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How does Climate Change Affect the Transition of Power Systems: the Case of Germany

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Summary

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Keywords: Electricity, Energy, Energy Utilities, Gas, Hydrocarbons, Climate, Climate Change, Desertification, Drought, Global Warming, Weather

JEL Classification: Q4, Q54

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How does climate change affect the transition of power systems: the case of Germany

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Abstract

The effects of extreme weather events, such as heat waves and droughts are taken into account in both global and European policies. Accordingly, the protection of critical infrastructures and in particular, the resilience of the energy sector was the subject of intense research. There are regional differences in the degree of exposure to extreme events. In Northern Europe, their intensity has increased dramatically within a decade. In our analysis we identify emerging risks of extreme weather events, in particular, droughts and high temperatures, for the German power sector. Furthermore, we consider how European policy addressed these severe risks. Our analysis is based on extensive datasets covering temperature and drought data for the last 40 years. We find evidence of a higher frequency of power plants outages as a consequence of droughts and high temperatures. We investigate increases in the wholesale electricity price and price volatility and develop a capacity-adjusted drought index. The results are used to assess the monetary loss of power plant outages due to heatwaves and droughts. We stress that increasing frequencies of such extreme weather events will aggravate the observed problem, especially with respect to the transition of the power sector.

Keywords: JEL Q4: Electricity, Energy, Energy Utilities, Gas, Hydrocarbons; JEL Q54: Climate, Climate Change, Desertification, Drought, Global Warming, Weather.

Highlights

- Outlining the interactions between extreme weather events and the electricity market.
- Assessment of intensity and risk of extreme droughts at power plant locations.
- Estimation of monthly capacity-adjusted drought index and wholesale price volatility.
- Analysis of the effect of high temperatures on power plant outages.
- Calculation of the value of generation capacities lost due to power plant outages.

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1. Introduction

The link between climate change and a higher frequency of extreme weather is gaining international recognition of policy makers and attention of the scientific community. The IPCC special report defines extreme events as “risks/impacts to human health, livelihoods, assets and ecosystems from extreme weather events such as heat waves, heavy rain, drought and associated wildfires, and coastal flooding” [1, see p. 11]. Climate change is already posing new region-specific challenges on technical and socio-economic systems. The summer of 2018 gave us a preview of possible adverse future developments. Heatwaves were observed in North America, Western Europe and the Caspian Sea region while rainfall extremes occurred in South-East Europe and Japan [2]. It was characterized by an enduring heat wave accompanied by droughts in various regions throughout Europe that lasted until the end of Autumn [3]. In the summer of 2018, France and Germany reported cuts of nuclear and coal-based electricity generation. Wholesale market prices were hitting highest in Italy and Spain where weather forecasts predicted temperatures to rise [4]. Being the largest contributor to greenhouse gas emissions in the EU, the electricity sector itself is vulnerable to climate change. While national and EU energy policies aim towards an increased deployment of renewable energy capacities to reduce the CO_2 intensity of the energy sector, their availability is highly dependent on weather conditions. The combination of cold spells and lack of sun in February – March 2018, as well as wind lulls and high temperatures as in July 2018 [4] can be a hard test for an energy system in transition that still relies on conventional generation capacities. The electricity supply risks during the transition process towards a more climate-friendly electricity supply system have become more severe. The stability of a power system with a high share of variable renewable energy generation will depend on the existence of flexibility options and balancing capacities [5, 6]. Key opportunities for the provision of flexibility and balancing capacities within the transition period are thermal power plants like coal, natural gas and nuclear power plants. In hot seasons these plants’ functionality crucially depends on sufficient cooling water supply. Consequently, they are heavily affected by changes in cooling water temperature and availability.

These challenges are not only faced in Europe, but as Van Vliet et al. [7] show by 2040-2069 thermoelectric power plants worldwide will experience reductions in usable capacities associated with insufficiency of cooling by up to 84-86 %.

This study aims at further improving the understanding of possible effects of climate-change induced extreme weather events on power systems and thereby at improving the risk-preparedness of the electricity sector. The findings will help to better understand the vulnerability of critical infrastructures in the electricity generation sector and identify the assets that are subject to high risk. The findings applicable in the assessment of the need for renovation or phase-out of old capacities, taking into account the cost of renovation against phase-out. The analysis requires meteorological and electricity market data with a high geographical and temporal resolution. The availability of the data sets limits to the scope of this study. Thus, we focus on the impacts of extreme weather events on the German electricity market. Econometric analysis tools are used to quantify the physical effects of climate conditions on power plants production schedules.

In the paper, we provide a holistic analysis of climate change effects for the German power sector. In contrast to studies analysing long term mean temperature increases, we focus on hot extremes, the higher probability of droughts and precipitation deficits as highlighted in [1]. The issue of interdependencies between water availability and use of water for producing fuels, generating electricity and cooling power plants is receiving increasing attention [8]. The soil moisture index (SMI) and temperature extremes are taken as a proxy for the climate change hazards of various intensity across different parts of Germany. The difference in the exposure levels is studied, taking into account the locations of power generation facilities in Germany. Superimposing installed generation capacities over the hazard map, we quantify risk for specific locations across different generation technologies. Then we examine data on forced outages of power plants both at the times of an intermediate exposure of the energy sector to weather extremes and over the year. Following the reports on multiple outages of thermal generation units in European countries and Germany during recent heatwaves [4], we estimate an effect of water shortages on power generation. We provide estimates of current economic damages caused in the form of risk-adjusted cost of outages.

For the German power sector, we are able to assess the risk-adjusted economic costs of climate change for the given composition of the power system. For our analysis, outages are quantitative indicators of vulnerability determined by hazard and exposure. The risk-adjusted cost of outages characterizes current economic damage to power generation from climate change. About 70 years of location-specific historical data on moisture helped us to reveal current trends and connect the deterioration of water resources with the global temperature increase.

Up to now, long-term plans of the transition of the power generation capacities are focused on the decarbonization of energy production. Our research draws attention to the vulnerability of power generation to climate change. Any long-term plans to rebalance generating capacities should take into account possible external shocks on the energy system attributed to climate change: a large number of studies focuses on temperature-sensitive demand side impacts, impact on wind and solar resources, deterioration of water supply for cooling and lowered potential of run-of-river generation [9, 10]. Since most of these studies emphasize uncertainty stretched decades into the future, we attract attention to a new aspect of interest for the study of electricity markets: spatial dimension of the planning problem in the short-run for the German power market. Assessment of generation capacities installed and their exposure to weather extremes can serve as a starting point for dealing with planning in the electricity sector: investments, renovation and phase-outs. Our analysis can be replicated for other countries based on the availability, granularity and transparency of the weather and power system information.

The research aims to present the relevant foundation for the identification of measures that reduce overall vulnerability of the electricity system and to provide guidance for policy measures on how to design the energy transition while accounting for current effects of climate change.

The paper is organized as follows. In Section 2 we present the key challenges recognized and addressed by policy and research in the domain of climate change effects on the infrastructure and power sector in particular. Section 3 provides a description of the main datasets. The analysis, methods applied, and results of the analysis are presented in Section 4. Section 5 highlights main discussion points underlined in the analysis. In Section 6 we elaborate policy remarks.

2. Key challenges for the power sector exposed to the effects of climate change

Climate change affects countries around the world to a varying degree. Even under intially more rigorous climate conditions in southern regions as water scarcity and hazards induced through long-term poor land-use practices, climate change puts additional stress on developing power systems and affects future planning decisions: as in Sudan Sahel region of Nigeria [11], Bangladesh [12] and Pakistan [13]. Negative extreme events, as heat waves and droughts, became to be particularly intensive in Northern and Central Europe over the recent years [8, 14, 15]. Another significant regional aspect that defines the resilience of the power system is the policy framework that sets objectives and regulations for the power sector approaching ambitious mitigation and adaptation goals. In this regard, Germany is a good example of the complex system in the transition to a low carbon future that is subject to climate change effects. In this section we will analyse the key aspects of a broad range of extreme effects of climate change in the view of recent policy and research developments. Our motivation for the analysis is driven by the findings described in the following paragraphs.

2.1. Elements of the European policy framework addressing extreme events

The European electricity system moves towards a high level of integration, which requires higher resilience and cooperation between member states but also redistributes risks of cross-border failures in generation and transmission capacities [16]. At the European level, the threats of extreme weather events are addressed in multiple ways. Among the EU's activities to counter risks of extreme events is the recent adoption of the regulation on risk-preparedness in the electricity sector (in June 2019) [17]. In accordance with Article 5 of this regulation, the

European Network of Transmission System Operators for Electricity (ENTSO-E) shall submit to the European Union Agency for the Cooperation of Energy Regulators (ACER) a proposal for a methodology to identify “the most relevant *regional* electricity crisis scenarios”. Concerns about the vulnerability of energy systems are also expressed in the European Commission’s programme for critical infrastructure protection (EPCIP) that regards both energy and transport sectors as “European critical infrastructures” (ECI) [18]. The programme pays specific attention to terrorism but highlights the vulnerability of network infrastructures in case of extreme natural events that “are not constrained by international borders”. The European regulatory framework plays an important role in national-level policies of the member states towards the availability and the usage of cooling water for power plants. The Water Framework Directive [19], which came into force in December 2000, provides a common framework for the management and preservation of European water networks. In 2006 it was replaced by the European Freshwater Directive [19] that sets boundaries to the amount and maximum temperatures of the mixed water at the discharge point and to the maximum heating range. Not only the electricity generation but also inland waterways are recognised as ECI, which stresses the perceived risk of possible failures in bulk delivery of energy carriers and other goods. Thus it highlights the aspect that not only power outages due to the lack of cooling waver undermine the generation sector, but also on-time deliveries of energy carriers as steam coal are at risk. According to the German Coal Importers Association (Verein der Kohlenimporteure e. V.) [20], up to 50 % of imported coal is transported via domestic waterways (see Appendix, Table A 1). The complexity of these interactions between the sectors can be addressed by the *new approach* to making ECI *more secure* introduced by the EC in 2013 [21] that drives specific attention to interdependencies between critical infrastructures and industry [22].

In 2018 the EC set out reporting requirements to the member states about their national adaptation actions (in particular availability of cooling water for power plants) to access an effect of introduced climate policies and recent climate effects [23]. Struggling for a decarbonised electricity system, some of these measures may enhance its vulnerability to extreme weather events, e.g. carbon capture and storage (CCS) techniques. The EU’s emission reduction goal aims at an increasing share of variable renewable energies with fossil-based generation providing balancing power to the electricity system. Under these conditions, the key role is given to carbon capture techniques. The last available EU reference scenario projects moderate development of CCS until the end of 2050 [24]. However, while the deployment of carbon capture allows to decarbonize the electricity system, the water intake of power plants equipped with this technology is considerably higher than that of conventional plants [25]. This implies an increasing threat of insufficient cooling water availability at the time of droughts and high ambient temperatures, as well as a need for additional investments in cooling technologies.

2.2. Key aspects recognised in the scientific literature

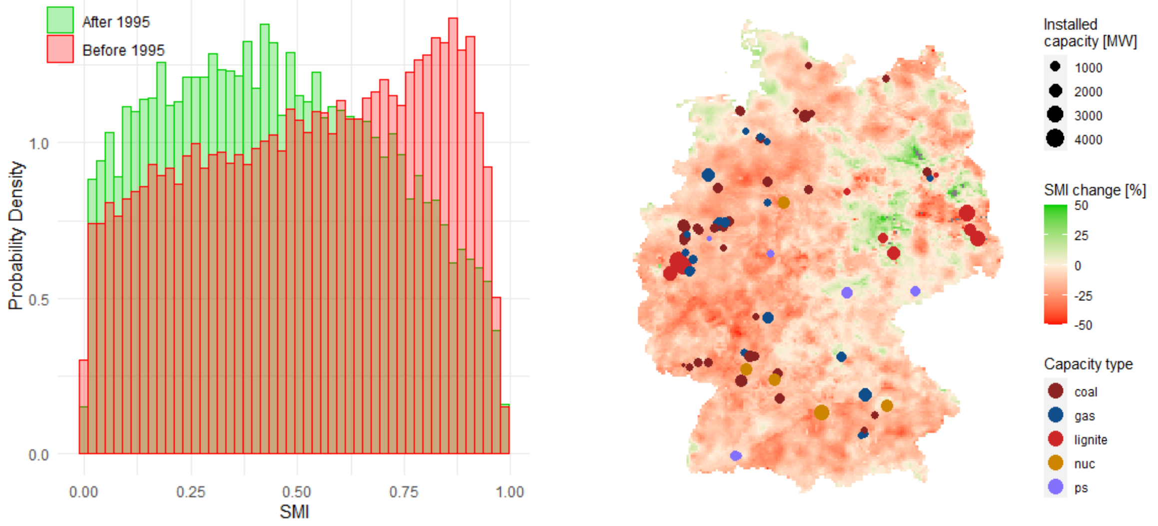
Table 1 provides an overview of the scientific studies that contribute to the understanding of extreme weather events on the power system and interconnected services as the delivery of energy carriers. The studies have different temporal and spatial resolutions, as well as methods to analyse effects on the aggregate power sector, including different mathematical modelling approaches. They are based on the assumptions of long-term temperature and precipitation trends, as well as structural changes in the electricity demand and future generation mix. In contrast, our analysis is focused on the assessment of the increased risk of extreme climate effects at high spatial resolution in the medium and short-term, where they represent highest threat to the system security as mentioned in [26].

Table 1 – Critical infrastructures and climate.

Hazards	**Energy**		**Transport**	
Heat	Reduced power output:		Direct damages to infrastructure:	
	- decrease in efficiency due to high ambient temperature	[27-29]	- road ways: material fatigue due to thermal expansion	[30] [31]
	- the decrease in efficiency due to cooling system failures	[7, 28, 32]	- electricity transmission and distribution grids: efficiency losses, physical damage due to heat stress	[27, 29, 30]
	- the decrease in PV efficiency due to high ambient temperature	[29, 30]	- gas transmission grids	[30]
	- high electricity demand for cooling (households, food industry)	[30]		
Drought	Reduced power output:		Strained navigation of river ways	
	- hydropower	[7, 33, 34]	- delivery of goods: restriction of loading capacity	[30]
	- CCS (water intake and discharge for cooling)	[25]	- delivery of fuel (e.g. bulk ships for coal delivery)	[30]
	- biofuel production			
	- nuclear (regulation on water intake for cooling)	[7, 35-37]		
	- thermal power plants with water cooling systems – gas and hard coal	[25, 28, 30, 34, 37]		

The recent findings highlight that drought and heat damages will jointly comprise 94% of all hazard impacts on the European energy sector by the end of the 21st century [38]. Based on historic data from 1971 to 2000, Van Vliet et al. [32] highlighted tense conditions regarding availability and high temperatures of cooling water for a future scenario from 2031 to 2060. In a similar way, Van Vliet et al. [34] investigate the effects of water constraints in European electricity markets and their effects on wholesale electricity prices. Hoffmann [28] uses a control period of 1960 to 1990 for the climate data in order to assess the water-electricity-nexus for the future periods from 2011 to 2040 and 2041 to 2070. Both studies apply a comprehensive approach to estimating the risks for the European electricity sector under new climate challenges. They accounted for climate change and their cumulative effects until the end of the 21st century. In short-term (last 20 years), the growing frequency of extreme events against the persistent growth of global temperature trend represents an additional stress to the electricity generation and transportation systems. Most of studies in Table 1, following the studies in [9, 10] focus on long-term mean surface temperature changes, disregarding the intensity of extreme events. Although the latter tend to increase in time and magnitude. Figure 1 a) depicts the probability density of SMI values for the two periods 1951-1995 (red) and 1995-2018 (green).

The necessary actions may diverge with consideration of the different time-frames of climate change impacts. For example, Rübbelke and Vögele [33] analyse local weather changes that affected nuclear and hydropower plants, under the assumption that gas- and coal-fired power plants will be used to fill supply gaps due to restricted water availability. Their findings foresaw and sketched the current situation on the power market as of summer 2018 [4] with heat and wind lull produced temporarily gains for coal generation until the point when their availability also shrieked at rising temperatures. Since last decade an assessment of adaptation measures for the energy sector highlighted high annual costs required to deal with climate change impacts in Europe [30]. The trade-off between investment in new cooling systems and incurring losses is highly dependent on the location of power plants and regions with high electricity demand. High granularity of the introduced analysis allows to identify generation capacities at risk based on multiple criteria, including exposure to restricted cooling water and high ambient temperatures.



(a) (b)

Figure 1 – (a) Histogram and probability density (y-axis) of SMI values (x-axis) for two periods, and – (b) Ratio [%] of average SMI index from 1995-2018 to the long-term average 1951-1995
Data source: Own compilation based on German Drought Monitor [39], Entso-E [40].

Taking the German power market as a study focus is justified by its central geographical location, a high volume of interconnections with neighbouring markets, and the highest installed power plant capacity in Europe. Figure 1, b) relates the locations of power plant capacity types to regions with higher (green) and lower (red) levels of moisture relative to the long-term trend. The colour of the dots represents the power plant type, while the diameter indicates the installed capacity in [MW] of each capacity type. The impairments of extreme weather events on thermoelectric generation in Germany can be observed during the heatwave and drought in 2018 (see Figure 1, b), which resulted in multiple forced shutdown of thermal power plants in some areas of Germany [4]. Dry and hot summers from 2015 to 2018 resulted in average annual moisture levels well below the long-term averages of 1951-2015 for most regions, except the northern seashore (in green colour in Figure 1, b). With some regions revealing only minor changes (in white), most of central Germany experienced extreme low precipitation levels. These alarming observations necessitate improving the understanding of the effects of climatic changes on the stability of future power systems and of the implications for the security of electricity supply, in particular as extreme weather conditions tend to further exacerbate in the future. In the following analysis, we assess the risk of future extreme events, in particular droughts and heatwaves, on the German power system.

3. Data description

For an analysis of the interrelation between the security of electricity supply and extreme weather events, attention has to be paid to a diverse set of aspects. These include, e.g., reduction in the availability of generation capacities, long-term data on temperatures and droughts, as well as electricity price peaks. In the current study, we aim to evaluate environmental conditions and associated risks, by analysing meteorological and electricity market data at each power plant location. Table 1 presents an extract of the main data sets.

Table 2 – Data sources.

Data	Source	Period
Spatial precipitation data	German Drought Monitor (UFZ Leipzig)	1951-2018
Spatial temperature data	Climate Data Center (Deutscher Wetterdienst - DWD)	1983-2018
Forced unplanned unavailability of generation units	ENTSOe Transparency data: ENTSOe dataset [15.1.B]; error codes: B18 (failure), B20 (shutdown), A95 (failure - no reason)	2015-2019

Two stress factors for the electricity system, which are caused by extreme weather conditions, are taken into consideration: (i) droughts and (ii) high temperatures (heatwaves). Drought data is used to evaluate hydrological droughts, which can affect power plant cooling systems. Precipitation data with a high regional and special resolution is derived from the soil moisture index (SMI) database of the German Drought Monitor (GDM) [39]. The GDM provides drought data in a 4 km raster grid. Following the SMI specification, the index ranks the severity of droughts from 0 to 1. The index displays daily data and dates back to 1951. The second meteorological dataset, which is used to identify heatwaves, is the Climate Data Center of the German Meteorological Service (DWD). In this dataset, temperature data is available at hourly, daily, monthly and yearly resolution.

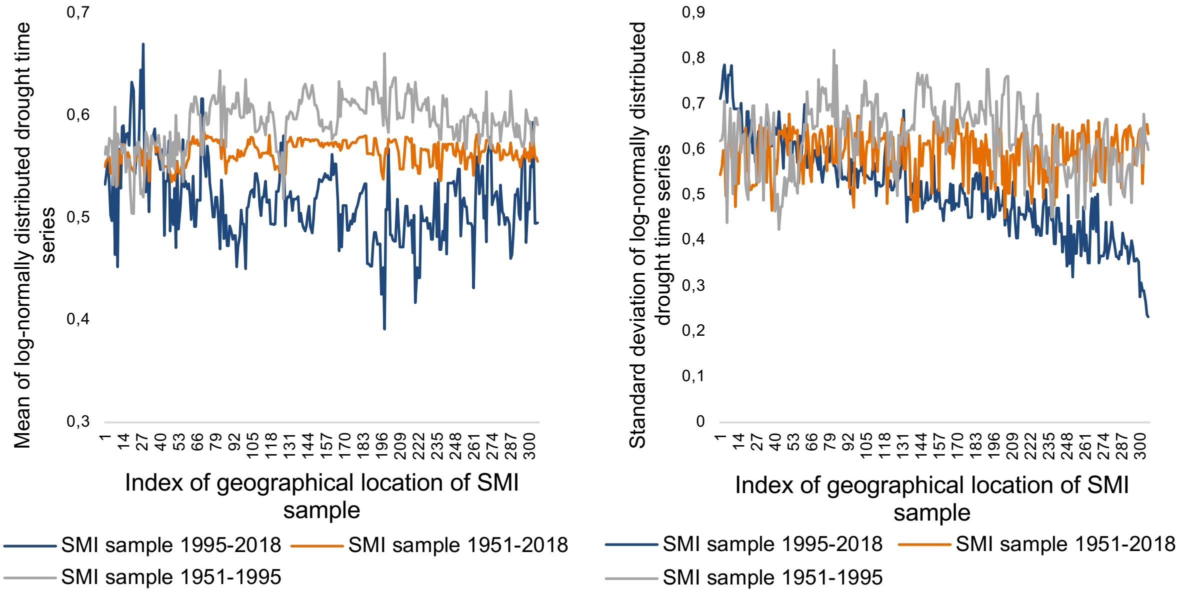
The Transparency Platform of the European Network of Transmission System Operators (ENTSO-E) lists individual generator and power plant (utility) outages in the European electricity market. The outage data includes both full (shutdown) and partial outages. Information on the outages and the associated power plant names, their Energy Identification Codes (EICs) published by [40] is matched against a database of German power plants, made available by the German Federal Ministry of Economic Affairs and Energy, which contains the geographical location of the individual power plants.

Applying econometric analysis tools allows this study to quantify the physical effects of climate conditions on power plants production schedules. The research aims to present relevant results for the identification of measures that reduce overall vulnerability of the electricity system and to provide guidance for policy measures on how to design the energy transition while accounting for current effects of climate change.

4. Analysis and Results

4.1. Assessing the risk of droughts in the nearest future

The distribution of mean SMI in most parts of Germany changed considerably during the period from 1995 to 2018. The investigated sample accounts for 307 geographic locations with thermal power plants that are operational as of 2019. SMI is itself an uncertain variable. For each site, it is known up to probability distribution. The data analysis revealed some important changes it the shape of the distribution. The probability of mass shifts left (Figure 1), which means a reduction of the mean value of SMI over time and a decrease in standard deviation. This tendency is observed for about 80% of all locations (see Figure 2). This means that over time the power generation has been exposed to an increasingly negative impact of droughts when we consider the availability of water for cooling purposes.



(a) (b)

Figure 2 – Recent developments in the intensity of droughts and increasing risk of extreme droughts in the future
Source: Own compilation based on [39]

From the dynamics of SMI means for the different geographical locations represented in Figure 2 (a), we can draw the conclusion that droughts have become more severe within the last 23 years. The risk is significantly higher than that gasped by the studies estimating the effects of climate change on water availability and the generation system mentioned in the introduction [7, 34, 35]. The volatility of the SMI for each location shows a trend towards consistently dryer weather conditions in most parts of Germany and increasing risk of severe droughts for particular regions (see Figure 2 b). Nearly 300 sites were considered in this analysis, focusing on locations of thermal power plants and their whereabouts. Continues exacerbation of droughts will expose the power sector to even higher climate related risks in the future.

4.2. Cointegration of droughts and temperatures

Not only the frequency and duration of droughts will increase due to climatic change but also temperatures. Based on IPCC's projection for the 21st century, fewer cold temperature extremes, and an increase in mean temperatures can be expected [41]. Furthermore, it is assumed that heatwaves will occur with a higher frequency and duration with summer temperature extremes over central and southern Europe. Data analysis reveales connections between temperature increase and SMI decline in Germany.

The Johansen test is applied to verify cointegration – the relationship of two time-series: temperatures and droughts. Temperature data is provided by the German Meteorological Service for the period from 1951 to 2018 in a monthly resolution – i.e. as monthly mean values of the average soil temperature at 5 cm depth. In the framework of the test the H_0 the hypothesis of $r = 0$ assumes no cointegration of time series. For all locations considered, the test statistics exceed the test critical value already at 1% level of significance (see Table A **2**). Thus, we have strong evidence to reject the null hypothesis of no cointegration. The second test for $r \leq 1$ also allowed us to reject the hypothesis since the test exceeds the 1% level significantly.

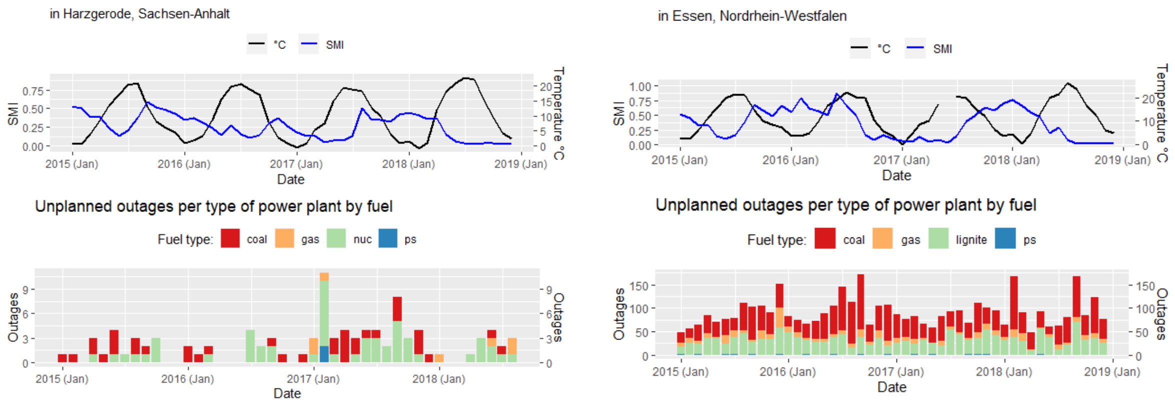


Figure 3 – Temperatures and droughts time series against power plant forced outages.

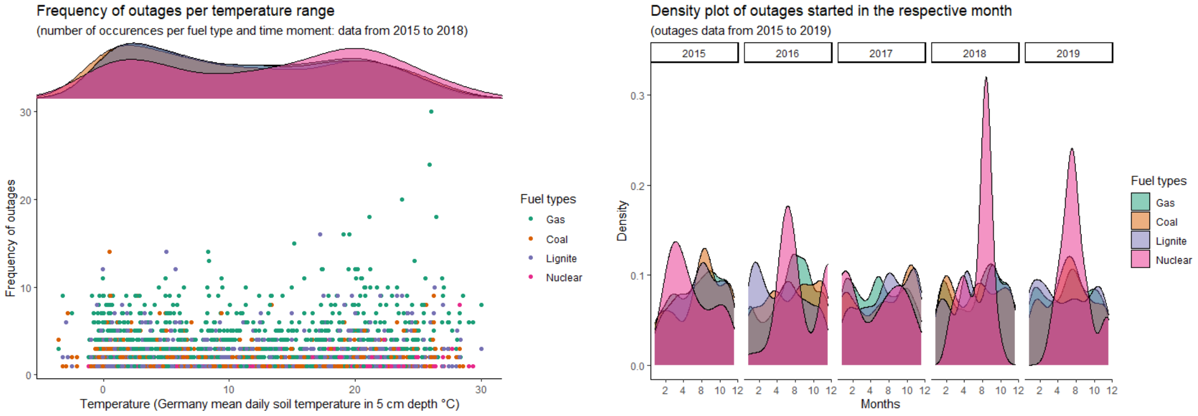
The results of the Johansen test indicate a significant connection between temperatures and droughts. Previously we have estimated probability distribution and risk of extreme dry events based on the data over the last 70 years for German territory. Referring to the analysis done for SMI, results of the cointegration test and the rising global temperature trend shown in the IPCC report, we conclude that droughts and temperature extremes will become more severe (Figure 2, b). The likelihood of low precipitation level has already almost doubled for particular locations: compare right-hand side values of the standard deviation curves for SMI 1951-1995 and 1951-2018 in Figure 2, b. The result of the cointegration test suggests that future increase in the global temperature will result in a decline of SMI and increased probability of severe droughts.

Furthermore, there is an unambiguous interrelation between temperatures and droughts on power plants' forced outages rate. Low temperatures (as in European cold spell in January 2017 and February 2018, (see Schulze, Glowacka [42])), as well as a combination of high summer temperatures with low precipitation level during summer and early autumn (see Figure 3), coincide with a high level of forced outages of thermal power plants and pump storages. The level of exposure to extreme events varies between the regions and depend on their location with some regions, especially exposed to droughts (as will be shown later in Figure 5).

4.3. Droughts, high temperatures and forced outages of thermal power plants

The scatterplot below in Figure 4 (a) maps daily temperatures and the number of forced outages of thermal power plants per unit of time in all locations in Germany from 2015 to 2018. Nearly 30 outages of thermal capacities, namely coal, simultaneously in the period from June to August for the years 2016-2018 coincide with the hottest days. The density of outages for each fuel type shows that nuclear capacities tend to have more outages at higher temperatures compared to low and mid-season. Moreover, outages that occur in summer or subsequent dry moths of autumn tend to last longer, reaching nearly 20 days (see Figure A 1 (b) in the Appendix). The u-shape of density plots against the moderate mid-season temperatures show that hard coal, lignite and gas capacities also have a seasonal pattern speaking in favour of seasonal behaviour of outages. Frequency of outages (y-axis), defined here as the number of outages at the same moment of time as reported to ENTSO-e, is distinctively higher at warmer temperatures. The density plot in Figure 5 (b) highlights the difference of outage occurrence between the years with explicit heat-waves (2015, 2018, 2019) [15] against the years with milder weather conditions in Germany. In 2019 gas, nuclear and coal capacities experienced multiple outages in the summer months, illustrating a distinctive effect of the 2019 heatwave.

The left-side hump on Figure 4 (a) is a result of many factors, as cold, dry spells appearing at times “when the minimum temperature is below the ten-percentile threshold, and the maximum temperature is below its ten-percentile threshold” [43] combined with less solar availability, and low levels of water due to hydrological droughts in previous periods. The hump on the right side of Figure 4 has similar reasons behind, innate to the warm periods: heatwaves with “the maximum temperature are above its ninety-percentile threshold, and the minimum temperature is above its ninety-percentile threshold", accompanied with wind lulls and increasing demand for cooling and air conditioning. As described in the introductory parts, this study focuses on implications of climate change on the supply side of the power systems. Thus, we disregard effects on the demand side, as shifts in demand structures or increases in overall electricity demand.



(a) (b)

Figure 4 – Scatter plot of temperature changes vs outages.

4.4. Estimating capacity- and location-specific costs of extreme weather events

The available data does not allow a comprehensive analysis of cost of climate change for power generation. However, we established a robust connection between a shortage in water resources and price volatility in the power market. Also, we found a notable increase in the frequency and duration of the forced outages in response to low SMI and high ambient temperature. The electricity price volatility creates an additional financial burden on consumers. One way to calculate economic damage of price volatility is to estimate an implied value of call option on electricity (for application of options pricing methodology to calculate financial cost of price volatility see [44], and for the application of real options analysis to calculate risk adjusted cost of climate change see [45, 46]. To guaranty price stability, consumers should pay an insurance premium witch is equal to the value of call option with a strike price equals to the expected price of electricity. Higher volatility implies higher risk adjusted costs of electricity. In addition to the price volatility there are direct economic costs of forced outages calculated as a lost revenue due to decrease of power production.

Figure 5 links low SMI and price volatility. The capacity adjusted aggregated SMI index (see Figure 5) is the sum of multiplication results of a site-specific SMI index by the share of generation capacity located in the site's proximity. I.e. for each type of power generation, the aggregated index is the sum of site-specific capacity adjusted indexes and reflects the share of installed capacities in the German generation mix. A low value of the index indicates a higher exposure of the entire countrywide production (technology-specific – i.e. coal, gas, nuclear, etc.) to droughts. The aggregated index reveals the difference between capacity types most likely to be exposed to the risk of droughts. Hard coal and lignite accounting for nearly 44 GW (as of 2020) of installed generation capacity appear to be more sensitive to having cooling problems at the time of droughts. Nuclear with “only” 9.5 GW installed as of 2020 and gas with 29.8 GW, behave comparatively similar – thus speaking in favour of rising concerns for the future of gas-fired capacities under current nuclear and coal phase-out policies in Germany. The price index on the graph allows comparing its volatility against SMI index. Although only relatively short time-series are available, we can see that the lower value of the index corresponds to higher price volatility and therefore to higher *risk-adjusted cost of electricity*. Winter 2017-2018 seems to be an outlier under this analysis, with December – January 2017 being warmer than usual in Europe until February broke with temperatures colder than the 1981-2010 average for that month [4].

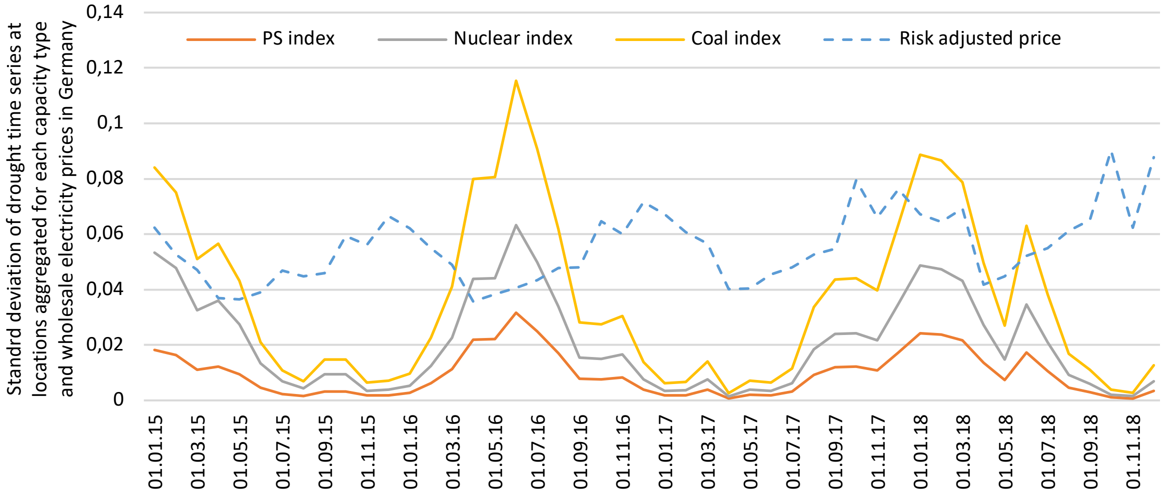


Figure 5 – Drought risk and wholesale price volatility.

Besides forced outages, significant changes in the fleet of generation capacities may also affect the volatility of prices. To take this into consideration Table A 3 in the Appendix provides an overview of commissioning and decommissioning of power plant types in the German power market in order to. Almost 4 GW of thermal power plant capacity was decommissioned from the market in 2017, while nearly 8 GW variable wind capacity was added to the generation mix in preceding years.

We have discussed the occurrence of capacity outages, however not less appealing is the quantity of the capacity excluded from the merit order due to the forced outage and duration of the outage. Figure 6 illustrates the maximum capacity mix unavailable per hour among all hours of the month. Highest values around 8 GW can be seen in summer 2018 and 2016. The hourly plot is given in the Appendix, Figure A 2.

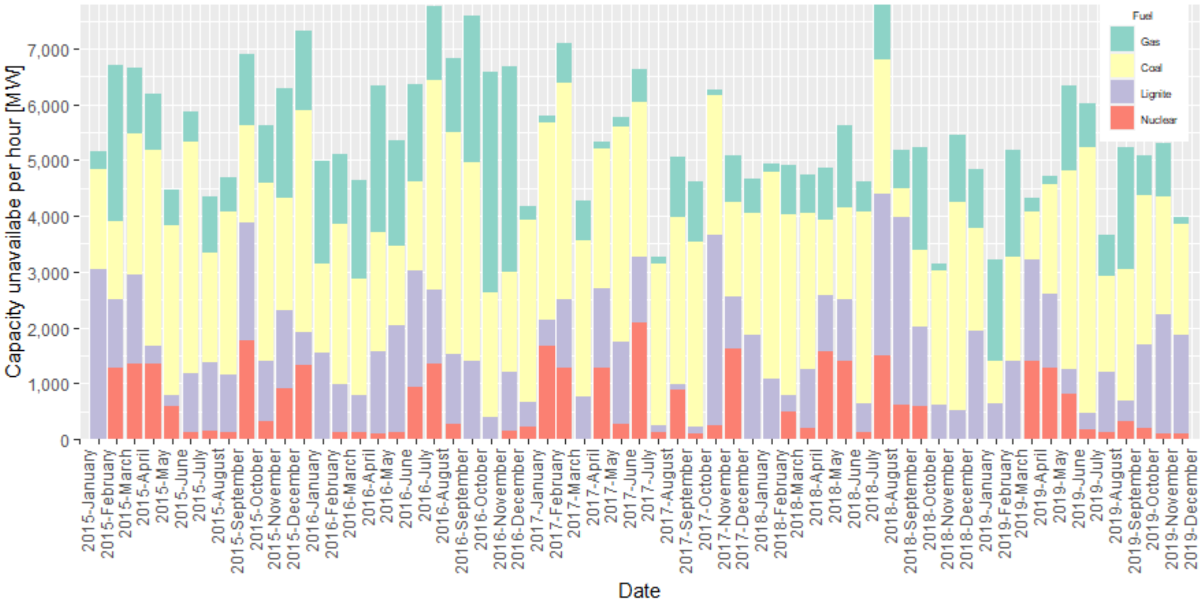


Figure 6 – Month highest quantity of capacity in forced outage between 2015-2019.

To determine the monetary loss of the outages, we can estimate the proxy value of the capacity removed from the market by multiplying the given quantity by the spot market electricity price and subtracting the variable generation costs for each technology type (for detailed costs estimation see Table A 4). The electricity price is an hourly spot market price from EEX available for the period from 2015 to 2018. The following analysis is highly aggregated and serves only for the purpose to estimate the proxy generator’s value lost due to the capacity withdrawn from the market. Table 3 describes the order of values for the estimated indicator. The year 2018 is the most distinctive in this period reaching nearly 127 Million Euro, with 37 % allocated in the summer months. For nuclear generation, the share of value “lost” from June to August is more significant and reaches 63 %. Not only losses can be generated by the extremely high temperatures. The gradual advancement of the heatwave and low wind availability advancing Europe in June 2018, resulted in additional income for German nuclear and coal power plant operators who ramped up exports to the north (reduced hydro) and south (reduced thermal power plant availability) of Europe [4]. These conditions pertained only until mid-August when temperatures rose, and nation-wide thermal plant restrictions came into force in Germany.

Table 3 – Value of capacity lost due to outage.

Fuel	2015			2016			2017			2018		
	Million Euro											
	Jan-Dec	Jun-Aug	%	Jan-Dec	Jun-Aug	%	Jan-Dec	Jun-Aug	%	Jan-Dec	Jun-Aug	%
Coal	50,70	16,42	32%	54,03	4,90	9%	72,99	13,01	18%	110,80	40,66	37%
Gas	0,48	0,02	4%	3,07	0,00	0%	2,84	0,00	0%	8,40	1,11	13%
Nuclear	7,39	0,50	7%	8,10	4,86	60%	3,75	0,30	8%	7,83	4,97	63%
Total:	58,57	16,95	29%	65,20	9,76	15%	79,58	13,31	17%	127,03	46,75	37%

Whether gains outweigh losses, depends on the one hand, on how German thermal power generators adapt to the extremes and on the other hand, on the spatial and time advancement of the heat waves at the growing share of renewable generation. The proxy costs of the forced outages can be compared to the cost of dispatch and feed-in management of renewables that mounted up to 351,5 Million Euro in 2018 [see Table 4, 47]. The re-dispatch will increase in the coming years due to the integration of European electricity markets, the share of the variable renewables, delays in grid expansion and nuclear and coal phase-out until 2038 [48]. Similar reasons affect the "loss" of thermal generation capacities, adding weather extremes to the named factors.

5. Discussion

This study provides an in-depth analysis of the risks of climate change, and specifically extreme weather events, for the German electricity system. However, our results can be generalized for other North-European countries that undergo an energy transition process. We identify regions with higher hazard levels for generation capacities by introducing a capacity adjusted drought index.

The prospective effects of climate change pose negative impacts on power systems. In our study, focusing on Germany, we show that the occurrence of heatwaves and droughts will significantly increase in the coming years. We estimated their likelihood and the range of risk for at high granularity, assessing locations of thermal units. Meteorological trends suggest that hydrological droughts and water scarcity, coupled with heatwaves, became more severe within the last decades. Assuming this trend continues, future power systems have to be adjusted to increase their resilience. At the same time, many technological options that are targeted towards decarbonizing future electricity markets (e.g., renewable energy sources, CCS) will be affected by changing climate conditions themselves.

Several studies have assessed the costs of cooling systems for thermal power plants. Due to the nature of those facilities, cost estimations are highly location-specific. However, they can be used as a point of reference for estimating necessary investments to the current generation fleet. In general, water once-through options tend to be the most cost-efficient solutions, while dry-cooling technologies are the most expensive solutions by far. Recirculating wet cooling systems increase water needs and are restricted by water availability and temperature regulations for intake and discharge. Alternatively, dry cooling is of particular interest since it can be utilized at low water availability. However, it uses ambient air to cool the exhaust steam from the turbine that is exposed to the risk of high temperatures in summer seasons [29, 49]. Table 4 displays the cost assumptions of several studies, with differentiation of power plant technologies and cooling technologies.

Adaptation of the existing power plants by investment in the more efficient cooling technologies, as dry cooling, different configurations of wet cooling towers pose high additional annual costs to the generators (see Table 4) plus running operational costs and loss of the efficiency, e.g. by 2 % [30]. And in the case of Germany, these additional costs occur for capacities that are subject to phase out in the next decade (see Table A 5). The necessity of these investments should be evaluated by taking the risk of extreme weather events, the growing share of variable renewables, targets of interconnection capacities between the regions. Long-term investment decisions should rely on spatially explicit understanding of infrastructure vulnerabilities to climate change [see e.g. 29, 50].

Table 4 – Overnight investment costs of cooling systems by power plant technology

Cooling systems	Capital costs of cooling per kW installed capacity		
	Euro / kW p.a.		
Water once-through	15,2***		
Water recirculating	22,5***		
Water ponds	21,7***		
	Combined-cycle	Coal-fired	Nuclear (2 reactors)
Dry cooling towers	33,8 – 41,*9	98,9-108,1*	
Wet cooling towers	9,2-10,4*	29,9-34,*5	22,3**

Source*:* Own compilation based on [51]*, [52]**, and [49]***

6. Conclusion and policy remarks

Taking into account the recent developments of the German power market, coal-fired and nuclear power plants will be decommissioned within the next decade [53, 54]. With nuclear going offline in 2023, our arguments for resilience of coal-fired capacities remain valid until 2038 (see Table A 5). Altvater et al. [30] point out that overall, 637.3 Million p.a. will be necessary to adapt European power plants to changing climatic conditions. For Germany, they estimated an amount of 8.8 Million Euro/p.a. accounting only for cooling needs of gas power plants for the long-run.

In the near future, a major share of balancing energy will be provided by gas-fired power plants. Considering the results of this study, additional adaptation measures in order to strengthen the resilience of the German power system towards more extreme weather conditions will become more important in the future. Based on the calculation presented in this study, the losses in revenue due to forced outages at extremely high temperatures amounted to 13-17 Million Euro p.a. and 46 Million Euro p.a. in 2018 when high temperature coincided with low wind generation. Assuming a trend towards more frequent occurrences of such events, the potential losses will increase as well. As a result, the decision on adapting the power system to changing climate conditions will not only become a question of system resilience but also of profitability. The planning problem of future electricity market designs must be analysed under consideration of multiple dimensions: not least by taking into account the spatial and temporal scale of its exposure to weather extremes. While occurrences of weather extremes have to be regarded as uncertainties beyond influence, the resilience of the system can be managed. The use of highly granular data for policy assessment planning models can help policymakers and public utilities, generation utility companies, transmission and distribution system operators. Comparing to climate risks, not a lesser source of uncertainty are electricity market reforms, regulatory initiatives, incentives for new generation technologies adopted in the face of changing climate. It is profoundly necessary to account for both sources of uncertainty ensuring the effectiveness of mitigation (as phase-out of fossil generation capacities, deployment of bioenergy, CCS technologies) and adaptation (investment in cooling systems, grid expansion) policy options. One of Europe's core instrument for climate change mitigation is the European Trading Scheme for emission certificates. Its underlying idea is that CO_2 emissions should be reduced where it is most cost-efficient. However, our analysis shows, that this approach might result in a system, which is in turn less resilient to the effects of climate change itself. Hence, when designing a future low carbon power system, the effects of climatic changes on the system have to be considered as well.

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Appendix

Table A 1 - Transport routes of imported coal in Germany.

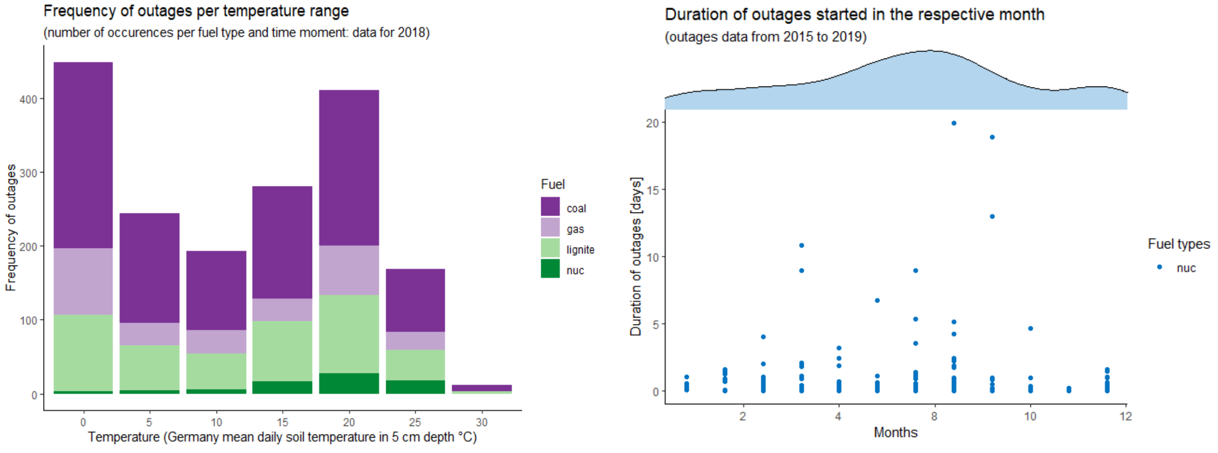
	2010	**2011**	**2012**	**2013**	**2014**
Means of transport	Mio. t	Mio. t	Mio. t	Mio. t	Mio. t
Inland vessels from ARA* ports	15	23,7	24,4	27,7	26
Total of all means of transport	45	48,4	47,9	52,8	56,2
%	33%	49%	51%	52%	46%

*ARA ports ARA - Seaports of Antwerp (Belgium), Rotterdam (Netherlands) and Amsterdam (Netherlands).
Source: [20]

Table A 2 - Johansen test.

City	**Land**	**PLC**	$r = 0$		$r \leq 1$		
			test	critical value	test	critical value	
Potsdam	BB	3987	429.96	23.52*	60.71	11.65*	cointegrated
Berlin	BE	403	343.65	23.52*	27.11	11.65*	cointegrated
Ellwangen (Jagst)	BW	1197	177.66	23.52*	20.94	11.65*	cointegrated
Augsburg	BY	461	177.66	23.52*	20.94	11.65*	cointegrated
Hof	BY	2261	386.06	23.52*	58.34	11.65*	cointegrated
Altenkirchen	MV	232	429.96	23.52*	60.71	11.65*	cointegrated
Marnitz	MV	3196	349.44	23.52*	33.28	11.65*	cointegrated
Lingen	NI	3023	262.19	23.52*	48.86	11.65*	cointegrated
Essen	NW	1303	356.80	23.52*	69.31	11.65*	cointegrated
Alzey	RP	150	85.66	23.52*	14.18	11.65*	cointegrated
Erfde	SH	1266	264.38	23.52*	54.07	11.65*	cointegrated
Wadgassen	SL	460	136.18	23.52*	25.22	11.65*	cointegrated
Chemnitz	SN	853	388.89	23.52*	47.53	11.65*	cointegrated
Plauen	SN	3946	303.87	23.52*	34.43	11.65*	cointegrated
Magdeburg	ST	3126	366.50	23.52*	22.79	11.65*	cointegrated
Harzgerode	ST	2044	228.42	23.52*	26.34	11.65*	cointegrated
Erfurt	TH	1270	351.62	23.52*	21.66	11.65*	cointegrated
Gera	TH	1612	337.72	23.52*	31.22	11.65*	cointegrated

significance levels: * 1%, ** 5%, ***10%



(a) (b)

Figure A 1 – Frequency and duration of outages.

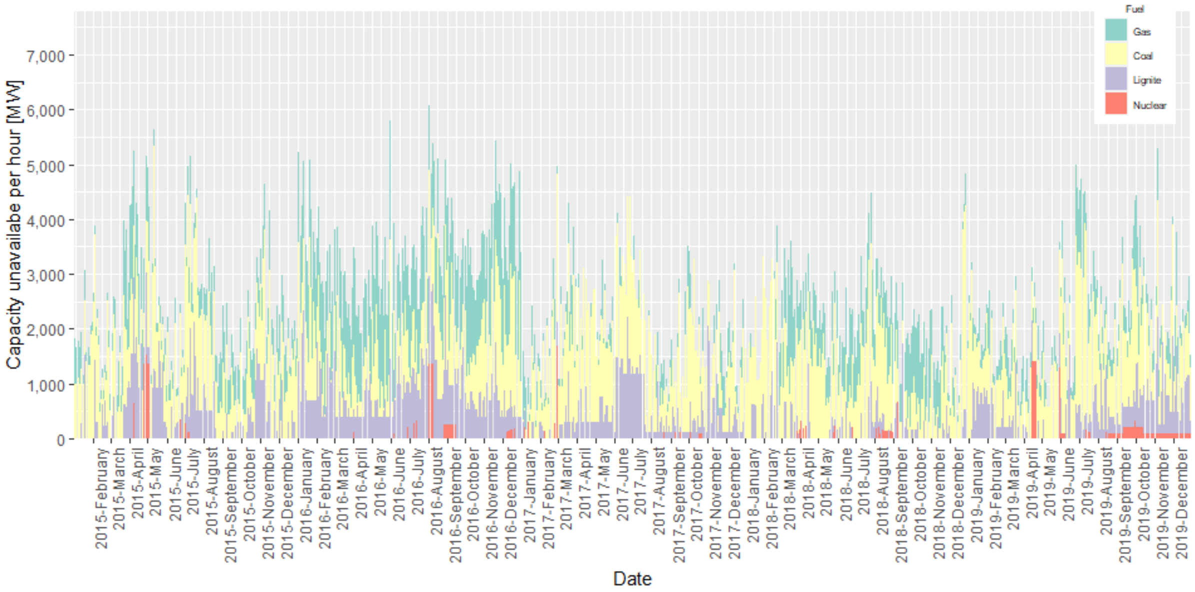


Figure A 2 – Hourly quantity of capacity in forced outage between 2015-2019.

Table A 3 – Commissioning and decommissioning of power plants. Source: [55].

	2013 [MW]	**2014** [MW]	**2015** [MW]	**2016** [MW]	**2017** [MW]	**2018** [MW]
decommissioned						
coal	684	2.159	708	1.234	2.370	1.352
lignite	60		45			
nuclear			1.275		1.284	
gas	54	245	624	433	69	271
biomass				20		
other non-res	113	19		19,7	254	41
total	911	2.423	2.652	**1.707**	**3.977**	1.665
commissioned						
coal	1.460	1.716	3.174			
lignite	23	20				
nuclear						
gas	920	277	257	**1.691**	56	128
pumped storage			195		12	360
biomass	21			14		
wind (on and offshore)	894	3.639	3.567	**1.016**	894	
other non-res	74	23		90		12,5
pv			10			
total	3.393	5.676	7.203	**2.812**	**980**	501

Source: BNA [55]

Table A 4 – Assumptions behind the calculation of value lost.

	Year	CO_2 price*	Efficiency**	Fuel cost	O&M cost	Emission coefficient	CO_2 cost	Total var costs
		Euro/t	%	Euro/MWh	Euro/MWh	t CO_2/MWh	Euro/MWh	Euro/MWh
Nuclear	2015	7,61	0,33	5,1	9	0,0	0,0	14,1
Lignite	2015	7,61	0,35	11,3	3,3	0,4	8,7	23,3
Coal	2015	7,61	0,39	21,2	3,3	0,3	6,6	31,1
Gas	2015	7,61	0,43	51,1	3	0,2	4,2	58,2
Nuclear	2016	5,24	0,33	5,1	9	0,0	0,0	14,1
Lignite	2016	5,24	0,35	11,3	3,3	0,4	6,0	20,6
Coal	2016	5,24	0,39	21,2	3,3	0,3	4,5	29,1
Gas	2016	5,24	0,43	51,1	3	0,2	2,9	56,9

Nuclear	2017	5,8	0,33	5,1	9	0,0	0,0	14,1
Lignite	2017	5,8	0,35	11,3	3,3	0,4	6,6	21,2
Coal	2017	5,8	0,39	21,2	3,3	0,3	5,0	29,5
Gas	2017	5,8	0,43	51,1	3	0,2	3,2	57,3
Nuclear	2018	15,56	0,33	5,1	9	0,0	0,0	14,1
Lignite	2018	15,56	0,35	11,3	3,3	0,4	17,7	32,4
Coal	2018	15,56	0,39	21,2	3,3	0,3	13,4	38,0
Gas	2018	15,56	0,43	51,1	3	0,2	8,5	62,6
Nuclear	2019	24,72	0,33	5,1	9	0,0	0,0	14,1
Lignite	2019	24,72	0,35	11,3	3,3	0,4	28,2	42,8
Coal	2019	24,72	0,39	21,2	3,3	0,3	21,4	45,9
Gas	2019	24,72	0,43	51,1	3	0,2	13,6	67,6

[*] CO_2 certificate prices from EXX, annual average European auction price.
[**] Efficiency, fuel and O&M costs, emission coefficients are taken from ENTSO-e, TYNDP 2018 market modelling data.

Table A 5 – Phase out of nuclear and coal capacities.

	Installed capacity		
	Hard coal	**Lignite**	**Nuclear**
	GW	GW	GW
2020[1]	21,4	20,92	9,52
2022	15[2]	15	4,05 (*in 2023* – 0)
2030	9	8	0
2038	0	0	0

[1] Capacities from BNA, KWK 2020.
[2] According to the phase-out strategy described in the „Entwurf eines Gesetzes zur Reduzierung und zur Beendigung der Kohleverstromung und zur Änderung weiterer Gesetze, 29.01.2020“.

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