Renewable Energy Generation and its Effect on Electricity Prices -

A case study of Germany

Abstract

The implementation of renewable energy sources should, according to economic theory, reduce electricity prices. The main reason behind this is the merit order effect, which describes the sequence of contributions from different power stations. Production from renewable energy sources, such as wind and solar, have very low operational costs and thus increasing the net-supply pushes the merit order curve to the right, lowering the price. This study investigates how the electricity prices have changed in Germany during the years 1991-2020. The study also investigates the before and after effect of the Renewable Energy Sources Act of 2000. The characteristics of the German electricity market makes it ideal to study.

The results from this study indicate a marginal decreasing effect of implementing renewable energy sources. The large amount of wind generation in Germany seems to have met its peak in the marginal cost curve, and from 2016 the growth of more wind generation increases prices. However, the growth in solar generation now drives the electricity prices downwards. The event study obtained similar results as the 2016 regression, which most certainly is due to problems stemming from highly aggregated data. Based on our results and previous studies in the field, we can observe a trend where renewable energies crowd out the more conventional power plants, resulting in a short term decrease in prices. However, in the long run, the results from the loss of traditional production capacity is unknown.

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Table of Content

1. Introduction

The introduction part of the paper raises the importance of studying the effect of the expansion of renewable energies on electricity prices. Here, the purpose and the research question will also be presented, along with the expected results. The delimitations for this study will be specified, and the section ends with a summarised disposition of the study.

1.1 Prelude

The electricity market of Germany has undergone a large transformation during the last thirty years. Germany has gone from using, almost exclusively, combustible fuels and nuclear energy to power its grid, to having a large portion of its electricity stemming from renewable sources, such as wind and solar generation. (Birol, 2020)

In the winter 2021-2022, the price for electricity rushed to previously unseen highs. This sparked a debate about the feasibility of the current growth and reliance of renewable energy sources. The growth of renewable energy sources increases the sensitivity of the grid to climate change. To identify how implementing renewable energy affects the energy markets, besides reducing emissions, is key to understanding how policy makers view the desirableness of expanding renewable energy generation.

The most used argument in favour of renewable energy is that they bid into the market at very low prices. This shifts the supply curve to the right, creating a new equilibrium market price. This is attractive for most politicians, since the direct effects of this is a transfer of wealth between the producers and the consumer. The challenges, however, are that these lower prices result in less investment and makes it harder for companies, who previously invested in conventional power generation, to recover capital costs. This may in turn reduce the available backup or press the prices for renewable energy up, if they are forced to include an amount of backup capacity for a certain amount of installed renewable generation (Würzburg et al., 2013, 160). The marginal costs of producing from the different sources, and when the production sources are activated, is called the merit order effect. Production sources, such as wind and solar, that are non-dispatchable, meaning they always produce when their respective conditions are met, have close to zero marginal costs. When the demand can’t be met by these sources, the next step is to activate the production source with the second lowest variable cost. Renewable energy productions also allow for more energy independence since it makes countries less reliant on imports (Birol, 2020, 19).

In 2000, Germany enacted the policy *Renewable Energy Sources Act* which aimed at forcing grid operators to buy renewable energy when it was available and at compensating producers monetarily. This was done to increase the pace in which wind and solar generation would be expanded into the energy mix. (The Federal Ministry for the Environment, 2000, 3)

1.2 Purpose

The purpose of this research paper is to evaluate the effect of increased shares of electricity generated from renewable sources on the German electricity market. Germany is selected for several reasons but mainly due to its unprecedented high growth of renewable energy sources, its liberalisation, and the implementation of green legislation. When investigating how the high growth in renewables affect prices, theories such as the merit order are central. More renewable energy from non-dispatchable sources has a lower marginal cost since they continue to produce even at negative prices. Given this information, the 2000 implementation of the Renewable Energy Sources Act, should impact electricity prices negatively.

Renewable energy is identified as a paramount part of tackling climate change. However, the effects of implementing renewable energy in the long run is a topic that, to our understanding, is not very well explored. Economic theory predicts that the low marginal costs of renewable energy sources will lower electricity prices, at least in the short run (Würzburg et al., 2013, 160). The effect on the suppliers, who previously have invested large amounts of capital in traditional energy production sources, are unknown in the long run. Some argue that their ability to recover costs are limited and that with the forced implementation of renewable sources, traditional power plants that could act as back-up to the grid are being shut down.

1.3 Framing of question

The research question this study aims to answer is:

How does implementing renewable energy sources into the energy mix affect energy prices on the German electricity market?

1.4 Delimitations

The focus of this study will be on the price trend changes in the German electricity market between the years 1991 and 2020 in regard to the implementation of the Renewable Energy Sources Act in 2000. The change in electricity price trends is in reference to the prices without taxes and levies. Increasing shares of renewably sourced electricity could have different impacts on prices, taxes, and levies, and for this study it’s been decided to examine prices alone. Regarding the type of renewable energy sources, the main focus will be on variable renewable energy sources; wind and solar power, and the dispatchable renewable energy source hydro power.

1.5 Hypothesis

Our hypotheses for the results of this study are as follows:

1. The implementation of non-dispatchable renewable energy sources lowers electricity prices,

2. The adoption of the Renewable Energy Sources Act has impacted electricity prices through the growth in the development of renewable electricity generation.

1.6 Disposition

This thesis is structured in 7 chapters with an appendix at the end. The chapters are structured in the following order. Chapter one starts with the introduction to the topic and establishes its relevance through the prelude and purpose. It also includes delimitations, our hypothesis and disposition. Chapter two contains background information about renewable energies and the policy *Renewable Energy*

Sources Act. Chapter three introduces necessary theoretical background information together with previous studies in the field, which will be motivating the methodology. Chapter four contains the methodology and data description. The methodology used is based on supply-demand and marginal cost theory with the specification on the merit order effect. Due to there only being low-frequency data available to us, we set up an ideal regression together with an ideal event study that we would have liked to run if high frequency data had been available to us. There are three regressions using low frequency data. The first regression is for the period 1991-2020 and will capture the historical effect of implementing renewables into the energy mix. The second regression is a before-after study that will investigate the effect of the policy implementation in 2000. The third and last regression will span the years 2016-2020 and capture more seasonal trends and the implementations of renewable energy into a market that already has integrated a large share of renewable energy. Chapter five contains the results of our regressions and a brief explanation of the values and direction of coefficients. Chapter six is the part where the analysis and discussion of the results of the regressions takes place. Chapter seven concludes the findings, reconnects to our research question, and informs about the contribution of this report to this field of science.

2. Background

To understand how the implementation of renewable energy sources affects electricity prices, one must first have an understanding of what renewable energies are and how they function. This chapter will give an introduction to renewable energy systems and the policy *Renewable Energy Sources Act.*

2.1 Renewable Energies

There is an urgent need for a global energy transition in order to reach the Paris Climate target of keeping the global surface temperature increase below 2°C. Energy related CO_2 emissions represent two thirds of the total global greenhouse gas emissions, entailing a transition from fossil fuels to low- carbon technologies is essential to reach the 2-degree goal. The means to make this transition will come from technological innovation within the renewable field, in which there has already been an increase in the amount of installed renewable energy capacity. Decreasing costs and the competitiveness of these technologies, mainly solar photovoltaics (PV) and wind power, are what has spurred this increase in renewable capacity (Gielen et al., 2019). The implementation of the Renewable Energy Sources Act in Germany aspires to help fulfil the Paris Climate target by encouraging an expansion of renewable electricity in the country (Gründinger, 2017). In their paper from 2019, Gielen et al. conclude that the share of renewables in total energy supply can grow from 15%, in 2015, to 63%, in 2050. The authors further argue that this increase combined with higher energy efficiency can reduce emissions with 94% of what is needed for staying within the limits of the Paris Climate Agreement. They specify that the absolute number of this reduction varies between different studies, but that there is a consensus surrounding renewable energy and energy efficiency; this is the most feasible way to meet climate goals (Gielen et al., 2019).

There is one downside to renewable energies: most are variable and difficult to manually control in such a way that the electricity supply meets the time-fluctuating demand. This is one of the main differences between renewable and fossil sources of electricity. Due to their ability to be manually turned off and on when needed, their energy density, and flexibility, fossil fuels such as coal, oil, and gas have dominated the energy mix since the Industrial Revolution. The downside of fossil fuels is their external costs, such as CO_2-emissions, local pollution, and human toxicity, which are what the Paris Agreement and the sustainable development goals (SDG: s) are aiming to mitigate. These are the reasons why there is a need to switch to regulatable renewable sources and variable renewable energies (VREs). Renewable energies, whose generation can easily be turned off and on when needed, have limited potential and consist only of bioenergy, hydropower, and geothermal energy. The focus has then been on developing and expanding VREs, such as solar PV, onshore and offshore wind power, which only generate electricity when it's windy or sunny. The expansion of VREs and regulatable renewable energies will be problematic. These technologies are not able to fit into the traditional electricity market with high regulability, resulting in an ineffective market (López Prol & Schill, 2021). This will be further explained in sections 3.4 and 3.6.

2.2 Renewable Energy Sources Act

The policy *Renewable Energy Sources Act (Erneuerbare-EnergienGesetz; EEG)* was enacted in 2000 and brought significant changes in the way the state would provide support for green energy (The Federal Ministry for the Environment, 2000). The policy aimed to standardise the German electricity market via costs charging throughout the states and provide stronger incentives for green energy. The main purpose of the EEG is to regulate the prioritisation of grid-supplied electricity. Grid operators would be obliged to install or update their facilities to purchase electricity available from renewable production facilities. The operator would also be forced to compensate suppliers monetarily, which would be determined depending on the size and the type of renewable installation.

The main objective of the policy was to at least double the share made from renewable sources by 2010. They also envisioned that the commitment would reduce emissions from greenhouse gases by 21 percent by 2010. CO_2 emissions would be reduced by 25% by 2005 from 1990 levels.

The existing renewable sources used before the policy was adopted were mostly made up of hydropower, specifically large dams, whose further growth is restricted due to geographical limitations. In order to meet the emission target, the generation of energy by wind, solar, biomass, and hydrodynamic power had to increase fivefold. The EEG also sought to lessen the dependency on foreign energy imports, which could only be done by harvesting domestic renewable resources. (The Federal Ministry for the Environment, 2000).

2.2.1 Revisions of the Renewable Energy Sources Act

There have been several revisions and corresponding updates on the Renewable Energy Sources Act since it came into effect in 2000, and this following part will give a brief overview of these updates. The first revisions occurred in 2004 and 2009 and can be summarised as mainly concerning improving the conditions for renewable energy producers and an increase of the expansion target for these producers (Gründinger, 2017; Amelang & Appunn 2016). A third revision was made in 2012 where a support system for electricity producers from renewable sources or gas mining was introduced, which ensured a higher price for their electricity than the market price. This system was supported through the 'EEG surcharge'; a surcharge on the suppliers that ultimately was paid by the consumers that matched a 20-25% share of the total amount of an average final consumer's bill. The fourth revision was made in 2014. Its most important point was the proposal of introducing an auction-based system, with the purpose of allocating the funding for the EEG through it, starting from at least 2017 (Amelang & Appunn 2016). This auction system did come into effect during the last to-date revision in 2017, accompanied by three underlying principles aimed to promote a steady expansion of renewables that is cost-effective and to keep strong public support. The auctioning system was used for installation of on- and offshore wind energy and large-scale solar PV. The design of the auctions were tailored to the different technologies and their specific needs (BMWi, 2015).

3. Theoretical background

This section provides the necessary information to be able to understand the mechanisms relevant to this study. The information given here will also be important in terms of interpreting the results and as discussion points. At the end of this section, there will be a short review of earlier, similar studies to establish what the general consensus is and for comparison with our own results.

3.1 Electricity markets

Electricity markets are designed with the purpose to provide electricity in a reliable way with the lowest cost for consumers. These markets have not occurred through a marketplace without government intervention, as the two goals of electricity markets are short-run efficiency and long-run efficiency, which need careful design to achieve. This market design has occurred through a regulatory process partially on the basis that electricity is seen as an essential service, and partially because of its technical properties. The design of the market is constantly changing, mainly because of the present expansion of the electrical generation from renewable sources. Two core elements of electricity markets today are the use of a day-ahead market, which allows for the best scheduling of resources, and a real-time market, that enables security-constrained economic dispatch. These two together make up the spot-market, where locational marginal pricing is used in settlement, since these reflect the marginal value of energy at each time and location. This kind of spot market lays the ground for forward contracting that enables participants to handle risk and better the bidding incentives on the spot-market. (Cramton, 2017)

3.1.1 Liberalisation

Liberalisation, in terms of the electricity market, is a political regulatory process that brings competition to markets that have previously been monopolies trading with electricity and gas. This is achieved through a privatisation process, where previously state-owned utilities become privatised or partially privatised. In a liberalised electricity market, there’s traditionally competition in the areas of power generation and sales activities, while other areas, such as network activities and transport, are regulated. The sought-after goals of liberalisation is to increase efficiency and motivate innovation in the electricity industry. In the European Union, liberalisation of the electricity market took place between 1999 and 2007. (Financial Times Lexicon, 2022)

3.1.2 The German electricity market

The electricity market in Germany is liberalised where the distribution of electricity and the operation of transmission lines fall on two different actors, or operation systems; a Transmission Operating System (TSO) and a Distribution System Operator (DSO). The difference between these two operating systems is basically on what scale they operate on. The TSO operate and distribute electricity through high-voltage transmission lines throughout the country, while the DSO operates and distributes electricity through medium- and low-voltage transmission lines within their respective regions. The TSO and DSO are system operators that are independent from large electricity producers and companies that sell electricity. The implementation of these system operators have removed the natural monopoly of networks from large electricity producers, as well as the ownership of networks by suppliers to final consumers within regions. These system operators are expected to charge for their services, ultimately affecting the electricity price, where the amount is decided by law. The German electricity market is also characterised by the highest electricity taxes in Europe; a little over half the price paid by retail consumers is taxation and fees. (Rodionova et al., 2018)

The growth of renewably generated electricity in Germany's mix, particularly solar and wind power, can be observed in **Figure 1** below. This increase would not have been possible without the liberalisation of the electricity market (Rodionova et al., 2018). The liberalisation made the market more flexible and better able to handle the volatile renewable generation efficiently (DENA, WY). With the increase of electricity generated from renewable sources, there’s also an increase in trade of renewable energy on the spot market. The electricity prices on spot markets are minimal and oftentimes don’t cover the production costs, which was the reason behind implementing a surcharge through the EEG in 2012. It almost goes without saying that the EEG is an important policy for the German electricity market, as it brings benefits to producers of renewable energy. One such thing is the priority dispatch of electricity from renewable sources. However, it is worth noting that in the year 2017 Germany reached a point where it became clear their network system at that point wasn’t constructed in a way to be able to handle more additional energy. For instance, during a stormy day the powerlines could become too congested to deliver electricity from wind power. For that reason, grid operators would be allowed to order wind power producers to disconnect from the grid, but would in return have to compensate these producers’ costs. This also led the government to limit the measure of state support towards renewable energy source producers (Rodionova et al., 2018).

Figure 1.

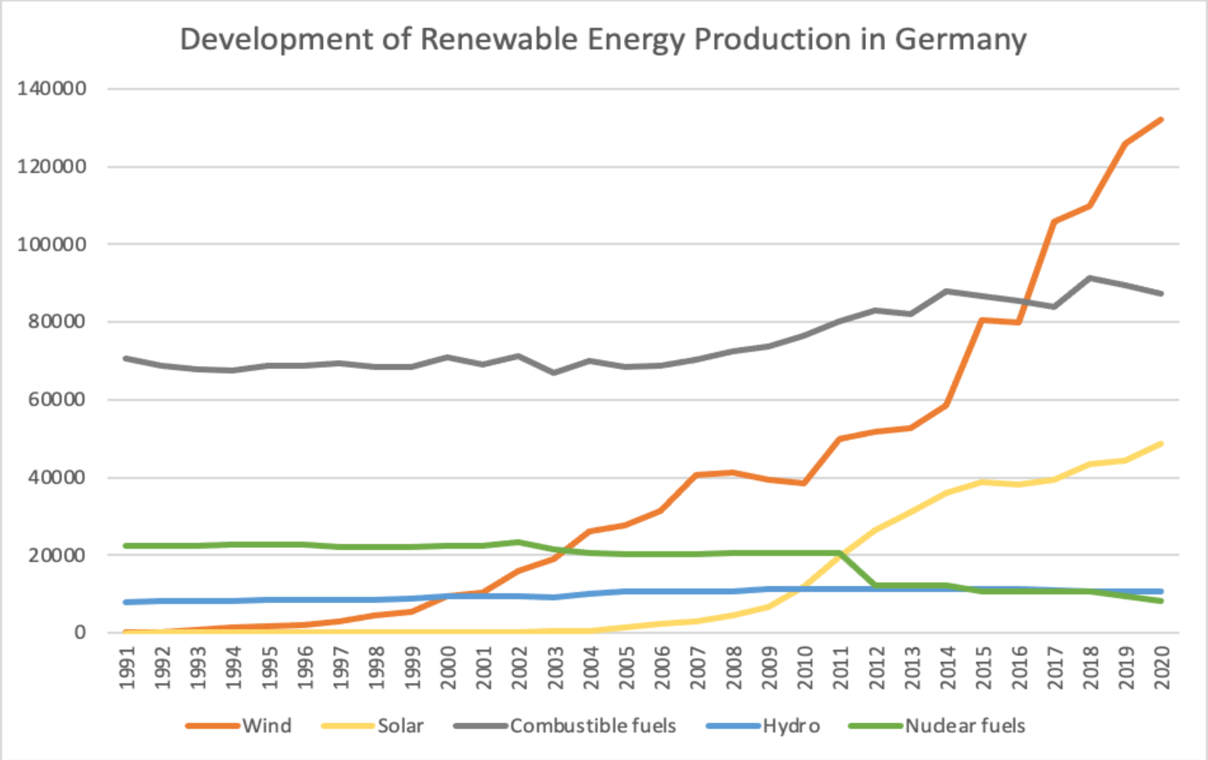


Figure 1 shows the amount of electricity produced from different energy sources in Germany between the years 1990 and 2020. The amount is shown in megawatts and the figure also allows observation of the increased and decreased use of different energy sources over time.

3.1.3 Market power

We have looked at the market power of the big four energy companies operating in Germany. The data available was from the most recent years but they indicate that there is only one company over what is considered by the competition agency of Germany as a monopoly status (Bundeskartellamt, 2022). This company is RWE, and it is responsible for over 20% of the energy capacity and over 25% of the actual production. This might have an effect on pricing, but due to the limitations in the data available we aren't able to control for it.

3.1.4 Connection to European markets

The European energy grid operates in several bidding zones with the aim of intraday trade between different zones. Germany, Luxembourg, and Austria constitute the same zone. The bidding zones are constructed in a manner that reduces or even eliminates structural congestions (Gomez, 2019, 22). The aim is to create a pan-European energy market which shares a common merit order in the activation of balancing energy. One benefit of the integrated market is that energy can be transported to the areas with the highest prices, and this will in turn create investments in additional capacity to tackle the scarcity (Gomez, 2019, 25-29). The way this mostly affects our research question is that the ability to export renewable energy surpluses will decrease prices in neighbouring countries. Further development in renewable energy sources in Germany can thus help lower emissions in other parts of the European union. Even though we don’t investigate spillover effects from the growth in renewable energy, it's important for policy makers to understand the market structure in a broad sense (Birol, 2020, 129-131).

It’s interesting to study the relative contribution of different sources of electricity, since Germany has a liberalised electricity market which should allow the electricity prices to follow the dynamics of supply and demand. However, this should be assumed on the condition that they are characterised by different cost structures and dispatchability, which will be explained further in the next section.

3.2 Dispatchability

The use of dispatchable generation technologies has historically been the primary choice to generate electricity due to the need for the supply-end to be able to continuously adapt and meet demand. **Dispatchability** indicates how controllable an energy source is. Generation technologies with low dispatchability are called baseload technologies, and this is where e.g., nuclear energy falls, since it’s characterised by an even production across almost all hours. The opposite of baseload technologies are peak load technologies, which have high dispatchability. An example of peak load technologies is gas turbines, which can be turned off and on to only produce electricity when demand is high, thus having high operational flexibility. Peak load technologies can then ensure supply and demand to be equal at every point in time. This is needed in electricity systems to keep a stable grid frequency. (López Prol & Schill, 2021)

Dispatchability is an important factor to take into account when increasing the VREs in the electricity market in order to mitigate climate change. This was the objective with the German EEG policy, since VREs are sources that only produce electricity under the right conditions and are not dispatchable. This makes it hard to match demand at every point in time. Increasing the shares VREs also pose an efficiency and economic threat, as these have a lowering effect on wholesale prices, known as the merit order effect (see section 3.6) (López Prol & Schill, 2021; Breakthrough Energy, WY). There needs to be a redesign of the energy market and the standing regulatory frameworks to attract investment for VREs and dispatchable renewable technologies (Breakthrough Energy, WY). The importance of this gradual change towards higher VRE penetration shouldn't be understated, as the IEA estimates that these technologies need to provide for 42% of the total global electricity generation by 2040 if the Paris Agreement is to be met. For comparison, in 2018, VREs stood for 7% of the total global electricity generation (López Prol & Schill, 2021).

3.3 Dispatch model

A dispatch curve summarises the order in which electricity from different generation sources is dispatched. The order depends on the variable costs of different electricity sources, where, generally, the source with the lowest variable costs is dispatched first, and the source with the highest variable cost last. The amount of electricity dispatched, and thus the cost of the electricity, increases with the demanded amount at a certain time. This sequence of electricity by source dispatched is reflected in the electricity supply curve, which can be used synonymously with dispatch curve. Baseload generating sources and variable sources are represented on the dispatch curve's left side, as these types of sources have low to no variable costs. Peak load generators are represented on the right side, as these have higher variable costs and thus mainly generate power during the highest hourly demands. The intermediate generating units, or cycling units, are represented on the curve between baseload and peak load generators. The output level from these sources generally varies as the demand changes during the day and year. The main objective to take from this is that the dispatch decisions made by electric power systems are primarily driven by the variable operating costs (EIA, 2012). The implementation of the EEG came with the criteria that the TSO and DSO must prioritise and dispatch renewably sourced electricity first (Rodionova et al., 2018) and thus Germany's dispatch curve would have to look very similar to the dispatch model described in this paragraph.

It is important to understand the mechanisms behind dispatchability for this paper as this informs our hypothesis and needs to be considered when analysing our results.

3.4 The Merit Order Effect

The VREs lowering effect on wholesale electricity prices is called the **merit order effect** and is caused by the increase in capacity of renewable energies (López Prol & Schill, 2021). This will be an important effect to take into account when studying the results of the regressions in this study, since they may be linked to this effect. The merit order effect is beneficial for consumers but is, as mentioned earlier, of economical concern (Antweiler & Muesgens, 2021). VREs have no variable costs as they only generate electricity when, for example, wind or sunshine is available, as well as have no capacity to store energy worth mentioning. If their share in the energy mix increases, it will lead to a depression in wholesale prices. This poses a risk for investors, whose gains come from the wholesale market revenue from the VREs. One strategy to avoid this risk is through government support of long-term power purchase agreements at predefined prices. A strategy like this may also enable early-stage deployment of low-carbon dispatchable generation technologies, such as geothermal or thermal generation (Breakthrough Energy, WY).

In the electricity market, the equilibrium price and quantity are determined at the point where they intersect. Assuming demand in the short term is inelastic because most consumers don't respond to real-time prices, the demand curve is represented as a vertical line in **Figure 2**. The supply curve for this market has a staircase-shape, which represents the variable cost for the different energy sources, going from lowest to highest. These steps also match the dispatchability for the different sources since baseload technologies are characterised by lower variable costs than peak load technologies. Starting from the demand perspective, we see that increasing VREs in the electricity mix results in a larger share of zero variable cost sources, which can also be represented as lower net load demand (López Prol & Schill, 2021) (the total electric demand in the system minus wind and solar generation) (Bredehoeft & Krall, 2014), which in turn creates a shift of the demand curve to the left, resulting in a lower wholesale price. On the supply side of things, we will see the same end-result. Increasing VREs to the mix will cause a shift of the supply curve to the right, as this is equivalent to an increased supply of zero variable cost technologies, or lower net load supply, and the wholesale price depresses (López Prol & Schill, 2021).

Figure 2.

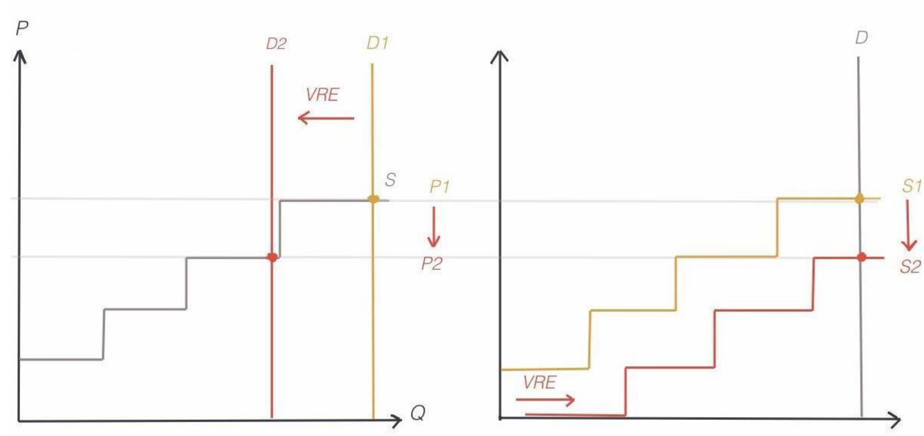


Figure 2 illustrates the merit order effect on the demand side (left) and the supply side (right), where *P* stands for Price, *Q* stands for Quantity, *D* stands for demand, *S* stands for supply and *VRE* Variable Renewable Energy sources. The arrows indicate the direction in which the curves shift when the amount of VREs in the electricity mx changes.

Not many papers discuss the long-term effects of the merit order effect. One paper that mentions it briefly is Gelabert, Labandeira, and Linares (2011), arguing that it theoretically should only be temporary. The authors explain this should be true because a decrease in electricity price due to higher shares of renewable electricity on the market should cause a reduction in the long-term signal for investment. This, in turn, would lead to a deterioration of future investments that ultimately results in an increased electricity price, since there is a limited supply of renewably sourced electricity (Gelabert et al., 2011). Antweiler and Muesgens (2021) have dedicated an entire paper to researching this question; whether large shares of renewable energy simply are permanently accompanied by a merit order effect, or if this is a temporary phenomenon. The authors created a simple theoretical model where intermittent renewable energies are introduced to a conventional mix of base load and peak load technologies. The authors then investigate the effect of this introduction in the short-term, when the base- and peak load technologies have not adjusted, as well as in the long-term, when base- and peak load technologies have completely adjusted to this introduction. As a result, they found the merit order effect to be temporary and that it is a consequence of a slow-paced capacity adjustment (Antweiler & Muesgens 2021).

The merit order effect is a key phenomenon to consider in our study, since this is the theory behind the change in price due to increasing shares of renewable energy.

3.5 Earlier Studies

This section will review some methods and results from previous and similar studies for later comparison with the results of this study. For this purpose, five different papers on the effect of increasing shares of electricity from renewable sources on the electricity prices have been chosen and are summarised here.

Maciejowska (2018) uses a quantile regression approach to estimate the impact of solar and wind power on electricity price level and variability. The study uses hourly data between the years 2015 to 2018, which has been transformed into daily peak and off-peak indexes. The regression model contains dummy variables to capture seasonality on a weekly level. The results of Maciejowska's study show decreasing electricity prices with increasing shares of solar and wind generated electricity due to the merit order effect, and this could be observed in all quantiles. The results also showed there are different risks with solar and wind power; wind power increases variability during low demand levels and solar stabilises variability during intermediate levels of demand (Maciejowska, 2020). Other studies that use quantile regression for similar research questions are Hagfors et. al (2016), Sapio (2019) & Do, Lycósa & Molnár (2019). One example of this approach applied on renewable's effect on merit order is Sirin & Yilmaz, 2020.

Gelabert, Labandeira and Linares study from 2011 is the inspiration for our analysis, where the authors use a multivariate regression model to estimate "[...] the average effect of a marginal change in the special regime on electricity prices" * (Gelabert et al., 2011). The study was conducted between 2005 and 2009, using hourly data that was transformed into a daily average. The authors control for different levels of seasonality by including dummy variables for the different levels. This study's results show a reduction of the electricity prices when there's a marginal increase in electricity generated from renewables, however, it's lower than has been observed in previous studies. The study concludes that the impact of renewables on electricity price decreases with time; a marginal decrease of the merit order effect (Gelabert et al., 2011). Some studies that use the multivariate regression method for the same or similar purposes are: Zipp (2017), Pilli-Sihvola et al. (2010), Janda (2018) and Francisco Alves & Diogo Pinto (2021).

The third study examines the growing relationship between the effect on electricity prices by renewable energy sources, and how these production sources are affected by changes in weather conditions relating to climate change. The focus is on the market in the Netherlands but take into account weather conditions in Germany. This is done due to the large interconnection of the two markets. The regression model uses the log of variables due the expectancy of non-linear impact on price, which is the dependent variable, by the explanatory variables (Mulder & Scholtens, 2013, 95). To explain the change in price the variables demand, production, import, export, RSI, and the price of natural gas is used. The findings are that demand, and gas prices have a positive effect on electricity prices, meaning as they increase the electricity price increases. The wind speed in Germany has a negative effect on the price in the Netherlands due to the integration and the imports of wind from Germany. The study's findings suggest that the merit order effect does not influence the Dutch energy market in a significant way and that conventional power plants are the ones setting the prices. The authors do, however, point out that the findings could be very different if they looked at prices during the peak demand hours and not the daily averages. It's also important to note that the timespan used are the years 2006-2011 but is divided into three subgroups 2006-2007, 2008-2009 and 2010-2011. This may provide too little variation for any meaningful effect to be seen (Mulder & Scholtens, 2013,96- 98).

The study written by Woo et al. (2014) investigates the impact of shutting down nuclear power plants in California. Three different regressions are set up using hourly real-time market prices as the dependent variable. The explanatory variables are natural-gas prices, hourly system loads, nuclear MW available, hourly small-hydro generation in MW, hourly total solar generation (MW) and hourly total wind generation in MW (Woo et al., 2014, 239). The results and conclusion of this paper is that the shutdown of nuclear power plants resulted in a price increase of $6-9 per MWh. However, the coefficients of the variables representing renewable production are negative, indicating a price reduction with higher implementation of renewable energy production. The paper concludes that the growth of renewable energy production sources could mitigate the price increase caused by the shutdown of nuclear power (Woo et al., 2014, 242-243).

The last study investigates the true effect of the merit order. The question of scope is does the merit order effect contribute to lower energy prices in the long run. The study focuses on Austria and Germany and how historic implementation of renewables affect pricing (Würzburg et al., 2013, 159-160). The study chooses these two markets due to their large interconnection and Germany's implementation of renewables. The study employs a multivariate regression for its model using load, production from solar and wind, gas price and imports and exports as variables, together with dummies representing day, week, and month (Würzburg et al., 2013, 165). It is important to note that the regression spans only the years 2010-2012 and is thus unable to capture any long-term effects of the merit order. The coefficients from the regressions are, as expected, negative for the renewable sources and thus in line with other contemporary studies and with the merit order effect. The conclusion drawn from the study is that the growth in renewable energy sources help decrease pollution, lessen dependence on foreign energy imports and that it crowds out other energy sources with higher marginal costs. The effect of the merit order is found to be highly variative but on average the implementation of renewables lowered the price by 2% for every GWH produced (Würzburg et al., 2013, 168).

4 Method

The methodology chapter will first present an ideal regression model together with an ideal event study and these models would be based on high frequency data. The chapter continues with expected results, data sources, low frequency regression models and descriptive statistics.

4.1 Ideal Regression Model

There are many factors that influence the price of electricity. When considering results and regression models from earlier studies, we can make an estimation of an ideal model that would have been utilised given accessibility to higher frequency data. The previous studies also give us an indication and explanation of variables that most likely affect electricity prices. Factors that affect the price of electricity are economic and environmental factors. The economic factors are tightness in the market (demand), intensity of competition, marginal cost of production, and the source production, import and exports. The environmental factors include total amount of sun hours, total amount of wind measured in average speed, temperature in the water, temperature on land and rainfall (Mulder & Scholtens, 2013). However, the total amount of production from wind and solar are able to capture the differences in weather conditions.

The frequency of the data would ideally be hourly. Hourly measures can control for the peak demand during the day and can be averaged out into other times series such as daily and monthly which we would also utilise. Daily data would be used to control for differences during the week and monthly data would be used to control for seasonality over the years.

We will now elaborate on why these variables are important to our research question. This will be done by describing each variable in detail.

4.1.1 Tightness of the Market (Load)

The way that tightness in the market affects price is due to the inflexibility of the producers to mitigate volatile demand of electricity in the short run. Higher demand leads the demand curve to shift to the right and thus, according to the merit order, the producers can sell over marginal cost up to the point of activating more dispatchable sources. Tightness is also interesting due to the fact that if a lot of capacity is being used, the amount of reserve capacity may not be sufficient to handle more demand. In the Netherlands study, the authors observed that peak demand was about twice that of the minimum. (Mulder & Scholtens, 2013, 95-96)

4.1.2 Intensity of Competition (RSI)

RSI of residual supply index is a measurement on how much production capacity there is left after subtracting large suppliers. In our case we would subtract the supply given by RWE since its share of the market is above the threshold of 20%. We know from macroeconomic theory that when a company gains over a certain amount of market power it is able to extract higher prices from its consumers. (Mulder & Scholtens, 2013, 96)

4.1.3 Marginal Cost (Natural gas)

Since natural gas is a big part of Germany's energy supply, the cost of natural gas will be used as a measure of marginal cost of production. If the amount of gas is increased, the supply curve will shift upwards, meaning the price of electricity should increase. (Mulder & Scholtens, 2013, 96)

4.1.4 Non-dispatchable Generation Sources (ND)

We will use variables to include the total amount of energy generated by wind and solar respectively. The more we increase wind or solar the more the merit order shifts to the right, since these sources have low to zero marginal costs (Mulder & Scholtens, 2013, 96-97; Würzburg et al., 2013, 160). The non-dispatchable variables are measured in actual production and not capacity and thus captures changes in the weather conditions.

4.1.5 Dispatchable Generation Sources (D)

We will include the capacity of nuclear and combustible sources since these are semi-to full dispatchable (Mulder & Scholtens, 2013, 97). Nuclear power is in theory dispatchable but shifting the production is time consuming and adjustments to the output stresses the reactor and could poison the core. This is why nuclear energy is often used as base load energy (Woo et al., 2014, 239). Combustible fuels are to be seen as a competitive source and also as a back-up to the non-dispatchable renewables. The capacity of hydro generation is also important since it acts as a back-up to the system (Woo et al., 2014, 235; Würzburg et al., 2013, 165).

4.1.6 Imports and Exports (NX)

Observing imports and exports tells us about the dependency of the system from foreign actors. We can analyse on an hourly basis how imports and exports affect the system. Germany is exceeding its neighbours immensely when it comes to implementing renewables such as wind generation and is thus a big exporter of renewable energy (Mulder & Scholtens, 2013, 96). We would want to investigate the relationship of net exports-imports with that of high load hours (HLH). The prices for imports and exports are set the day prior to the trade, but the actual flow of imports and exports can change by the minute. This is due to the connection to the European market.

4.1.7 Time Indices. (D, M, Y, HLH)

In order to capture different trends and one-time events we create time dummies. These dummies will be structured into daily (D), monthly (M) and yearly (Y). The reason why it's important to structure the regression in this way is to capture how prices fluctuate daily, weekly, monthly, and yearly. We know that demand changes hourly, with peak demand sometimes being twice that of low demand. It is of interest to investigate how renewable energy sources behave and affect prices during these hours. The price also changes during the week with weekends typically experiencing lower demand. Monthly is perhaps the most interesting time variable since it captures the different seasons and how those affect the price of electricity and the production of renewable energy. The yearly dummy enables observations on how the prices change in the long run and thus captures the long run effect of changing the energy mix.

We would collect data from all time frames for solar and wind production together with load and NX. For hydro, nuclear, and combustible fuels, capacity is measured daily, so we will include all time frames except HLH. The changes in RSI are usually measured yearly by the government's own agencies, but some of the data might be available from the interim reports from the different companies and thus monthly changes could be relevant as well.

4.1.8 Test for Autocorrelation

Time series data might suffer from autocorrelation or serial correlation, meaning that the outcome is highly affected by the previous data. To eliminate much of the autocorrelation one can create lags or for example look at percentage changes instead of changes in the actual number. Durbin-Watson test controls for correlation with one point lag (first-order autocorrelation). We could also perform a Breusch-Godfrey (BG) test if we suspect autocorrelation of an order higher than one. In the BG test the null hypothesis is that there is no autocorrelation at any order less than or equal to p, where p represents a certain order. (Bobbitt, 2021)

4.1.9 Test for Stationarity

When working with time series data, it is important to check for stationarity, which in that case would entail the data is not affected by seasonality, changing variance or prone to trends and changing levels. In other words, stationary data has properties that don't depend on the time at which it’s observed (Rob et al., 2018). Three out of the four previous studies used the augmented Dickey-Fuller (ADF) test to test for stationarity, making it a compelling test to use for our ideal regression as well, since the data used and the research question is comparably similar to these studies. This test can be used for testing for unit roots as well, and for determining if the series needs first differences or not, which would be appropriate to check for this ideal model as well. (Maciejowska, 2020; Gelabert et al., 2011 & Würzburg et al., 2013)

4.1.10 Ideal Regression Equation

We would construct a multivariate regression model taking inspiration from previous studies. We set the dependent variable to be electricity price. Since we expect a nonlinear relationship in the impact of the independent variables on the dependent variable, we set the variables in log. The variables will be summarised in a single variable to make the equation more interpretable, for example ND and D are the amount of production and capacity of non-dispatchable and dispatchable energy sources. We also include the variable Treatment, which is supposed to capture the effect of the Renewable Energy Sources Act on the production from solar and wind. This results in the following equation:

$$\begin{aligned}
&Log(Price\ Electricity)_{HDMY} = \beta_0 + \beta_1 * log(Load)_{HDMY} + \beta_2 * log(RSI)_{MY} \\
&+ \beta_3 * log(Natural\ Gas)_{DMY} + \beta_4 * log(ND)_{HDMY} + \beta_5 * log(D)_{DMY} + \beta_6 * log(NX)_{HDMY} \\
&+ \beta_7 * Treatment + \beta_8 * (log(ND)_{HDMY} * Treatment) + \beta_9\, DummyHLH \\
&+ \beta_{10} * DummyDaily + \beta_{11} * DummyMonthly + \beta_{12} * DummyYearly + \varepsilon_{HDMY}
\end{aligned}$$

It's interesting to investigate the interaction effect of the variables with HLH to see how the prices move during peak demand which can be twice the size of low load hours. Increased costs, such as CO_2 tariff, are taken into account through the price on natural gas since it would increase if it was subject to tariffs. The amount of electricity generated by oil in Germany is negligible since it’s coal and natural gas that acts as the main components of combustible fuels.

4.2 Ideal Event Study

This model would include many of the same variables described in the ideal regression model, but we would create a dummy variable to represent the time before and then a time variable that would cover the whole period.

$Gen\ Treatment = Year > 2000\ \&\ Year <= 2010$
$Gen\ Timeperiod = Year <= 2010$

The regression would be $Reg\ PriceElectricity\ \$x\ Treatment\ if\ Timeperiod\ == 1, robust$ where the \$x would represent all the other variables listed above in 4.1. Y_{1i} = treated and Y_{0i} = untreated. $Y_i = Y_{0i} + (Y_{1i} - Y_{0i}) * T_i$ where T_i =1 if treated.

We could do a difference in difference study where we compare with a nation similar to Germany, but that has not implemented a likewise policy, to have a control group. However, this comes with its own problems as the European electricity grid is closely integrated and nations experience different climate changes that could explain differences that's hard to observe, creating omitted variable bias. Another approach could be a synthetic control where one would create a “new country” as a control group, made up by a combination of other countries, with almost the same trend as Germany before the policy was enacted, and see how this synthetic country behaves after the EEG policy. This, however, requires a lot of data from other nations and is therefore not applicable to our case due to limitations on the scope and accessibility of data.

This event study helps explain the connection of renewable policy implementation on the price of electricity. The geography of Germany is similar to many other nations and therefore indications on how well this policy implementation worked is important, since, given that it is beneficial, it could be implemented in those countries as well.

4.3 Expected Results

After performing a thorough investigation on the subject, through reviewing literature stemming from similar studies and catching up on relevant economic theory, are we able to make qualified predictions about the impact each variable should have on electricity price. The expected sign of the coefficients in the regression are the following.

Table 1.

Variable	Expected sign of coefficient	***Variable***	Expected sign of coefficient
Consumption	Positive	***Nuclear***	Negative
RSI	Negative	***Combustible fuels***	Positive
Natural Gas	Positive	***Hydro***	Negative
Wind	Negative	***Imports***	Negative
Solar	Negative	***Exports***	Positive

Table 1. The ideal independent variables and their expected effect on the dependent variable price.

The motivations behind the direction of the coefficients are the following. The more *Consumption* increases, the more resources with higher marginal cost have to be activated. The lower the *RSI* is, the more power one company possesses. We therefore expect a negative relationship since increasing *RSI* means more competition in the market. *Natural Gas* will increase prices since it's on the right on the merit order scale. *Wind* and *Solar* generation have close to or zero marginal costs and thus they should, in theory, lower prices. Nuclear power plants are very expensive to build but cheap to run, thus we expect a negative relationship. We expect *Combustible fuels* to have positive coefficients since their marginal costs are higher than *Nuclear* or renewable sources. *Hydro* is a renewable source, and its marginal costs are very low. *Imports* should in theory have a negative coefficient and *Exports* positive since imports are done to offset even higher prices due to shortfall in supply. The reverse would be true for exports; if prices are low in Germany, companies will reduce supply there and export it to other markets.

4.4 Limitations

Due to the limitations in both frequency and availability of the variables listed in 4.1 we are not able to run the regressions listed in 4.1 and 4.2. The data available is in annual form, spanning the years 1991-2020 and bi-annual from the years 2016-2020. We will run three different regression models: two annual regressions where one is a plain regression spanning 1991-2020 and the other is a before-after study spanning 1991-2010, while the third is the bi-annual spanning 2016-2020.

4.5 Data Sources

The data material used for our regression is extracted from the Eurostat database (*Database - Eurostat*, n.d.). The reason behind the exclusive use of Eurostat stems foremost from the lack of accessibility but also the lack of good data from other sources. It was also the case that most reports covering the same topic referenced Eurostat.

Bi-Annual data converted through averaging out the prices over the year to annual data.

ELPrice (household). Price of electricity for households consuming 3500 kWh. **GASPrice (household):** Price of natural gas for households consuming 20-200GJ converted into €/kWh.

Annual data:

Consumption of electricity (GWH): Consumption of electricity annually in Germany (GWh).
Wind (GWH): Total production of electricity in Germany in GWh coming from wind. **Solar (GWH):** Total production of electricity in Germany in GWH coming from solar. **CF (MW):** Total capacity of electricity in Germany in MW coming from combustible fuels. **Hydro (MW):** Total capacity of electricity in Germany in MW coming from hydro. **Nuclear (MW):** Total capacity of electricity in Germany in MW coming from nuclear power plants.

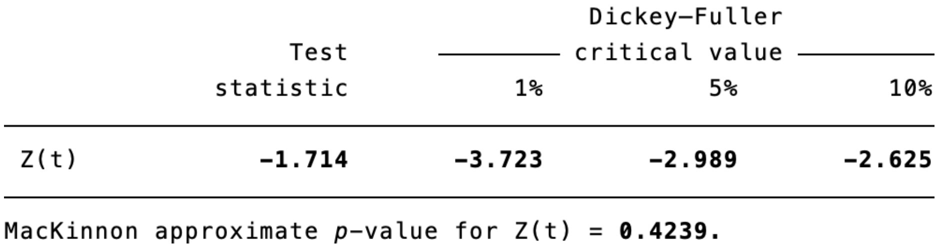
4.6 Estimated model using low frequency data

4.6.1 Autocorrelation and Stationarity tests

Stationarity tests are important to conduct when working with time series data, as this will help with determining the trend in the data, such as trending and non-stationarity in the mean. Both types of trending behaviour can be observed in economic time series. Testing for stationarity allows for a more critical analysis of the regression results, as these results could be fabricated due to non-stationarity. The reason why non-stationary time series is undesirable is because future values can be predicted by previous values; there is a link between the values displayed at different times in the data. Regressing non-stationary time series data will then produce misleading results. (Mushtaq, 2011)

Figures 3, **4**, and **5** respectively show the results for the Dickey-Fuller test over the data used for the 1991-2020, event study, and 2016-2020 regressions. The t-values obtained are larger than the critical values of each significance level (1%, 5%, and 10%). This indicates that the underlying series for each regression are non-stationary and do have unit root. In order to avoid this, we need to perform first or second order differences, meaning there’s a need to add lags (Mushtaq, 2011). These tests were made, but the non-stationarity could not be removed (see appendix 1. Dickey-Fuller).

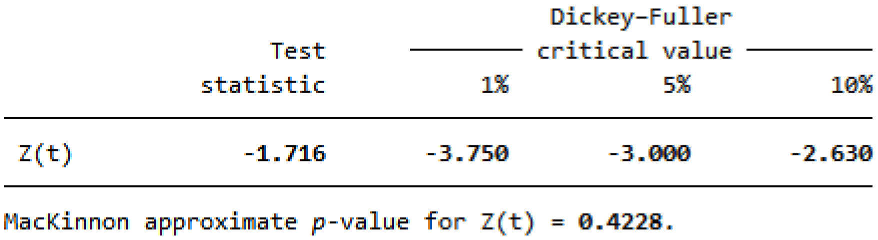
Figure 3.



```
                                   Dickey–Fuller
                 Test     ——————— critical value ———————
            statistic          1%           5%          10%
────────────────────────────────────────────────────────────
 Z(t)          -1.714       -3.723       -2.989       -2.625
────────────────────────────────────────────────────────────
MacKinnon approximate p-value for Z(t) = 0.4239.
```

Figure 3. Depicts the output from Stata after running the Dickey-Fuller test on our dependent variable for the data set 1991-2020.

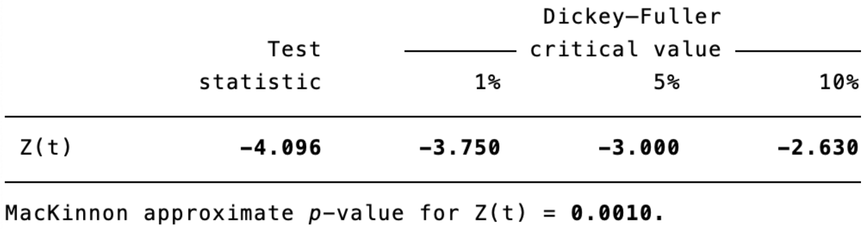
Figure 4.



```
                                   Dickey–Fuller
                 Test     ——————— critical value ———————
            statistic          1%           5%          10%
────────────────────────────────────────────────────────────
 Z(t)          -1.716       -3.750       -3.000       -2.630
────────────────────────────────────────────────────────────
MacKinnon approximate p-value for Z(t) = 0.4228.
```

Figure 4. Depicts the output from Stata after running the Dickey-Fuller test on our dependent variable for the data set 1991-2010.

Figure 5.



```
                                   Dickey–Fuller
                 Test     ——————— critical value ———————
            statistic          1%           5%          10%
────────────────────────────────────────────────────────────
 Z(t)          -4.096       -3.750       -3.000       -2.630
────────────────────────────────────────────────────────────
MacKinnon approximate p-value for Z(t) = 0.0010.
```

Figure 5. Depicts the output from Stata after running the Dickey-Fuller test on our dependent variable for the data set 2016-2020.

The Durbin-Watson test for the 1991-2020 regression assumed the d statistic 1.187621, using 8 parameters and 30 observations. The corresponding p-values can be found in the Durbin-Watson significance table and for the lower limit (dL) this value is 0.684 and for the upper limit (dU) is 1.925. The d statistic from Stata lies between the dL and the dU statistic, indicating that it’s not possible to determine if there is autocorrelation. (Sajwan & Chetty, 2018)

The autocorrelation test for the before-after study obtained the d statistic 1.85 from Stata, where the number of parameters was 11 and the number of observations 20. The corresponding p-values can be found in the Durbin-Watson significance table and for the lower limit (dL) this value is 0.178 and for the upper limit (dU) is 2.914. The d statistic from Stata lies between the dL and the dU statistic, indicating that it’s not possible to determine if there is autocorrelation. (Sajwan & Chetty, 2018)

A test was made for autocorrelation using the Durbin Watson test for the 2016-2020 regression, but the number of observations is too small in relation to the number of parameters, and thus the p-value from the table is missing. The d statistic obtained from Stata, however, was 1.66 which either would suggest that there is autocorrelation, that autocorrelation can not be ruled out or that there isn’t autocorrelation, depending on what the values in the Durbin Watson significance table would have been. (Sajwan & Chetty, 2018)

4.6.2 Regression models

There will be two regression models, model A and model B, where model A will contain the regression spanning 1991-2020, but also the event study 1991-2010, while model B contains the bi-annual data between 2016-2020. For regression 1, T = 1 means the years 2001-2010. The Y stands for time (year):

$$
\begin{aligned}
Log(Price\ Electricity)_Y &= \beta_0 + \beta_1 * log(Consumption)_Y + \beta_2 * log(Price\ Natural\ Gas)_Y \\
&+ \beta_3 * log(Nuclear)_Y + \beta_4 * log(Combustible\ fuels)_Y + \beta_5 * log(Hydro)_Y \\
&+ \beta_6 * log(Wind)_Y + \beta_7 * log(Solar)_Y + \beta_8 * Treatment_{YT} \\
&+ \beta_9 * (log(Wind) * Treatment)_{YT} + \beta_{10} * (log(Solar) * Treatment)_{YT} + \varepsilon_{YT}
\end{aligned}
\tag{1}
$$

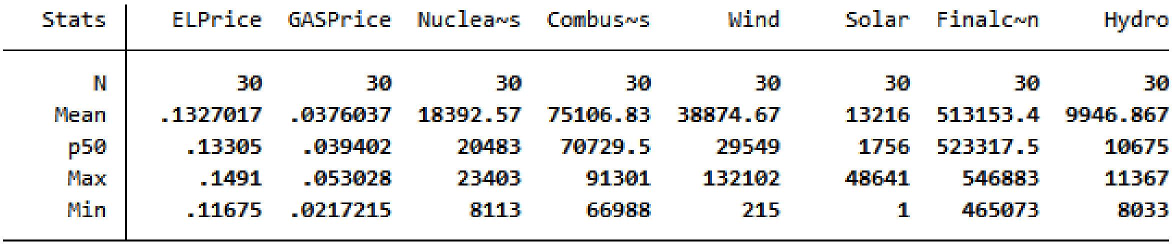
The second regression will be the bi-annal, spanning 2016-2020 with the S standing for season one or two:

$$
\begin{aligned}
Log(Price\ Electricity)_{YS} &= \beta_0 + \beta_1 * log(Consumption)_{YS} + \beta_2 * log(Price\ Natural\ Gas)_{YS} \\
&+ \beta_3 * log(Nuclear)_{YS} + \beta_4 * log(Combustible\ fuels)_{YS} + \beta_5 * log(Hydro)_{YS} \\
&+ \beta_6 * log(Wind)_{YS} + \beta_7 * log(Solar)_{YS} + \beta_8 * i.Season_{YS} + \varepsilon_{YS}
\end{aligned}
\tag{2}
$$

4.7 Descriptive statistics

The following table shows the number of observations, the mean, median, max, and minimum values of the variables used in the regression spanning 1991-2020.

Table 2.



```
   Stats |   ELPrice  GASPrice  Nuclea~s  Combus~s      Wind     Solar  Finalc~n     Hydro
---------+--------------------------------------------------------------------------------
       N |        30        30        30        30        30        30        30        30
    Mean |  .1327017  .0376037  18392.57  75106.83  38874.67     13216  513153.4  9946.867
     p50 |    .13305   .039402     20483   70729.5     29549      1756  523317.5     10675
     Max |     .1491   .053028     23403     91301    132102     48641    546883     11367
     Min |    .11675  .0217215      8113     66988       215         1    465073      8033
------------------------------------------------------------------------------------------
```

Table 2. Descriptive output on the variables used in the regression models.

The number of observations is 30 which represent the number of years. The average price for electricity during the period was 0.1327 €/kWh and the median price was 0.13305€/kWh. The highest price for a year was 0.14981 €/kWh and the minimum price was 0.11675 €/kWh. The price of natural gas averaged 0.0376 €/kWh and the median was 0.394 €/kWh. The maximum and minimum price for a year, observed during the period was 0.053 €/kWh and minimum was 0.0217 €/kWh.

The following variables *Nuclear*, *Combustible fuels*, and *Hydro* are measured in available capacity of MW. The mean capacity of these variables was 18392.57, 75106.83 and 9946.867 with medians of 20483, 70729.5 and 10675, respectively. The maximum capacity was 23403, 91301 and 11367 with a minimum of 8113, 66988 and 8033, respectively.

Wind and solar are measured in actual production of GWh. The mean production during the years was 38874.67 and 13216 with median productions of 29549 and 1756. The maximum amount produced was 132102 and 48641 with the minimum amount of 215 and 1, respectively. Lastly, we can observe that the mean consumption of energy, also measured in GWh, during these years, were 513153.4 and the mean 523317.5. The maximum consumption was 546883 and the minimum consumption was 4565073.

4.7.1 Time series data

The production mix of Germany throughout the years can be observed in **Figure 6**. In 1991 the amount of energy produced by renewable sources was almost 216 GWh and in 2020 the amount had risen to 180743 GWh. For reference, in 1991 the amount of energy generated by wind and solar constituted only 0.05% of what was produced by combustible fuels at that time. In 2020 energy coming from renewable sources had grown to 60% of what came from combustible fuels.

Figure 6.

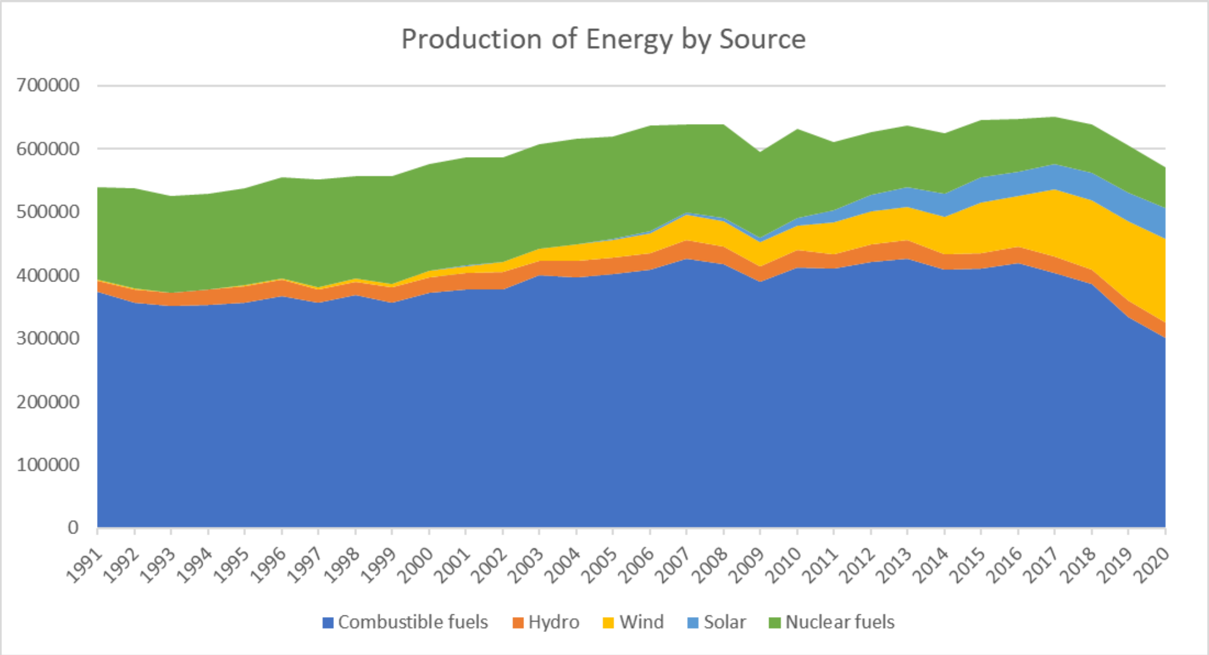


Figure 3. Illustrating the change over time in production output by source measured in GWh.

If we observe the development of consumption during the years, we get the following graph. We can observe that the amount of energy increased between 1991 and 2011 and from then the amount of energy consumed has steadily reduced. We can see a big mark in the curve in 2008-2010 stemming from the financial crisis. If the graph was to continue past 2020, we would probably observe a sharp decrease due to the societal shutdown in response to covid-19 pandemic.

Figure 7.

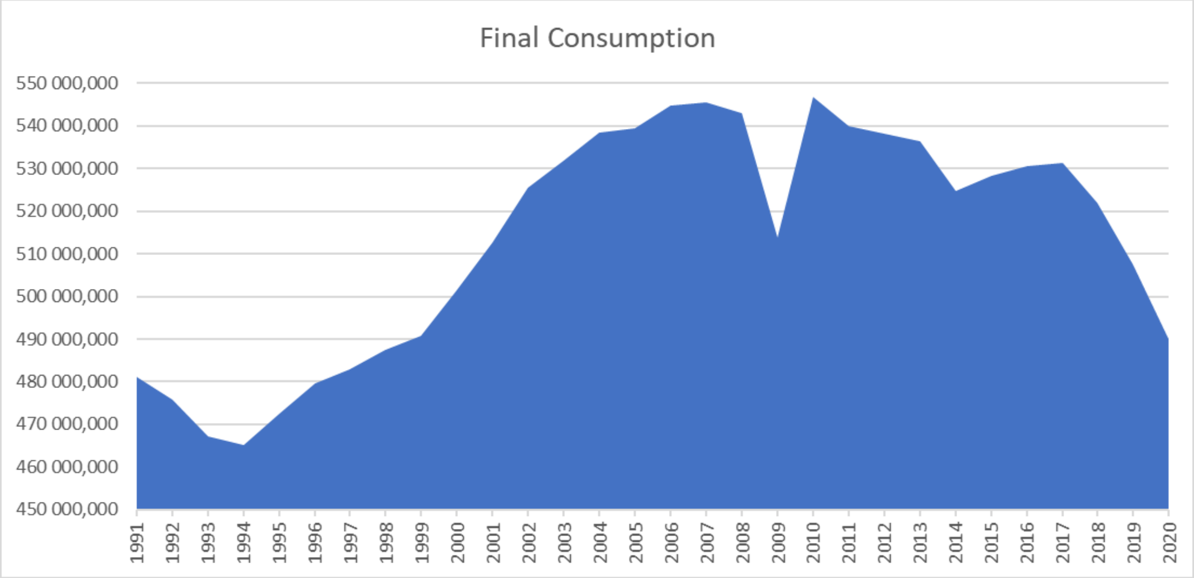


Figure 7 Illustrating the change over time in final consumption measured in GWh.

Lastly, we can observe the price of electricity throughout the years. The price increases from 0.1167 euro to 0.1441 which is a 23,4% increase during the entire time.

Figure 8.

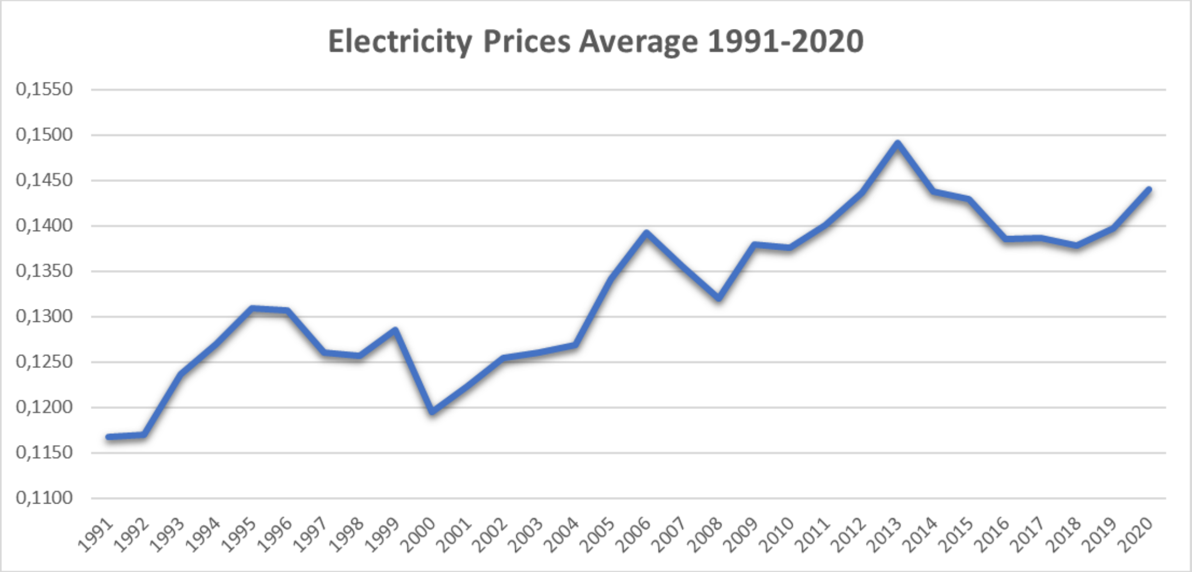


Figure 8. Illustrating the change over time in yearly averaged prices of electricity for households.

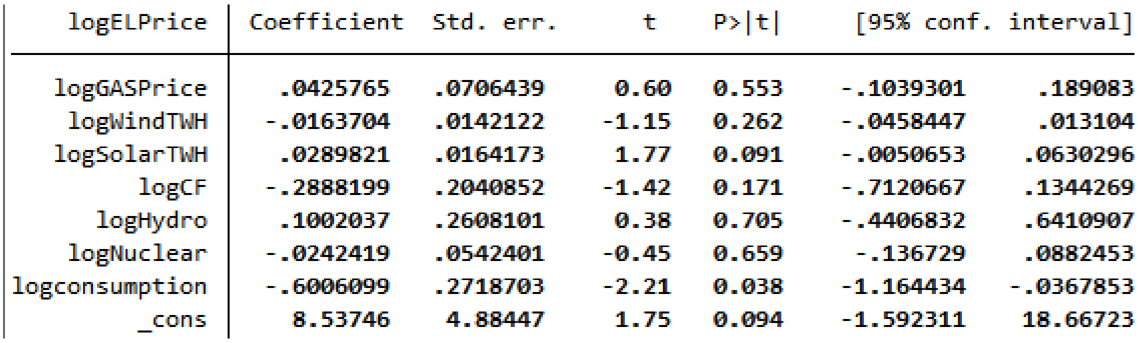
5 Results

In this chapter the results from each of the regressions made will be presented. Since the regressions used are log-log regressions the coefficients can be seen as an estimation of the respective variables' elasticity. These regressions are made and shown even though the data was found to be non-stationary for demonstration purposes; how log-log regression results are interpreted so that this can easily be applied in future studies where high-frequency data is available and the ideal regression model can be used.

5.1 Regression results (1991-2020)

The output of the first regression using annual data between the years 1991 and 2020, thus containing 30 data points, is shown in **Table 3**. The only variables that are of significance are solar power and final consumption of electricity, where *Solar* is significant on a 10% level and the latter variable on a 5% level. By observing the coefficient corresponding to these variables an estimation can be made about their respective effect on electricity prices. Solar power has a positive coefficient, revealing that, according to this regression, if generated electricity from solar power increases with 1% the electricity prices will increase by roughly 0.03%. The second significant variable has a negative corresponding coefficient, meaning if the amount of electricity consumed increases by 1% electricity prices will decrease by 0.60%.

Table 3.



```
      logELPrice | Coefficient  Std. err.      t    P>|t|     [95% conf. interval]
-----------------+----------------------------------------------------------------
     logGASPrice |   .0425765   .0706439     0.60   0.553    -.1039301     .189083
      logWindTWH |  -.0163704   .0142122    -1.15   0.262    -.0458447     .013104
     logSolarTWH |   .0289821   .0164173     1.77   0.091    -.0050653    .0630296
           logCF |  -.2888199   .2040852    -1.42   0.171    -.7120667    .1344269
        logHydro |   .1002037   .2608101     0.38   0.705    -.4406832    .6410907
      logNuclear |  -.0242419   .0542401    -0.45   0.659     -.136729    .0882453
  logconsumption |  -.6006099   .2718703    -2.21   0.038    -1.164434   -.0367853
           _cons |    8.53746    4.88447     1.75   0.094    -1.592311    18.66723
```

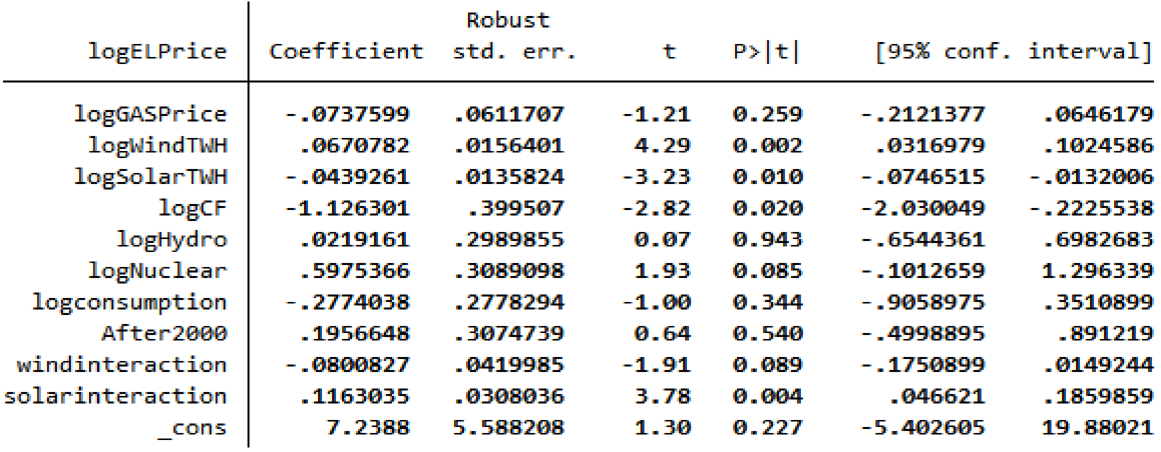
Table 3. Regression output from Stata showing the coefficient of the independent variables (in log) together with its significance level.

5.2 Before-after study

The second regression is the before-after study. Its output, using annual data between the years 1991 and 2010, and thus using 20 data points, is shown in **Table 4**. The variables that are significant in this regression are: *Wind*, *Solar*, *Combustible Fuels*, *Nuclear*, *windinteraction*, and *solarinteraction*. *Solar* and *Wind* are significant on a 1% level and have a negative respectively positive effect on electricity prices, where if solar generation increases with 1% the electricity prices will decrease with 0.04% and an increase in wind capacity with 1% will increase electricity prices with 0.07%. The *solarinteraction* variable is significant at a 1% level, and has a positive coefficient, suggesting that while the policy has been in force, an increase in solar generation by 1% has increased the electricity price by 0.12%. *Combustible Fuels* is significant at a 5% level, where its corresponding coefficient is negative, suggesting an increase in electricity from combustible fuels by 1% would decrease electricity prices by 1.13%. The *windinteraction* variable is significant at a 10% level and has a negative coefficient, meaning that, while the policy has been in force, an increase in wind capacity by 1% has decreased the electricity price by 0.08%. *Nuclear* is significant at a 10% level and has a positive coefficient that suggests an increase of nuclear generation by 1% would increase electricity prices by 0.60%. The variable *After2000* is not significant, but its coefficient can give an indication of the effect of the policy's implementation. The coefficient is positive, suggesting that the electricity prices have increased since the implementation of the EEG policy, with 0.20% according to the regression result.

Table 4.

Table 4. Regression output from Stata showing the coefficient of the independent variables (in log), the interaction terms and the treatment together with its significance level.

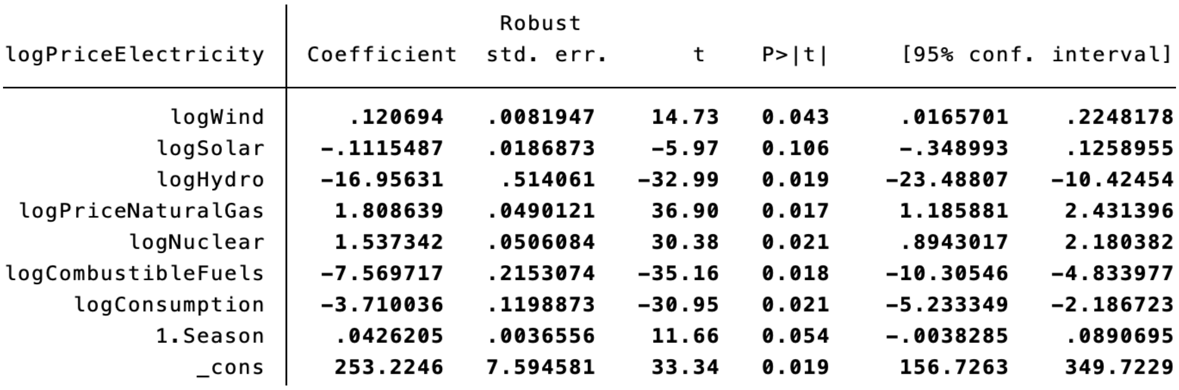


```
                  |               Robust
       logELPrice | Coefficient  std. err.      t    P>|t|     [95% conf. interval]
------------------+----------------------------------------------------------------
      logGASPrice |  -.0737599   .0611707    -1.21   0.259    -.2121377    .0646179
       logWindTWH |   .0670782   .0156401     4.29   0.002     .0316979    .1024586
      logSolarTWH |  -.0439261   .0135824    -3.23   0.010    -.0746515   -.0132006
            logCF |  -1.126301    .399507    -2.82   0.020    -2.030049   -.2225538
         logHydro |   .0219161   .2989855     0.07   0.943    -.6544361    .6982683
       logNuclear |   .5975366   .3089098     1.93   0.085    -.1012659    1.296339
   logconsumption |  -.2774038   .2778294    -1.00   0.344    -.9058975    .3510899
        After2000 |   .1956648   .3074739     0.64   0.540    -.4998895     .891219
  windinteraction |  -.0800827   .0419985    -1.91   0.089    -.1750899    .0149244
 solarinteraction |   .1163035   .0308036     3.78   0.004      .046621    .1859859
            _cons |     7.2388   5.588208     1.30   0.227    -5.402605    19.88021
```

5.3 Regression results (2016-2020)

The output of the third regression using biannual data between the years 1991 and 2020, thus containing 10 data points, is shown in **Table 5**. It's important to note the number of data points used for this regression when reading the significance level. Even if most of the variables are significant on a 5% level, the number of observations is still low and should therefore be interpreted with caution. The only variables that are not significant on a 5% level are solar generated electricity and the season dummy. The season dummy is, however, significant on a 10% level. The variables with negative elasticity are combustible fuels, hydro power, and final consumption, meaning if the capacity of electricity from hydro power, combustible fuels, or the amount of electricity consumed increases by 1%, the electricity price will decrease by 16.96%, 7.57%, and 3.71% respectively. The rest of the electricity sources; wind, gas price, and nuclear have a positive coefficient. This entails an increase in production of wind or capacity of gas and nuclear will cause an increase of electricity price by 0.12%, 1.81%, and 1.54%, respectively.

Table 5.



```
                     |               Robust
logPriceElectricity  | Coefficient  std. err.      t    P>|t|     [95% conf. interval]
---------------------+----------------------------------------------------------------
             logWind |    .120694   .0081947    14.73   0.043     .0165701    .2248178
            logSolar |  -.1115487   .0186873    -5.97   0.106     -.348993    .1258955
            logHydro |  -16.95631    .514061   -32.99   0.019    -23.48807   -10.42454
  logPriceNaturalGas |   1.808639   .0490121    36.90   0.017     1.185881    2.431396
          logNuclear |   1.537342   .0506084    30.38   0.021     .8943017    2.180382
  logCombustibleFuels|  -7.569717   .2153074   -35.16   0.018    -10.30546   -4.833977
      logConsumption |  -3.710036   .1198873   -30.95   0.021    -5.233349   -2.186723
            1.Season |   .0426205   .0036556    11.66   0.054    -.0038285    .0890695
               _cons |   253.2246   7.594581    33.34   0.019     156.7263    349.7229
```

Table 5. Regression output from Stata showing the coefficient of the independent variables (in log) together with its significance level.

6 Discussion

As previously mentioned in this report, the data that was accessible were limited to yearly and bi-annually frequency. This presents several challenges since the ability to capture externalities or seasonal trends are severely limited or even impossible. When data is aggregated into annual and bi-annal, then changes during peak hours together with weekly and even monthly changes in demand and production are not able to be interpreted. This causes problems since most of the production from renewable sources, such as solar, are restricted during the winter months. We can't thus observe the true effect of implementing renewable energy if we can't identify its production and contribution during peak demand hours or its monthly output. The merit order effect shifts to the right when renewable energy output grows, which indicates that the large absence of renewable energy production during the winter months should result in higher prices and that prices during the summer should decrease with more renewable output. When data is aggregated, we get a distorted picture of how the implementation affects prices and this is most probably the reason why we get more significant coefficients, even though we have a smaller sample, in the bi-annual regression spanning 2016-2020.

We could not find that the energy market is subject to a merit order effect, at least not in a significant way. This is in line with some other studies such as Mulder and Scholtens (2013) and could be explained by a lack of more frequent data, as mentioned above. We know that, for example, solar produces the most of its energy during peak hours, i.e., daytime. Since we aren't able to capture that, our results become distorted with the direction coefficients being opposite of what was expected. It's also interesting to point out that Gelabert et al. (2011) observes a decrease in how much renewable energy production lowers prices over time. The study examines the electricity price development during the year 2005–2009 and found that the implementation of wind lowers prices and that solar does the opposite. This is also in line with our results and can be an effect of the cost-benefit ratio of solar increasing over time. We obtained a positive coefficient for solar in the regression 1991-2020 and a negative 2016-2020, indicating that solar has gotten more cost effective and that implementing it on a scale now lowers prices.

Some of the results shown in the regressions suggest that the merit order effect decreases in the long run, which is in line with Gelabert et al.’s (2011) brief argumentation on the subject and Antweiler and Muesgens’ (2021) paper. Apart from the before-after study and 1991-2020 regression having very aggregated data, another reason behind the inconsistency of the signs of the renewable variables could be a decreasing merit order effect. Conventional technologies could be assumed to have enough time to adjust their capacity levels to the new levels of renewables in the mix over a 20- or 30-year period. We could investigate this by dividing a higher frequency dataset into separate time periods to observe a possible marginal decrease of the merit order effect and to understand if it is observable in some periods and not in others. This could help in understanding if there exists a peak limit whereby including more renewable energy does not lower prices. A third possible explanation for/to the illogical results could be that our data is non-stationary, causing the results to possibly be fabricated by the predictability of the values.

The results from the 1991-2020 regression contradict our expectations regarding solar, combustible fuels and demand. We anticipated, in regard to the merit order effect, that solar would have a negative coefficient, since it has low to zero variable costs and continues to feed the grid even at negative prices and should thus displace power generated from sources with a higher variable cost. The negative coefficient of capacity of combustible fuels could maybe be explained by the fact that the capacity does not adapt its supply fast enough to not over supply the market, or that it acts as a back-up and thus prevents higher prices that would have been in absence of the spare capacity. It is puzzling to observe that hydro capacity has a positive coefficient since its variable costs are lower than combustible fuels. The last coefficient, *Final Consumption*, tells us that the more energy consumption there is, the more the price paid is reduced. When looking at conventional supply and demand theory, increasing the demand would shift the demand curve to the right indicating that producers can extract higher prices for that good. This does not go together with the negative coefficient of the demand variable.

The before-after study has 6 variables that are significant: wind, solar, nuclear, combustible fuels, the interaction between the policy and the amount of solar production, and the interaction between the policy and wind capacity. The effects of wind and solar on electricity prices, are positive respectively negative. The negative effect from solar power would support the merit order effect, while the positive effect of wind capacity goes against this phenomenon. The capacity for combustible fuels has a negative effect, while the effect of nuclear generation is positive. This is also counterintuitive since the former has higher operating costs than nuclear power. It also goes against the findings in Woo et al. (2014), whose results showed a price increase with the shutdown of nuclear power plants. The wind interaction term indicates that, given the policy is in force, wind capacity expansion has a decreasing effect on electricity prices, which would be in line with the hypothesis. Why this is could be because the policy has been able to subsidise wind capacity expansion through the EEG surcharge. If that is so, then the fact that solar generation has an increasing effect on electricity prices while the policy is in force is very counterintuitive. The key variable for this regression is the After2000 since it represents the policy. The direction obtained for this variable is the opposite of what was expected; the results show electricity prices were lower before the implementation of the EEG than after. The Renewable Energy Sources Act was introduced to facilitate the expansion of renewable energy. The increase of these technologies should be accompanied by the merit order effect, and it is then to be expected that the electricity price should decrease after it was adopted. However, an explanation to this development could be that the long-term merit order effect is equal to zero, as was found by Antweiler and Muesgens, and that 10 years is a long enough time-period for conventional technologies to adjust their capacity levels. If so, that would explain why there is a continued slight increase in electricity price.

The only variables in the 2016-2020 regression that follows the hypothesis, and are significant, are gas price and hydro power. The coefficients of the renewable technologies mostly follow our hypothesis, where both solar and hydro power have negative coefficients, indicating that these have a merit order effect. Wind power, on the other hand, has a positive coefficient which is not what we had expected. The cause behind this result may be that this technology is well-established and thus conventional technologies have had time to adjust to its input to the electricity market.

By summarising the effect of the different variables, without considering if the variables are significant or not, we would like to study the coefficient's general effect and if it follows our hypothesis and the economic theory. Over the three regressions on the electricity price, the effect of combustible fuels and final consumption are the same across the regressions, where both might have a negative effect. According to our hypothesis, combustible fuels and final consumption should have a positive effect on electricity prices. The price should increase as combustible fuels are dispatched to generate electricity to meet demand when renewable electricity isn’t enough. This would cause an extra cost since combustible fuels have variable costs. Since demand follows the dispatch curve, the price of electricity increases, indicating that a higher demand for electricity for final consumption should make electricity more expensive. The obtained results thus defy economic logic.

The remaining five variables; wind, solar, hydro, gas price, and nuclear power, have somewhat differentiating effects across the three regressions. According to two of the regressions, wind power might have a positive effect on electricity prices, going against our hypothesis, but this may indicate the existence of a decreasing merit order effect long-term. However, the regressions that indicated a positive effect are the two using data with a shorter timespan, while the regression with the largest time span indicated a negative effect. Two of the regressions indicated that solar might have a negative effect on electricity prices, which is in line with our hypothesis. Two regressions indicated that hydro and nuclear power might have a positive effect on electricity prices, which goes against our predictions. Hydro was negative for the last regression indicating that there might be more room for expansion before we see the marginally decreasing merit order effect. Gas prices obtained a positive effect in two regressions. The effect of gas prices in all but the event study follows economic theory and our hypothesis; that it should be positive as gas is regarded as a substitutional good. Nuclear power is known to be in the process of being phased out in Germany. This disestablishment may have the same effect that not fully established renewable energy technologies have and we might then be observing the merit order effect in this result.

The electricity price data used in this paper is the price excluding taxes and levies, which may be an important discussion point since more than half of the electricity prices for retail consumers consists of taxes and fees. As can be seen in **Figure 8**, the prices have changed very little compared to what one might expect; only a 23% increase since 1991. A possibility then is that the taxation on the electricity price for retail consumers has changed more than the price and may have influenced the final consumer price that way, whether that be a positive or a negative effect. Another possibility is that the increase in price has not changed all that much due to the implementation of more renewably sourced electricity and its merit order effect. In that case, rather than seeing a decrease in prices over time, the expansion of renewable generation technology has kept the prices from rising more over the years.

The studies that have been summarised in this paper have collectively reached the conclusion that an increasing share of renewably sourced electricity lowers electricity prices through the merit order effect. These studies have used high frequency data, which arguably makes their results more trustworthy than the results in this study and may also show the importance of using data with higher frequency for obtaining more accurate results and catching seasonality. It is however noteworthy that the before-after study and the first regression uses data that spans over a longer period of time than the data used in the previous studies. Had there been access to high frequency data, so that we could have used the ideal regression model, this would have been the most interesting point of comparison; if there actually is a different effect of renewable electricity expansion on prices in the long run than in the short run. Such a study would also allow for a closer look at the true long-term merit order effect using historical data, which is a research area that is lacking greatly. An indication of a different effect in the long run, and in what direction, would be useful for the expansion of renewable energies. Whether the effect is positive or negative, it can be useful for forward-planning and a way to avoid or mitigate potential economic problems that could appear with this expansion.

7 Conclusion

This report explains thoroughly how energy markets in general, but specifically Germany, is structured. After surveying studies previously written about energy markets, and specifically the implementation of renewable energy sources, we are able to paint an overall picture on the market structure and use it when motivating our question of scope, but we also utilise it when deciding the methodological approach appropriate for this study. We present an ideal model to answer our research question, but, due to limitations in the accessibility to both consistent and high frequency data, run a regression with the data available. The inconsistent results provided in the regression are explained by the low number of samples but foremost the aggregation of the data into years. We do, however, in accordance with all of the literature in section 3.7, find that implementing more renewable energy into the mix does lower electricity prices, albeit with various results. However, these studies have data points spanning only a few years during periods when established renewable energy production was relatively low in comparison to today's production numbers. Our results also indicate, albeit with uncertainty, that the implementation of renewable energy sources lower electricity prices. We interpret our results such that there exists a marginal decreasing return, where after a certain point, implementing more renewable energy does not lower prices, at least not in Germany. According to our before-after study, wind generation overall has a positive effect on the price but negative when considering the interaction term. This seems to imply that the amount of electricity stemming from wind generation would not be enough to affect price. As mentioned in previous parts, the low frequency of data skews our results. Our study's contribution to the field of science is that it strengthens the already established view of price reductions with the implementation of renewable energy sources, at least in countries where current production from these sources is underdeveloped as we observed a marginal decrease in the merit order effect. Further research on the topic where one is able to utilise more high frequency data would assist in resolving the inconsistent results stemming from the aggregation of data. It would also give more insight into what might be a marginal decreasing merit order effect.

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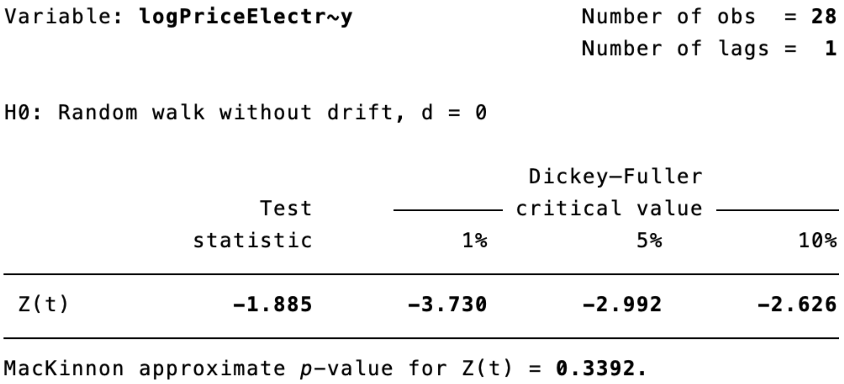
Appendix

1. Dickey-Fuller test

1.1 1991-2020: first difference

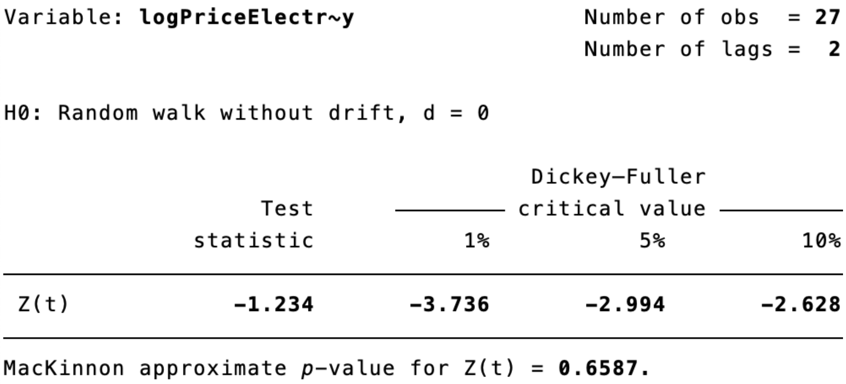


```
Variable: logPriceElectr~y                     Number of obs  = 28
                                               Number of lags =  1

H0: Random walk without drift, d = 0

                                        Dickey–Fuller
                   Test          ──────── critical value ────────
              statistic           1%           5%          10%
─────────────────────────────────────────────────────────────────
 Z(t)            -1.885       -3.730       -2.992       -2.626
─────────────────────────────────────────────────────────────────
MacKinnon approximate p-value for Z(t) = 0.3392.
```

1.2 1991-2020: second difference

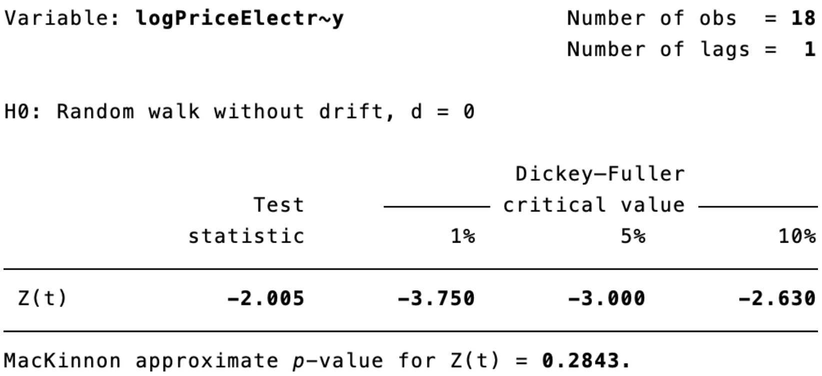


```
Variable: logPriceElectr~y                     Number of obs  = 27
                                               Number of lags =  2

H0: Random walk without drift, d = 0

                                        Dickey–Fuller
                   Test          ──────── critical value ────────
              statistic           1%           5%          10%
─────────────────────────────────────────────────────────────────
 Z(t)            -1.234       -3.736       -2.994       -2.628
─────────────────────────────────────────────────────────────────
MacKinnon approximate p-value for Z(t) = 0.6587.
```

1.3 Event study: first difference

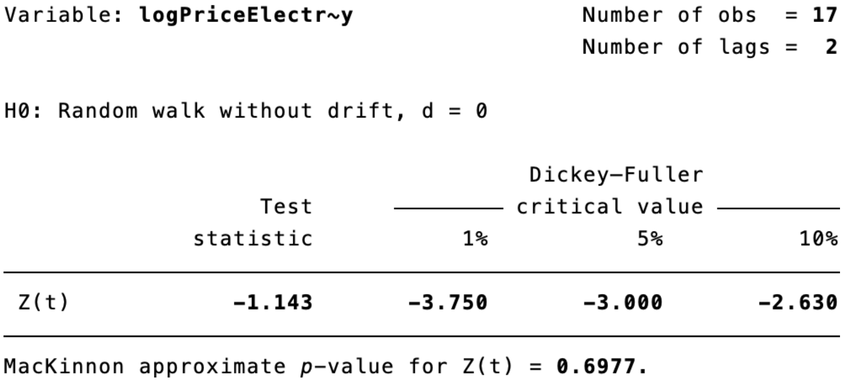


```
Variable: logPriceElectr~y                     Number of obs  = 18
                                               Number of lags =  1

H0: Random walk without drift, d = 0

                                        Dickey–Fuller
                   Test          ──────── critical value ────────
              statistic           1%           5%          10%
─────────────────────────────────────────────────────────────────
 Z(t)            -2.005       -3.750       -3.000       -2.630
─────────────────────────────────────────────────────────────────
MacKinnon approximate p-value for Z(t) = 0.2843.
```

1.4 Event study: second difference

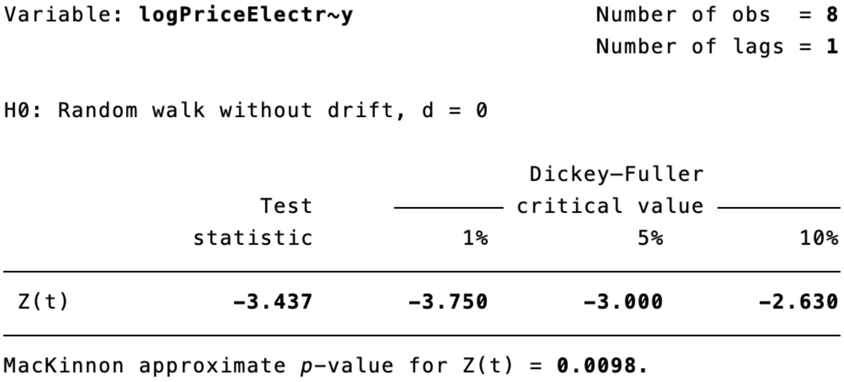


```
Variable: logPriceElectr~y                    Number of obs  = 17
                                              Number of lags =  2

H0: Random walk without drift, d = 0

                                       Dickey–Fuller
                   Test         ———————— critical value ————————
              statistic           1%           5%          10%
──────────────────────────────────────────────────────────────
 Z(t)            -1.143       -3.750       -3.000       -2.630
──────────────────────────────────────────────────────────────
MacKinnon approximate p-value for Z(t) = 0.6977.
```

1.5 2016-2020: first difference

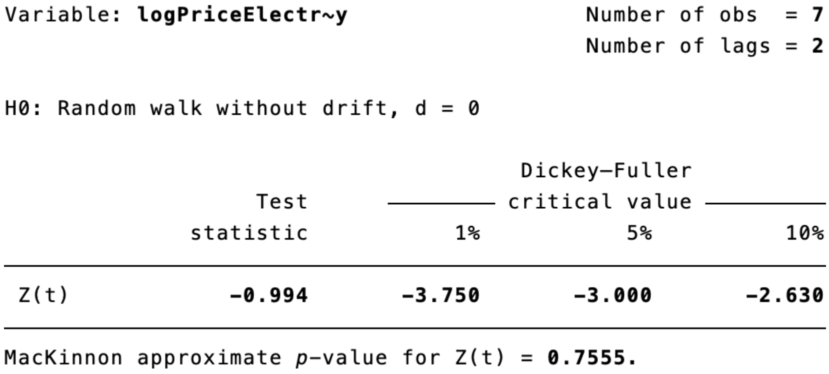


```
Variable: logPriceElectr~y                    Number of obs  = 8
                                              Number of lags = 1

H0: Random walk without drift, d = 0

                                       Dickey–Fuller
                   Test         ———————— critical value ————————
              statistic           1%           5%          10%
──────────────────────────────────────────────────────────────
 Z(t)            -3.437       -3.750       -3.000       -2.630
──────────────────────────────────────────────────────────────
MacKinnon approximate p-value for Z(t) = 0.0098.
```

1.6 2016-2020: second difference



```
Variable: logPriceElectr~y                    Number of obs  = 7
                                              Number of lags = 2

H0: Random walk without drift, d = 0

                                       Dickey–Fuller
                   Test         ———————— critical value ————————
              statistic           1%           5%          10%
──────────────────────────────────────────────────────────────
 Z(t)            -0.994       -3.750       -3.000       -2.630
──────────────────────────────────────────────────────────────
MacKinnon approximate p-value for Z(t) = 0.7555.
```