie-uniper-idDEKCN1MM0PY (accessed 9.6.19).
Spodniak, P., 2017. Determinants of Power Spreads in Electricity Futures Markets: A Multinational Analysis.
Umweltbundesamt, 2018. Konventionelle Kraftwerke und erneuerbare Energien [WWW Document]. URL https://www.umweltbundesamt.de/daten/energie/konventionelle-kraftwerke-erneuerbare-energien (accessed 9.24.19).
Umweltbundesamt, 2015. Strommarktdesign der Zukunft.
U.S. Energy Information Agency, 2019. Natural Gas (Henry Hub) Historical Future Prices on NYMEX [WWW Document]. URL https://www.eia.gov/dnav/ng/NG_PRI_FUT_S1_D.htm (accessed 9.12.19).
World Bank, 2018. State and Trends of Carbon Pricing 2018. Washington, D.C.
World Resources Institute, UNEP Finance Initiative, 2016. Carbon Asset Risk Discussion Framework.