Master Thesis

German Electricity Wholesale Prices – Energy Transition and German Renewable Energy Sources Act Amendments

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Abstract

This paper examines the impact of the German renewable expansion and regulatory measures on German wholesale electricity prices for 2015-2020. Renewable electricity production has increased significantly over the last years, leading to decreasing wholesale electricity prices, reflected by the merit-order. The resulting merit-order effect symbolises the positive impact of renewable production on wholesale prices. However, regulations repeatedly curtailed these positive effects. The introduction of the EEG 2017 led to a short-term drop in the expansion of renewable electricity production, from which the market was only able to recover slowly in the following years. The expiry of some twenty-year subsidies in 2020 brought similar negative effects as the discontinuation of unconditional subsidies for facilities and the switch to competition through tenders of the EEG 2017. Despite some setbacks, the energy transition programme in Germany leads to lower wholesale electricity prices in the long term, based on previous studies and the period under consideration.

Keywords: Electricity prices, Merit-order, Renewable electricity, German Renewable Energy Sources Act

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1. Introduction

In the course of climate change, Germany has set itself the goal of making electricity production more climate-friendly. The "Energiewende" in Germany is a policy response to society's pressure to act on behalf of the environment. Therefore, many measures have been introduced in the past that have been instrumental in expanding electricity production from Germany's renewable sources (German Federal Government, 2020). The most important factor in Germany favouring renewable production is the Renewable Energy Sources Act (EEG), the nuclear phase-out, and the coal phase-out. The German government decided to phase out nuclear power after the nuclear catastrophe at Fukushima (German Federal Government, 2018; Huenteler, Schmidt, & Kanie, 2012). This phase-out will be completed by 2022. Some nuclear power plants were immediately shut down, and a phase-out plan was drawn up for the nine remaining plants by 2022 (German Federal Government, 2018; Süddeutsche Zeitung, 2011). The decision to phase out coal took place only recently. All coal-fired power plants will be shut down by 2038. The German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU, 2020) published a statement to the effect that this process will be faster than initially planned. The intended phase-out of nuclear and fossil power generation has profound consequences. Through these programs, German policy has laid the foundation for the necessity of renewable energies in electricity production. Thus, without alternative production methods, a supply of citizens is hardly possible anymore. In this context, introducing new laws continuously accelerates the expansion of renewable energies. By 2030, at least two-thirds of electricity generation should be renewable (BMU, 2020).

In addition to the measures implemented to expand renewable energies in Germany, the Federal Government introduced some adjustments to the EEG during the underlying period. The EEG 2017, introduced on 01.01.2017, replaced the fixed and state-regulated feed-in tariffs for renewable electricity production from this date. The implemented tendering procedure intends to ensure more competition through auctions and thus promotes only economically efficient plants. It is also important to note that in 2020 the first twenty-year subsidies will expire, and thus producers will take facilities off the grid as they are no longer economically efficient. That reduces the share of renewable electricity production, as new plants must first get subsidisation before production capacity returns to the pre-2020 level.

This paper aims to investigate the impact of the expansion of renewable energies, especially electricity production, on wholesale electricity prices in Germany. That includes not only the expansion itself and the impact on the merit-order but also the effect of political measures and interventions on the market mechanism. The underlying analyses use a dataset consisting of current market data. The European Energy Exchange, the European Network of Transmission System Operators for Electricity, and the German Federal Network Agency provided these data. The use of time-series analyses examines the effects of the expansion of renewable electricity production, particular policy measures, and changes in the electricity market in the years 2015-2020.

First, I examine the influence of renewable electricity production on wholesale prices. Over time, the steady expansion and the resulting change in the “merit order” influence the effect. The merit order determines which power plants satisfy the demand for electricity at the lowest cost. Increasing renewable generation leads to declining prices. The merit-order, which favours renewable power sources in the pricing process, also reflects this effect.

In a further step, I analyse the adjustments to the regulatory framework of the German electricity market. First, I look at the introduction of the EEG 2017 and the resulting changes on the electricity generation side. In this context, I examine the introduction and the development in the following years. The EEG 2017 leads to a decline in the expansion of renewable energies, as the price effects reflect. In subsequent years, renewables have a greater influence on prices. The development declines in the following years and converges to the situation before the implementation. In addition, this paper deals with the expiry of subsidies for some plants in 2020. That year, the twenty-year subsidy period expired for the first time for some facilities. In 2020, there is a renewed decline in renewable electricity production. Consequently, the effects on wholesale prices increase again. As a result of these political measures, the dependence of German wholesale electricity prices on renewable production increases.

As a first analysis of the impact of the expansion of renewable energies in combination with evaluating the influence of current political measures, this paper provides an essential overview of the current market situation for the German electricity market. That allows future policy measures to consider precisely those aspects that currently affect the market.

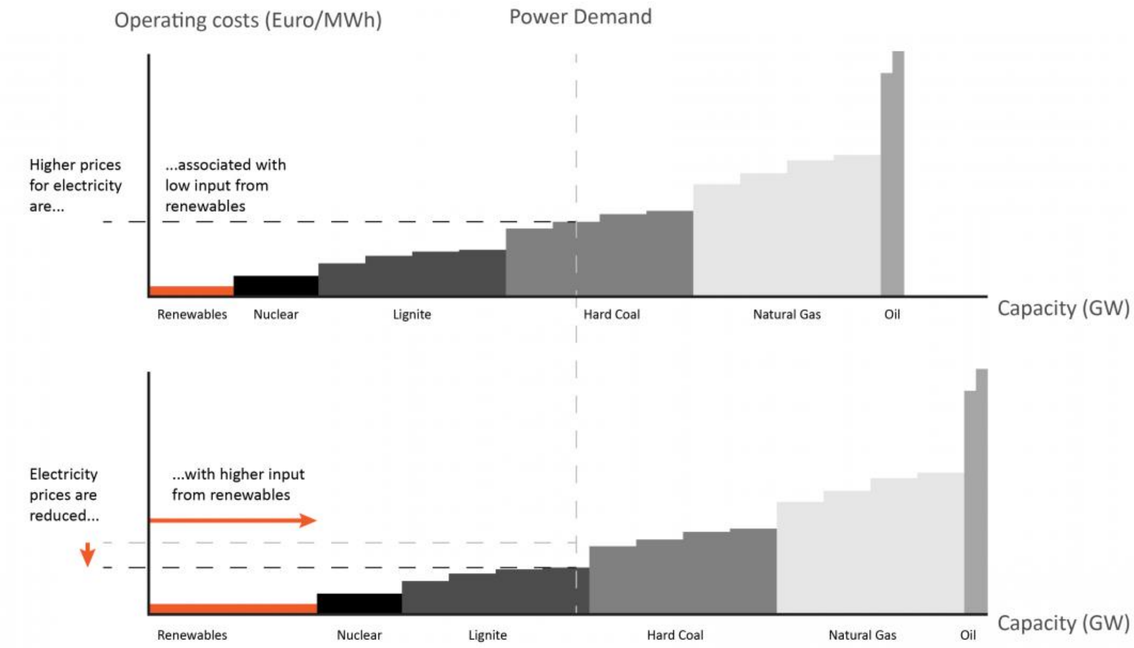
The structure of the remainder of this paper is as follows. Section 2 presents an overview of the German electricity market. In Section 3, I provide a summary of previous research done in this area. Section 4 presents the underlying data and methodology, followed by the results reported in Section 5. In Section 6, I discuss the implications of the results, potential policy measures, and limitations. Section 7 concludes.

2. German electricity market

2.1. Structure and pricing

The German electricity wholesale market combines spot market and over-the-counter transactions. For Germany, the European Energy Exchange (EEX) trades the day-ahead spot prices, which trades all electricity and power generation forms. The intersection of supply and demand sets the price. There are clear guidelines and regulations for trading on the electricity market and the sales order of quantities. First, the EEX sells quantities of the plants with the lowest variable costs to minimise the electricity supply costs (EPEX SPOT, 2021). The so-called "merit order" describes this phenomenon, reflecting the sorted marginal cost curve of electricity generation. It determines which power plants satisfy the demand for electricity at the lowest cost. The exchange price for electricity operates as the marginal cost price, the Market-Clearing-Price (MCP). It represents the currently most expensive generation plant's variable costs, the "marginal power plant". Decreasing electricity generation costs shift the order of power plants along with the merit order. The steadily increasing feed-in of renewables demonstrates this effect. These produce at marginal costs of or close to zero and push peak load power plants far back in the merit order. This effect is called the merit order effect (MOE) of renewables. As this development progresses, conventional power plants will remain necessary only for balancing production peaks. Figure 1 illustrates this effect in a simplified way.

Figure 1: The merit-order effect



Source: Clean Energy Wire (2016)
Notes: This figure illustrates the merit-order effect by demonstrating a shift in electricity production to more renewables. Due to this shift, the demand is covered by less costly production methods and, therefore, electricity prices decline.

Traditionally the left part of the graph covers conventional methods with lower marginal costs, such as hard-coal and lignite, whereas the right part consists of more expensive generation methods like oil and gas (Kyritsis, Andersson, & Serletis, 2017). The additional renewable electricity production in the second scenario covers the demand at a lower price compared to the first one (Clean Energy Wire, 2016). By increasing the overall capacity, entire generation types could become unnecessary to provide the demanded quantity. These types come into use only during peak electricity periods. The merit-order effect's magnitude hinges on three elements: the electricity demand, the supply (merit-order) curve's slop, and the share of renewables. A significant influencing factor is electricity generation costs. If these are too high for one type of production, the merit order excludes that technology (Keles, Genoese, Möst, Ortlieb, & Fichtner, 2013; Sensfuß, Ragwitz, & Genoese, 2008).

Although these exchange trades account for only about 20% of the total trading volume, the German Federal Network Agency (2021) considers these prices an indicator of general electricity wholesale prices. The German market area comprises Germany and Luxembourg since 01st October 2018. In this market area, electricity trading is unlimited. Before this, Austria was also part of the same market area. Due to this restructuring, only electricity transmittable via the grid is now tradable between these market areas. This step led to an improvement in grid stability. The German market area also links to 15 other countries. As a result, a joint and coordinated procedure determines the EEX electricity price on the day-ahead market for these markets (German Federal Network Agency, 2018).

2.2. Historical development

The development of the German electricity market is essential. The deregulation of the German electricity market in 1998 set the stage for development (Growitsch & Müsgens, 2005). By liberalising the electricity markets, the legislator enabled free competition. The central aspect was to lower costs and reduce overcapacities. However, the markets are subject to state regulations. In 1991, Germany introduced the first legal precursor of the EEG, the Electricity Feed Act. It served as a pioneer in steering the electricity market in an environmentally friendly direction. The EEG, introduced on 01st April 2000, is the central regulatory instrument for expanding renewable energies in Germany. It aims to transform Germany's energy supply and increase the share of renewable energies to at least 80 per cent by 2050. In addition to climate and environmental protection, as a basis for the expansion of renewable energies, it also contributes to reducing the economic costs of energy supply (German Federal Environment Agency, 2019). A feed-in tariff and feed-in priority were introduced for renewable energies (German Federal Environment Agency, 2019). These fees, combined with the EEG levy, finance state investments for the expansion of renewable energies. The EEG levy, paid by consumers, compensates for the German government's guaranteed direct feed-in of renewable electricity. Electricity producers feed renewable electricity at a fixed rate into the grid, which is therefore cross-subsidised by the EEG levy.

The development of the EEG and the resulting promotion of renewable energies is crucial for the intended analysis. The constant adaptation of the law and the subsidisation of the expansion of electricity production through renewable energies have had a lasting impact on the German electricity market. For this paper, the 2014 and 2017 adjustments are crucial. The observation period in this analysis is from 2015 to 2020.

In 2014, the expansion of renewable energies was enshrined in law. It provides the fundamental basis for the change in the use of renewable energies. This legal anchoring has made renewable energies the mainstay of German electricity production (German Federal Ministry for Economic Affairs and Energy, 2021). Renewable energies shall account for 40-45%

of electricity production by 2025 and 55-60% by 2035 (German Federal Ministry for Economic Affairs and Energy, 2014). However, this expansion also led to an increase in the EEG levy.

A system change occurred with the EEG 2017. A tendering procedure replaces the former state-regulated and dictated feed-in tariffs. Providers are now competing to feed their produced electricity into the grid (German Federal Ministry for Economic Affairs and Energy, 2017). Participation in the tenders is mandatory for subsidies for new installations from a minimum capacity onwards. From then on, that is the only way for production plants to receive subsidies. Successful bidders receive a market premium for 20 years. The introduction of the EEG 2017 caused severe cutbacks in the industry. In this newly created competition, the producer who produces most cost-efficiently gets support from the government. The subsidy goes to companies that claim to need as little financial support as possible to produce electricity. The realisation of new projects only takes place after a successful tender and the receipt of governmental funding. This system change should lead to a controlled, continuing and efficient further expansion of renewable production. Due to these changes, the support of the expansion by subsidies has been made more difficult and reduced. However, there are differences in the tenders for the individual generation types.

The German Federal Ministry for Economic Affairs and Energy (2016) states that photovoltaic plants, making a significant contribution to electricity generation in Germany, are subject to mandatory tendering from an output of 750 kW. Plants with a lower capacity get their subsidies via fixed remuneration. Biomass generation is currently the most essential and versatile method. Besides producing electricity, it is also usable for the heat and transport sectors. Unfortunately, the development of new facilities is costly. Plants with more than 150 kW must participate in the tendering procedure to receive EEG support. The German government aims to increase the installed capacity of offshore wind parks to 15 GW by 2030. To this end, projects that receive subsidies in the tenders will also get a grid connection to feed the produced electricity into the grid. Onshore wind parks are one of the most cost-efficient production facilities, which majorly supports the expansion of renewables in Germany to reach governmental goals. Not only the 2017 EEG change determines the further expansion of onshore facilities, but above all, the limited available areas. Therefore, the primary strategy is to replace old facilities with more modern technologies. Like photovoltaic, onshore wind parks with a capacity above 750 kW are subject to mandatory tendering. Excluded are pilot plants with innovative technology.

The established tendering should minimise the costs of the EEG so that the continuous expansion of renewable electricity production does not become too expensive. The amendment intends to ensure both the financing of the renewable expansion and the achievement of the governmental targets (Busse, Campen, Conrads, Dagasan, & Trockel, 2016). The amendment intends to increase the diversity of market players further. Therefore, the tendering obligation exempts smaller installations to enable private installations and citizens' initiatives to receive support. However, the particular regulations were kept to a minimum for these players (German Federal Ministry for Economic Affairs and Energy, 2016). These occurring changes and how they affect the expansion and, consequently, the electricity prices need further investigation.

3. Literature Review

Several studies have already addressed the impact of renewable energies on the electricity market. Some studies focus on consumer markets, and others observe the effects on wholesale. These serve as a basis for this work. This section provides an overview of these previous studies, categorised in simulation-based approaches and empirical analyses.

3.1. Simulation-based approaches

Simulation-based studies are approaches which use models based on past and hypothetical forecasted data. These analyses consider potential long-term market development under specified assumptions.

A key factor considering the price development of German wholesale electricity prices are government regulations and subsidies combined with economic effects due to the nuclear phase-out implemented by the German government after the Fukushima catastrophe in 2011. The marginal costs of renewables are substantially lower than for conventional power plants. As a result, they state that electricity prices fall in all markets. Consequently, fossil production is gradually being forced out of the market (Bode and Groscurth, 2006). Replacing fossil plants leads to decreasing net commercial exports and increasing prices, especially consumer prices, because the industry can pass down essential costs to the customer (Fürsch, Lindenberger, Malischek, Nagl, Panke, and Trüby, 2011). The EEG and the expansion of wind and PV production impact the German electricity spot market (Cludius, Hermann, Matthes, and

Graichen, 2014). Besides, the German Feed-in tariff (FIT) and policy regulations decrease German industry prices, whereas they increase consumer prices (Traber and Kemfert, 2009). The EEG and the increasing renewable energy production account for a reduction in wholesale prices favoured by the FIT, whereas the consumer prices increase due to higher forwarded taxes (Traber, Kemfert, and Diekmann, 2011).

The expansion of renewable production decreases the German electricity wholesale price over time, even considering commercial exports. Furthermore, this effect increases with the expansion. Due to the expected increase in the expansion of renewable energies and increased renewable production, wholesale prices for electricity in Germany will fall. This effect continues to increase due to the political regulations for expanding renewable energies and the dismantling of fossil generation until Germany reaches specified figures (Fürsch, Malischek, and Lindenberger, 2012). Weigt and von Hirschhausen (2007) analysed the development and market power in the German wholesale electricity market, finding an increase in prices between 2002 to 2006. Weigt (2009) expands on this analysis and examines the opportunities offered by implementing wind energy in Germany. The implementation of wind energy does not yet enable a reduction of fossil production plants. However, the cost-saving potentials concerning the merit order are already substantial and outweigh the subsidies. During peak periods, electricity production through wind results in decreasing market prices. The additional use of other renewable energies strengthens this effect exhibited on electricity prices not only during peaks. Still, decreasing marginal costs of electricity generation, such as falling gas prices, lower the price-reducing effect of renewables.

Sensfuß, Ragwitz, and Genoese (2008) analysed the renewable electricity production effect on electricity market prices in Germany in the period 2001-2006 based on the PowerACE[1] model by Genoese, Sensfuß, Möst, and Rentz (2007) and Sensfuß (2007). Renewables have a reducing impact on electricity prices and the merit-order. Forecasted calculations expect a change in the German net commercial electricity exports over time, impacting the merit order to a not yet defined amount (Sensfuß, 2011).

[1] PowerACE is a method to analyse wholesale electricity markets. It simulates these markets using an agent-based, bottom-up model.

3.2. Empirical approaches

Empirical analyses are economic models based on past data to compute the actual effects of the expansion of renewables on prices. There are very few papers present for the German electricity market, especially the wholesale market, which observe these effects.

From September 2004 until August 2005, German electricity day-ahead spot prices decreased for every added wind power generated gigawatt. The impact of wind on EEX prices is very high and will continue to increase as expansion proceeds (Neubarth, Woll, Weber, and Gerech, 2006). Comparing production from the wind with the overall production and electricity generation costs for 2007 and 2008 shows a reduction in market prices due to wind generation and reduced incentives to invest in fossil production facilities as gas-fired units. However, the price-reducing effect is markedly lower than the resulting emission-saving effect. In particular, this is due to the high fluctuation of electricity production from wind power (Traber and Kemfert, 2010). Assuming no available photovoltaic and wind generation, fossil electricity generation would not cover the German demand for 269 hours during the observed period, resulting in an apparent price-reducing effect of renewables on the German electricity market (Dillig, Jung, and Karl, 2016).

Considering the merit-order effect, it is noticeable that renewable generation and the German nuclear phase out influence the merit-order (O'mahoney and Denny, 2011; Würzburg, Labandeira, and Linares, 2013; Tveten, Bolkesjø, Martinsen, and Hvarnes, 2013). Solar electricity production, replacing coal, gas and oil, decreases average prices. Additional solar capacity leads to declining volatility in wholesale electricity prices. The pricing structure prefers the newly built solar capacities in the merit order model due to their lower marginal costs. Increasing renewable electricity generation leads to decreasing electricity day-ahead prices (Mulder and Scholtens, 2013). In this respect, Germany and Europe differ from other parts of the world. In Texas, this effect is not as evident because of a difference in the energy mix (Nicholson, Rogers, and Porter, 2010; Woo, Horowitz, Moore, and Pacheco, 2011).

Apart from analyses regarding the German electricity wholesale market, some further studies examine the effects of renewable energies on wholesale prices for other countries. Spain, like Germany, subsidises the expansion of renewable electricity production. For the years 2005-2009, expanding these productions substantially impacted Spanish prices. Thus, a steady expansion causes an increasing downward trend (Gelabert, Labandeira, and Linares, 2011).

3.3. Impact of EEG amendments

Further models investigate German policy effects on the electricity wholesale market. These focus primarily on the consequences of amendments to the legal framework.

During the years 2007-2014, day ahead spot prices dropped by 40%, primarily due to renewables. Policy implications and amendments can affect the electricity market in an unexpected and unforeseen way since the equilibrium in the market is not very stable. Such governmental interventions with significant potential to influence the whole market are very risky (Kallabis, Pape, and Weber, 2016). One of the main factors in such previous studies was the impact of the EEG and, above all, the adjustments made in 2017 on the market. From 2017 onwards, prices decrease for onshore wind actions, leading to a declining producer rent. These findings are consistent with the photovoltaic actions, which also show declining lower prices over time. As a particular disadvantage of the announced auctions, the authors identify emerging difficulties for smaller market players, which have a negative impact on market power in the long run (Anatolitis and Welisch, 2017).

Due to the 2017 EEG adjustments, the promotion of renewable energies switched from the previous price-controlled to quantity controlled. Transaction costs can negate the cost advantage of the tenders, which could cause difficulties in the future, as targeted generation goals will be more challenging to achieve or may not be achieved at all. The higher cost efficiency cannot compensate for these disadvantages (Meya, Neetzow, Neubauer, and Pechan, 2016). Continuing, Gawel and Purkus (2016) emphasise the differentiation of support between the various technologies as particularly positive, as this includes electricity generation costs, which they consider the most important instrument for price formation. However, the interplay of the various actions and tenders leads to a way more complex subsidy system. Subsequently, the costs of the EEG to rise, which will have a negative impact on both producers and especially consumers. The introduction of auctions and favouring the most cost-effective production sites will severely limit the expansion of renewable electricity production. Since the realisation probability depends on the market development, which results from the subsidies, they forecast a decline in the expansion of renewables from 2017 (Gawel and Purkus, 2016).

Besides, the EEG adjustment also impacts the expansion of renewable production methods for electricity. In 2017 newly built offshore wind facilities did not rely on subsidies in three out of four cases and just financed the development by the wholesale market price (Greve and

Rocha, 2020). In 2018, the number of upcoming projects increased but so did the auction prices compared to 2017. On average, the price was ten times higher than in the previous year. In addition, almost all projects won the tenders in both years. Although this results in an increasing expansion of offshore wind production, it also makes electricity production more expensive. That also influences prices, which as a result, will decline less or even rise. This phenomenon arises from the nature of the German tenders. The bidding format does not provide an efficient outcome due to its discriminatory format. Over time, a negative impact of the EEG adaptation approaches, leading to demand-orientated production facilities in the short run. In the long run, these adjustments result in a declining expansion of biogas plants in Germany without sweeping subsidies. Due to the subsidy cuts of the EEG amendments, it will be difficult to counteract (Balussou, McKenna, Möst, and Fichtner, 2018).

3.4. Focal points of investigation and hypotheses development

Previous empirical studies observed price-decreasing effects of renewables in the electricity wholesale market for earlier years. Additional renewable capacity and production, especially wind and solar generation, change the merit-order decisively. Therefore, an increasing share of renewables in electricity production should also have a price-reducing effect in the underlying period of my study. This study will investigate whether the expansion of renewable energy production significantly impacted the average German electricity price in 2015-2020. The focus is on the effects of the various determinants of production and expansion on the price, which will be clarified further in the following sections, leading to the first hypothesis:

Hypothesis 1a: *German day-ahead electricity wholesale prices tend to decrease due to the expansion of renewable electricity production.*

An expansion of renewable electricity production also has an impact on the merit-order. Increasing renewable electricity feed-in decreases wholesale electricity prices through the merit-order. In the short term, the expansion of renewable electricity production results in a change in the merit-order, as displayed in previous studies. This change can negatively impact individual electricity production methods in the long term because the process can exclude certain methods due to higher generation costs. The resulting merit-order effect illustrates this, as the equilibrium price decreases due to lower total marginal generation costs, which leads to the following hypothesis:

Hypothesis 1b: *The continuous expansion of renewable electricity production strengthens the negative merit-order effect.*

Other studies examining not the German electricity market but those of other European countries also support these assumptions. Previous simulation-based research focusing on forecasting the German electricity market, using different scenarios to predict future changes in the German market, also supports these hypotheses. If the development continues as envisaged by the government so far, these studies provide a good picture of possible impacts. In this thesis, I examine these expectations, among others. The crucial point of this analysis is the combination of data on renewable energy expansion, especially electricity, with production and price effects. In particular, the increase in renewable and the decrease in fossil production are necessary to observe.

Previous research examined data on prior periods and the impact on wholesale prices (Dillig et al., 2016; Mulder & Scholtens, 2013; Paraschiv, Erni, & Pietsch, 2014). The analysis of the period 2015-2020 allows this study to include the last significant changes in the EEG. Research regarding EEG amendments shows that there are initially different effects of political interventions on the electricity market in Germany. Liberalisation and additional subsidies have a price-reducing effect and are favourable for the market. In contrast, stronger regulations and changes in subsidy models can have negative, unforeseeable consequences. Comparing the changes of the EEG 2017 to the previous versions and amendments leads to the following hypothesis:

Hypothesis 2a: *As a result of the 2017 EEG, the effect of the share of renewable energies on wholesale prices changes compared to before the implementation*.

The change in subsidisation in the EEG 2017 follows a short-term decline in additionally installed and used renewable electricity generation capacity. In the long term, the expansion of renewable energies for electricity generation returns to the previous trend to achieve the federal government's targets. This development in the desired direction also relates to the shutdown and disconnection of conventional plants from the grid. These factors lead to the resulting hypothesis:

Hypothesis 2b: *The effect of the share of renewable energies on wholesale prices decreases in the years after introducing the policy change in 2017.*

Another significant factor influencing the performance and impact of renewable electricity production occurs in 2020. In 2000, the German government granted the first large-scale subsidies for plants. These subsidies will now expire after 20 years (Renewable Energy Sources Act, 2012). As a result, many plants will no longer be economically viable, or the installed components will need replacement. For this reason, facility operators took many of these plants off the grid in 2020 (PwC Germany, 2018). That means that they no longer contribute to electricity generation until they receive renewed subsidies or build a new plant. In turn, this has a negative impact on the expansion of renewables, which might also influence prices. These new circumstances lead to the subsequent hypothesis:

Hypothesis 2c: *The effect of the share of renewable energies on wholesale prices increases in 2020 due to the expiry of many facility subsidies.*

Combining the analyses of these hypotheses is particularly relevant for future policy decisions regarding Germany's renewable electricity production expansion. With the help of the results, future legislation can be derived favouring those parties that will subsequently provide the country's largest possible benefit as a whole. In this way, the government can promote the general acceptance of the energy transition.

4. Data and methods

4.1. Database

In order to evaluate how the transition of electricity generation from fossil to renewable would influence German electricity prices, this paper uses data from the European Energy Exchange (EEX), the German Federal Network Agency (BNetzA), and transparency data provided by the European Network of Transmission System Operators for Electricity (ENTSO-E). The sample includes the period from January 2015 until December 2020. All monetary values are in Euro (€), and the electricity units are in megawatt (MW), kilowatt (kW) and megawatt per hour (MWh). The resulting dataset is a time-series dataset and represents the change over time in the underlying period. Using the data published by these three institutions leads to high comparability of the effects to other periods and countries. Table 1 presents the descriptive statistics of the main variables of interest. One can clearly see that there are large variations for the different values in the years 2015 to 2020. The average wholesale price per day for electricity is €34.54/MWh. Despite large fluctuations, the standard deviation is relatively low, which can be attributed to a few peaks. Similarly, the share of renewable electricity production is relatively low. The daily average in the period studied is 38%. This could be traced back to the small variations in the cumulated renewable and fossil capacity, but also in the actual electricity production by the different methods. Only a few production methods have a high standard deviation.

Table 1: Descriptive statistics

	Mean	Std. Dev.	Min.	Max.
Wholesale price [€/MWh]	34.54	13.42	-54.29	101.92
Net commercial exports [MWh]	5,363.02	3,900.24	-8071.96	14,645.75
Renewable share [a]	0.37	0.12	0.11	0.76
Realised consumption [MWh]	14,227.57	1,666.32	9,997.24	17,889.57
Gas price [€/MWh]	16.28	5.29	3.58	58.78
Cumulated renewable capacity [MWh]	93,136.57	1,831.80	8,8920	95,352.56
Cumulated fossil capacity [MWh]	105,368.80	3,292.61	99,585.10	110,457.00
Biomass production [MWh]	1,122.72	86.05	41.03	1,258.16
Hydropower production [MWh]	446.67	98.13	13.71	754.00
Wind-Offshore production [MWh]	511.00	365.74	1.85	1,510.76
Wind-Onshore production [MWh]	2,428.80	1,853.42	58.76	9,516.11
Photovoltaics production [MWh]	1,111.19	723.30	52.02	3,025.42
Other-Renewable production [MWh]	41.48	10.28	1.54	64.95
Nuclear production [MWh]	2,093.18	379.73	75.64	2,860.88
Lignite production [MWh]	3,362.94	848.15	143.61	4,898.36
Hard-Coal production [MWh]	1,814.81	1,053.24	104.74	4,444.27
Natural-Gas production [MWh]	1,052.27	650.54	14.06	3,335.35
Pumped-Storage production [MWh]	270.55	79.27	5.58	540.38
Other-Conventional production [MWh]	815.24	631.08	50.45	5382.70

[a] Share of renewable electricity production in total electricity production, 1 corresponds to 100%.
Notes: This table presents summary statistics of the underlying dataset for wholesale electricity prices in the period from January 2015 until December 2020.

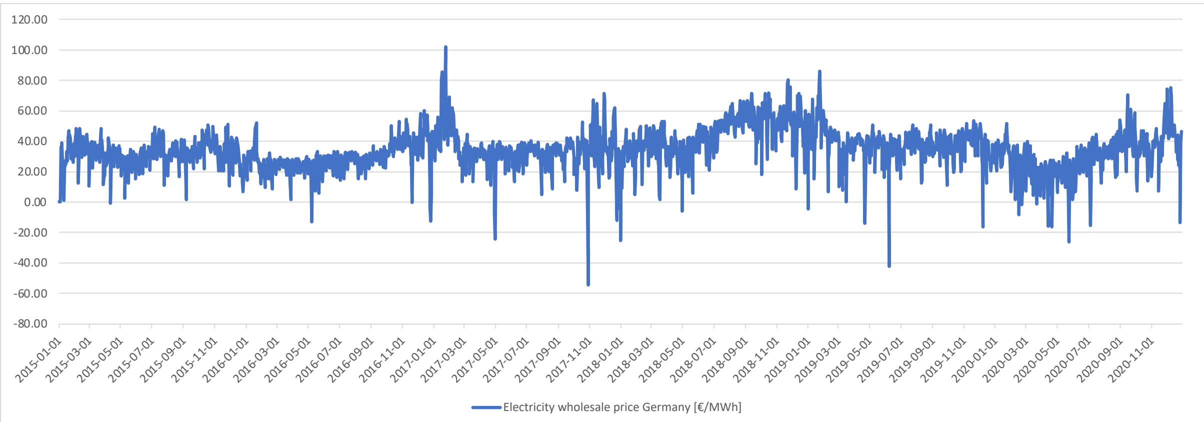
4.2. Dependent variable

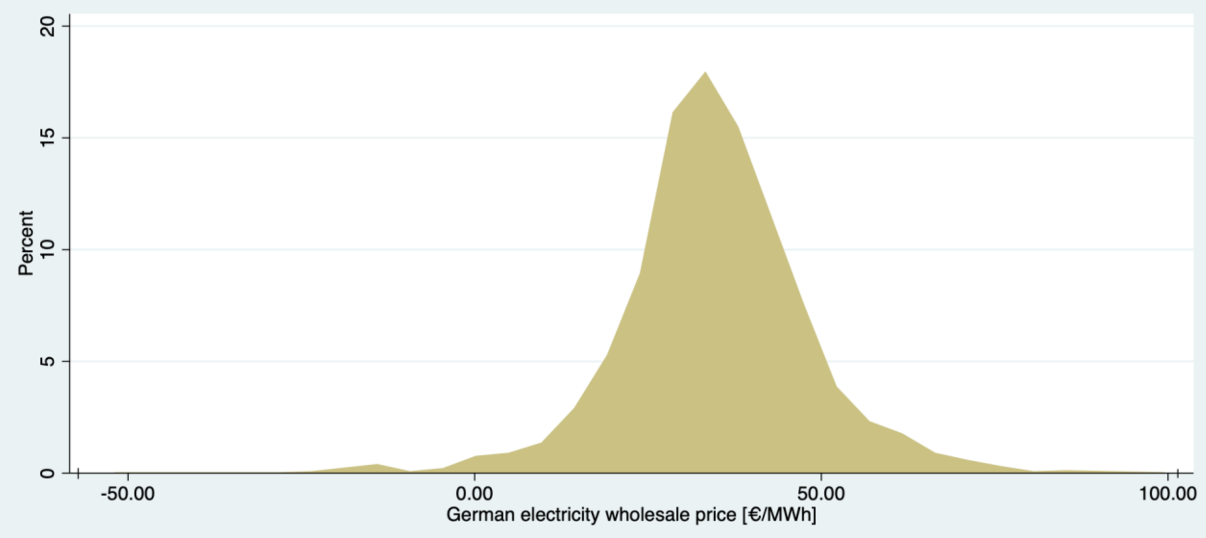
The German EEX day-ahead electricity spot price (P) is the dependent variable, representing the wholesale prices of the market area in Germany. The variable captures nationwide prices.

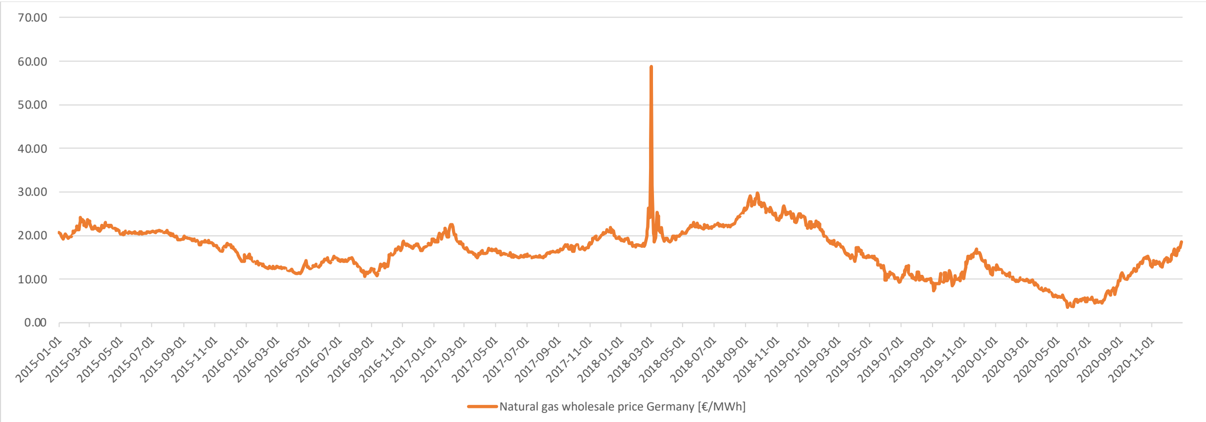
Hourly auctions determine these prices for the following day. The measurement of this value is €/MWh, and the data is present in 1-hour intervals. The wholesale electricity price represents the pure procurement price for electricity quantities traded on the exchange and over the counter. EEX prices result from the intersection of supply and demand. To minimise electricity supply costs, generation plants with the lowest variable costs come first (merit order). Therefore, the electricity exchange price corresponds to the variable costs of the most expensive generation plant in use. Although power exchange trades only account for about 20 per cent of the total traded volume, EEX electricity prices are a good indicator of general wholesale prices (Bundesnetzagentur, 2021; Von Roon & Huck, 2010). Since some variables are only available daily, I use the daily average price for this model. There have been significant variations in these prices over the years, but the average remained relatively constant. There is high volatility in the period under consideration. The values range from € 101.92 on 24th January 2017 to € -54.29 on 29th October 2017. The fact that negative prices occur shows that supply exceeds demand, and the additional supply cannot be exported.

Figure 2 illustrates the movement of the electricity wholesale price in comparison to the gas wholesale price. Both prices trade on the EEX. Below I explain the explanatory variables of the model.

Figure 2: Wholesale prices Germany







Notes: These figures plot German wholesale prices for electricity and natural gas in the period from January 2015 until December 2020. All values are the average daily nationwide price.

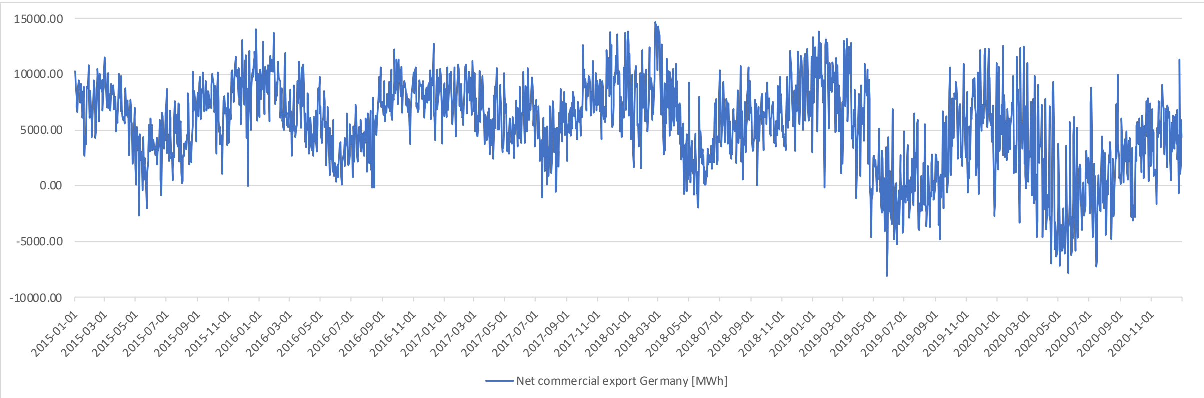
4.3. Independent variables

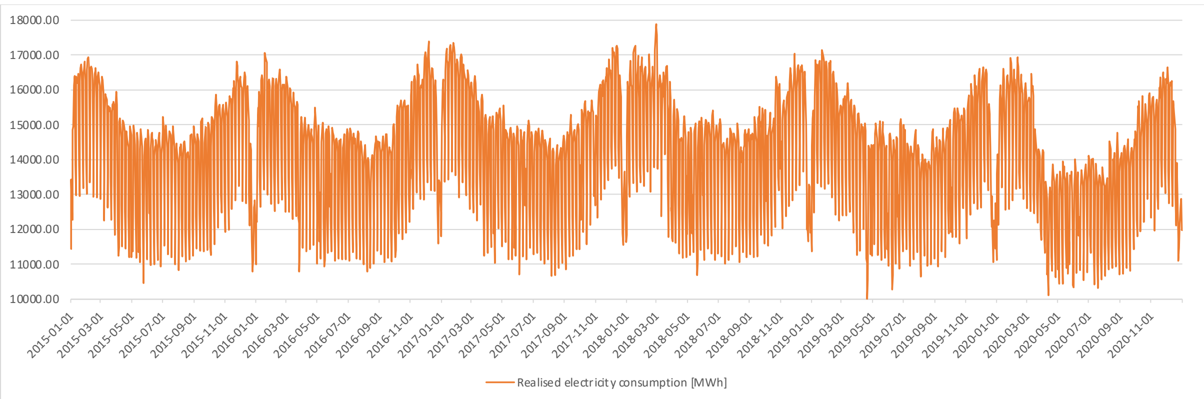
4.3.1. Commercial exports

Electricity foreign trade has a significant impact on the wholesale prices in a country. Higher exports suggest that the country has a large quantity not in use and producers generate too much electricity. The country covers its electricity demand, and producers and suppliers try to dispose of the remaining electricity. Therefore, prices tend to decrease as the remaining quantity increases. As a result, positive net exports would decrease the German wholesale prices. The transparency platform ENSTO-E publishes the foreign commercial trade data of all European countries. The German Federal Network Agency calculates the net commercial exports of Germany based on this data and provides the data for the observed period in MWh in hourly intervals. In the analysis, I will use the average daily net commercial exports (NE). Germany has a positive balance of foreign trade in electricity for most of the period under review. However, the trend in net electricity exports is declining cf. Figure 3. That means that

Germany exports continuously decreasing electricity quantities. There are also phases in which Germany imports more electricity than it exports, and thus net electricity exports are negative. The highest value was 14,645.75 MWh on 23rd February 2018, and the lowest value was -8,071.96 MWh on 28th May 2019. Particularly from 2019 onwards, Germany repeatedly has phases with negative net exports.

Figure 3: Realised Consumption and commercial exports



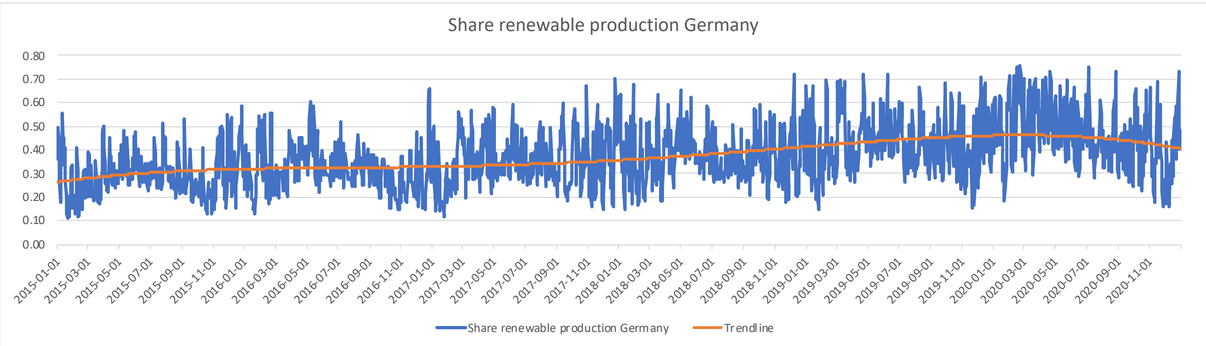


Notes: These figures plot German net commercial exports and the realised consumption of electricity in the period from January 2015 until December 2020. All values are the average daily nationwide numbers.

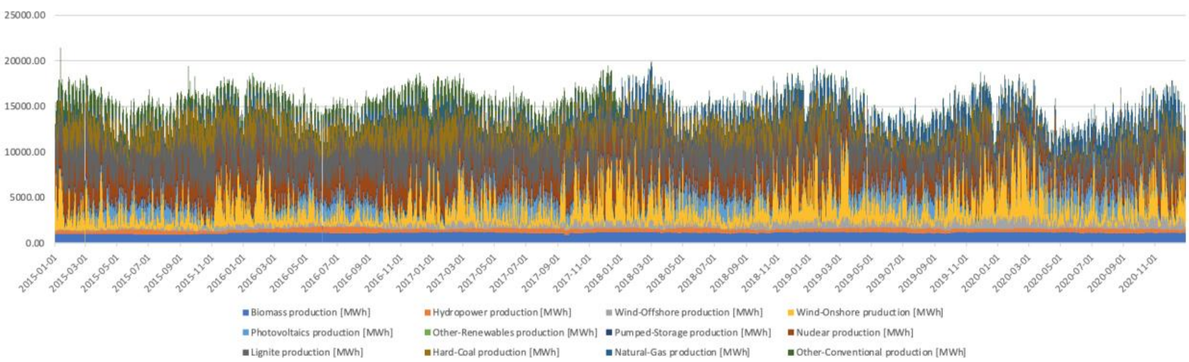
4.3.2. Share of renewables

The expansion of renewable energies in Germany and the resulting reduction in average marginal electricity generation costs fundamentally impact German wholesale electricity prices. For renewable energies, literature generally assumes marginal costs of zero, which is advantageous due to the merit order, favouring electricity production with lower costs (Krewitt & Schlomann, 2006). If the share of renewable energies in electricity production increases, this leads to lower costs, which causes wholesale prices to decline. The share of renewables is permanently increasing due to the German government's policies and guidelines. The German government subsidises investments in the construction of production plants for electricity from renewable energies and gradually shuts down fossil-fuel power plants, and ceases electricity production at these locations. At the beginning of the considered period in 2015, the average renewable share was roughly 30 per cent, while by the end, it was markedly above 40 per cent. The German Federal Network Agency provides data on the distribution of production methods at quarter-hourly intervals. Accordingly, I use the daily average share of renewable production (SR) for the analysis. On average, the value was 37.25 per cent and varied heavily between 10.79 and 75.75 per cent. These high variations, shown in Figure 4, result not only from the expansion of renewables but mainly from the production conditions. Good weather conditions boost the share considerably, and the merit order system strictly favours electricity from renewable energies.

Figure 4: German share of renewable electricity production and production capacities



Note: Share of total electricity production in Germany (1 corresponds to 100%)



Notes: These figures plot the share of renewable electricity production in Germany and the overall electricity production in Germany in the period from January 2015 until December 2020. The graph at the bottom shows the total daily production and the mix of the different production methods for each day. All values are the average daily nationwide numbers.

4.3.3. Electricity demand

Electricity demand is one of the key influences on electricity prices as it is highly volatile in the short run compared to electricity generation capacity. Higher electricity demand shifts the demand curve along the merit-order to the right. Companies can charge a price above the marginal cost until the last not dispatched unit (Wilson, 2000). The realised electricity consumption in MWh for Germany is an appropriate measurement to model the electricity demand during the observed period. For the analysis, I use the average daily realised electricity consumption (RC), calculated from the quarter-hourly data published by the German Federal Network Agency. In market equilibrium, higher consumer demand leads to rising prices. This phenomenon applies to the electricity market. Thus, higher realised electricity consumption leads to higher wholesale prices in Germany. In the period under review, the average daily realised electricity consumption is relatively stable over time and ranges from 9,997.24 MWh to 17,889.57 MWh a day, with an overall average of 14,227.57 MWh. Germany's overall electricity consumption slightly decreased over the years, and in the last week of the year, the daily average always drops immensely, which could be due to a decrease in household consumption favoured by travelling and holidays. Figure 3 displays this phenomenon.

4.3.4. Marginal costs of electricity production

To measure marginal costs of electricity production, I use the German daily day-ahead natural gas wholesale prices (GP). In Germany, gas-fired power plants become more and more critical as lignite, and hard-coal electricity generation decreases over time. In addition, trading for hard coal and lignite is hardly relevant in Germany, as electricity producers who use these technologies extract these raw materials as well. The Institute of Energy Economics at the University of Cologne (EWI) explains that from 2019 on, the merit order has changed in favour of natural gas. Thus, natural gas is further ahead in the order of producing power plants. That results primarily from emission certificates (Schulte, Schlund, & Arnold, 2020). Increasing gas prices symbolise an upward movement of the supply curve. Therefore, natural gas prices affect electricity wholesale prices positively and lead to an increase in these. The German natural gas price fluctuated between € 3.58 and € 58.78 in the underlying period, measured in €/MWh. Mainly, the gas price ranges between € 5 and € 25. However, at the end of February 2018, it exploded dramatically and reached its highest level of € 58.78 on 01st March 2018.

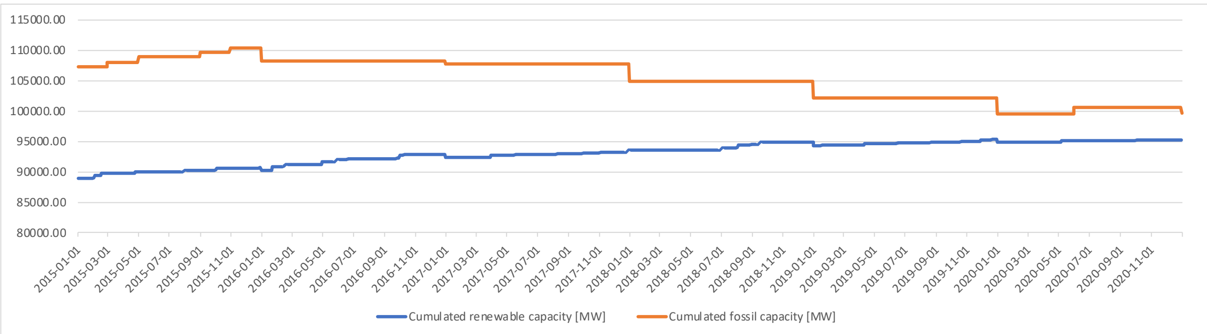
Due to a technological issue at the European Energy Exchange, it is not possible to access the spot price data for the interval between 01st January 2019 and 16th May 2019. During that period, the EEX adapted their data processing system. Therefore, I use monthly futures for this period in consultation with EEX experts. These reflect the daily spot prices very well so that the explanatory power of the marginal costs is maintained. Like spot prices, futures trade through daily auctions, which are much more detailed than the spot price auctions, so that the setting of prices is very comprehensible. Compared to wholesale electricity prices, gas price is relatively constant over time and not as volatile. From 2019 onwards, the price slightly decreases and then increases again at the end of the period under review, cf. Figure 2. Both prices develop relatively parallel.

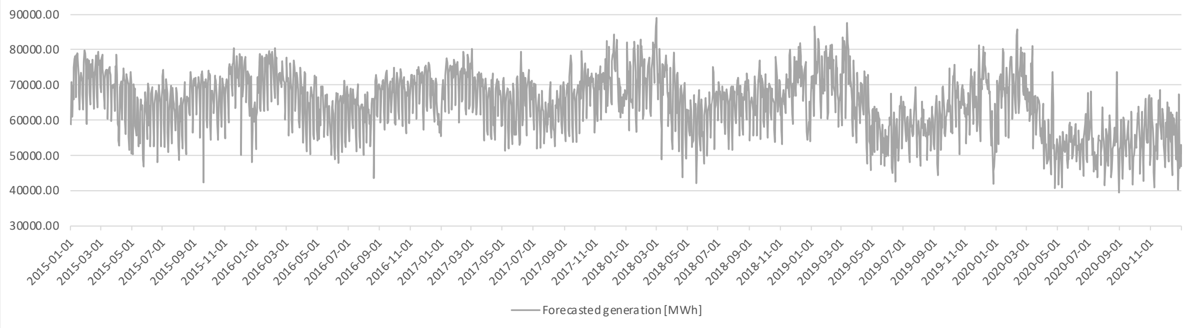
4.3.5. Production capacity

Installation and shutdown of electricity generation plants and production facilities have had an important impact on electricity prices over the years, considering the forced shutdown of fossil electricity production in Germany. Since these events do not occur regularly and the shutdown or launch of production facilities does not take place over a long period but somewhat is dated on a specific day, it is difficult to determine an effect on the wholesale price over time. However, shutdowns of nuclear, hard coal and lignite plants lead to enormous losses in the potential electricity supply. In contrast, integrating new renewable electricity production sites into the grid may compensate for these losses. Therefore, I consider cumulated renewable and fossil production capacity in MW for each day of the period. The cumulated net renewable capacity per day in MW (CR), and the cumulated net fossil capacity per day in MW (CF), represent these factors. Over time, the aggregated installed capacity remained relatively constant. That reflects the sharp decline in fossil-based electricity generation and the ongoing expansion of renewables. Compared to the constant installed capacity, however, the forecasted capacity becomes much more volatile over time. It is also noticeable that after the system change in 2017, the increase in the cumulated capacity for renewables declined, shown in Figure 5.

In the further course of the analysis, I use the daily productions in MWh of each electricity generation type instead of the cumulative capacities. The descriptive statistics of these variables are in Table 1. For these measurements, I also consider the daily average for the entire period in the analysis. Appendix II shows the changes for these generation types in the electricity market. Based on these patterns, it is also possible to derive the renewable electricity production share for Germany. One should note that the graphs show renewable and fossil electricity generation separately. In the further course, I also consider the total renewable electricity production. It sums up all renewable capacities used for electricity production. The underlying unit is identical for all generation types (MWh). While photovoltaic production is mostly constant during the entire period with repetitive fluctuations during the year, production by wind shows more noticeable changes. Wind-onshore generation increases slightly over time, with severe fluctuations during each year. In the period under review, wind-offshore production increases most significantly among the renewables. Apart from the fluctuations during the year, one can recognise an evident growth. Biomass and other renewable electricity production methods remain roughly constant over the entire period, while hydropower production declines slightly. Over time, electricity generation from conventional sources declines for most methods. While lignite, hard coal, and nuclear production decreased slightly over time, a substantial decline occurred for other conventional at the beginning of 2018. Lignite and hard-coal production develop relatively similarly in the underlying period. Pumped-storage, on the other hand, is relatively constant over time. The only positive trend appears in natural gas generation, which increases to such an extent that it exceeds the production output of most conventional methods by the end of the period.

Figure 5: Cumulated Capacity and Forecasted Generation





Notes: These figures plot German daily cumulated capacity of renewable and fossil energy production and the overall forecasted electricity production in Germany for each day in the period from January 2015 until December 2020.

Table 2: Average annual values of main variables, 2015-2020

	2015	2016	2017	2018	2019	2020
Wholesale price [€/MWh]	31.49	28.98	34.19	44.47	37.66	30.47
Net commercial exports [MWh]	6,428.78	6,601.67	6,863.98	6,185.07	4,007.24	2,096.94
Renewable share [a] [%]	29.71	31.74	35.48	37.60	42.56	46.44
Realised consumption [MWh]	14,275.81	14,288.03	14,417.01	14,479.53	14,143.26	13,762.87
Natural-Gas price [€/MWh]	19.89	14.12	17.39	22.85	13.85	9.59

[a] Share of renewable electricity production in total electricity production
Notes: This table presents the yearly average value for the main variables of interest in the period from January 2015 until December 2020.

Table 2 describes the average annual values of the main variables used in the analysis for the underlying period. The comparison of these values clearly illustrates the trend in the share of renewable production. In combination with net commercial exports, this leads to the apparently constant development of wholesale electricity prices in Germany.

4.4. Methodology

To investigate the effect of renewable electricity production expansion on wholesale prices in Germany, this paper controls for factors that affect electricity production costs and reflect the expansion of renewables. I consider the main factors influencing daily electricity prices during the expansion of renewables in Germany's energy transition. The use of daily averages is advisable, as this prevents distortions in production capacities due to varying degrees of availability of energy sources of the renewable methods. In the analysis, the estimation of the model is in logs for most variables because the effect of these explanatory variables on wholesale electricity prices is not likely to be linear. However, the wholesale prices and the net commercial exports for Germany consist of negative values and are not expressible in logs. The analysis uses the following base model regression for the wholesale prices in the sample:

$$P = \beta_0 + \beta_1 NE + \beta_2 \log(RE) + \beta_3 \log(RC) + \beta_4 \log(GP) + \beta_5 \log(CR) + \beta_6 \log(CF) + \varepsilon$$

where

P represents the average German daily day-ahead electricity wholesale price in €/MWh
NE represents the average German daily net commercial exports in MWh
RE represents the average German daily share of renewable production (0-1, 1 corresponds to 100%)
RC represents the average German daily realised electricity consumption in MWh
GP represents the average German daily day-ahead natural gas wholesale price in €/MWh
CR represents the cumulated net renewable capacity per day in MW
CF represents the cumulated net fossil capacity per day in MW

The time-series model estimates the German average daily day-ahead electricity wholesale prices based on daily data over the underlying period 2015-2020. For comparability between studies and robustness, previous literature prefers time-series models. These models suit the available data of the electricity market particularly very well. Table 1 consists of the descriptive statistics of the main variables of interest, whereas Appendix I gives the correlation matrix. Before using the data for the regression analysis, I applied statistical tests. I examined whether the data is stationary by performing the Augmented Dickey-Fuller test for unit roots. In case of failure and rejecting the null hypothesis, the test reruns for differenced variables. The procedure repeats until the test rejects the null hypothesis, meaning that the p-values are lower than the 5% confidence level.

With the base and specified models, I test the effect of renewable production on German electricity wholesale prices. Therefore, the base model consists of the renewables' share and the cumulated installed capacity of fossil and renewable electricity production. The first specified model relaces the renewable share with the actual daily production and the second with the production per generation method and thus removes the cumulated capacity. I tested the control variables used for correlation. By using the three different models, I checked whether the different independent variables influence each other and how the effect changes when certain variables are exchanged or removed from the regression. I tested the data for seasonal and monthly effects, as electricity prices could depend on the seasons and the course of the year. There were no indicators for that. Therefore, I will not consider seasonal effects and monthly fixed effects in the following. I used different statistical models and methods to analyse the effects, all of which show the same effects for the determinants examined. Therefore, I use two models here that are representative of these analyses. The interpretation mainly takes the form of a level-log model. If the independent variable increases by one per cent, the wholesale price changes by $\beta_i/100$ units, ceteris paribus. For net exports, the interpretation is in level-level form.

In further analyses, I controlled for variations in the effects before and after the policy change in 2017. The first post 2017 model uses an interaction term calculated from the period post-2017 and the share of renewable generation to visualise the effect of the EEG adjustment in 2017. The second post 2017 model reproduces the base model for the period from 2017 onwards and considers the development of the share of renewable energies over the remaining period. Besides, I compared the 2020 effects to those from 2019, using 2019 as the reference year. I used dummy variables and interaction terms of the renewable electricity production share and a post-regulation, respectively, 2020 dummy. To further check if the impact of the variables changes over time, I also estimated the model for three subsequent periods (2015-2016, 2017-2018, and 2019-2020) and every year. The models each reflect the effects of the explanatory variables on the average daily German electricity wholesale prices in the year under investigation. For these analyses, too, I present only the most explanatory models that reflect the effects of all the methods used.

5. Results

First, I run stationary tests for the main relevant variables. The Augmented Dickey-Fuller (ADF) test for the presence of unit roots suggests that the data is stationary at the 1% confidence level in the underlying period. The last column of Table 3 shows the p-value, which is lower than 1%. Therefore, all variables are stationary, and the analyses do not require first differences (Dong, 2012). Furthermore, I perform a variance inflation factor (VIF) test. The mean VIF of each model is below the threshold of 5. Therefore, there are no concerns for multicollinearity in the used models (Hair, Hult, Ringle, & Sarstedt, 2015).

Table 3: Augmented Dickey-Fuller test results of main variables

Variable	ADF test statistic	1% critical value	p-value
Wholesale price [€/MWh]	-20.329	-3.430	0.0000
Net commercial exports [MWh]	-17.283	-3.430	0.0000
Renewable share[a] [%]	-18.325	-3.430	0.0000
Realised consumption [MWh]	-23.618	-3.430	0.0000
Natural-Gas price [€/MWh]	-3.935	-3.430	0.0018

[a] Share of renewable electricity production in total electricity production

Notes: This table presents the augmented Dickey-Fuller test for the main variables of the underlying dataset for the period 2015-2020. All variables are stationary at the 1% confidence level.

The use of the control variables in the following models is based on previous research and the recommendation of EEX. In this way, I examine not only the actual production but also the impact of the maximum total capacity available for that day.

5.1. Effects of renewable expansion

Hypotheses 1a and 1b deal with the general effects of the expansion of renewables. I examine the effects on electricity prices and the merit order to demonstrate that these processes go hand in hand.

Hypothesis 1a stated that the expansion of renewable electricity production decreases wholesale electricity prices in Germany. Using the base and specified models proves this. As shown in Table 4, the share of renewable electricity production and every single renewable generation method has a price-decreasing effect on Germany's electricity wholesale prices. Thus, an additional megawatt-hour of these electricity generation types or an increase in the share of renewable electricity production leads to declining electricity wholesale prices.

The base model regression, presented in Table 4, examines the effect of renewable production on German electricity wholesale prices. In the base model, the share of renewables in the electricity generation process has a negative effect on German electricity wholesale prices. As the share increases by one percentage point, German electricity wholesale prices decrease by 0.23 €/kWh, ceteris paribus. This effect is significant at a 1% significance level. The second specified model provides a more detailed overview. As illustrated in Appendix II, there are significant differences in production capacity between the types. Therefore, this additional model shows which of the methods has the highest impact on the overall effect of renewable production. Ceteris paribus, renewable electricity generation has a price-reducing effect, whereas conventional electricity generation has a price-increasing effect. All production types reflecting this are significant at a 1% significance level, whereas other generation types, which show other effects, such as nuclear and hard-coal, are little to insignificant.

Hypothesis 1b addresses the impact of the renewable electricity production expansion on the merit-order. In Table 4, the models present clear evidence that increasing production by renewables leads to decreasing electricity wholesale prices in Germany. Compared to the base model, the first specified model does not consider the share of renewable electricity production but the total production of renewables. The coefficients of renewables are mostly negative in all models, which indicates a price-reducing effect. In the first specified model, an increase in renewable production by one percentage point decreases German electricity wholesale prices by 0.22 €/kWh, ceteris paribus. This effect is significant at a 1% significance level. Fossil generation methods, which are at the higher end of the merit order curve, increase wholesale electricity prices. The results demonstrate the presence of a negative merit-order effect for 2015-2020. Considering the increase in the share of renewable electricity production over the years of the underlying period illustrates an increase in the merit-order effect, cf. Figure 4. The varying coefficients in the second specified model indicate that the different methods influence the merit-order differently. The merit-order effect, therefore, varies between the methods. There are opposing effects between fossil and renewable methods. Hence, the effect of additional production of one MWh per type of electricity generation amplifies. Thus, the expansion of renewable electricity production leads to lower wholesale electricity prices in Germany due to the merit-order effect.

Appendix III shows the development of the merit-order in Germany for the underlying years. Despite a decline in lignite, hard coal and nuclear production, other conventional power generation sources are being pushed out of the merit order. That is mainly due to the substantial increase in production from wind, both onshore and offshore. Such a development clearly shows the trend in electricity production for the upcoming years. With the expansion of renewable electricity production, generation methods will gradually become unnecessary and renewable generation can compensate for the dismantling of all conventional plants.

Table 4: Effects of explanatory variables on the average daily German EEX price

Explanatory variables	Base model 1	Specified model 1	Specified model 2
Net commercial export [MWh]	-0.0006601***	-0.0003171***	0.000120
	(0.0000472)	(0.0000507)	(0.0000771)
Ln(Share renewable production [%])	-23.24***		
	(0.522)		
Ln(Realised consumption [MWh])	27.10***	44.91***	41.26***
	(1.296)	(1.227)	(3.219)
Ln(Natural gas price [€/MWh])	14.92***	15.15***	17.53***
	(0.505)	(0.501)	(0.501)
Cumulated renewable capacity [MWh]	374.88***	267.70***	
	(13.538)	(34.43)	
Cumulated fossil capacity [MWh]	-13.32	34.10**	
	(9.631)	(15.94)	
Ln(Renewable production [MWh])		-21.58***	
		(0.516)	
Biomass production [MWh]			0.0139***
			(0.00222)
Hydropower production [MWh]			-0.00913***
			(0.00160)
Wind-offshore production [MWh]			-0.00173***
			(0.000599)
Wind-onshore production [MWh]			-0.00410***
			(0.000260)
Photovoltaics production [MWh]			-0.00134***
			(0.000315)
Other renewable production [MWh]			-0.328***
			(0.0202)
Nuclear production [MWh]			-0.000847*
			(0.000461)
Lignite production [MWh]			0.00181***
			(0.000364)
Hard-coal production [MWh]			-0.000222
			(0.000352)
Natural-gas production [MWh]			0.00362***
			(0.000460)
Pumped-storage production [MWh]			0.00116
			(0.00192)
Other conventional production [MWh]			0.00237***
			(0.000357)
Constant	-4,421.007***	-3,713.9***	-418.70***
	(251.674)	(335.2)	(29.64)
R^2	0.7525	0.739	0.822
Adj. R^2	0.7518	0.738	0.820
N	2,192	2,192	2,192

Standard errors in parentheses
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Notes: This table presents the effects of the explanatory variables on the average daily German EEX price. The base model regression examines the effect of renewable production on German electricity wholesale prices. The specified models do not consider the share of renewable electricity production. The first specified model includes the total production of renewables, and the second specified model includes each single production method to track their different impacts.

5.2. Effects of regulatory adjustments

Hypothesis 2a elaborates on the effect of the EEG policy change in 2017 on German electricity wholesale price. It predicts an increase in the renewable share effect on wholesale prices compared to before the implementation. Due to the policy change in 2017, the expansion of renewable electricity production facilities declined because investors built less new renewable capacity. Thus, the effect of the share of renewables in electricity production on wholesale prices is stronger from 2017 onwards compared to the past. An interaction term calculated from post-2017 and the share of renewable generation determines this effect.

Table 5 presents the impact of the regulation change of the EEG 2017 and the subsequent impact on the German wholesale electricity market. The first model for post-2017 clearly shows that the effect of renewable electricity production is lower after the introduction of the EEG 2017. Compared to the period before the EEG amendment, the effect on German electricity wholesale prices decreases due to an increase in the share of renewable energies in electricity production by one percentage point, ceteris paribus. All effects are significant at a 1% significance level.

Hypothesis 2b considers this effect of declining of a declining effect over the years post the EEG 2017 implementation. Post-2017, the change in subsidies and incentives for installing renewables causes the effect of the renewable share on wholesale prices to increase over time. Decreasing government support leads to an increasing impact of the renewable electricity production share on wholesale electricity prices. I determine this effect by dividing the sample into different annual periods based on the underlying years.

Table 5: Effect of EEG 2017 and changes in 2020 on German EEX prices

	Post-2017 model 1	Post-2017 model 2	2020 model
Net commercial export [MWh]	-0.000557***	-0.000716***	-0.000445***
	(0.0000467)	(0.0000650)	(0.0000753)
Ln(Realised consumption [MWh])	26.44***	25.33***	27.62***
	(1.282)	(1.730)	(2.233)
Ln(Natural gas price [€/MWh])	16.10***	17.44***	7.978***
	(0.552)	(0.714)	(0.961)
Ln(Share renewable production [%])	-16.90***	-105.80***	-24.69***
	(0.797)	(31.18)	(1.292)
Post-2017	-11.61***		
	(1.287)		
Post-2017 * ln(Share renewable production [%])	-10.54***		
	(0.957)		
Date		0.0159***	
		(0.00160)	
Date * ln(Share renewable production [%])		0.00368**	
		(0.00145)	
$Year^{(2020)}$			-7.532***
			(1.652)
$Year^{(2020)}$ * ln(Share renewable production [%])			-4.469***
			(1.639)
Constant	-289.6***	-615.8***	-276.0***
	(11.95)	(38.05)	(21.47)
R^2	0.755	0.741	0.768
Adj. R^2	0.754	0.740	0.765
N	2,192	1,461	731

Standard errors in parentheses
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Notes: This table presents the effects of the explanatory variables on the average daily German EEX price. The first post 2017 model uses an interaction term calculated from the period post-2017 and the share of renewable generation to visualise the effect of the EEG adjustment in 2017. The second post 2017 model reproduces the base model for the period from 2017 onwards and considers the development of the share of renewable energies over the remaining period. The 2020 model compares the effects in 2020 to the reference year 2019.

The annual model in Table 6 clearly shows that the impact of renewables' share of electricity production on German EEX prices decreases in the following years, ceteris paribus. For all years, the effect is significant at a 1% significance level. The second post-2017 model in Table 5 reinforces this effect. The model reproduces the base model for the period from 2017 onwards. In addition, it considers the development of the effect of the share of renewable energies over the remaining period. An interaction term consisting of the advancing date and the share of renewables in electricity production describes this. An additional day increases the wholesale price while the share of renewables remains constant. Thus, the price-reducing effect of renewables decreases over time, ceteris paribus. This effect is significant at a 5% significance level.

Table 6: Post-2017 annual model

Explanatory variables	2017	2018	2019	2020
Net commercial export [MWh]	-0.000172	-0.000460***	-0.000292***	-0.000424***
	(0.000204)	(0.000108)	(0.000105)	(0.000117)
Ln(Share renewable production [%])	-29.88***	-29.65***	-26.32***	-27.61***
	(1.426)	(1.179)	(1.436)	(1.455)
Ln(Realised consumption [MWh])	35.44***	26.14***	30.50***	29.58***
	(3.297)	(2.806)	(3.056)	(3.186)
Ln(Natural gas price [€/MWh])	8.474*	18.22***	0.907	5.958***
	(4.733)	(2.761)	(2.285)	(1.264)
Constant	-352.9***	-369.8***	-251.2***	-330.2***
	(28.58)	(27.43)	(29.95)	(32.05)
R^2	0.793	0.832	0.723	0.795
adj. R^2	0.790	0.830	0.719	0.792
N	365	365	365	366

Standard errors in parentheses
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Notes: This table presents the effects of the explanatory variables on the average daily German EEX price. The models each reflect the effects of the explanatory variables on the average daily German electricity wholesale prices in the year under investigation.

Hypothesis 2c observes the impact of the expiring subsidies in 2020, granted in 2000. The effect of renewables on German electricity wholesale prices increases again in 2020 because some of the facilities, initially opened in 2000, lose their subsidies and are no longer profitable. The operators shut down these plants in 2020 and will either replace them with new production facilities at the same site or remove them completely. Due to the decrease in renewable production capacity, an additional kilowatt-hour has a greater impact on wholesale prices. Thus, the impact of the renewable share of electricity production increases slightly.

The model in Table 6 clearly shows this phenomenon. In 2020, the coefficient increases again for the first time and reaches -27.61, ceteris paribus, and is significant at a 1% significance level. That process also becomes clear once again by comparing the values for 2020 with the previous year. The 2020 model in Table 5 shows this. In this model, I compare the values of 2020 with those from 2019. The year 2019, therefore, serves as the base year for the analysis. The results clearly show the increase in the effect in 2020. Compared to 2019, the effect on German electricity wholesale prices decreases due to an increase in the share of renewable energies in electricity production by one percentage point, ceteris paribus. This effect is significant at a 1% significance level. The negative effect illustrates an increase in the price-reducing effect in 2020 compared to 2019. In 2020, the share of renewable electricity production has a stronger impact on wholesale prices again.

6. Discussion

6.1. Research Findings

The objective of this study was to examine the impact of the expansion of renewable electricity production in Germany during the years 2015-2020 on German electricity wholesale prices. The following section will give a summarised overview of the findings and discusses them with regard to existing literature.

The use of time-series models for the investigated period 2015-2020 shows various influences affecting German electricity wholesale prices. Increasing renewable electricity production capacity reduces German wholesale electricity prices and thus increases the merit-order effect. The merit-order effect differs greatly between the generation methods in some cases and can show opposite directions. In particular, this is the case when comparing renewable and fossil methods. The 2017 EEG reform of feed-in and subsidisation has a strong effect on the price effects of renewable electricity production. It is clear to see that the effect initially increases in the short term, but it converges back to the situation before the adjustment in the long term. A significant price effect of renewable electricity production is also evident in 2020 when many subsidies for production facilities expire. The observed price effects also reflect this. Several issues arise that need further discussion for the expansion of renewable energies in Germany and, as a consequence, of renewable electricity production.

First of all, I examined the relationship between additional renewable electricity production and German electricity wholesale prices. The findings show that an increase in the renewable production capacity share has a price-reducing effect in the underlying period. Previous empirical literature already found a similar relationship for earlier periods for both Germany (Traber & Kemfert, 2010) and other Countries (Gelabert et al., 2011; Mulder & Scholtens, 2013). However, the impact of the renewable share was not as high as during the observed more recent period. Besides empirical approaches, the findings are also in line with simulation-based approaches covering the observed period. These studies predicted similar results regarding the price-reducing effect of a renewable energy expansion (Fürsch et al., 2011; Traber et al., 2011). This study extends on the former literature as it includes not only the renewable electricity production but also its share and each single production method to compare the resulting effects of each type and controls for cumulated installed capacities.

In addition to the impact on German electricity wholesale prices, this study also observes the emerging merit-order effect resulting from the renewable expansion. The increasing share of renewables increases the merit-order effect in Germany. That becomes particularly clear when considering the different production methods. Compared to prior studies focussing on the merit-order in earlier years (Tveten et al., 2013; Würzburg et al., 2013), this study confirms the expectation of Fürsch et al. (2012) for 2015 and 2020 and even extends the used models by adding more individual factors to increase the comparability for future research.

The second part of this study focuses on the impact of regulations and policy changes. Therefore, I took the EEG amendment in 2017 into account. The findings present a decline in the effect of renewables on German electricity wholesale prices after introducing the EEG 2017 at the end of 2016. The underlying change in subsidisation and feed-in tariffs leads to a decreasing expansion of renewable production and, therefore, to an increasing impact on the German electricity day-ahead spot prices. Existing studies have investigated the effects caused by specific regulatory changes. Contrary to Traber & Kemfert (2009), who predicted declining industry prices resulting from regulatory changes, Anatolitis & Welisch (2017) and Meya et al. (2016) found overall negative effects of the EEG 2017 due to some advantages in cost efficiency, which cannot compensate the disadvantages. On top of this, the changed tenders for subsidies restrict the expansion of renewable energies due to their complexity and increased competition (Gawel & Purkus, 2016).

In the next step, I investigated the effects in the following years post the EEG amendment in 2017. The short-term shock caused by the adjustment in subsidies and feed-ins for renewables reverses over time. In the following years, the price effect of the renewable share slowly decreases. That results from the increasing expansion of renewable electricity production. The findings show this clearly. The market subsequently adapts to the new situation. The ongoing transition of the electricity supply based on the government's targets also favours this positive development. This development is contrary to the expectations of earlier analyses (Balussou et al., 2018; Meya et al., 2016). In addition, only a few renewables (wind onshore and biomass) meet the previously required target quantities at the time of the 2017 EEG amendment. Therefore, conversions towards an improved market and system integration were necessary (Gawel & Purkus, 2016). However, Greve & Rocha (2020) state that many new facilities are profitable even without subsidies due to the created competition. That development seems to be successful at first sight.

The last section reflects the effects resulting from the expiry of the 20-year subsidies for some renewable plants in 2020. Due to the limited duration periods, old plants are no longer economically efficient after 20-25 years, and therefore, operators shut them down and dismantle or renew them. The results for 2020, in comparison to the previous year, also show that the effect of the renewable share increases. The effect also appears when considering the individual years. 2020 is the first year in which the effect increases again after a continual decrease. There is no scientific work on these effects yet, although there are predictions and confirmations from consultancies operating in the energy industry (PwC Germany, 2018).

The expansion of renewable energies shows many advantages to the price development of wholesale electricity prices in Germany. However, consideration of the actual development is essential. Looking at the average monthly values in Appendix IV, it is noticeable that despite the progressive expansion of renewable electricity production and the renewable share, wholesale prices do not decrease permanently but tend to fluctuate. Suppose one compares the complete development of German wholesale electricity prices, cf. Figure 2, it seems that these remain more or less stable over time. An examination of the average annual values in Table 2 confirms this phenomenon. However, there are fluctuations, which are also distinctly attributable to renewable electricity production in the graphs in Appendix IV. However, renewable electricity production does not increase linearly, as can be seen in Figure 4. The development displayed in this graph is also traceable to the framework conditions of the German electricity market, as analysed in the second part of the paper. As a result of the introduction of the EEG 2017, wholesale prices first rose in 2017 and 2018 and then slowly converged back to the initial level in the following years. Since the expansion of renewable energies in the years analysed is mostly progressing substantially, exogenous shocks could be responsible for these developments. Future political decisions should therefore take this major influence into account.

6.2. Policy implications

The underlying analyses showed that the expansion of renewable energies in Germany positively impacts the country's wholesale electricity prices. The construction of further plants and facilities is therefore beneficial to reduce electricity prices in the long term. As a result, the German energy transition has additional positive effects, not prioritised at its introduction. Initially, the aim was to avert natural catastrophes and to give climate protection a higher priority. By influencing the merit order, even generation methods can fall out of the pricing process in the long term and thereby lower prices even more drastically. Thus, the energy transition can produce economically positive long-term results, despite massive initial investments to enable the expansion of renewables.

These findings suggest that the German government should not only consider the expansion of renewable energies from the point of view of climate-neutral production in connection with the self-set targets. An essential aspect in the constant development and pursuit of these goals should also be considering further subsidies for newly constructed facilities to continue making the expansion economically efficient. Therefore, the German federal government's implementation of supportive programmes should continue to maintain the positive trend and achieve the self-imposed goals.

In a further step, policymakers should consider the future changes from the point of view of potential impacts and possible further adaptations. Previous studies and the results of this thesis indicate that parts of the policies have failed to achieve the initially envisaged effects. For example, an increase in competition does not only lead to the desired economically more efficient development of new projects and production facilities but also brings negative consequences. It is necessary to weigh up these consequences not to curtail the expansion of renewables in the long term and thus drive up electricity prices. Previous actions and amendments to the basic requirements in the Renewable Energy Sources Act reduced the expansion and the price-reducing effects in the short term. It, therefore, remains questionable whether this reflects the goals of the political interventions.

Therefore, future political measures should ensure more stability in the development of the market and, accordingly, the expansion of renewable electricity production. The examination of previous self-created situations and the development to date is critical. As can be seen, the market initially reacts negatively to externally imposed changes. Future adjustments to the Renewable Energy Sources Act should take these market reactions into account. That should be the case for governmental desired adjustments and the reaction to expiring mechanisms or regulations. In cases of foreseeable negative consequences for the expansion of renewables and electricity prices, the German federal government should proactively achieve the intended targets. Otherwise, reaching these goals will be a severe challenge.

6.3. Limitations and future research

A potential limitation could be the market coupling with other countries (15), which leads to prices not falling as assumed or reflected price effects, which are different than initially expected. Furthermore, the market coupling and the resulting identical price for the countries leads to a conglomeration of potential effects and therefore, it is not possible to conduct a precise analysis. Thus, the full extent of the effects on the German market is not determinable, as it reflects the effects in the other countries as well.

Another limitation of this study could be the assumption made regarding the EEX natural gas prices. The use of futures instead of day-ahead spot prices may slightly distort the resulting effects. However, the four and a half months are relatively short and therefore negligible compared to the six years considered. Moreover, the values only serve as a controlling factor for the analysis of the price effects of renewable electricity production.

Future studies should address the long-term evaluation of the expansion of renewable energies and the achievement of the set capacity targets. Both the price effects resulting from the energy transition and the effects of the implemented measures and legislative adjustments should play a decisive role. Due to the numerous reforms in recent years, it was not possible at the current time to conduct a long-term analysis of the German electricity market based on a constant market situation in order to ensure comparability of the results. The analysis of the overall development of renewable energy expansion, especially for electricity production, can provide a benchmark for developing projects in Germany on a similar scale.

7. Conclusion

Using a unique dataset for the German wholesale electricity market, provided by the European Energy Exchange, the European Network of Transmission System Operators for Electricity and the German Federal Network Agency, this paper illustrates a first empirical study of the current development and impacts of specific measures. The expansion of renewable production capacities and a price-reducing effect on German wholesale electricity prices show a clear correlation. The merit-order, which favours the use of renewable energies, reinforces this influence. However, the positive effect could get repeatedly curtailed by governmental interventions. Regulations that affect the expansion of renewable energies might lead to a substantial increase in the effect of an additional installed or used renewable megawatt-hour. Therefore, legislators should think through and constantly monitor adjustments to the underlying conditions for market development.

The findings are mostly consistent with previous studies regarding earlier periods. They clearly show that the expansion of renewable electricity production decreases wholesale prices over time. The analysis of these factors considered the renewable electricity production share and actual production capacities. However, government interventions and the absence or expiry of subsidies lead to a slowdown in the process. The introduction of the EEG in 2017 had a noticeable negative impact on the development of prices, and the market recovered slightly over the years. Likewise, the expiry in 2020 of some subsidies granted for twenty years led to adverse effects. In the course of the energy transition and the self-imposed targets, Germany needs to significantly adjust the market conditions and make them more producer-friendly to achieve the targets in the intended time.

This paper aimed to create a dataset based on recent reliable data to examine the current effects that actually occur in the German electricity wholesale market instead of using predictions to calculate potential future impacts of the renewable expansion and EEG amendments. This study, therefore, offers several opportunities for future research to compare arising effects over time. Further expansion of the dataset is possible in the future by adding data from upcoming years. This unique comparability without a multitude of assumptions or phenomena thus offers a high degree of unprecedented comparability. Apart from direct market effects, the dataset also allows an analysis of policy measures and their impact on the expansion of renewable electricity production. This interplay of possible analyses of endogenous and exogenous influences becomes increasingly relevant with the growing complexity of the market and regulatory conditions. Over time, regulations in the German electricity market increased, and today it is one of the most regulated markets in the world (Grave & von Blücher, 2015). Thus, future studies can examine long-term effects with the help of this paper.

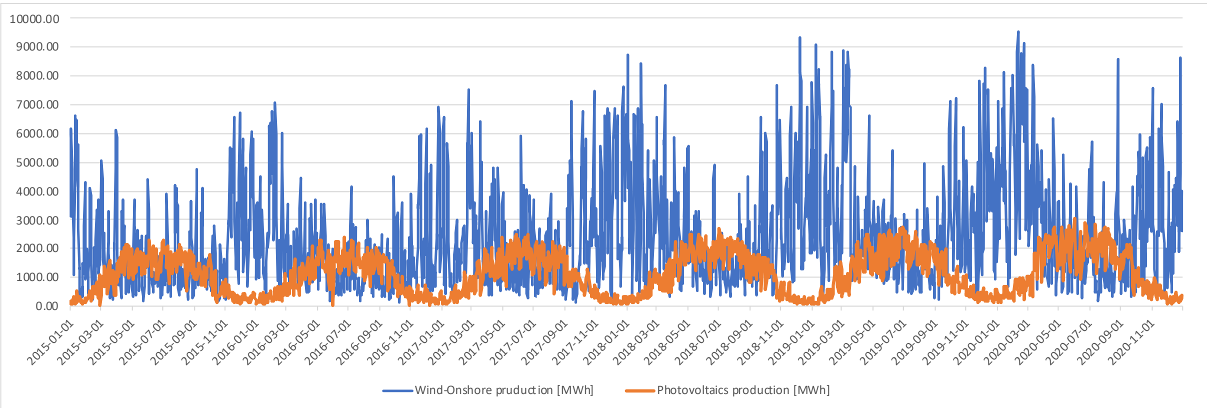
8. Appendix

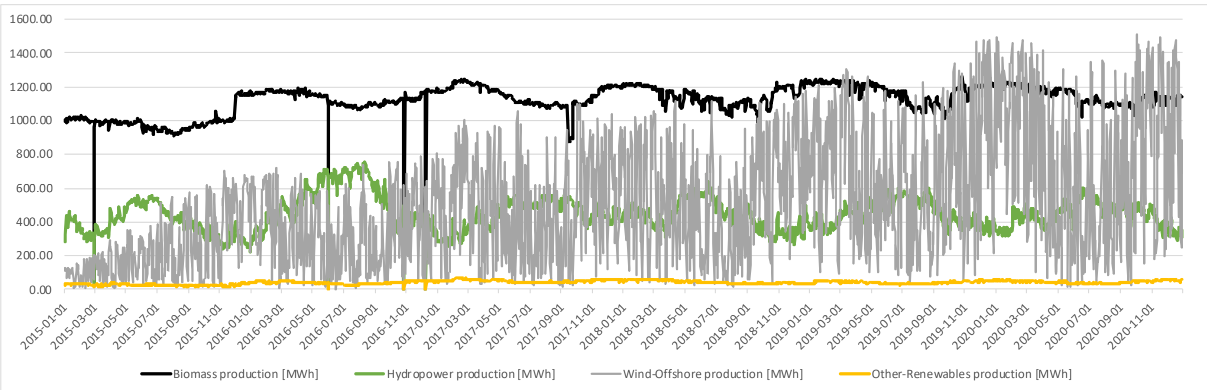
Appendix I: Correlation matrix base model

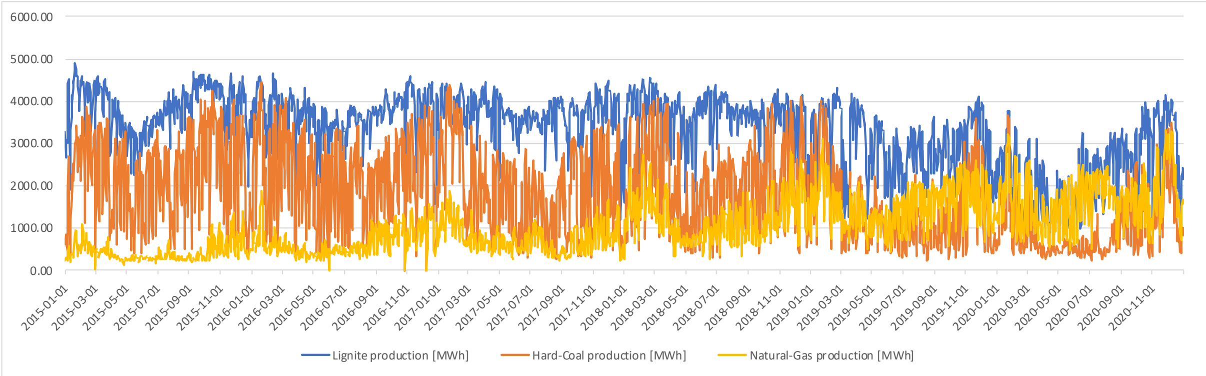
	P	NE	Ln(SR)	Ln(RC)	Ln(GP)	CR	CF
Electricity wholesale prices (P)	1						
Net commercial exports (NE)	-0.14	1					
Ln(Share of renewable production; SR)	-0.58	0.05	1				
Ln(Realised electricity consumption; RC)	0.45	0.19	-0.30	1			
Ln(Natural gas wholesale price; GP)	0.36	0.51	-0.32	0.27	1		
Ln(Cumulated renewable capacity; CR)	0.21	-0.31	0.41	-0.08	-0.38	1	
Ln(Cumulated fossil capacity; CF)	-0.06	0.42	-0.44	0.10	0.54	-0.37	1

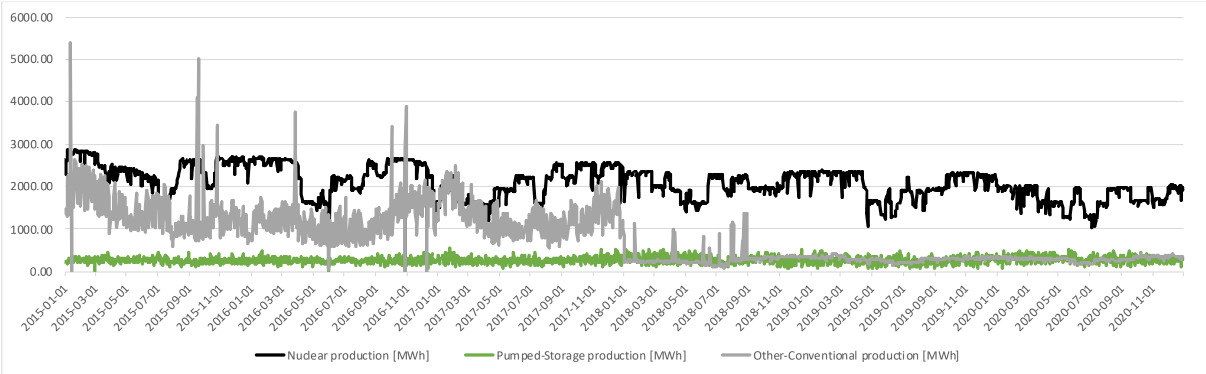
Notes: This table presents the correlation matrix for the main variables of interest used in the performed regressions.

Appendix II: German electricity production patterns



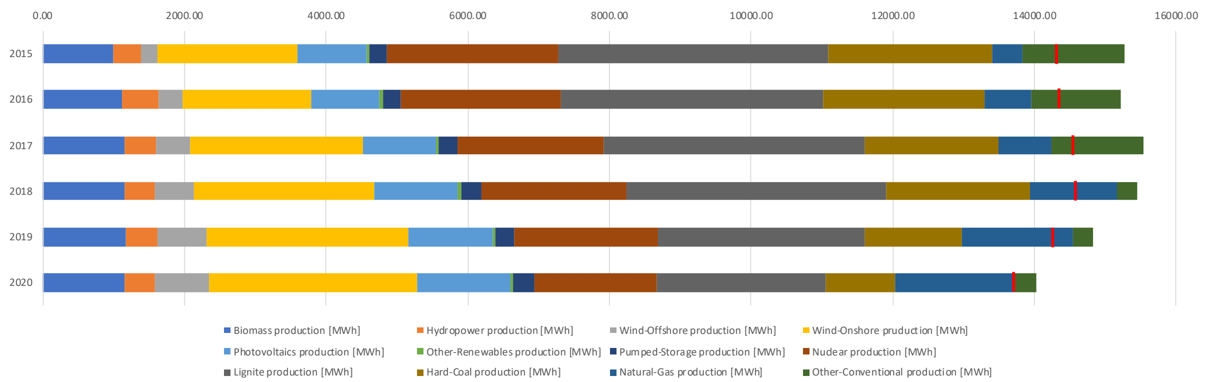






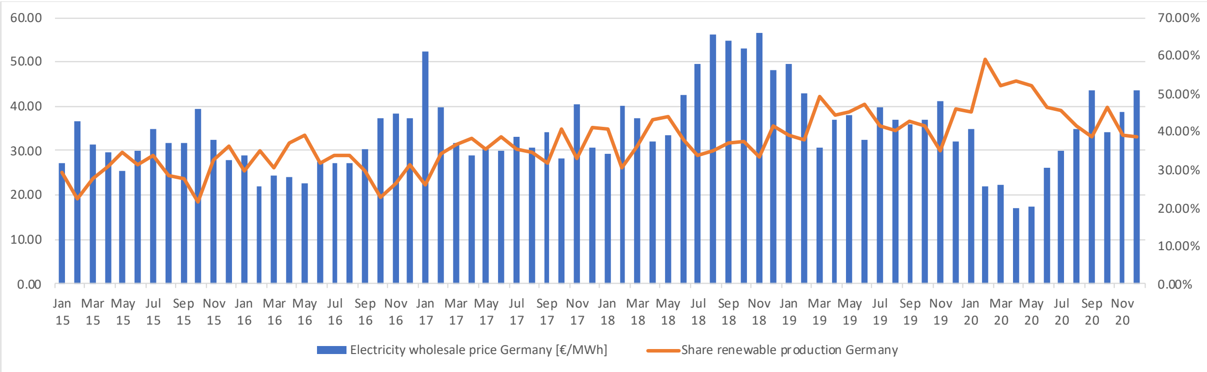
Notes: These figures plot the total amount of the average daily German electricity production for each method in the period from January 2015 until December 2020. All values are the nationwide numbers.

Appendix III: Merit-order development 2015-2020

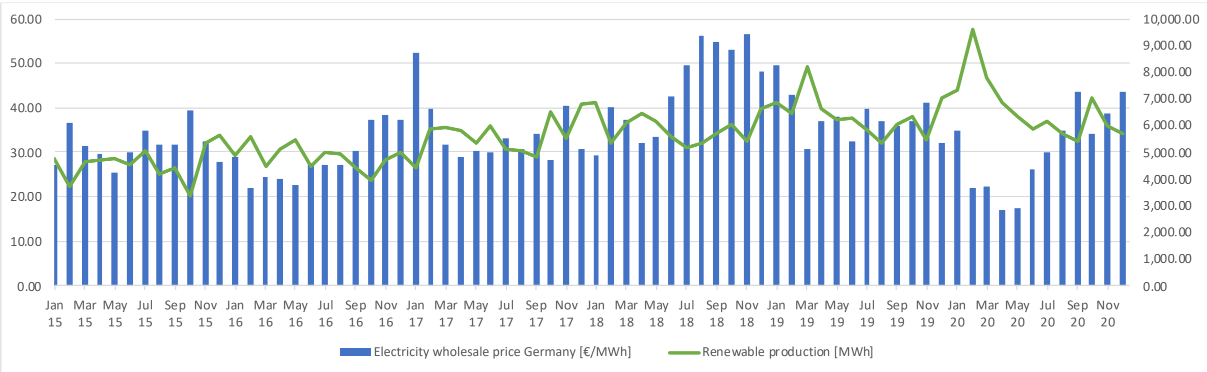


Notes: This figure plots the merit-order development in Germany for each year in the period from January 2015 until December 2020. All values are the average nationwide numbers. Red markers illustrate the average merit-order for each year.

Appendix IV: Monthly development of wholesale prices and renewable production



Note: The right y-axis reflects the share of renewable electricity production in Germany.



Note: The right y-axis reflects the renewable electricity production in Germany.

Notes: These figures plot the development of the German electricity wholesale prices compared to the development of the share of renewable electricity production (top) and the total renewable electricity production in Germany in the period from January 2015 until December 2020. All values are the average nationwide numbers.

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