B.Sc. In Economics

An analysis of the Hagenwerder-Mikułowa phase-shifting transformer and its impact on redispatch in Germany

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Abstract

The increase in renewable energy generation and the push towards closer electric grid integration in Europe has increased the necessity for both domestic and cross border redispatch in many countries across Europe to solve congestion in the meshed European grid. Recently countries have started implementing phase shift transformers (PST) to reduce the loop flows and control unscheduled flows between countries, which are becoming more frequent. In this paper, the implementation of the Hagenwerder-Mikułowa PST and its impact on redispatch in Germany is explored. Multivariate OLS regression was used for the study, and the results showed that redispatch in Germany had decreased after the implementation of the PST.

Keywords: Redispatch, Phase shift transformer, Interconnectors, Loop flows, Germany

Prefix

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1. The introduction

Germany's energy mix has changed significantly in the 21st century and has seen a massive proliferation of intermittent energy generation such as wind power and photovoltaics (PV) that have replaced highly pollutive sources of energy such as coal and lignite. The rising share of intermittent production has led to an increase in the number of corrective congestion measures due to the fluctuations in energy generation and concentration of energy production in the north. The increase in renewable energy generation has resulted in frequent negative price periods in Germany. The meshed German grid was not designed to handle high intermittent energy production, and national transmission system operators (TSO) have had to grapple with maintaining the stability of the network. This sudden and high proliferation of renewable energy production has also come to affect Germany's neighbors, specifically Poland and the Czech Republic. Through the use of interconnectors, once completely national electrical grids are becoming more intertwined, thus increasing the integration of European electricity systems. The result is an increase in loop flows between Germany and its eastern neighbors. As a response, a phase shift transformer (PST) has been constructed, aiming to reduce the loop flows and alleviating the congestion problems. The paper will also give some insight into the Inter TSO Compensation (ITC) mechanism, which was created to compensate countries for hosting cross border flows. Still, it has not managed to create the right incentives for investment between countries and does not compensate countries accurately for hosting every type of flow. The focus of this project will be on the interconnectors between Poland and Germany and the cross-border flow trade between the two countries. The paper will outline why Germany and Poland agreed to implement a phase shift transformer and talk about the effects it had on trade and cross border flows. In this thesis, I will try to answer the question of whether or not redispatch costs for Germany have increased with the advent of phase-shifting transformers. I do this by running a regression to estimate the effect the PST had on the total German redispatch from 2015 to 2017. The following research question is the one this thesis attempts to answer:

- *What were the effects of the phase-shifting transformer installed on the Polish-German border on redispatch in Germany?*

The thesis is organized as follows. Section 2 describes the evolution of the German electricity market and explains its current condition. Section 3 presents the details of cross border flows and the details of the German-Polish PST, while section 4 describes the econometric model and discusses the determinants of redispatch as well as the data and identification strategy. The results and robustness checks of the data are presented in section 5. Section 6 includes the discussion and the findings from research and what can be learned from them.

2. German electricity sector

Since the 1990s, there has been a push towards an integrated European energy market by linking up different countries and their grids to allow producers and consumers from different countries to buy and sell across national boundaries. Combining the European energy market involved the breaking up of vertically integrated energy companies and the creation of the three distinct actors (Chick, 2004). The three actors were the Producers who would produce the energy, Transmission Service Operators (TSO) who would tackle moving large scale energy across the grid. Germany is unique in that it sports a total of four national TSOs instead of the traditional one TSO. Many are binational such as TenneT, who is by far the biggest of the four national TSOs in Germany and is also the national TSO for the entire Netherlands. While the Belgium national TSO Elia owns the eastern German TSO 50Hertz, the other two smaller TSOs in Germany are TransnetBW and Amprion, which service the western side of German and have no affiliation with other national TSOs (*Transmission System Operators | Grid Development Plan*, n.d.). Lastly, Distribution Service Operators (DSO) would distribute energy directly to consumers, such as households and companies. The idea was to introduce competition and increase efficiency in an industry that had consisted mainly of state and national energy monopolies and move towards a system of small energy producers all competing to offer the cheapest energy with the best reliability. One of the most significant paradigm shifts has occurred in Germany, which lies at the heart of Europe.

2.1 Energy Transition / Energiewende

Already in the 1990s, Germany began to flirt with the idea of generating electricity with renewables (Nicolosi, 2010). For that to become a reality, Germany had to solve the problem of renewables being comparatively more expensive than conventional and established nuclear and coal alternatives. They would, therefore, not be competitive under the current market conditions and not gain any traction. To incentivize people and companies to invest in renewable power generation, Germany passed a feed-in tariff law in 1990 called the Stromeinspeisungsgesetz. The law required electric utilities to purchase the electricity generated from renewable energy producers, which covered at this time hydropower, wind energy, solar energy, landfill gas, sewage gas, and biomass. The electric utilities also had to guarantee the producers of solar and wind power a payment that would be at least 90 percent of the average revenue per kilowatt-hour from the delivery of electricity by electricity utilities to all final consumers. (*Zeitreihen Erneuerbare Energien*, 2020). After the agreement at the Kyoto protocol Stromeinspeisungsgesetz was restructured into the Erneuerbare-Energien-Gesetz (EEG). The first significant change came with how the feed-in tariff would be calculated. It was no longer dependent on the price of electricity; instead, every kilowatt-hour generated from renewable electricity was guaranteed a fixed remuneration based on the cost of the technology for a duration of up to 20 years (World Bank, 2009). The expectation was that the costs associated with renewables would decrease over time; with this in mind, they created a degression mechanism, which meant that the remuneration for new installations would drop at a rate determined in the legislation (Appunn, 2014). The EEG surcharge that would be used to finance this would be paid by all electricity utilities instead only by regional utilities like it had been before, meaning every consumer of electricity would have to pay the surcharge. However, these ambitious reforms were not without their critics. Economics ministry took umbrage with a proposal favoring instead a system of small market introduction programs and introduce a voluntary renewables quota which would have been determined by the energy suppliers themselves (Gründinger, 2015). An amendment to EEG in 2004 allowed specific energy-intensive industries to be given an exemption from having to pay the surcharge (Töpfer & Gawel, 2013). The exemption was continually expanded to include more companies in future amendments to the EEG to safeguard the industry jobs that would have been lost as a result of the increase in the price of electricity (Dinkloh, 2014). The big change, however, was the priority grid access that was given to renewable energy producers; this meant that renewable energy generation would always take precedence over conventional energy generation. The law made it so that renewable generation could not be curtailed in the event of an oversupply of energy. The law also stipulated that connecting renewable generation to the grid would be prioritized since producers would only gain the remuneration that was promised to them if there was a grid connection in place (*Renewable Energy Sources Act*, 2017). A failure to connect renewable energy producers to the grid would mean that they would be entitled to receive compensation for the lost revenue for not being able to produce (Appunn, 2014). It is important to understand that it only stipulated connecting renewables to the grid was a priority but not alleviating the congestion that would come as a result of additional renewable energy that was being generated. A significant change came in 2011 after the Japanese Fukushima Daiichi plant meltdown, which caused German policymakers to mothball eight of their nuclear reactors in Germany and set up a plan to phase-out all 17 nuclear reactors in Germany within a decade (*German Developments Following Fukushima*, 2015). Nuclear power had been Germany's largest single source of electricity before the event. Taking its place would be the plethora of new subsidized renewable energy technologies[1]. There were a couple of revisions of the EGG in 2009 and 2010, but nothing major until 2012; the German government sought to introduce a market premium scheme and therefore move away from the predetermined feed-in tariff. The government also changed the laws so PV could now be curtailed to avoid an overload on the grid but only as a last resort[2]. The 2014 amendment to the EEG continued the trend of making EEG more market-oriented by removing fixed remunerations. The new system incentivized producers to sell their energy directly into the market. Producers would receive an average monthly wholesale price as well as an additional market premium on top of the price they sell the energy for (Appunn, 2014). The law also introduced a system of auctions where projects are chosen based on offering the lowest costs, which were pilot tested with photovoltaics in 2015 (Klessmann & Tiedemann, 2017). While it did make the allocation process more transparent and efficient, the bidding allocation has favored solar installations over onshore wind installations. The 2016 revision of EEG tried to address the problem of increasing concentration of onshore wind production and the congestion that came as a result of it by limiting investment in areas known as grid congestion zones and forcing new installations to stay within the deployment corridor that was set up (Appunn, 2016).

[1] Technically speaking the remunerations are not subsidies since they are not derived from taxation instead financed by the EEG surcharge which is levied on consumers. For that reason, I will refer to them as remunerations going forward.
[2] This was likely in response to the 50.2 Hertz problem (*The German 50.2 Hz problem*, n.d.)

EEG guaranteed high prices for producers of renewable energy and priority access to the market. This made investments in renewables more predictable, and therefore renewables became a safer investment for investors. EEG had the desired effect of increasing demand for solar panels, and that led to increased investment in solar technology. With help from other countries who also started to invest in PV during the same time, the price of solar photovoltaic modules decreased significantly, in 2012 the price was less than 10% of what it had been in the 1990s (Lafond et al., 2018). The combination of falling costs and EEG remunerations finally made photovoltaics competitive. In Germany, solar increased its share significantly, going from being almost 0% of the total energy consumption in 2002 to be 8% in 2019 (Wehrmann, 2020). Similarly, wind power generation went from around 1% of generation in 2002 to 21% in 2019 (Wehrmann & Amelang, 2020). Wind and solar have grown to a more significant percentage of the energy mix than ever before, currently at over a third of the energy mix. The rest of the energy mix is lignite 18%, natural gas 15%, coal 9.4%, and lastly, nuclear 12.4% (Appunn et al., 2020). It is expected that combined wind and solar will cover half of Germany's electricity demand in the coming years (Hirth et al., 2019). EEG managed to solve the problem with renewables being too expensive to operate. Still, it did not, however, manage to solve the inherent problem of intermittent production, which has been a barrier to large scale implementation of renewable technology (Cavallo, 2007). The reality is that solar and wind can go from meeting 100% of the energy demand in Germany as happened on New Year's Day 2018 at 6 am, all the way down to 0% depending on the conditions (Amelang & Appunn, 2018). While wind is considered more stable since it does not fluctuate as much during the day as solar, it still has the same problem where depending on the conditions, its capacity to meet demand is unreliable.

Even though the costs of renewables have decreased significantly, the retail price of electricity paid by Germans has doubled in the last 20 years. Germany has become one of the most expensive places to purchase electricity in Europe on average. German prices are about 45% higher than the European average of 20.54 ct/kWh (Bundesnetzgentaur, 2017). The main reason for the increase in prices in Germany is the increase in the costs associated with financing the renewable surcharge, which funds the market premiums that renewables producers get paid, This has increased from 4.5% to be 21.2% of the total price (Wehrmann & Thalman, 2015). One easy explanation for this is that Germany is investing in more green energy, and therefore naturally, the subsidies paid to the producers have also had to increase in tandem. Renewables usually have very low to zero marginal costs when it comes to production, which would lead one to assume that the market price for the electricity had decreased due to the low marginal costs of renewable energies and merit order effect pushing out more expensive energy producers. Comparing the price of energy in 2006 to the price in 2019, the price that the distribution system operators pay on average has increased from 4.92 to 6.88, which is a 42% increase (Thalman & Wehrmann, 2020). Considering inflation explains a large chunk of this change or about 50% of the difference in price; however, the other half cannot be explained by inflation alone. Many factors could explain this, but one factor that has increasingly become a mainstay of German grid operations, and that is redispatch.

2.2 Redispatch / Einspeisemanagement

The growth of renewables has caused an increase in redispatch and feed-in management[3] to bring order to the sporadic generational habits of renewables. Total redispatch costs in Germany have increased by 70% from 2011 to 2015 (Schmitz et al., 2013), and the costs for congestion management in Germany from 2015 to 2017 were 2,21 billion Euros (Staudt et al., 2018). Redispatch costs are expected to continue to increase in Germany going forward to 2030 (Hirth et al., 2019). Redispatch is like its name implies a reordering of dispatches. A dispatch is merely a detailed order of how much production producers are cleared to produce in the energy markets. In the energy markets, individual producers offer to produce X amount of energy for Y amount of money. TSOs take these offers and bids from electric producers and consumers, and then they match them together. Once the market has been cleared, when every bid has been fulfilled, the producers that won are dispatched. However, if the orders cannot be fulfilled, such as where there is insufficient transfer capacity between the buyer and seller, it means that there is congestion. Congestion in the grid means that there is insufficient transmission capacity to move the energy from where it is produced to its destination. Under such circumstances, the TSOs must engage in redispatching to alleviate the congestion on the lines. Redispatch refers to when TSO must intervene in the market-based schedules of power plants. The aim of the TSO is to

[3] Feed in management is the regulation of and curtailing of renewable energy since renewables are given priority access they are regulated differently. Feed in management is only used in very rare cases (Hirth et al., 2019). In this paper I will be referring to Feed in management as redispatch also and make no distinction between the two.

shift the feed-in and prevent power overloads in the electricity grid by altering the regional distribution of production (BDEW, 2019). There are two types of redispatch: negative and positive redispatch. Positive redispatch is when producers are called to increase their production in exchange for compensation. The TSO will compensate them for their operation with a predetermined fixed amount of compensation that includes fuel and carbon emission costs, wear and depreciation of the power plant, and opportunity costs of subsequent markets, among other things (Staudt et al., 2018). Negative re-dispatched is when the producer has to stop producing and has to pay the TSOs amount equal to his marginal cost of production since he's no longer producing and can, therefore, save on components. The producer, however, gets to keep the proceeds from the sale of his electricity that he got from the spot market (Staudt et al., 2018). Redispatch can create strategic opportunities for power plant operators to exploit the redispatch mechanism (Hirth et al., 2019). Power plant operators change their behavior based on anticipated redispatch. The idea that redispatch is unforeseeable and, therefore, unpredictable is not entirely accurate as it has been shown before that plant operators can achieve a precision of close to 100% predictive capacity. Producers can thereby factor redispatch into their decision making (Staudt et al., 2018). The ability to predict redispatch allows producers to take them into account when making their bids. They might strategically underbid if they expect to be negatively re-dispatched and the opposite for producers that expect to be positively re-dispatched. The result is a distortion in market prices and rent-seeking behavior, where the incentive is to maximize the redispatch to maximize profits or reduce the costs of not being able to produce. Therefore it can be summarized that redispatch is a necessary correction of generation to make all dispatches feasible in a zonal market; however, there is potential for gaming the system to increase profits.

There are two main ways to organize redispatch, and that is either through a market redispatch system that uses a secondary auction system to correct the market. The other is a cost-based redispatch system wherein participation is mandatory for all electricity producers, and producers are redispatched based on their costs. Germany uses a cost-based redispatch system for its congestion management system[4]. However, it allows generators under 10MW[5] not to participate (Hirth et al., 2019). Cost-based redispatch systems have several problems. The first

[4] A market redispatch mechanism is not necessarily better than a Cost based redispatch mechanism
[5] In the future only plants under 100 kW will be able to shirk the responsibility of having to participate (Hirth et al., 2019)

being that a cost-based redispatch does not provide the market with the proper price signals; instead, it distorts them. Both the short-term and long-term efficiency price signals in the market are questionable. The system does not create a locational steering mechanism to determine where it is optimal to invest in generation and storage (Hirth et al., 2019). Due to the lack of locational steering mechanism, there are power plants in specific locations that are kept operational only as a resource to be redispatched due to their positioning and not due to their economic value or competitiveness in the market (Hirth et al., 2019). In a cost-based redispatch system, the expectation is that every producer is indifferent to being redispatched. In reality, that is not the case; some have incentives to evade the responsibility of participating by reporting unavailability if they assume the compensation will be less than what is needed to cover the actual costs of operation (Hirth et al., 2019). The risk is the majority of producers would try to avoid the responsibility of being redispatched, leaving only producers that have determined that they could gain from being redispatched, This, therefore, creates nonoptimal redispatch as a result of weak incentives for producers to participate. Germany's negative redispatch amounts to around 19.2TWh in energy; meanwhile, its positive redispatch is only 10.5TWh (Staudt et al., 2018).

2.3 Merit order

In the electricity market, energy producers are dispatched according to their position on the merit order. The merit order is the ordering of production types according to their marginal cost. Figure 1 shows where the projected current average demand and supply intersect; at that intersection point is where the last power plant that is dispatched to supply the market and meet demand. In Germany's case, the variable production factor had been natural gas. However, it is now vulnerable to being pushed out of the market because it can no longer compete at the lower prices (*Setting the Power Price*, 2015) as the renewables have pushed the curve farther to the right. The benefits of moving the curve further to the right are that the expensive energy sources like natural gas and oil are no longer being used. Replacing natural gas as the variable factor is coal and lignite, which now together comprise 6.967 GWh or 90% of the negative redispatch (Bundesnetzagentur, 2019). When demand fluctuates throughout the day, it is the coal plants that must either ramp up their production or reduce their production. to keep up with the changes, but demand is no longer the only variable factor that coal plants have to contend with.

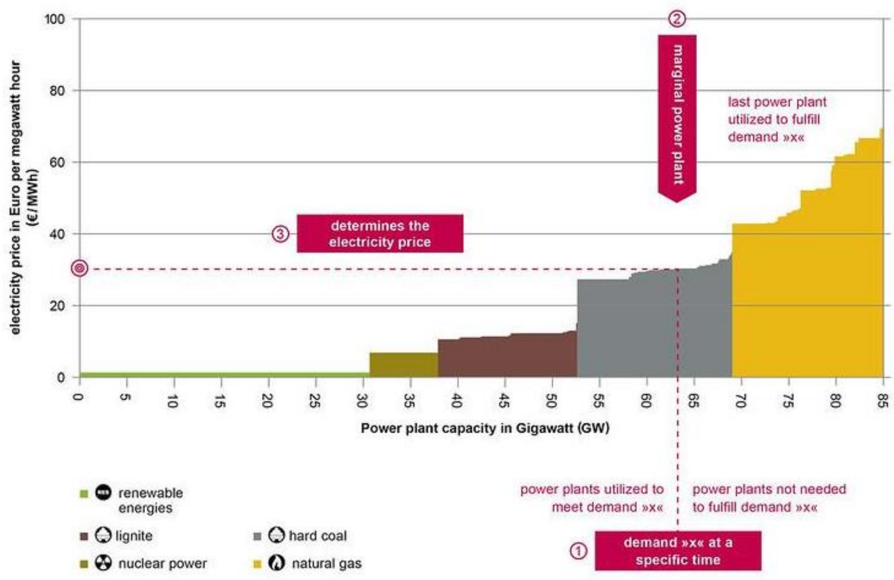

Figure 1: The expected German merit order in 2020 (Source: Oeko-Institut e.V., February 20, 2018)

Historically, demand had always been the most significant variable factor as households were not always consistent in their usage of power throughout the day, which resulted in peaks and troughs in demand. To counteract the variable nature of demand, peaking generators would be available for hours of high demand. At the same time, baseline production would produce all the time in order to meet the consistent demand requirements. The main problem with having a large percentage of renewables in the energy mix is that they only produce when there is either strong wind or clear skies and sunshine (Appunn, 2016). Renewables have taken over as the baseload generation and conventional power now tackles the residual demand that renewables cannot cover (Nicolosi, 2010). If there is a day where there is neither an abundant amount of sunshine nor wind, in this case, the spot price for energy will increase as there would not be enough supply of electricity to meet the demand. Other energy producers would increase the amount of electricity they produce to meet the supply shortage similar to what happens when there is a change in demand. The same applies to a situation where there is an abundant supply of wind and sun. In this case, prices should decrease, and supply should decrease as well, but it is not that simple because there are a multitude of factors at play here. Like was mentioned before, coal has become the factor that is most affected by changes in prices due to its positioning on the merit order curve. Therefore, when there is a lot of wind, the production of coal power plants is reduced to accommodate the extra wind energy on the grid (Oates & Jaramillo, 2013). Having natural gas as the variable production factor is less of a problem as the ramping up and down of natural gas generation is relatively fast and inexpensive (IRENA, 2019). Coal had traditionally only provided baseload energy, which covered the minimum load throughout the day. However, a variable production schedule is problematic for coal energy producers due to the inherent high startup costs for coal power plants. It has been established that coal producers who deal with irregular demand have higher maintenance costs than coal power plants that operate in a baseload regime (Keatley, 2014). Cycling forces coal power plants to factor these costs into their marginal cost calculations. The result is that these extra costs go into the market price and therefore increase the prices (Oates & Jaramillo, 2013). This strategic behavior means that coal producers are not bidding according to their marginal costs of production; instead, they are bidding with the expectation of having to reduce or increase their production based on market conditions.

In 2008 German day-ahead market started to observe negative prices in certain hours during the day (Lewiner, 2010). Negative prices are not innately problematic but are an indicator of a nonoptimal market situation, which could lead to conditions in which the market fails to clear and consequently showcases the drawbacks of the current market design (Nicolosi, 2010). Recurring negative prices can be attributed mostly to the introduction of renewables, which are both intermittent and very price inelastic due to the guaranteed profits from the feed-in tariffs and the close to zero marginal cost of production. Since energy storage is expensive, most of the energy that is produced has to be consumed when it is produced. There is little incentive for renewable producers to stop producing during negative prices; renewable energy producers continue to produce as they can still turn a profit due to the guaranteed prices. Coal and lignite energy producers might also continue to produce as they are willing to accept a negative price due to the fact that the costs from decreasing and increasing production are higher in the long term. Therefore, negative prices offered during off-peak hours are merely the cost of investment intended to be able to increase gains during peak hours (Crampes & Ambec, 2017)

2.4. Capacity constraints

Free trade in electricity requires a reliable electricity grid that allows the distribution from any given generator to any consumer. When Germany was designing its grid, it did so with the knowledge it had at the time, before the 1990's grids were designed to accommodate a more balanced generation and load. Local producers were established to service a specific area such as a town, city, or village. The area would then be hooked up to a grid that would deliver that energy to consumers such as homes and industry. The power production facility would usually service only this small area (Chick, 2004). Now 30% of household customers are serviced by a supplier other than their default regional supplier (Bundesnetzgentaur, 2017). The old system of centralized regional energy production is giving way to a system of multiple decentralized energy producers. The properties of conventional power plants such as nuclear power plants allow them to be placed almost anywhere and still perform like any other nuclear power plant. However, renewables are very dependent upon the geography and weather conditions in the location they are installed; this means that renewables are more efficient and produce more energy in certain areas around the country. This geographical bias can be seen by looking at a map of where wind energy production is located in Germany. The windmills in Germany are generally clustered in the North of Germany due to the favorable wind conditions there (Wehrmann & Amelang, 2020), with a particularly high concentration near Germany's coastlines, as can be seen in figure 2. If we compare the deployment of wind power plants against the location of the German industry and manufacturers, which can be seen in figure 3, it is clear to see that industry tends to be more concentrated in the south. Currently, the industry in Germany comprises the highest share of the demand for energy at around 50%, with commercial enterprises at 20% (Amelang, 2019). Germany's industry is principally located in the south in the federal states of Baden-Wurttemberg, Bavaria, Thuringia, and the Rhineland area. The excess wind energy produced in the north of Germany has to be transmitted to the south to meet the energy demand there. Presently, there is a surplus of energy produced in the northern state of Schleswig-Holstein; meanwhile, the Bavarian state government in the south is estimated to face a 3GW capacity shortfall once all the nuclear power plants have been phased out in 2023 (Appunn, 2018).

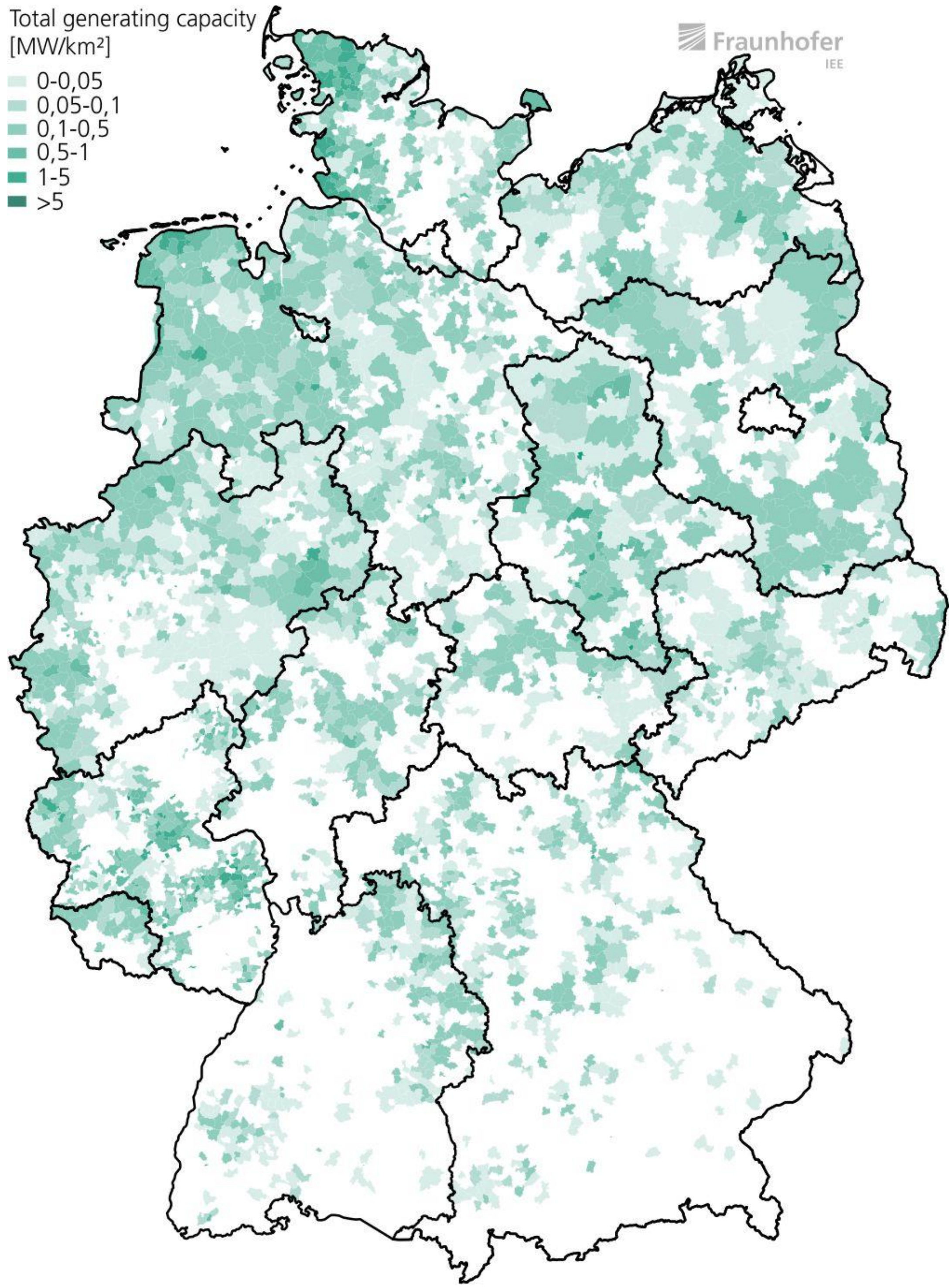

Figure 2: Exact postcode distribution of installed onshore wind capacity in Germany in 2018 (Source: Fraunhofer IWES, 2018)

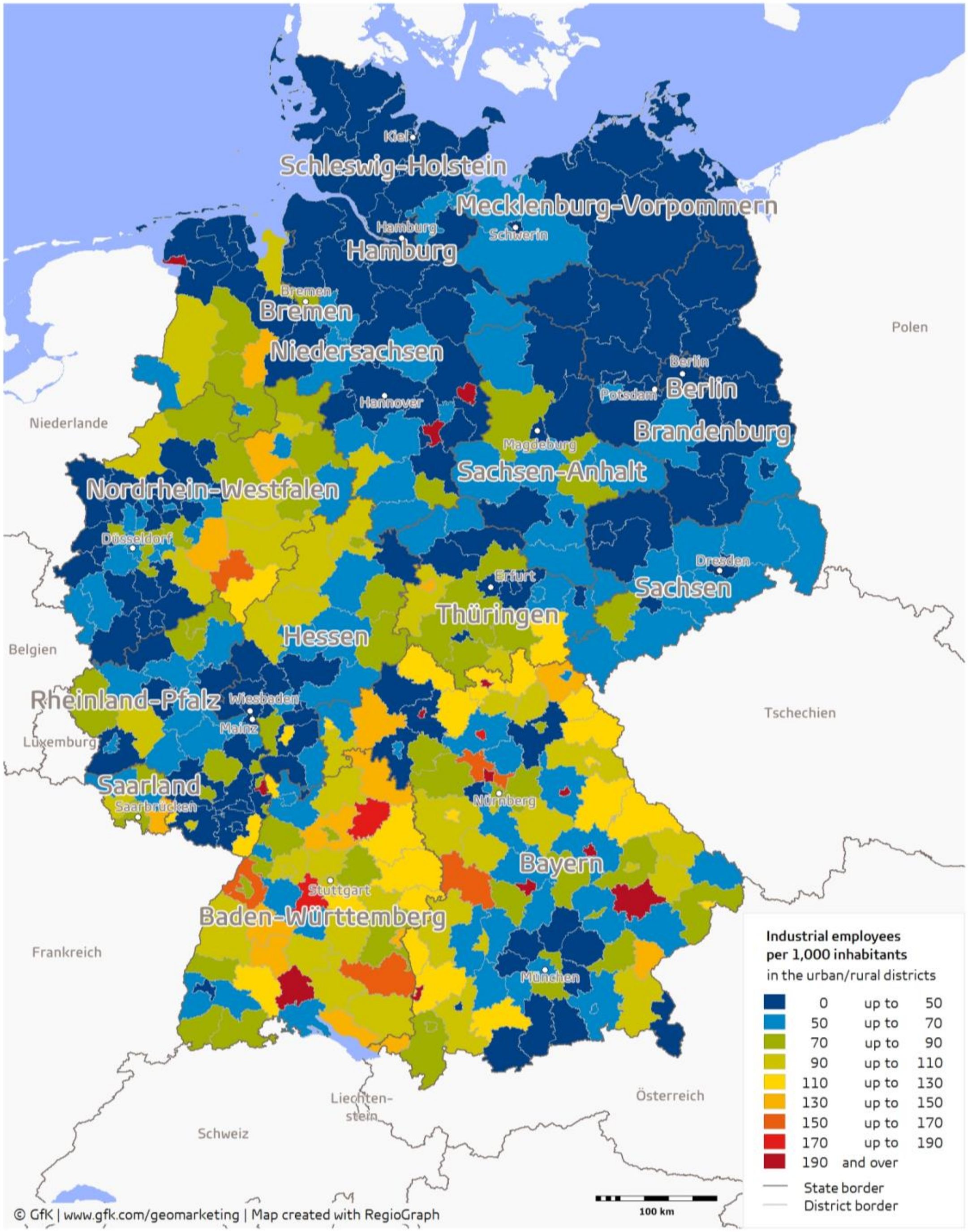

Figure 3: Industrial density Germany 2016 (Source: GFK, January 19, 2016)

The surplus wind production in the North would not be a problem if there were sufficient internal transfer capacity within Germany for energy to be transmitted to where it is needed. However, the crucial improvements to the transmission grid infrastructure are progressing at a much slower pace than the deployment of new renewable energy plants (Singh et al., 2016). Grid expansion investment projects need much more time to be realized at around an average of ten years compared to a power plant investment that can take only five years (Nüßler, 2012). Another reason for disequilibrium is partly due to the fact that cost-based redispatch does not produce accurate locational steering of investments within the zonal market. Consequently, new investments are not directed towards where they are needed; instead, new investments are made completely independently of grid congestion. Because the zonal market prohibits a trade-off between network development and effective steering of investments to locations with sufficient capacity, it necessitates a degree of network expansion greater than the economic optimum (Hirth et al., 2019). The grid, therefore, is having a challenging time accommodating the increase in renewables, and looking at the state of grid expansion, it is likely that this will not be changing any time soon. Since 2009 less than 15% of the planned developments are in operation in Germany, and none of the priority grid development projects have yet to be completed since 2014 (Singh et al., 2016). Projects like the Suedlink, which would connect Schleswig-Holstein and Bavaria areas, would greatly alleviate the congestion between the North and the South are not estimated to be completed until 2025 at the earliest (*New north-south electricity highway takes shape*, 2019). The bottlenecks (Amp2/Amp4 and Te5/TrBW1), as well as already existing ones (Thüringer Waldleitung 50Hz3/Te5), have contributed to a doubling of redispatch in 2015 compared to 2011 (Schmitz et al., 2013). Due to the concentration of windmills in the north, they often put stress on the transmission grid during peak wind production. The TSO’s have to accept any energy produced by these windmills into their grids due to the priority access of windmills in the energy markets (Wehrmann & Amelang, 2020). Germany has taken to curtailing the installation of additional wind power in places that already have congestion, the effect of this that companies installing windmills must show that there is already sufficient transfer capacity. Already around 5% of renewable energy generated is never utilized due to congestion in the grid. (Bundesnetzagentur, 2017)Even though the German grid is highly congested during peak production periods, it is still one of the most reliable energy grids in Europe, with an average yearly interruption in supply per customer being only 12.8 minutes in 2016 (Bundesnetzgentaur, 2017). Compare this to the 53 minutes in Great Britain and Spain's 93 minutes; both countries also invested heavily in renewables (Appunn & Russell, 2015). It is clear to see that Germany has managed to maintain distribution and supply stability even with the increase in renewables.

2.5 Price Regions

Grid-based congestion would not be a market problem if the German electricity market were designed in such a way that it considered these congestion problems, and ideally, the market should function unaffected by possible grid congestion, but that is simply not the case (Hirth et al., 2019). Germany has one uniform bidding zone, which means the price of electricity is the same everywhere in Germany. While an equitable initiative, it brings with itself a couple of problems, one being what happens when there is a surplus of wind generation in the North and strong demand from manufacturers in the South of the country like was showcased before. In this scenario, there is considerable pressure on the transmission lines that connect the North and South. As was outlined before, these lines were not designed to handle high capacity transfers and have not been sufficiently upgraded to handle the increased trading volume between the North and the South. When a line is congested, it has reached its maximum safe operating rate of transfer and, therefore, cannot transfer additional electricity. The result usually means that the four German national TSOs must engage in redispatching and countertrading. Countertrading measures aim to remove network restrictions between two bidding zones. There is no specific intervention in the deployment of power plants. Instead, targeted transactions across bidding zones are used to alleviate the restriction on the interconnection line (Bundesnetzagentur, 2019). In Germany's case, this would mean that 50Hertz, the TSO in the north of Germany, would decrease its energy production, and Tennet, another German TSO in the south, would increase energy generation in his area. There are several problems with this. The first and foremost being that this skews the actual price difference between the two areas. Redispatching and countertrading are antithetical to a market-oriented energy system because they do not provide the markets with the proper price signals. Instead, they only alleviate short-term problems while not improving incentives for investments in the long term. In the south, the price of electricity should be higher than the national price, and the opposite applies to the north where prices are lower than they should be. The reason why this difference should exist is due to the transmission constraints in Germany's grid, which is unable to cope with these massive internal flows. In reality, the north is subsidizing the south by way of having one national price. Estimates indicate that energy prices would increase by 11 euros per megawatt-hour if the north and south of Germany separated into two different price regions (*Interconnectors & blockages* 2018). Daniel J and Anke Weidlich wrote a paper (Veit et al., 2009) on an agent-based analysis of the German electricity, which attempted to simulate the German grid to analyze the effect of congestion, significant wind, and strategic behavior. They started by splitting Germany into six regions and then looking at what happened to the prices if there was high congestion in the grid and what happens when there was no congestion on the grid. It showcased that if there is congestion in the grid, the price in southern Germany was almost twice as high as the price in Northern Germany, and the prices in Northern Germany decreased due to the congestion. They also looked at the impact of high wind generation and low wind generation, and that revealed that high wind penetration, on average, decreases prices. In their results, they showed that high congestion and strategic behavior, both decrease social welfare. However, increased feed-in of wind increases social welfare but is itself so costly that, in the end, it decreases social welfare overall. Another inefficiency has to do with the way countertrading and redispatch work. A relevant example for Germany would be when the north wants to decrease its energy production to deal with the overproduction. It must compensate the energy producer who is forced to curb his production temporarily, meaning the TSOs have to pay producers not to produce in order to balance the market. The same applies to the south, where they must use relatively more expensive energy production, which is usually above the market price in terms of its operating costs. These redispatch costs, in return, get passed on to consumers in the form of higher energy prices as a part of the grid fee households pay via their electricity bills (Appunn, 2016).

3. Cross border flows

Now that the conditions and structure of the German electricity market have been established and outlined. Now I will consider the broader European effects of such a change in policy and explain some of the developments in cross border flow trade in Europe concerning Germany.

3.1 Interconnectors and the German Austrian connection

European markets were in the past organized as national systems with limited interconnections and exchanges between them. However, since the liberalization that began in the 1990s, European electricity markets have been progressively developed and integrated (Singh et al., 2016). Germany is at the heart of Europe; therefore, it is exceptionally well connected with other countries in Europe, and currently, Germany has the most interconnectors in all of Europe (Puka & Szulecki, 2014). Germany has an interconnector with every European country that it borders except Belgium. However, Belgium and Germany are in the process of constructing an interconnector that is expected to be completed in 2020 ("Interconnecting Belgium and Germany," 2016). An interconnector allows countries to trade electricity between each other. Usually, this takes the form of exports from countries with low energy prices to countries with relatively higher energy prices. The cross-border exchange of electricity is expected to increase as the recently adopted European Electricity Market Regulation aims to have at least 70 % of the physical transport capacities of critical grid elements be available for electricity trading (Hirth et al., 2019).

The objective of a deregulated power market is efficiency in the short and long term with efficient utilization of existing resources, as well as an optimal long-term development of the power system (Bjørndal et al., 2013). To achieve market efficiency, it requires that there be locational price models or predefined price regions. The most straightforward price regions are national zonal price regions, where there is just one price for the entire country like France or Spain. In some countries, there can be a number of national price regions, such as in Sweden, which has four or Norway with five (Bjørndal et al., 2013). Germany opted for a single-price region for the entire country, which extended to include Austria and Luxembourg in 2002 (*German-Austrian electricity pricing zone*, 2017). The integration of multiple price regions was all part of a bigger goal of the European Union to create a single price region for the entirety of Europe by slowly integrating different countries and price regions. Realistically achieving this goal requires enough interconnection capacity between countries in the same price region to be able to even out the price differences between all the countries in the union. Germany had not sufficiently invested in the development of its internal grid to sustain this kind of union. Germany was already having trouble with its internal grid delivering energy from the North to the South. With its ever-greater investments into renewables, it placed increased pressure on the already congested grid. The result of the union was that the North-South congestion problem had now become a North-South and Austria congestion problem. With the addition of the increased demand from Austria to purchase comparatively cheaper wind energy from the North that could not possibly be delivered through Germany, other avenues of delivery came to be utilized. The properties of energy are such that it will flow wherever there is the least amount of resistance. Instead of the energy being transported through Germany and from there to Austria, It has circumvented the congestion by going through Poland and then into the Czech Republic and from there into its destination in Austria. In the end, the European Union threatened to partition Germany, which historically has not gone well for Germany (*Appunn, 2018*). The partition would have led to Germany being carved into two price regions, one for the South and one for the North. Seeing that their position had become untenable, Germany opted to terminate the price region union in 2018 between Austria and Germany. However, Luxembourg remained a part of the German price region; it then became the De-Lu price region.

Francois Benhmad and Jacques Percebois wrote a paper in 2016 (Benhmad & Percebois, 2016) on how wind power affected Germany's electricity prices. It showcased how the increase in wind power had reduced the spot prices for energy in Germany while also increasing the volatility of prices. His results reaffirmed the idea that the low marginal costs of wind energy could drive down energy prices. However, it also highlighted the negative factor of the increased volatility of prices that came with the increased feed-in wind power. Benhmad and Percebois argued that the way to counter this was to distribute the volatility with the use of interconnectors between different countries; this would have the opposite effect, limiting the price decrease and while also reducing the volatility. Therefore, the solution to the problem of increased volatility caused by the feed of wind power was for Germany to engage in market coupling and increase its interconnectivity with its neighbors.

3.2 Loop flows and Unscheduled flows

Now that the process of how energy is traded between countries has been outlined. It is essential to go over the flows themselves that go through the interconnectors and the effect of increased interconnection. Two different types of flows: market flows and physical flows, market flows are calculated in advance in the energy markets, and then there are the physical flows on the lines themselves. Usually, there is close to parity between the two, but when there is a large amount of congestion in the grid, they will sometimes diverge. For example, the trade between Poland and

Germany, Poland, in terms of market flows, should be exporting energy to Germany. However, in reality, the physical flows from Germany to Poland are often actually going in the opposite direction in 15–20% of the time, the trade direction was different to the one signaled by the day ahead price difference (50Hertz & PSE, 2014). The physical flows are going in reverse compared to the market flows, and these differences between market flows and physical flows are what are referred to as unscheduled flows. These unscheduled flows can then take the form of either transit flows or loop flows. Transit flows are unscheduled external flows stemming from a scheduled flow between two adjacent control areas or bidding zones. An example of this might be Germany exporting energy to Belgium through France. Loop flows are different in that they are unscheduled flows stemming from scheduled flows within a neighboring bidding zone (Skånlund et al., 2013). An example of a loop flow is Germany moving energy produced in the north of Germany through Poland, and from there into Czechia, then into southern Germany in this example, there is no energy trading happening as the energy is both bought and sold in Germany. The energy merely travels through the two other price regions but does not interact with them. There are currently three-loop flows that afflict Germany, but this thesis is only going to focus on one of them: the eastern loop flow. This loop flow includes Germany, Poland, Czechia, Austria, and sometimes also includes Hungary and other periphery countries, but to simplify, I will not be discussing them in this report. The eastern loop flow is the result of insufficient energy transfer capacity between the north and south of Germany. These unscheduled flows are implicitly prioritized in the current market solution, as the transmission capacities made available to the market are reduced ex-ante to accommodate expected loop and transit flows (Skånlund et al., 2013). Loop flows also cause an increase in the amount of redispatch that is needed and, in certain situations, can double the amount of redispatch that is required (Van den Bergh et al., 2015). A large proportion of interconnection capacity between Germany and Poland is currently being utilized to transfer energy around inside the borders of Germany, not as exports or imports between Germany and Poland. The loop flows, therefore, significantly inhibit trade between the two countries with the available transmission capacity in terms of exports being continuously reduced, and the import capacity has, in recent years, been virtually non-existent in a vain attempt to reduce flows from Germany (Puka & Szulecki, 2014). This practice has recently been regulated, and now countries can no longer cap cross-border trading capacity to accommodate loop flows and internal flows (Hirth et al., 2019). The unscheduled flows from Germany to Poland, and Czechia were also having a real impact on their respective grids. In Poland, there was a 25% higher loading on sections of its transmission grid due to these unplanned flows (Singh et al., 2016). This increase started to create additional congestion on Poland's western grid and put Poland in a difficult position as to how to deal with the problem. The loop flows between Germany and Poland reached critical conditions on the 7th of December 2011 when more than a half of the 5.3 GW scheduled exchange between Germany and Austria went through the Polish grid (Puka & Szulecki, 2014). Ideally, Poland should be indifferent to whether they host the cross-border flows of other countries. It should not matter how the electricity that is produced in Germany gets to its destination. However, this all relies on there being a system that accurately compensates countries for hosting the cross-border flows of other countries. If there were not such a system in place, then the incentives to build additional national grid capacity would be reduced.

3.3 Inter TSO Compensation

When energy is transmitted between countries through the use of an interconnector and travels through a third party, that party is compensated for power losses, and network reinforcements needed to host those cross-border transit flows (Hadush et al., 2015). In the past, this was done by the cross-border access tariffs that countries levied on other countries using their grid to transmit energy. This system of tariffs was replaced by the Inter TSO compensation (ITC) in 2009, which was designed to remove market and regulatory obstacles to trade and simplify compensation between countries. The ITC mechanism works by calculating a fund whose size is determined by the Agency for the Cooperation of Energy Regulators (ACER) according to the long-run average incremental cost (LRAIC) methodology, which takes into account the amount of transit flows between countries (Hadush et al., 2015). This fund is then distributed to compensate countries that host the transit flows of other countries like, for example, Switzerland, which receives a comparatively high share of compensation due to its geographical position in Europe (Acer, 2019). The fund is then distributed to the countries that hosted cross border flows based on the Provisional Method (PM), which is similar to the With and Without Transits (WWT) method (Olmos Camacho & Pérez-Arriaga, 2007). The problem with these methods is that they are limited only to transit flows and specific network costs (Daxhelet & Smeers, 2005). What they do not compensate countries for is hosting loop flows since loop flows are not treated as transit flows; rather, the exports and imports between countries are merely evened out. The mechanism cannot determine who is causing the loop flows and who is hosting the loop flows inside their grids. ITC compensation, therefore, leads to a suboptimal result and a system of unfair compensation and payments in which some countries are not accurately compensated for the loads on their respective grids. It can even be argued, looking at historical data, that there is no connection between actual transits and ITC compensation (Stoilov et al., 2011). The result of this is that countries hosting loop flows have an incentive to limit loop flows or at least not encourage them as they are not compensated for building the capacity within their own grids for hosting these flows. A free-rider problem appears where countries that lack transmission capacity can utilize the transmission grids of the neighboring countries to move energy through their grids and not assume the costs associated with such a measure. The ITC mechanism's current design does not provide the right incentives for countries to invest in strengthening their grids; instead, it favors compensating countries based on their market transactions instead of the actual physical flows.

3.4 German-Polish interconnectors and the PST

Now it is time to go into detail into the interconnector on the border of Poland and Germany. Something was cooking in the emperor's kitchen, which had for millennia served as emperor's breadbasket and now housed one of the nation's most essential interconnectors. At the easternmost tip of the province of Saxony near the city of Görlitz, the Hagenwerder-Mikulova 380kV line was put into operation in 1999; it had the effect of more than doubling the transfer capacity between Germany and Poland. Cross-border flows between Germany and Poland began to reach the secure limit in specific situations in 2007, which was the first red flag (50Hertz & PSE, 2014). Poland had tried to reduce cross border trading capacity by limiting the market transfer capacity on interconnectors with Germany in an attempt to reduce the total cross border flows, but that was never going to be a stable long term solution to the problem. In response, the two countries decided to engage in a bilateral cross border redispatch, for which Germany and Poland would share the costs equally. At this time, it was considered a relatively novel solution as cross border redispatching was uncommon. The European Electricity market regulator had not made it mandatory for TSOs to make their redispatch potential available to other countries (Hirth et al., 2019). Germany and Poland signed the agreement in 2008; the focus was on relieving (N–

1)-security violations on tie lines and any grid elements connected to border substations (50Hertz & PSE, 2014). To achieve this, Germany and Poland took measures to develop a day ahead capacity forecast and Intraday capacity forecast to be able to predict flows to a greater extent than before. The idea was to create a proper calculation for the day ahead market's transfer capacity, allowing them to avoid most of the congestion by limiting the interzonal transaction to only what was possible in the day-ahead market. The polish TSO PSE also started cooperating with the Scandanavian TSOs to use the high voltage direct current (HVDC) connection in the Baltic Sea as an outlay for Germany's energy coming into Poland to reduce the congestion in western Poland. The rescheduling of the direct current Baltic line had virtually no costs associated with it. Still, its availability as a solution for the congestion was, however, limited.

In mid-2012, the Polish TSO PSE entered into talks with the eastern German TSO 50Hertz to find a solution to the unplanned loop flows between Germany and Poland, which had only increased in magnitude (50Hertz & PSE, 2014). 50Hertz and PSE decided on a pilot agreement on virtual phase-shifting transformer or vPST that would allow German and Polish TSOs to coordinate better their redispatching and other corrective measures (50Hertz & PSE, 2014). vPST is simply an agreement between multiple TSOs to coordinate their redispatch and countertrading more efficiently. Pooling their redispatch efforts together offers the option of not just reducing production and demand in one country but mixing increases in supply in one country and demand decreases in another. It has also been noted that foreign grid reserve plants are often more efficient in terms of having a better network-related effect on restrictions than domestic grid reserve plants. The TSOs require less capacity to fire up foreign grid reserve plants than if they use domestic positive redispatch capacity. As a result, smaller volumes are required by the TSOs to ease congestion; this can reduce the risk of error in carrying out redispatching measures, and improve system security (Bundesnetzagentur, 2017). The three main goals of the vPST pilot agreement were to assess the costs, test technical redispatching capabilities of both the German and Polish power systems, and the neighboring countries and see if they could increase the transfer capacity between Poland and Germany. The program started in January and concluded in late April during that time. They managed to keep flows lower than the agreed-upon 1600mw[6] for 77% of the time. However, on the 25th of March, the secure N-1 operation of

[6] This changed to 1,500 MW from 10 April to 30 April.

both the German and Polish grid was violated. None of the predetermined vPST measures were enough to alleviate the problem even with help from neighboring TSOs such as the Austrian TSO APG, who contributed 600 MW towards redispatch and the Czech TSO CEPS who contributed moral support (50Hertz & PSE, 2014). A violation of N-1 means that if a transformer or circuit fails, the network security can no longer be guaranteed, and a forced outage of any transmission element would lead to unacceptable overloading of any other transmission elements. (*N-1 criteria | Grid Development Plan*, n.d.). In the end, 50Hertz and PSE had managed to increase day ahead net import capacities available for trade between Poland and Germany by 50% compared to the same time the year prior. During the 25th of March, 50Hertz used 2620 MW for down-regulation to combat the congestion; however, it had not been sufficient, and it had been unable to increase it any further without causing increased congestion in the internal German grid. It was now evident that the redispatch measures available to the TSOs were not unlimited and could be exhausted (50Hertz & PSE, 2014). After much deliberation, the two TSOs agreed that the situation necessitated a physical phase-shifting transformer on both of the interconnectors between Poland and Germany. Construction began in 2014 on the project, but it was decided that until it was completed, the vPST agreement would remain in effect. During a particularly hot month in 2015, solar production increased significantly, and redispatch measures compared to the previous year in that same month were nine times higher. This event acted as an impetus to move faster to implement the changes. The idea had always been to build PST on both the Hagenwerder-Mikułowa line and the Vierraden-Krajnik line. However, due to a delay in obtaining a building permit on the German side, it was decided that only the Hagenwerder-Mikułowa interconnector would be outfitted with a PST and the Vierraden-Krajnik interconnector would be switched off for upgrades[7]. On June 22nd, 2016, the Hagenwerder-Mikułowa phase-shifting transformer was finally operational. Allocated transmission capacities between Poland and Germany in the latter half of 2016 wound up being significantly higher than in the first half (National Report, 2017). The cross-border flows on the German-Polish border changed drastically, with a decrease of 22% from 2015 to 2016. The reverse occurred between 50Hertz and Czech TSO, where the flows on their border increased by 28% (National Report, 2017). It was expected that the use of the PST would only be necessary for maintaining the safe operation of interconnected electricity systems. However, the experience

[7] The line was upgraded from 220 kV to 400 kV

of the first few months showed that, in practice, it had to be used almost every day (National Report, 2017). The PST also did not solve the problem of unscheduled flows. It did, however, substantially reduce the negative impact of unplanned energy exchanges (Morawiecki, 2017).

3.5 German redispatch from 2013 to 2019

In this thesis, I want to focus on establishing the impact of installing PST on an interconnector between Germany and Poland on the redispatch in Germany. My hypothesis is that the total redispatch, which includes both negative and positive redispatch, should increase in Germany due to reduced cross border flows between Poland and Germany. Since there are both static and dynamic costs associated with redispatch, an increase in redispatch is an increase in costs for the national TSOs. As was stated prior, the amount of negative redispatch and positive redispatch is not a 1:1 relationship. Germany currently does more negative redispatching then positive redispatch, meaning Germany curtails more production then it increases its production. Therefore, as cross border flows decrease because of the PST, it is expected that the difference between positive and negative redispatch should narrow as a result and that German TSOs will have to tackle the increased redispatch. Looking at how cross border redispatch between Germany and her neighbours has evolved in the last few years. The blue line in figure 4 below shows the total amount of redispatch requested by the Polish TSO PSE from 2013 to 2019. A reduction in annual total redispatch requests from PSE going from a high of 2146.9GWh in 2015 to 34.2GWh in 2019. The significant increase of redispatch in 2015 can be explained by the vPST agreement between Germany and Poland. The substantial reductions in requested redispatch from 2016 to 2017 can be attributed to the installation of PST on the Polish-German border, which made cross redispatch less necessary. Looking at the red line in figure 4, there is a considerable reduction in redispatch for the Czech TSO CEPS in 2017; this is a similar case to Poland, where they also installed a PST on their border with Germany. However, it was commissioned six months later than Poland, which is why the reduction in redispatch appeared later. The purple line in figure 4 shows the development of the Austrian TSO APG’s redispatch requests to Germany. APG has a significant increase in redispatch requests to Germany in 2017, most likely caused by the installation of PSTs in Poland and Czechia. The redispatch requests decreased the year after this could be attributed to the fact that Austria left the German-Austrian price region union. Lastly, looking at the green line in figure 5, which shows the total redispatch in Germany on the graph, there is a point where redispatch tripled from 2014 to 2015. The increase was due in part to the increased wind generation in that year (Wohland et al., 2018) and the shutdown of the Grafenrheinfeld nuclear power station ahead of schedule (Homann & Mundt, 2016). Redispatch decreases in 2016 can mostly be attributed to the 25% fewer peaks in feed-in from wind farms compared to the previous year (Bundesnetzagentur, 2017). Starting in December 2016 and going into January 2017, there was a shortage of coal in southern Germany, causing the coal power plants to be unavailable for production. The plants could not be resupplied during this time due to lower water levels caused by lousy weather and compounding; this was the non-availability of power plants in southern Germany (Bundesnetzagentur, 2019). The result was a drastic increase in redispatch during these months due to reduced production availability in the energy-starved south. The situation was rectified in February of 2017 when the warmer weather allowed shipments to resupply the coal power plants to come in (Bundesnetzagentur, 2019). This situation helps to explain the considerable spikes in redispatch during that period, which were twice as high as the peaks in 2015. In 2017 the four TSOs started using model calculations to carry out joint planning of redispatching. The goal was to optimize the deployment of redispatching power plants at an early stage so that power plants that take longer to start up can be requested in a reasonable time. The idea was to improve the efficiency of the redispatch mechanism. The four TSOs' joint redispatch made up 29% of the total redispatch and grid reserve volume for 2017 (Bundesnetzagentur, 2019). It is this period from 2015 to 2017 that I will be examining whether the installation of PST on the Polish-German border had any effect on the total redispatch in German. The research question for this thesis will be

- *What were the effects of the phase-shifting transformer installed on the Polish-German border on redispatch in Germany?*

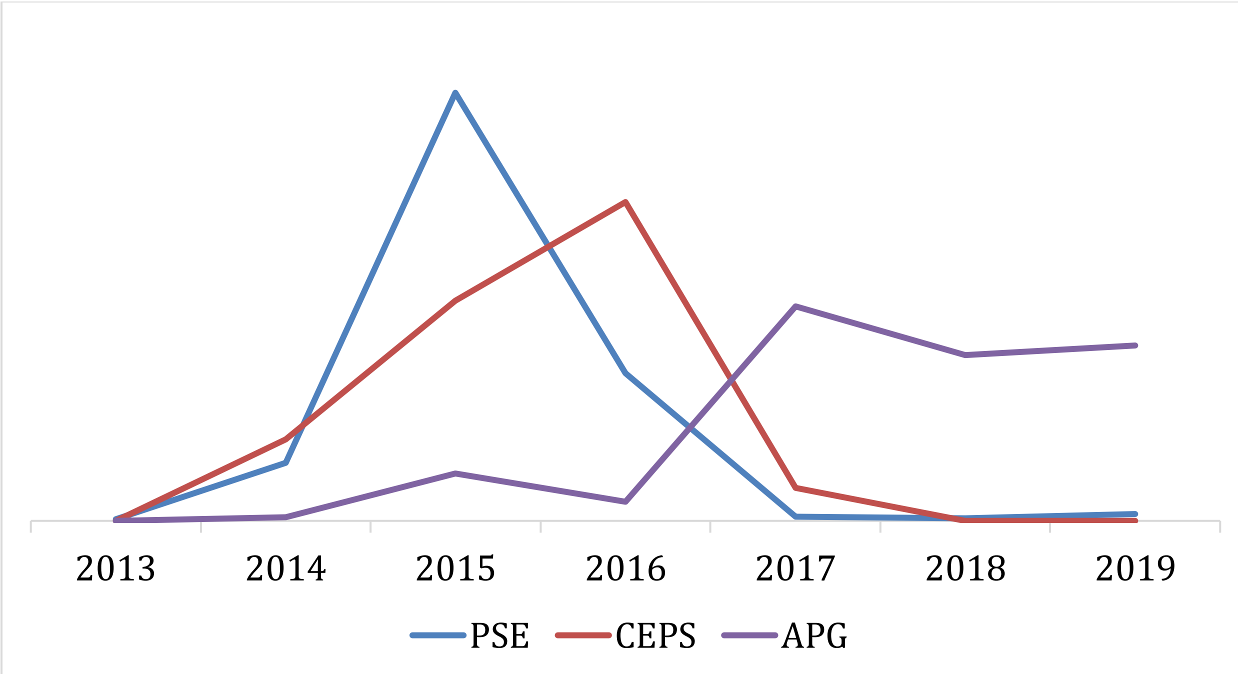

Figure 4: German redispatch requested by PSE, CEPS, and APG from 2013-2019 (Source: Author, data provided by Netztransparenz)

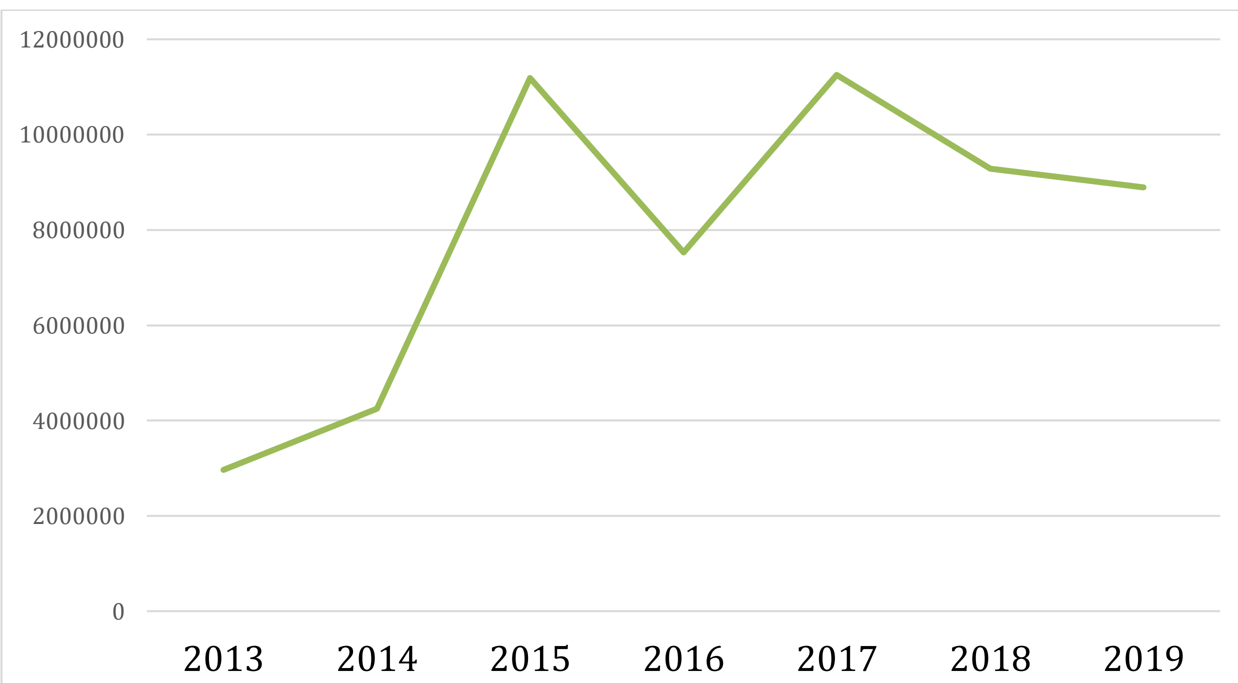

Figure 5: Total German redispatch from 2013-2019 (Source: Author, data provided by Netztransparenz)

4. Methodology and Data

4.1 Methodology

There have been papers looking at the impact of phase-shifting transformers on cross border flows between Poland and Germany, such as (Korab & Owczarek, 2016). There have also been many papers on unscheduled flows in eastern Europe and their effects such as Puka and Sczulecki's Beyond the "Grid-Lock" in Electricity Interconnectors: The Case of Germany and Poland (Puka & Szulecki, 2014). The market effects of such measures have not been adequately looked at, such as redispatched costs and price dynamics. The focus of this analysis is to look at what were the effects of the interconnector on the internal redispatch within Germany and the wider impacts on its market structure. I will be using the program SPSS to run the majority of my analysis and using the method of Least-Square Multiple Regression. Total German redispatch will be the dependent variable and the Polish-German PST as a dummy independent variable to ascertain the impact of the PST on redispatch in Germany.

4.2 Model

To analyze the German redispatch, I have constructed a model that tries to control for all the factors that impact redispatch in Germany based on prior models such as in (Staudt et al., 2018) and also (Duso et al., 2017). The most crucial variable is the renewable generation, especially wind generation, both onshore and offshore, which has been shown to be highly correlated to the amount of redispatch in the German grid (Benhmad, 2016). I also used data on solar generation for the same reasons as outlined above. Solar generation is highly likely to be correlated with redispatch because of its intermittent production periods similar to wind power. I also factor in net cross border flows between Germany and the neighboring countries which have an interconnector with Germany. The capacity to forecast renewable generation should reduce the need for redispatch as that means market participants have more knowledge over how much renewable energy will be produced. Therefore, they can better predict how much non-renewable energy is needed. I consider both the forecasted day ahead of solar and onshore wind energy. The forecasted error variable is constructed by taking the day ahead forecasts and actual generation and getting the difference; this reduces the multicollinearity of having both forecasted and actual generation in the model. I use in my model the non-renewable energy generation to control for the general increase in energy. I also calculate the average day ahead prices for each day in the German price region, which ideally should be correlated with the redispatch. This is because a lower price means more electricity is generated, and the likelihood of congestion increases. The monthly seasonality variable was added to control for expected differences in redispatch between the months in December and January, where the redispatch is generally higher than in May and August. An overview of this can be seen in figure 6 below, which shows redispatch in Germany from 2015 to 2017. There are 11 monthly dummies Jan-Nov with December being omitted as the model only needs k-1 variables to control for the monthly seasonality. Lastly, the primary dummy variable which is equal to one after the implementation of PST and zero before the implementation of the PST. The dependent variable of German redispatch is the total redispatch amount both negative and positive redispatch in MWh. In addition to the primary model, I have constructed a secondary model that has all the same variables as the primary model but with the addition of Peak day ahead energy prices. The reason for the additional model was to see if the result were to change with the addition of another variable.

$$\begin{aligned} Redispatch = \alpha + \beta Solar_t + \beta OffWind_t + \beta OnWind_t + \beta ImportExport_t + \beta ForeWind_t \\ + \beta ForeSolar_t + \beta Generation_t + \beta Price_t + \beta Month_t + \beta Weekend_t \\ + \beta PolishPST_t + (\beta PeakPrice_t) + \varepsilon_t \end{aligned}$$

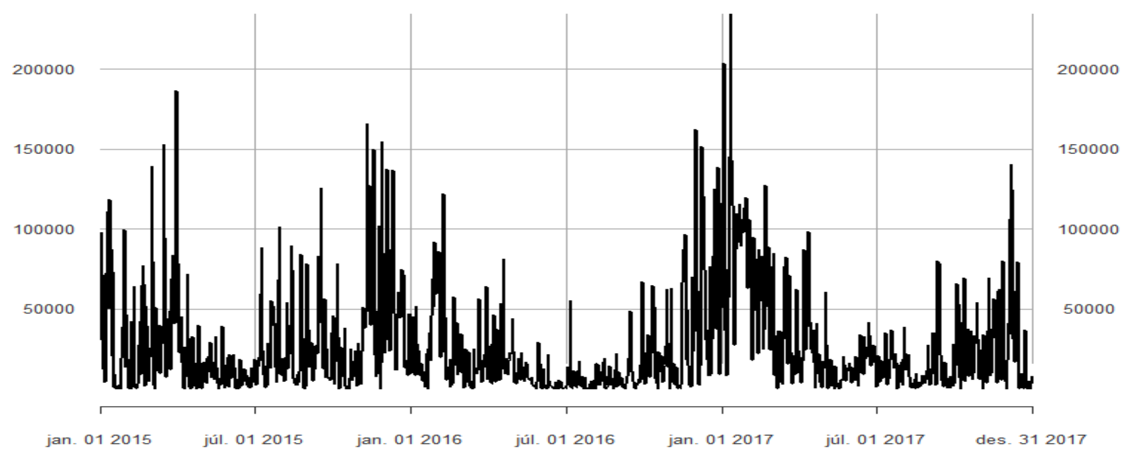

Figure 6: Total redispatch in Germany from 2015 to 2017 (Source: Author, data provided by Netztransparenz)

4.3 Data

The data I used for this analysis was gathered from three sources. Firstly, the German redispatch data was retrieved from an information platform of the German transmission system operators[8]. Netztransparenz provides public data on the activities of the four German transmission operators 50Hertz, Amperion, Tennet, and Transnet BW. The majority of the data was gathered from the website of the European Network of Transmission System Operators for Electricity (ENTSO-E) on their transparency platform. They have information on the activities of every TSO in Europe.[9] Here I was able to collect information on German wind and solar generation as well as overall generation excluding wind and solar. Data from December the 9th on generation per type was missing. Therefore, it had to be substituted with data from the combined German-Luxembourg-Austrian price region (Lu-DE-AU) data from Austria and Luxembourg, which then had to be subtracted to get the generation numbers for Germany that day. The data for the net export-import of cross border flows between Germany is from SMARD, which is a German electricity market information platform[10]. SMARD is a part of the German Federal Network Agency, which is the regulatory office for electricity, gas, telecommunications, post, and railway markets in Germany. The data spans roughly one-and-a-half years before and after the implementation of PST, which means the data is from January 6th, 2015 to December the 31st 2017. The reason for not starting on January 1st is because the data from the day ahead prices in Germany for the first five days of the year is missing. The omission of these five days should not affect the results significantly since the data set is already large enough. Most of the data were converted from hourly data to a daily format to analyze the data better and interpret it. There are 1091[11] total observations for each variable. A summary of the fundamental variables and their descriptive statistics can be found in Table 1 below. All the variables are denominated in MWh.

[8] https://www.netztransparenz.de/EnWG/Redispatch
[9] https://transparency.entsoe.eu/dashboard/show
[10] https://www.smard.de/en
[11] That is 3 years times 365 days - 5 days off for starting and on December 6 and plus one for the leap year in 2016.

Table 1: Summary statistics of the dataset

	Obs	Minimum	Maximum	Mean	Std. Deviation
Generation (MWh)	1091	208683	6658515	4594981	840598
Solar (MWh)	1091	0,00	966329	381842	247335
WindOffshore (MWh)	1091	685	422808	136383	100108
WindOnshore (MWh)	1091	22559	2938371	798009	622391
ExportImport (MWh)	1091	-47868	62319	4298	18149
Redispatch (MWh)	1091	0,00	234478	27344	32891
ForeSolar (MWh)	1091	-396784	173112	-7082	42962
ForeOnshore (MWh)	1091	-529422	401730	3779	93950
Price (EUR / MWh)	1091	-52,00	102,00	31,65	11,25
Peak_Price (EUR / MWh)	1091	9.96	163.52	46.29	15.31

5. Results and robustness checks

5.1 Results

The results from the regression showed that most of the variables are indeed significant determinants in the amount of redispatch in Germany; this can be seen in Table 2. In this report, any variable with a p-value lower than 5% is considered significant to reject the null hypothesis of no correlation. Starting with Wind onshore, which is positively correlated with redispatch, meaning an increase in wind power generated by onshore windmills increases the redispatch. The result is in line with other studies such as (Wohland et al., 2018). Both offshore wind and generation are both not significant in the results. Solar was positively correlated with redispatch but had less of an effect on redispatch then wind onshore. The difference can be seen by comparing the beta value of the onshore, which is 0.043 compared to Solar's 0.028. This means that every single MWh of onshore Wind-generated has nearly twice as high an effect on redispatch in Germany. The Import Export variable was significant and showed that when Germany was a net exporter, it reduced the total redispatch in Germany. This means for every net export of 1MWh, the total redispatch in MWh was reduced by 0.261. Only the forecasted variable for onshore Wind was significant; it showed that if the day ahead forecasted wind production was higher than the wind-generated that day, it led to a reduction in redispatch. The day ahead prices were significant and positively correlated with redispatch. For every single euro increase in the day ahead prices, the total redispatch in Germany increased by 1480 MWh. The dummy variable for the weekend was significant and showed that, on average, redispatch was 48MWh greater during the weekends than during the weekdays. The month dummy variables showed that redispatch from May to July was statistically different from the average redispatch in December. Therefore, redispatch in the summer[12] is, on average, around 15000MWh less compared to December. The Polish PST dummy variable was significant in the results and negatively correlated with redispatch with redispatch decreasing by 4612MWh per day on average. Then, it is possible to conclude that the redispatch decreased after the implementation of the PST.

[12] Summer in Germany is from June through to August.

However, if we look at the results from the second model, we can see that most of the variables in the other model are still significant, and their effect on redispatch is the same as in the main model. The Polish PST variable, which retains its negative sign and remains significant at the 5% level. The added variable of Peak price is not significant therefore it´s impossible to determine its effect on redispatch but the normal price variable increased its beta value from 1480 to 1676 which is a 13% increase.

Table 2: Results from the analysis[13]

	Main model		Secondary Model	
Peak Price			-160,4	(103,15)
Generation	-0,002	(0,002)	-0,002	(0,002)
Solar	0,028***	(0,006)	0,030***	(0,006)
Wind_Offshore	0,015	(0,010)	0,014	(0,010)
Wind_Onshore	0,043***	(0,002)	0,043***	(0,002)
ExportImport	-0,261***	(0,047)	-0,217***	(0,047)
ForeSolar	0,001	(0,017)	0,001	(0,017)
For_Onshore	-0,061***	(0,007)	-0,062***	(0,008)
Price	1480,814***	(112,453)	1676.52***	(168,619)
Polish_PST	-4612,956**	(1886,390)	-4680.7**	(1885,645)
Weekend	48,867**	(21,570)	49.01**	(21,313)
January	11782,899***	(3446,221)	12321***	(3568,136)
February	-1654,210	(3473,898)	-1632.05	(3574,696)
March	2656,121	(3698,588)	2352.8	(3812,640)
April	-3306,349	(4305,068)	43199	(4361,628)
May	-15886,294***	(4689,862)	-17145***	(4740,237)
June	-15824,165***	(4792,896)	-17303.693***	(4793,775)
July	-13898,056***	(4645,598)	-15481***	(4595,489)
August	-6637,071	(4579,631)	-8851*	(4527,497)
September	-1550,686	(3985,418)	-2455	(3943,495)
Oktober	-8613,987**	(3480,910)	-8405**	(3439,418)
November	-3352,469	(3380,154)	-2981	(3339,958)
R-Squared	55%		55%	

[13] Data is presented as Standard errors in parentheses, * $p<0.1$, ** $p<0.05$, * $p<0.01$.

5.2 Robustness of results

To evaluate the robustness of the results and therefore test the strength of the model, the regression model was tested for the presence of multicollinearity and stationarity. The results from the tests can be viewed in the appendix below.

ADF Stationarity test

To ensure that the equation that was estimated is not spurious, it is essential to test for nonstationarity. If you can show that the variables are stationary, then it is unlikely that there is a spurious regression (Studenmund, 2014). If the p-value from the results is greater than 5%, then you cannot reject the null hypothesis of nonstationarity. To determine whether the redispatch data was stationary or not an Augmented Dickey-Fuller (ADF) test was run with four lags to determine the result[14]. The null hypothesis was that there was a unit root, while the alternative was that the data was stationary. The results showed a test statistic of -8.68 and a p-value of >0.00, which means that it is highly likely that the data is stationary and that it does not have a unit root.

Variance inflation factors (VIF) Multicollinearity test

Variance inflation factors (VIF), testing for the presence of multicollinearity: Each explanatory variable k is individually regressed on the remaining explanatory variables. A VIF exceeding ten can indicate high collinearity between explanatory variables (Kennedy, 2008). Checking for collinearity in the variables, In the results, there are no variables that have a VIF that is greater than 10 with the largest VIF being a 5. The variables that have the highest VIF are Solar, onshore wind, and generation, which are variables that measure electricity production and most increase at the same time during peak demand periods. Due to the relatively low VIF scores, it is unlikely that the main model has severe collinearity between independent variables.

[14] R was used for the Augmented dickey fuller test instead of SPSS.

6. Discussion

In this paper, an analysis was done to determine the effect of the Polish-German phase-shifting transformer on domestic redispatch in Germany. The analysis used an OLS regression with redispatch as the dependent variable and its determinants as the independent variables. The analysis did not show support for the idea that redispatch had increased in Germany as a result of the PST and the reduction in unscheduled flows between Germany and Poland. Instead, redispatch decreased after the implementation of PST in June.

6.1 Determining the results

It was expected that redispatch would increase as the reduction in cross border flows has shown to increase the need for redispatch. It was also expected that redispatch would increase as more redispatch would be necessary to balance production and demand between the north and south in Germany. There could be many reasons for the PST reducing redispatch rather than increasing it. One being that the reduction in loop flows between Germany and Poland reduced the amount of redispatch that was necessary to maintain system stability. Another reason could be that cooperation between the four German TSOs in terms of redispatching improved over time and therefore reduced some of the need for additional redispatch which was not factored in the model. It could also be that the construction of both models has several issues, such as the choice of variables and the fit of the model. The fit of the model was weak as the models only manage to capture 55% of the variation in the redispatch. Another problem is the dummy variable that was used. When reading the results from the dummy variable, keep in mind that the variable measured both the installation of the PST and the closing of the Vierraden-Krajnik interconnector in northern Germany. Therefore the dummy variable cannot determine what percentage of increase in redispatch is due to the installation of a PST on the southern Polish-German interconnector and what percentage of the decrease is due to the closure of the north Polish-German interconnector. It is difficult to conclude that the PST was the only thing affecting the redispatch in Germany as there were many factors that could not be controlled for that were taking place at the same time, such as the coal shortage in southern Germany, which drastically increased the redispatch in 2017 in the months of December and January. It is impossible to easily determine how much of an effect the shortage had on redispatch. In reality, no figures are available to the author's knowledge that have estimated the effect therefore it was impossible to factor in its effect. In conclusion, it can be said that after June 22, 2016, the total redispatch in Germany decreased, and it cannot be entirely explained by the increase in solar and wind production or other traditional factors. It can be argued to some extent that reduction in transfer capacity and the change in cross border flows caused German domestic redispatch to decrease in the following months.

6.2 Future studies

The results from the analysis of this paper barely manage to scratch the surface of the topic and are not intended as the final authority on the subject. Firstly the research only focuses on the total redispatch and does not distinguish between negative and positive redispatch, which might be impacted differently by the installation of PST. The timeframe of the analysis is also brief, being only three years, and the analysis covering only a single country, Germany. An analysis of the French, Spanish, or other European countries might be in order to give a more definite answer to the question of the exact effects of PST on redispatch. As Europe moves closer to increased energy integration, the question of where phase shift transformers should optimally be located will become more critical. In this paper, only PSTs between two national price regions were considered and not any PSTs located inside national borders. An analysis of the optimal placement of PSTs when it comes to maximizing the gains for every country in Europe is needed to understand what the next steps are in integrating the varied electric European markets. A proper simulation analysis with methods such as power transfer distribution factor (PTDF) or alternating-current load flow (ACLM) would probably be required to do an in-depth analysis of the subject. Using a simulated approach would allow for more control over every individual variable and the ability to see how they affect each other.

6.3 Final words

The research for this paper was driven mainly by an interest in better understanding the changes that are happening in the European electricity market. With the increase in costly measures such as redispatch increasing in countries like Germany and with the push towards greater interconnection between European states, it is more important than ever to understand the impact of PSTs on the structure of both markets and electric transmission and distribution systems.

Identifying the winners and losers from such an initiative will be necessary as well as finding a way to create a system where the winners compensate the losers will be imperative. Otherwise, national interests will likely trump the broader European interests. The PST on the Polish-German border is a bilateral solution to the problem of insufficient transfer capacity in Germany and elsewhere in Europe. It is not evident that such a measure is in the interests of every European country or the most cost-effective solution to the problem of insufficient transfer capacity and outdated transmission grids. The question of how European energy markets will develop in the future is an uncertain one. The collaboration between countries is increasing, as demonstrated by the cooperation between Poland and Germany. Perhaps this trend will continue in the future, and there might be a shift from price regions being determined by political boundaries to a system of price regions that are determined by more objective criteria such as transfer capacity within the areas themselves. Perhaps there may even be two or more German price regions in the future. Speaking from a personal perspective, I love German regions so much; I wish there were two of them.

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Appendix

Results from the augmented dickey fuller test.

```
        Augmented Dickey-Fuller Test

data:  RedispatchData
Dickey-Fuller = -8.6851, Lag order = 4, p-value = 0.01
alternative hypothesis: stationary
```

Results from the Variance Inflation Factor test for the Main Model:

Variable																				
Solar	4,5		4,5	4,3	4,5	4,3	4,5	4,5	4,5	4,4	4,5	4,4	4,0	3,4	3,2	3,1	3,0	3,3	3,7	4,4
Wind_Offshore	2,4	2,4		2,0	2,4	2,4	2,4	2,4	2,1	2,4	2,4	2,4	2,4	2,4	2,4	2,4	2,4	2,4	2,4	2,4
Wind_Onshore	3,5	4,0	3,6		4,3	4,1	4,2	3,7	4,3	3,3	4,2	4,3	4,2	4,1	4,0	4,1	4,2	4,1	4,2	4,1
ExportImport	1,6	1,6	1,6	1,1		1,6	1,6	1,6	1,3	1,6	1,6	1,6	1,6	1,6	1,6	1,6	1,6	1,6	1,6	1,6
ForeSolar	1,1	1,1	1,1	1,6	1,1		1,1	1,1	1,1	1,1	1,1	1,1	1,1	1,1	1,1	1,1	1,1	1,1	1,1	1,1
For_Onshore	1,1	1,1	1,1	1,1	3,4	1,1		1,1	1,1	1,1	1,1	1,1	1,1	1,1	1,1	1,1	1,1	1,1	1,1	1,1
Price	3,0	3,4	3,5	3,1	5,0	3,5	3,5		3,0	3,3	3,5	3,5	3,4	3,5	3,5	3,5	3,5	3,5	3,5	3,5
Polish_PST	1,9	1,9	1,7	1,9	1,1	1,9	1,9	1,7		1,9	1,9	1,9	1,9	1,9	1,9	1,9	1,9	1,9	1,9	1,9
Weekend	1,5	2,0	2,1	1,6	1,5	2,1	2,1	1,9	2,1		2,0	2,1	2,1	2,0	2,0	2,0	2,0	2,0	2,1	2,1
January	1,9	1,9	1,9	1,9	2,1	1,9	1,9	1,9	1,9	1,9		1,5	1,6	1,7	1,7	1,8	1,7	1,7	1,6	1,5
Fen	1,9	1,9	1,9	1,9	1,9	1,9	1,9	1,9	1,9	1,9	1,4		1,4	1,5	1,6	1,6	1,6	1,6	1,5	1,4
March	2,3	2,0	2,3	2,3	1,9	2,3	2,3	2,3	2,3	2,3	1,9	1,7		1,5	1,5	1,5	1,5	1,5	1,5	1,7
April	3,0	2,3	3,1	3,0	2,3	3,1	3,1	3,1	3,0	3,0	2,7	2,4	1,9		1,5	1,5	1,5	1,5	1,8	2,2
May	3,5	2,7	3,8	3,6	3,0	3,7	3,7	3,7	3,7	3,6	3,4	3,1	2,4	1,8		1,6	1,7	1,7	2,1	2,8
June	3,6	2,6	3,8	3,7	3,8	3,8	3,8	3,8	3,8	3,7	3,5	3,1	2,4	1,8	1,7		1,7	1,7	2,1	2,8
July	3,5	2,5	3,7	3,6	3,8	3,6	3,7	3,7	3,7	3,6	3,3	3,0	2,4	1,8	1,7	1,6		1,7	2,0	2,7
August	3,4	2,6	3,6	3,4	3,7	3,5	3,6	3,6	3,6	3,5	3,2	3,0	2,3	1,8	1,7	1,6	1,6		1,9	2,6
september	2,6	2,1	2,6	2,6	3,5	2,6	2,6	2,6	2,6	2,6	2,2	2,1	1,7	1,5	1,5	1,5	1,5	1,4		1,8
Oktober	2,1	2,0	2,0	2,0	2,6	2,1	2,1	2,1	2,1	2,1	1,7	1,6	1,5	1,5	1,5	1,5	1,5	1,5	1,4	
November	1,9	1,9	1,9	1,9	2,0	1,9	1,9	1,9	1,9	1,9	1,4	1,5	1,5	1,6	1,7	1,6	1,6	1,6	1,5	1,4
Generation		4,9	5,0	4,1	1,9	4,9	5,0	4,3	5,0	3,6	4,9	4,9	5,0	4,9	4,7	4,7	4,7	4,8	5,0	5,0