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 in the light of the critical decision to phase them out by 2038. In a Monte Carlo simulation, the scenarios under consideration (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 €2.6 billion given the phase-out by 2038 and an additional €11.6 billion if the phase-out is brought forward by 8 years. This study also describes 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 discuss the immediate concerns for the share prices of the affected companies and help to close the research gap regarding stranded physical and financial assets.

Keywords: Coal Phase-Out, Energy Transition, Germany, Stranded Assets

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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) stresses the potential impacts of global warming greater than 1.5°C above the pre-industrial levels. It endorses the obligations set within the Paris Agreement to keep global warming below 2.0°C and, at best, to limit it to 1.5°C (IPCC, 2019). One step toward this end is to phase-out coal-fired power generation (Zhao and Alexandroff, 2019). This is especially important for Germany because, on the one hand, the country is struggling to meet its own 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 CO2 emissions in the German energy sector (Umwelt Bundesamt, 2021).[1]

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). Since then, the country has been prone to the so-called "carbon lock-in effect", i.e., the inability to facilitate the shift toward low-carbon technologies due to its coordinated energy market and historically strong political and institutional interest in coal-fired

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To achieve the national climate targets, the German Government has appointed the German Commission on Growth, Structural Change and Employment, commonly referred to as the Coal Commission, to develop a national emission reduction initiative. It presented its final report in early 2019 (Federal Ministry for Economic Affairs and Energy (BMWi), 2019). In this final report, the Coal Commission, which included representatives of all the major stakeholders (industry, consumer and non-profit groups, and environmentalists as well as federal and state governments), suggested phasing out coal-fired generation by 2038.[2] It has been argued that a phase-out by 2038 might be too late to meet the 2.0°C target by 2030 stipulated in the 2015 Paris Climate Agreement (Climate Analytics, 2018). While the Commission compromised on a national phase-out in 2038, a survey has shown that many German voters would prefer an even earlier phase-out even if it is associated with higher costs (Rinscheid and Wüstenhagen, 2019).

The Commission's suggestion raises the question of how the coal phase-out would affect the German coal industry's valuation. Thereby, the arising costs that adversely affect the commitment to phasing out coal can be specified as stranded assets (Jewell et al., 2019), which refer, in this 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, which the Coal Commission has proposed to alleviate the financial impact of the coal phase-out on the coal industry (Federal Ministry for Economic Affairs and Energy (BMWi), 2019).[3] On the one hand, some studies have argued that compensation is inevitable due to the size of the industry, which can be seen as "too big to fail" (Sen and Schickfus, 2018). On the other hand, recent studies have concluded that the coal phase-out is in line with the constitution and that compensation payments are legally controversial (Deutscher 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,[4] environmental groups especially assume that no compensation will be due (ClientEarth, 2019; Leipprand and Flachsland, 2018). If no compensation payments are made to reimburse energy suppliers, the potential decrease in valuation will be transferred to financial assets. Accordingly, this study also highlights the impacts of stranded asset risk on the financial sector as well as estimating the compensation payments resulting from the stranded asset value.[5]

In this study, we contribute to the stranded asset literature by quantifying the economic, financial, and industrial impacts of the coal phase-out in Germany under different scenarios:

electricity generation (Rentier et al., 2019). Since 2007, power generation from fossil fuels has, however, started to decrease and, at the same time, generation from renewable energy sources has increased, benefitting from continuous feed-in tariffs. Currently, Germany is entering the next phase of its energy transition to advance toward 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 the focus of discussion.

2. In addition to decommissioning the coal-fired power plants, the Commission recommended examining the possibility of converting the affected power plants into gas-fired plants. In view of the long lifetime of the power plants and the considerable costs involved, this option is not considered in the following (Bundesnetzagentur, 2021). Moreover, the plan is scheduled for a revision in 2023, 2026, and 2029. Hence, we note that it still might be changed in parts, in particular in terms of the decommissioning schedule.

3. The loss of valuation is a result from the economic perspective that does not consider the societal benefits of the coal phase-out, such as a reduction of air pollution (Epstein et al., 2011).

4. Expecting claims for compensation, the Coal Commission has recommended negotiations with energy utilities with proposed payments for reserve power of around €0.6 billion per GW (Federal Ministry for Economic Affairs and Energy (BMWi), 2019). In January 2020, the Minister of Finance announced that utilities will receive compensation payments of €4.35 billion over the next 15 years (German Government, 2020).

5. According to the applicable law, the German Government can change the regulatory policies and decommission certain power plants. However, the shareholders are entitled to compensation for the amount of the lost profits.

1. An unanticipated early phase-out by 2030 (the Enforcing the Paris Agreement Scenario, EPAS)
2. A scenario following the scheduled phase-out of German coal-fired power plants by 2038 (the Maintaining Climate Action Scenario, MCAS)
3. A reference scenario in which the current hard coal and lignite power plants operate until the end of their technical lifetime (the Delaying Climate Action Scenario, DCAS)

For each scenario, the valuation of the German coal industry is estimated using the overall net present value of the industry.

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 DCAS and the EPAS) reaching €14.2 billion. Moreover, the stranded asset value for the scheduled phase-out by 2038 only amounts to €2.6 billion, which is significantly below the values approximated by the Coal Commission and the industry. In addition, if no compensation is paid, stranded asset risks will affect the 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 the feed-in from renewable energy sources have been found to be important factors that decrease the valuation for both hard coal and lignite.

Using a Monte Carlo analysis in combination with a discounted cash flow model to assess the three different pathways, we account for various uncertainties but also dependencies within the scenarios. Our findings are robust to changes in critical input variables, such as the base load and the cost of capital.

The remainder of this study 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 the 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 for policy implications. The Supplementary Material to our study provides further technical details, data, and 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 an economic return. Since political decisions on the phase-out will terminate and impair the running of businesses 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 firms' valuation (Carbon Tracker Initiative, 2011). The subject of stranded assets due to environmental risks was discussed by Meinshausen et al. (2009). The authors investigated the remaining carbon emissions between 2000 and 2050 that will exceed the 2.0°C global warming carbon budget. They argued that the carbon reserves may not be fully exhausted.[6]

Stranded asset risk has, over the last decade, gained increased attention with the growing topicality of the climate change emergency, climate policy uncertainty, and financial implications

6. We note that the concept of stranded assets originated in the late 1980s. Krause et al. (1989) first outlined the relationship between unburnable carbon, fossil fuel assets, and the adverse financial impacts on financial markets. Michaels (1994) also discussed the 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).

through environmental hazards (Bloomberg, 2013; Breitenstein et al., 2021; Caldecott, 2017). Companies whose physical assets become worthless will suffer huge financial losses, and these will affect financial markets as a whole.[7] For instance, Atanasova and Schwartz (2019) examined the North American oil industry and concluded that adverse effects exist between firm value and proved oil reserves. Thus, the higher a firm's oil reserves, the greater its exposure to climate policy risk. The study by van der Ploeg and Rezai (2019) found that immediate climate action, for example a carbon tax, reduces the societal cost in terms of CO2 emissions but increases the value of stranded assets for exposed firms.

Current research on stranded assets is mainly driven by academic and non-academic research initiatives, including, among others, the University of Oxford's Smith School of Enterprise and the Environment, 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 about 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 the contributions published by the Oxford's Smith School, remains quite rare. Our literature review is not exhaustive, but we were able to find only limited scientific research on the magnitude of stranded assets due to climate change.

Table 1 provides the main features of the relevant literature that has recently assessed and estimated the financial impact of stranded assets. Ansar et al. (2013), Silver (2017), and World Resources Institute and Unep Finance Initiative (2016) have provided theories on the magnitude of stranded assets' financial impacts. Most of the other research has consisted of case studies, and most of these studies have focused on fossil fuels. The analyses have been 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) model or the E3ME-FTT-GENIE models. The effects of stranded assets on industries, companies, and individual financial assets have been studied using the discounted cash flow (DCF) and net present value (NPV) as tools. One-fourth of the studies that we found focused on firms in the fossil fuel industries.

All the case studies are scenario analyses undertaken to estimate the potential value of prospective stranded assets, over the short to medium terms, with respect to the impending policy, technology, and physical climate change hazards. Most of the studies that we examined did not specifically address the value of the stranded assets that would arise in the scenarios considered. Macroeconomic studies (such as the one by The Economist Intelligence Unit, 2015) have not allowed for the determination of the magnitudes of stranded assets by industry. In addition, only a few studies have accounted for the financial impairment of the stranded assets.

Our study adds to the literature using the DCF model by combining it with a Monte Carlo analysis. The methodology that we propose firstly includes different scenarios or policy pathways, on which we build a DCF model. Lastly, we account for various uncertainties (especially short-term

7. 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 is invested in natural resources and the 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 (2019) has also voiced concerns about the future impacts of stranded asset risk on the financial sector and advocated the study of emissions to the G7 finance ministers in the group.

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

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 (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
Cheuvreux (2014)	Lobby group report	DCF	NPV (of revenues)	Oil, gas, coal	Global
Mercer 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
Koehler and Bertocci (2016)	Lobby group report	DCF	NPV (of industry/peer group cash flows)/EV	Oil, gas	Global, focus, US, 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
IRENA (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	US 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 (IAMs), such as the dynamic integrated climate-economy (DICE) model and the framework for uncertainty, negotiation, and distribution (FUND), and the E3ME-FTT-GENIE models, internal rate of return (IRR), and capital asset pricing model (CAPM). The outcome metrics are the net present value (NPV), the enterprise value (EV), the gross domestic product (GDP), and the value at risk (VaR).

ones) within the DCF model by using the Monte Carlo technique. Our approach allows us to assess the consequences of a political decision over a long horizon.

Focusing on stranded asset risks for the German coal industry only, we argue that concentration on individual industries improves the understanding of stranded assets compared with a global perspective. An industry-specific assessment of potential stranded assets will help institutional investors, asset managers, and asset owners to improve corporate governance and manage climate change risks better (Breitenstein et al., 2021; Ernst & Young, 2016).

3. METHODOLOGY

Generally, climate change risks are uncertain and driven by policy and market developments. Following the argument by World Resources Institute and Unep Finance Initiative (2016), there might not be sufficient data for parameter estimation. Therefore, we employ an industry-focused scenario analysis of the coal-fired power industry in Germany in which we further distinguish between hard coal and lignite. In particular, our approach has three steps:

1. We define three scenarios or policy pathways (Section 3.1).
2. For each scenario, we estimate the valuation of the hard coal and lignite industry based on a discounted cash flow model (Section 3.2).
3. We run a Monte Carlo simulation to account for the uncertainties of the assumptions in the scenarios and in the discounted cash flow model (Section 3.2).

3.1 Scenario Description

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 IEA (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, 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.

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 (Federal Ministry for Economic Affairs and Energy (BMWi), 2019). For lignite, the MCAS scenario closely follows the published decommission plan (Federal Ministry for Economic Affairs and Energy (BMWi), 2020). 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 IEA (2018). It is constructed along the planned decommissioning published by the Bundesnetzagentur (2021). Overall the MCAS has a low degree of uncertainty. However, the pathway does not follow the Paris Agreement and, therefore further actions are 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 CO2 equivalent. It includes a 42% decrease of CO2 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.

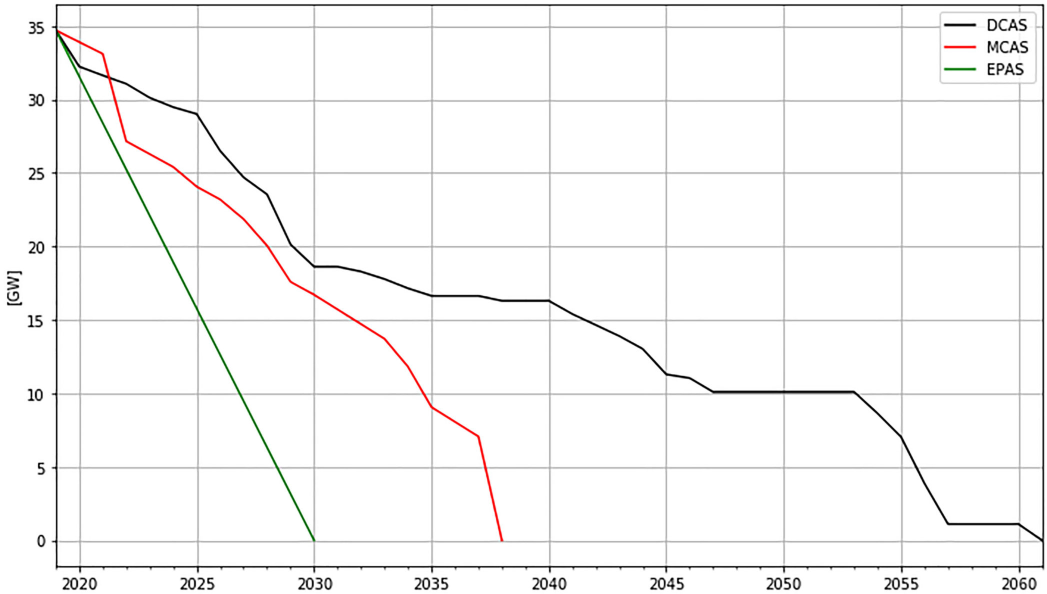
The EPAS induces extensive climate change mitigation action and resembles the Sustainable Development Scenario built by IEA (2018). Moreover, the scenario is in line with preferences of German voters as well as a wider public who favor the early coal phase-out within the next 10 years (Rinscheid and Wüstenhagen, 2019). In comparison to the MCAS, the phase-out by 2030 is not scheduled within the proposal by the Coal Commission.

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

3.2 Discounted Cash Flow Model and Monte Carlo Analysis

The analysis at hand covers a long time span from 2019 until 2061, and therefore uncertainty plays a substantial role. The parameters for macroeconomic models vary with climate change (Barnett et al., 2020; Cai and Lontzek, 2019). We assign specific parameters and use Monte Carlo simulation to estimate their statistical distribution for each scenario considered.

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



As profits fall, so do future cash flows. Earnings before interest and taxes and depreciation allowances (EBITDA) are calculated as revenues from the clearing price minus the sum of operation and maintenance costs and depreciation. Important assumptions about the cost (including fuel, carbon, variable, and fixed costs) are briefly presented in Table 2 and are displayed for all the years of the scenarios within the Supplementary Material. It is assumed that power plant operators hedge their positions and therefore receive either the price for the base load or the price for the peak load. The prices for the base and peak load are determined by applying a simplified merit order. Figure 2 depicts the modeling procedure for estimating the revenues for all the scenarios.

To calculate the cash flows, firstly, we assess 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) of 5.6% to discount the yearly free cash flows and derive the NPVs.

As shown 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. The need for flexibility in power plant operation will decrease the distinctions between base, mid-, and peak-load plants (Brunner et al., 2020). As the assumed base load depends heavily on the expectation of future renewable energy installations, the Monte Carlo analysis is conducted four times. The upper limit of the base load serves as the baseline analysis. 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 or its mean or by assuming an underlying stochastic triangular distribution based on the given lower, mean, and upper limits. The upper limit represents the current base load of 44.5 GW; the lower limit amounts to 30 GW for the DCAS, 20 GW for the MCAS, and 10 GW for the EPAS. The mean base load thus

Figure 2: Modelling procedure of the determination of revenues.

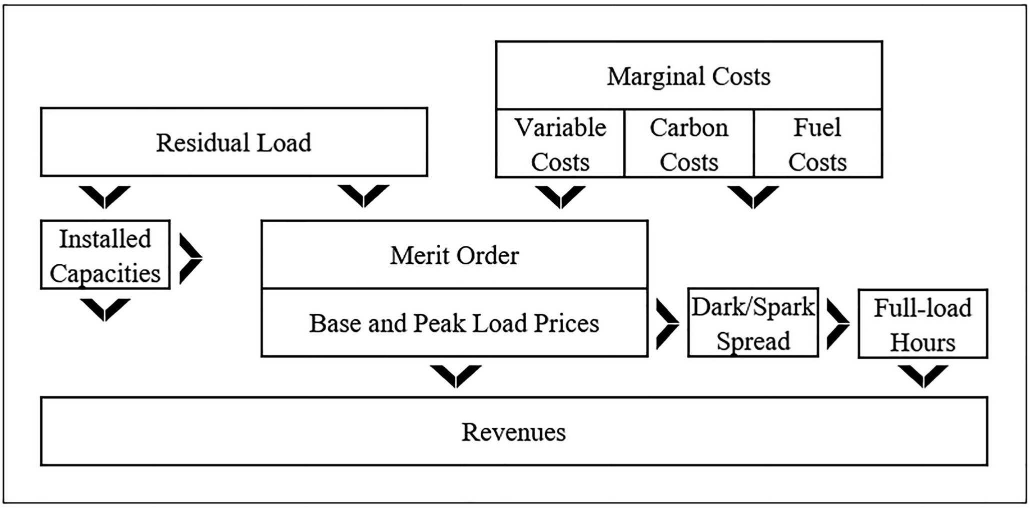


Table 2: Overview of the main input variables for the Monte Carlo simulation.

	EPAS	MCAS	DCAS
Hard Coal Prices [€/MWh]	7.89 to 7.54	9.14 to 9.71	9.60 to 11.20
Lignite Prices [€/MWh]		1.82 to 3.60	
Natural Gas Prices [€/MWh]	23.81 to 24.45	24.76 to 28.57	25.08 to 29.84
Carbon Prices [€/t]	35 to 180	20 to 87	18 to 80
Variable Costs [€/MWh]		Hard Coal: 1.39/Lignite: 1.76 Natural Gas Turbine: 5.89/Combined Cycle: 3.75	
Fixed Costs [€/kW]		Hard Coal: 59.80/Lignite: 53.50	
Full Load Hours†		Hard Coal: 3387.5 Hours/Year Lignite: 6951.2 Hours/Year	
Base Load [GW] (Lower/Mean/Upper Limit)	10/25/44.5	20/30/44.5	30/35/44.5

† If Clean Dark Spreads are positive.

varies for the scenarios as well (see also Table 2). The determined and randomly sampled base load remains constant for all the years in each scenario.

Our fundamental approach, which combines a scenario analysis with a Monte Carlo analysis, allows for the consideration of multiple risks and provides a robust basis for the calculation of cash flows for hard coal and lignite. In contrast to optimization models that calculate the power plant dispatch, the techno-economic interactions cannot not be modeled as the integration of new technologies (such as demand side management, DSM) is especially neglected (Möst and Fichtner, 2009). DSM is a short-term response of the demand when conventional power plants cannot meet the demand (Müller and Möst, 2018). Therefore, we underestimate the possible price spikes that might occur. However, since our results are based on scenario comparisons, the effect is likely to be very limited since the error is made in both scenarios.

The data, assumptions, and detailed descriptions of the Monte Carlo simulation are presented in the Supplementary Material appendix to our study.

4. VALUATION OF THE LIGNITE AND HARD COAL POWER GENERATION IN GERMANY

The results of the valuation for lignite and hard coal are presented in Table 3, which shows the NPV distributions and their respective summary statistics. Overall, lignite has a much higher valuation than hard coal, even though the two industries are comparable in size. The difference is caused by lignite's lower variable costs and higher full-load hours, which increase the current profitability of lignite, which can be lost due to the coal phase-out. In the following, the results for lignite and hard coal are presented and analyzed separately.

Table 3: Summary statistics of hard coal and lignite using the upper base load assumption.

	DCAS		MCAS		EPAS	
Parameter	**Hard Coal**	**Lignite**	**Hard Coal**	**Lignite**	**Hard Coal**	**Lignite**
Minimum	–3.71	11.56	–1.79	7.21	–3.94	–1.47
Maximum	–2.39	16.55	–0.50	11.64	–2.81	1.69
Mean	–3.06	14.04	–1.13	9.49	–3.40	0.14
VaR ($\alpha=0.05$)	–3.31	12.27	–1.137	8.33	–3.58	–0.66
VaR ($\alpha=0.01$)	–3.42	12.33	–1.46	8.00	–3.65	–0.92
St. Dev.	0.15	0.79	0.14	0.69	0.11	0.48

The different scenarios that we refer to are the Delaying Climate Action Scenario (DCAS), Maintaining Climate Action Scenario (MCAS), and Enforcing the Paris Agreement Scenario (EPAS). We denote the value at risk as VaR and the standard deviation as St. Dev. Numbers are in billion €.

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

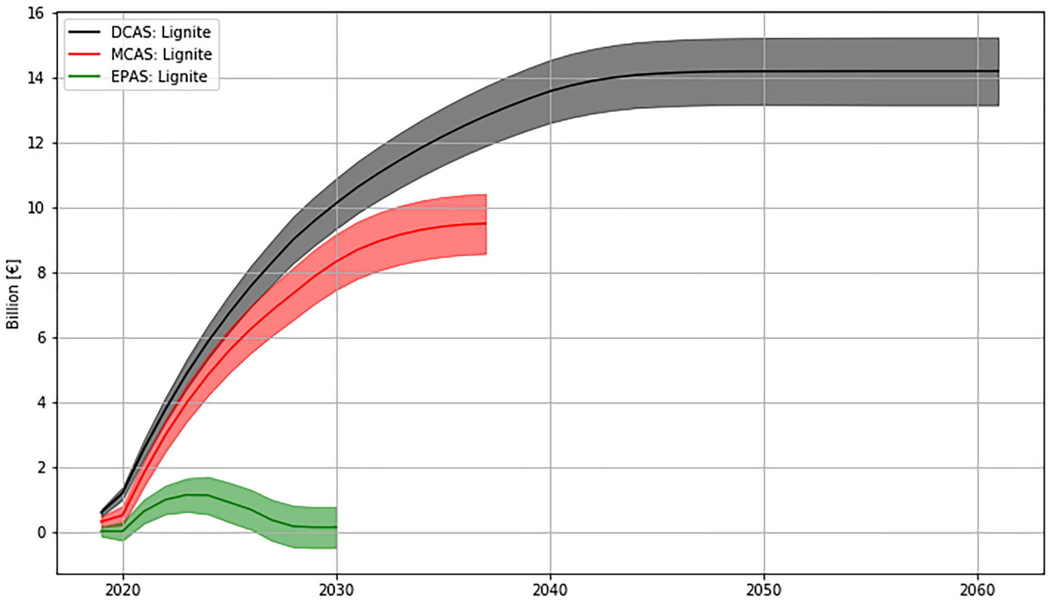
4.1.1 Lignite Power Plants

As presented in Table 3, the valuations in the scenarios for lignite range from €-1.47 to €16.55 billion (from the minimum EPAS to the maximum DCAS). Across the scenarios, the mean NPV decreases gradually from €14.04 billion in the DCAS to €0.14 billion in the EPAS, resulting in a loss in valuation of 99%. It is worth noting the absolute decrease of €4.55 billion between the DCAS and the MCAS in comparison with the absolute decrease of €9.35 billion between the MCAS and the EPAS, as is also evident in Figure 3. On the one hand, this suggests less profitable conditions for lignite past 2038. On the other hand, it shows a strong impact on the valuation resulting from high carbon and fuel prices combined with the strong decline in installed capacity in the EPAS.

In 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 on the marginal costs of hard coal, 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 the cash flows decrease to and even out at zero.

In the EPAS, a higher carbon price is assumed and leads to the assimilation of the marginal costs of all the technologies and in the end to a change in the merit order whereby gas replaces lignite at the front. Therefore, lignite provides mostly the 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 average peak load. Thus, the large profits of lignite are cut, resulting in the lower mean NPVs previously outlined. However, the change within the merit order also raises the question of

Figure 3: Development of the net present value (sum of discounted cash flows) over time for the lignite industry in each scenario with 80% confidence bands.



whether it is technically feasible for lignite to operate only during peak load hours. This could eventually result in lignite power plants becoming uncompetitive by 2024 or 2025.

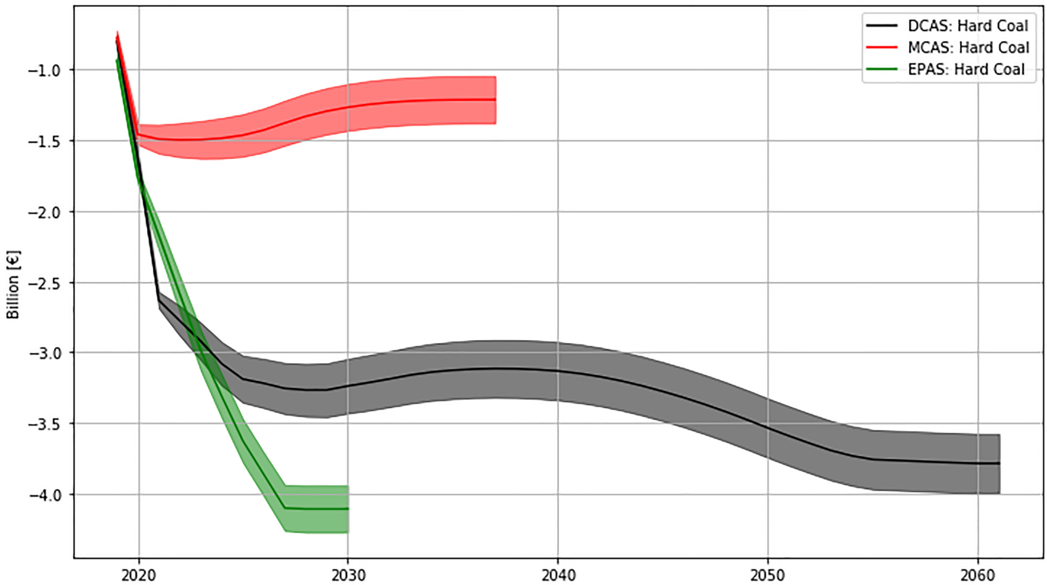
Furthermore, the risk measure value at risk (VaR) is estimated to determine the downside risk of the distribution. The VaRs at the 5% and 1% quantiles depict the severe decrease from the MCAS to the EPAS, reducing the NPV by over 100%. The mean NPV and the VaRs turn negative in the EPAS, indicating that, with a probability of 99%, the lignite NPV does not fall short of €-0.92 billion. The standard deviation (St. Dev.) of the empirical NPV distributions for each technology varies within the three scenarios, highlighting differences in the risk-return profiles.

Overall, the lignite plants lose money because of the coal phase-out and risk becoming stranded assets. Figure 3 depicts the sum of the discounted cash flows over time. A phase-out by 2038 limits the loss in valuation to about €4.5 billion, while an earlier phase-out leads to further losses with a valuation of about €9 billion.

4.1.2 Hard Coal Power Plants

The NPVs of the hard coal power generation industry range between €-3.94 billion and € 0.50 billion (from the minimum EPAS to the maximum MCAS). The main reason for the overall negative NPVs is the general alignment of the marginal cost of hard coal with combined-cycle natural gas power plants. The speed at which hard coal is replaced by natural gas as the price-setting fuel in the merit order depends on decommissioning and the way in which the merit order changes over time. In our scenarios, we impose a full-load limit of 3,387.5 hours/year and low positive spreads between coal prices and natural gas prices, which prevent hard coal plants from recovering their fixed costs. Nevertheless, the MCAS reveals the highest valuation in comparison with the almost equally negative NPVs in the DCAS and the EPAS (see also Figure 4) due to the earlier retirement of older power plants with higher fixed costs. To generate positive cash flows in our model, the market clearing price would have to be at least €16/MWh above the marginal cost of hard coal-fired power

Figure 4: Development of the Net Present Value (sum of discounted cash flows) over time for the Hard Coal industry under each scenario with 80% confidence bands.



plants. This could indicate that the 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 (Hogan, 2017).

Although the results of the DCAS and the EPAS are almost the same, the reasons are quite contrary. In the EPAS, high carbon prices increase the variable costs of hard coal over those of gas; therefore, these technologies switch their position in the merit order by 2024 or 2025. Hence, the earnings as well as the full-load hours decrease since they act as peak-load power plants, and this leads to a lower NPV than for the MCAS. On the other side, in the DCAS as well as in the MCAS, the cash flows are negative, leading 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.

This is corroborated by the VaRs, which display similar values of €-3.42 and €-3.65 billion in the 1% quantile in the DCAS and the EPAS, respectively. A strong incline of the VaRs, however, is visible in the MCAS. The MCAS suggests that, with a probability of 99%, the NPV will not fall below €-1.46 billion, economizing around €2.0 billion in losses in comparison with the DCAS.

Summarizing, a coal phase-out increases the valuation of hard coal (from €-3.06 to € 1.13 billion) due to a shorter period of negative cash flows. We assume that hard coal plants will be decommissioned before they become stranded assets.

4.1.3 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 their absolute value but also in their structure. The fact that lignite generally has a higher valuation when the two 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 it only considers existing power plants.

More interesting is the difference in the structure of the results: lignite has the highest valuation in the DCAS, while hard coal's valuation is almost as low as in the EPAS. Due to its low variable costs, lignite is constantly able to generate positive cash flows, which decrease over time due to the increasing carbon prices. In contrast, hard coal struggles to pay off its fixed costs in most years since it often sets the market clearing price. When setting the market clearing price, fixed 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 in their respective valuations. While, for lignite, the coal phase-out poses a risk, it does not for hard coal. In contrast, both technologies lose their entire value in the EPAS. The main reason is the feed-in from renewable energy sources and moreover the high carbon prices, which cut the profits and valuation compared with the MCAS for both hard coal and lignite.

4.1.4 Sensitivity Analysis

To assess our results critically, we incorporate several sensitivity analyses into our study. For the individual scenarios, we find that the assumption about the price developments of hard coal and natural gas are quite important and have the greatest impact on the overall NPV. However, since we assume different price ranges over the different scenarios, we implicitly account for this impact by comparing the scenarios. Further impactful assumptions are the base load and the cost of capital.

The base load constitutes a crucial input factor and can have a considerable impact on the profitability and thus on the NPVs of the two technologies. In this study, the 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.[8] 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), which we refer to as the "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 the lower limit to the mean to the upper limit).[9]

The results for the different base load assumptions are summarized in Table 4 (detailed results are reported in Table 6, 7, and 8 in the Appendix). 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.

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 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.

In addition to the sensitivity analysis of the base load, robustness is also checked by a sensitivity analysis on the WACC. In our analysis, we use 5.6% to discount the annual cash flows. We

8. This could be due to increased political ambitions or because their economic profitability increases when the investments decrease.

9. See Table 2 for the base load assumptions for each scenario. For the technical details, please refer to the Supplementary Material to this study.

Table 4: Mean NPVs of the simulation employing different base load assumptions.

	DCAS		MCAS		EPAS	
Base Load	**Hard Coal**	**Lignite**	**Hard Coal**	**Lignite**	**Hard Coal**	**Lignite**
Upper	–3.06	14.04	–1.13	9.49	–3.40	0.14
Mean	–4.15	8.21	–2.47	3.16	–2.98	–2.81
Lower	–3.16	2.43	–0.89	1.91	–2.65	–0.80
Stochastic	–4.10	8.74	–1.86	4.45	–2.98	–1.38

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 €.

repeat our analysis with 4.6 and 6.6%. 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.

Besides the input data, which have been critically reflected in the sensitivity analysis, the chosen approach should be considered. In contrast to a complex power market model that calculates the power plant dispatch, simplifying assumptions are made for the dispatch of power plants and thus also for their profitability. The result is that, on the one hand, all the power plants of a technology are treated equally and, on the other hand, medium-load power plants in particular are probably underestimated. Additionally, our approach allows us to work with a high temporal resolution and calculate each year in comparison with typical market models, which only account for a few years. The Monte Carlo analysis also absorbs uncertainties in the input parameters much better than other models.

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 the base load, for instance due to the expansion of renewable energies, reduces the valuation of lignite and therefore poses the risk of stranded assets. The impact of the cost of capital is the same for all the scenarios and does not influence the difference between the scenarios.

4.2 Economic and Political Implications

4.2.1 Compensation Payments

The decrease in valuation, shown in Section 4.1, highlights 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 that occurred 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 compensation, claiming damages to 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 as well as indicating the government's accountability for the closely linked losses resulting from the coal phase-out (Bos and Gupta, 2018).

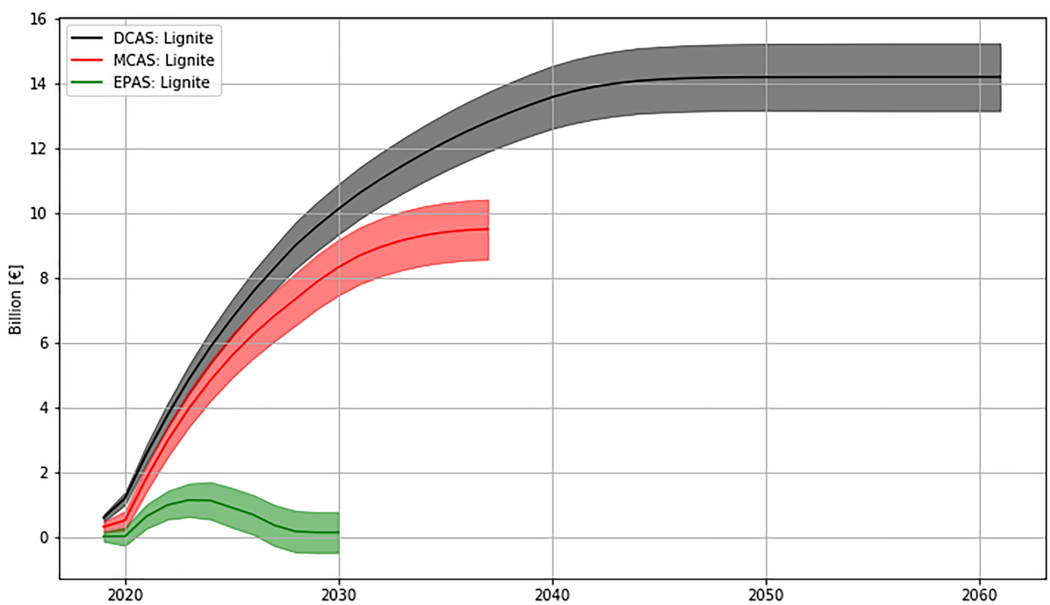
Due to the interdependencies between politics and the energy industry, compensation payments remain highly critical to policy makers (Bos and Gupta, 2019). In this regard, compensation payments for stranded assets could present a practical tool to achieve a reduction in the coal capacity. In the past, 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, ultimately from German taxpayers (Zhao and Alexandroff, 2019). This equals €0.6 billion per GW of installed capacity. The Coal Commission agreed with this payment in its final report, claiming that potential compensation payments for operating and yet-to-operate power plants may be orientated toward 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 due to be paid to lignite power plants in the security reserve mode (Federal Ministry for Economic Affairs and Energy (BMWi), 2019). On the other hand, the highly exposed energy supplier RWE raised a claim for compensation for decommissioning coal power plants estimated in the range of €1.2 to €1.5 billion per GW of installed capacity (Reuters, 2019). On that basis, the payments could amount 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. The different claims and proposals are summarized in Table 5.

Based on our results, we calculate a total stranded asset value of €2.62 billion for a phase-out by 2038 instead, which is also depicted in the difference between the respective end points of the DCAS and the MCAS in Figure 5. Even if we only take lignite power plants into consideration,

Table 5: Overview of current and past compensation payments.

	Fuel Type	Capacity [GW]	Sum [Bil. EUR]	Comp. per GW [Bil. EUR]	Source
Security reserve	Lignite	2.7	1.6	0.6	Zhao and Alexandroff (2019)
Coal phase-out	Hard coal & Lignite	~40	24	0.6	Federal Ministry for Economic Affairs and Energy (BMWi) (2019)
Industry claim				1.2–1.5	Reuters (2019)
Governmental proposal	Lignite	~20	4.35	0.22	Minister of Finance

Figure 5: Development of the net present value (sum of discounted cash flows) over time for the coal industry in each scenario with 80% confidence bands.



the total amount only sums up to €4.55 billion. Thus, our estimates are considerably lower than the compensation demanded by the industry but close to the compensation offered by the government.

On another note, an even earlier phase-out would be more costly but still below the raised claims. The survey by Rinscheid and Wüstenhagen (2019) suggests that German voters would accept additional costs of €8.5 billion for a phase-out by 2025 or €3.2 billion by 2030 compared with 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 €11.62 billion (€9.35 billion) for both technologies (lignite only). The large difference between the phase-out dates is depicted in Figure 5. Thus, the total stranded asset value for a phase-out in accordance with the Paris Agreement would sum up to €14.24 billion (€13.90 billion for lignite only).

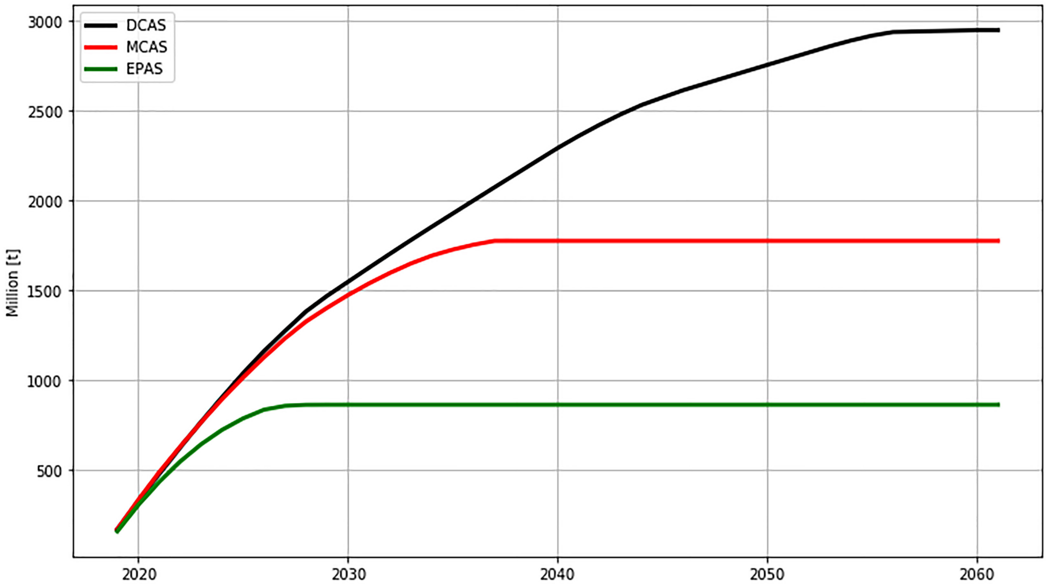
In addition to the far smaller decrease in valuation for an early phase-out, our study provides evidence that the phasing out of coal-fired electricity generation by 2030 does not require accelerated decommissioning. Instead, the introduction of carbon prices on adequate levels presents economic conditions in which 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 phasing out of lignite and hard coal simply based on economic conditions. This outcome confirms the argument of Michaels (1994) that stranded investment compensation solely represents the 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 suggested by Forum Ökologisch-Soziale Marktwirtschaft (2019). However, as of January 2020, the settlement price for CO2 emission allowance futures is about €25/t.

4.2.2 Carbon Dioxide Emissions

The yearly CO2 emissions from hard coal and lignite are calculated for the baseline scenarios to provide an overview of Germany's political ambitions for mitigating climate change's impacts. Note that our calculations do not account for emissions from substitutional power production, that is, gas-fired power plants. Figure 6 depicts the CO2 emissions accumulated in each scenario based on the mean values of the distribution. The reduction in CO2 emissions is in line with Jewell et al. (2019), who estimated the avoided emissions as being in the range from 0.6 to 1.6 Gt depending on the actual phase-out date. If the phase-out for Germany remains in 2038, 1.17 Gt of CO2 emissions are avoided compared with a phase-out in 2061. The early phase-out by 2030 scenario (EPAS) even has the potential to save up to 2.08 Gt of emissions. In comparison with the current phase-out by 2038, the accelerated phase-out of hard coal and lignite is able to cut the CO2 emitted by 51%. The comparison with the hypothetical emissions approximates the extent of emissions that result only from coal-fired power generation.

Without additional policy measures, emissions will decrease slowly due to the ageing of the coal fleet without retro-fits and new power plants starting operation. However, accelerating the phasing 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) has indicated that only a continuous reduction in coal-related CO2 emissions down to zero by 2030 will ensure compliance with the defined goals. Thus, Germany will not be able to meet its reduction goals set in the Paris Agreement in 2015 given the time frame of 2038 proposed by the Coal Commission. Combining the reduction in CO2 emissions with the associated reduction in NPV for the coal industry, we calculate that the coal phase-out essentially would pay €2.24/t CO2. In contrast, a phase-out conforming to the Paris Agreement would sacrifice €6.84/t CO2.

Figure 6: Cumulative development of CO2 emissions for each scenario.



4.2.3 Financial Market Implications

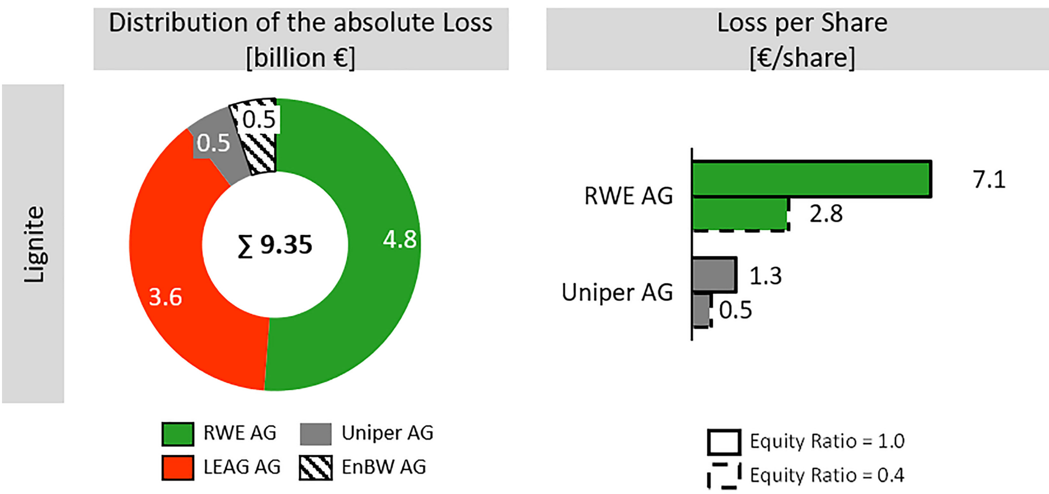
Our Monte Carlo analysis shows the extent of asset stranding in the coal power generation industry. The lignite and hard coal industries both suffer losses in valuation between a scenario with the current energy and climate policy objectives (MCAS) and a scenario with ambitious objectives to reduce greenhouse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

For further assessment, the MCAS displays the valuations of the hard coal and lignite power generation industries, which are considered in the current share prices of utility and power generation companies. To estimate the potential adverse impacts that stock prices of exposed companies may experience in the case of the EPAS, the decrease must be transferred to the shareholder value. We approach the individual stock devaluation by decomposing each company's stock price to the fraction concerned with coal-fired power generation.

In this study, the absolute decrease between the two scenarios is broken down into the affected portfolio of power plants. Neglecting municipal utilities, the companies EnBW, LEAG, RWE, and Uniper accounted for 100% of the lignite installed capacity in 2020. For hard coal, 79% of the installed capacity belonged to Uniper, EnBW, Vattenfall, ENGIE, STEAG, and RWE. Table 9 in the appendix presents the proportions of the hard coal and lignite capacities, respectively. It shows that EnBW, 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. Accordingly, the percentage of capacity is used to calculate the absolute loss between the MCAS and the EPAS. The absolute loss, and thus the stranded asset value, amounts to €9.35 billion for lignite and €2.27 billion for hard coal. Next, this absolute loss is divided by the shares issued by the company.

Since only lignite has positive cash flows in the MCAS, we focus our analysis on lignite only. Figure 7 displays the different extents of vulnerability of the investigated shares for lignite. Presupposing that equity capital also covers losses of debt, the accumulated losses for RWE's stock amount to €7.10/share, indicating that RWE, with its large lignite fleet, will be greatly affected by a coal phase-out prior to 2038. It is followed by Uniper's share, which suffers losses of €1.30/share from lignite alone; we should mention that Uniper has a hard coal power plant portfolio of about the same size. Given autonomous financing, losses for equity only occur for the share of equity in a power plant. Assuming a 60% debt-to-capital ratio (Fraunhofer ISE, 2018), the losses for RWE and Uniper are €2.80/share and €0.50/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—phasing out of coal by 2030 not only has visible valuation impacts but directly impairs the shareholder value of the affected companies, especially RWE and Uniper.

Figure 7: Absolute loss and loss per share of listed companies.



In summary, this study puts stranded assets into a direct relationship with equity prices, exemplarily 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 asset stranding. This finding corroborates the theoretical studies aiming at the potential impairment of bonds and equity in the financial sector, as discussed in Section 2.[10]

5. CONCLUSION AND POLICY IMPLICATIONS

The results from our scenario analysis show a decrease in valuation for lignite if the phasing out of installed capacities by 2038 and moderate carbon and fuel prices are assumed. Unlike lignite, the NPV of hard coal increases when assuming the phase-out by 2038. This difference is

10. Our approach is simplified in the sense that we do not adjust for the distribution of losses over time. The reduction in cash flows and installed capacities is not allocated equally across the years. However, this assessment presents an approximation to the extent of adverse impacts on stock prices.

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 with the scenario of phasing out by 2038.

Taken together, the time frame for phasing out coal by 2038, as proposed by the Coal Commission, would help the German hard coal and lignite industries to save €11.62 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 shifts 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 progressive policy measures, our findings ultimately call for the incorporation of these climate-related risks into the risk disclosure of companies (Düsterhöft et al., 2020) and 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 the stranding of physical assets and the implications for the financial sector. Research has yet to proceed with the quantitative assessment of stranded assets related to climate change 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 to academics and policy makers. Hitherto, most studies have used 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.

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APPENDIX

A.1 Sensitivity Analysis of the Base Load

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

	DCAS		MCAS		EPAS	
Parameter	**Hard Coal**	**Lignite**	**Hard Coal**	**Lignite**	**Hard Coal**	**Lignite**
Minimum	–4.75	6.20	–3.09	1.31	–3.57	–3.88
Maximum	–3.57	10.20	–1.89	4.92	–2.25	–1.75
Mean	–4.15	8.21	–2.47	3.16	–2.98	–2.81
VaR ($\alpha = 0.05$)	–4.36	7.04	–2.68	2.02	–3.19	–3.33
VaR ($\alpha = 0.01$)	–4.46	6.72	–2.77	1.71	–3.28	–3.51
St. Dev.	0.13	0.70	0.13	0.67	0.13	0.32

The different scenarios that we refer to are the Delaying Climate Action Scenario (DCAS), Maintaining Climate Action Scenario (MCAS), and Enforcing the Paris Agreement Scenario (EPAS). We denote the value at risk as VaR and the standard deviation as St. Dev. Numbers are in billion €.

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

	DCAS		MCAS		EPAS	
Parameter	**Hard Coal**	**Lignite**	**Hard Coal**	**Lignite**	**Hard Coal**	**Lignite**
Minimum	–3.88	0.95	–1.56	0.40	–3.32	–2.12
Maximum	–2.47	3.86	–0.10	3.35	–1.85	–0.31
Mean	–3.16	2.43	–0.89	1.91	–2.65	–0.80
VaR ($\alpha = 0.05$)	–3.43	1.60	–1.16	1.08	–2.88	–1.33
VaR ($\alpha = 0.01$)	–3.54	1.35	–1.27	0.84	–2.98	–1.52
St. Dev.	0.17	0.50	0.16	0.49	0.14	0.32

The different scenarios that we refer to are the Delaying Climate Action Scenario (DCAS), Maintaining Climate Action Scenario (MCAS), and Enforcing the Paris Agreement Scenario (EPAS). We denote the value at risk as VaR and the standard deviation as St. Dev. Numbers are in billion €.

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

	DCAS		MCAS		EPAS	
Parameter	**Hard Coal**	**Lignite**	**Hard Coal**	**Lignite**	**Hard Coal**	**Lignite**
Minimum	–5.25	1.33	–3.15	0.28	–3.84	–3.80
Maximum	–2.51	15.92	–0.35	11.22	–2.20	1.51
Mean	–4.10	8.74	–1.86	4.45	–2.98	–1.38
VaR ($\alpha = 0.05$)	–4.75	5.06	–2.59	1.40	–3.37	–2.82
VaR ($\alpha = 0.01$)	–4.95	3.74	–2.76	0.97	–3.50	–3.12
St. Dev.	0.47	2.60	0.52	2.57	0.21	1.00

The different scenarios that we refer to are the Delaying Climate Action Scenario (DCAS), Maintaining Climate Action Scenario (MCAS), and Enforcing the Paris Agreement Scenario (EPAS). We denote the value at risk as VaR and the standard deviation as St. Dev. Numbers are in billion €.

A.2 Financial Market Implications

Table 9: Percentages of hard coal or lignite capacity share.

Company	Power Plants	Capacity [MW]	Share of Capacity [%]	Shares Outstanding [Mio.]
Lignite				
RWE AG	16	8868	51.25	676
LEAG AG	11	6662	38.50	—
Uniper AG	2	900	5.20	366
EnBW AG	1	875	5.06	—
Hard Coal				
Uniper AG	6	3932	21.25	366
EnBW AG	5	2979	16.10	—
Vattenfall AB	4	2164	11.70	—
ENGIE SA	3	1553	8.39	2435
STEAG GmbH	3	1030	8.39	—
RWE AG	1	764	4.13	676
Others	15	3914	21.16	—

Capacity values and power plant ownership based on the power plant list as of February 2021. Source: Own presentation based on Bundesnetzagentur (2021).