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MASTER THESIS
MSc Economics and Business
Specialization: Financial Economics

DOES THE INCREASING SHARE OF RENEWABLE ENERGY LEAD TO MORE "EXTREME" ELECTRICITY PRICES IN THE DUTCH IMBALANCE MARKET? A QUANTILE REGRESSION ANALYSIS APPROACH.

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Abstract:

In response to the increasing focus on sustainable forms of electricity generation, this research investigates the effect renewable energy has on the peak electricity prices in the Dutch imbalance market. With solar and wind energy being the two primal renewable energy sources present in the Dutch energy mix, this research is limited by these two aforementioned energy sources.

The period analyzed stretches between 01-01-2015 to 20-09-2019 and contains a total of 16383 observations. By performing a quantile regression analysis, this research has aimed to quantify its results into three different models. Supported by existing literature, evidence is found that the increasing share of renewable energy indeed has an amplifying effect on the electricity price peaks. Hereby, this thesis contributes to policy makers, investors and entrepreneurs who are affected by, or see opportunity in, extreme energy prices.

1. Introduction

Ever since the 18th century, the worldwide demand for electricity has grown considerably (Nejat et al., 2015). Rapid urbanization and industrialization have sparked the growth of the global economy at the expense of the environment. With most electricity produced from fossil-fuel fired power plants, governments, individuals and companies, are taking their stance to alter this unsustainable growth. With countries such as Germany and Sweden pioneering in sustainable innovation, wind and solar farms have become part of the modern-day scenery (Jacobsson and Bergek, 2004). Grants and subsidies have achieved that Germany has been able to run for 100% on renewable energy in the summer of 2018 (Amelang, 2019). The Netherlands, however, is lagging on sustainable development (Radar, 2019). To achieve the required 14% sustainable energy production ratio proposed by the EU, the Netherlands has granted subsidies for solar farms, resulting in new business opportunities. Farmland is being transformed into solar farms, roofs are being leased out to utility companies and in order to lower the Dutch gas consumption, heat pumps are being installed at large scale (Vakblad-warmtepompen, 2018). How perfect this sustainable energy revolution may sound, thanks to the limited storability of electricity, this green dream proposes challenges that have to be well taken into consideration.

The first challenge is the overpowering of the electricity grid. Renewable energy sources such as Solar PV panels or wind farms rely on one very volatile ingredient: mother nature. Since the Dutch society currently does not function for a 100% on renewable energy sources, the Dutch energy mix consists of a hybrid between fossil fuels based plants, such as coal and gas, and an increasing share of renewables (Van der Heijden, 2019). The combination of a highly volatile energy generation source with an inflexible baseload, increases the probability overpowering the electricity grid (Jacobson et al., 2015). With limited energy storage options available, these power abundances will result in negative prices.

The second problem comes from the highly polluting nature of a hybrid energy mix (Proops et al., 1996). Electricity production peaks could cause moments of grid overpowering, strongly decreasing electricity prices. As prices drop below the variable cost of the energy producers, these companies have to stop their production until prices are break-even again (Zoppoli et al., 2015). The companies with the highest marginal cost are first in line, however, these production facilities are often highly inflexible by nature. While wind and solar farms could adjust their supply immediately, re-powering a large coal power plant could take up four to eight hours

(Reinders et al. 2018). A process during which the power plant is most polluting. The phenomenon can be illustrated by using a diesel car as an example.

When a diesel car drives at a steady pace, the diesel car emits gasses at a steady rate. It's when the car goes from 0 k/h to 100 k/h when it's most polluting. From an environmental view, it would be best it if the car could drive at an even pace, however, when there is too much traffic, the car needs to adjust its steady driving pace. The same happens when the fossil fuel power plant is forced to stop, resulting in higher emission levels (Harun et al., 2011).

From an economic perspective, the inefficient combination of a flexible and inflexible power source provides a third challenge: price. Electricity prices rely on a vast amount of factors, but all essentially comes down to the tradeoff between supply and demand. With an increasing demand on the one side and an increasingly volatile supply mix on the other, economists propose that a rapid introduction of large scale flexible energy production sites could cause prices to diverge (Woo et al., 2016). There has, however, not yet been done profound research about the challenges for the Dutch energy market. By performing a quantile regressions analysis on the Dutch electricity prices, this research contributes to existing literature by answering the following research question:

Does the increasing share of renewable energy lead to more "extreme" electricity prices in the Dutch imbalance market? A quantile regression analysis approach.

2. Theoretical background and literature review

To understand the imbalance market, this section will provide a theoretical background to the volatility in electricity prices, the management of the Dutch imbalance market and the characteristics of the Dutch energy mix.

2.1. Volatility in electricity prices

The price of electricity is extremely volatile. Whereas the price of electricity determined in the day ahead market remains relatively stable, the imbalance prices can change radically every 15-

minute interval. By looking at some direct and indirect price determinants, such as the Merit Order curve, renewable energy generation, the non-storability character of electricity and the occurrence of negative pricing, this section provides a theoretical explanation on why electricity prices can be volatile.

2.1.1. Demand and Supply

To create a stable power system, the supply of electricity delivered to the grid should constantly match the demand for electricity (Kanno, 2014). The demand for electricity is characterized by very low price-elasticity since electricity users mostly consume electricity out of necessity rather than price sensitivity (Bye and Hansen, 2008). Additionally, this effect further enhanced by the limited storability options available. With the supply side being the primary driver for the spot price, the expected spot price is dependent on the expected future marginal costs of the electricity supply (Geman and Roncoroni, 2006).

Both the supply and demand side submit bids for the price of electricity, thereby forming the basis of the merit order curve (Roldan Fernandez et al., 2016). The merit order curve shows how electricity sources are ranked based on their marginal costs. These electricity-producing plants are ranked in ascending order and thereby form the supply curve (Sensfuß et al., 2008). Power plants at the beginning of the merit order produce electricity with the lowest marginal costs, which means that their plant will determine the price until the demand exceeds their capacity. This process is repeated until demand meets supply, representing the spot price of electricity and forming the 'energy mix' of the country (Clo et al., 2015). To determine the effect of renewable energy on the merit order, and subsequently the spot price of electricity, the first hypothesis is proposed:

$H0_1$: *The imbalance price of electricity is insensitive to the introduction of new energy generation sources*

HA_1: *The increasing share of renewable energy sources has a negative effect on the imbalance price*

2.1.2. Renewable energy

According to Sorensen (2000), energy can only be called “renewable” when the rate of extraction is less than the rate that is used to supply the new energy. Fossil fuels, such as gas and oil, are depleting resources and their minimal recovery rate makes them non-renewable. Solar and wind energy are, on the other hand, never-ending in their terms of practice. Their extraction rate is equal to the rate at which the energy is provided, making them renewable at heart according to the definition of Sorensen.

Wirdemo (2017) and Blazquez et al. (2018) argue that ever since the share of renewable energy sources is increasing, electricity prices have become more volatile. Thanks to the widely granted feed-in tariffs, countries all over the world have seen a sharp rise in renewable energy production (Sensfuß, 2008). As these renewable energy sources use sunlight, wind or water as their primary production driver, their production comes with minimal, and sometimes even zero marginal cost.

By including renewable energy sources in a power grid, these renewables replace the electricity sources that earlier set the market-clearing price, shifting the merit order to the right. With equal supply, the electricity sources to the far right of the merit order curve might be pushed out of the bidding zone, causing a drop in the wholesale clearing price (Roldan Fernandez et al., 2016). Taking into consideration that these energy sources are can be inflexible by nature, such an event may create negative electricity prices (Sewalt and De Jong, 2013). With limited storability options available, a highly inflexible energy mix amplify this effect leading to more negative prices (Fanone et al., 2013).

2.1.3 Non-storability character of electricity

The fundamental reason why supply and demand need to match is because of the non-storable character of electricity. Currently, the ability to store energy on a large scale is still very limited (Connolly et al., 2012). On a smaller scale, countries could store electricity in batteries or hydropower reservoirs. Thanks to the geographical landscape of the Netherlands and high cost of battery storage, this is not done at a significant degree (van Leeuwen et al., 2017).

The segmentation that results from the limited-storability of electricity, creates opportunities for a wide range of trading mechanisms and markets with contrasting periods to delivery. These markets range from short-term speculation to long-term forward markets (Sewalt & de Jong, 2003). As of today, electricity cannot yet be stored in large scale, requiring suppliers to bring the electricity to the market at the current market demand, hereby amplifying imbalances (Jaeck & Kautier, 2016). Based on these researches, the differences between the day-ahead generation of renewable energy and the actual generation of renewable energy could have an amplifying effect on the price effect generated by renewable energy production. Hypothesis II is proposed:

$H0_2$: Electricity prices remain unaffected by differences between forecasted power and actual generated power

HA_2: The difference between actual generated renewable energy and forecasted renewable energy increase the volatility of the electricity imbalance price

2.1.4. Negative prices

Negative prices are a unique phenomenon in trading markets. When a commodity has a negative price, this implies that the demolition of that particular commodity would create more value than the actual creation of the commodity. When electricity prices fall below zero and the electricity provider is unable to halt its production, power suppliers have to pay customers for consuming electricity. At such a moment in time, electricity can be seen as a wasted product and hence it is disposed of in the market. The volatility of the Dutch imbalance market is displayed by the settlement price overview of TenneT in the graph below.

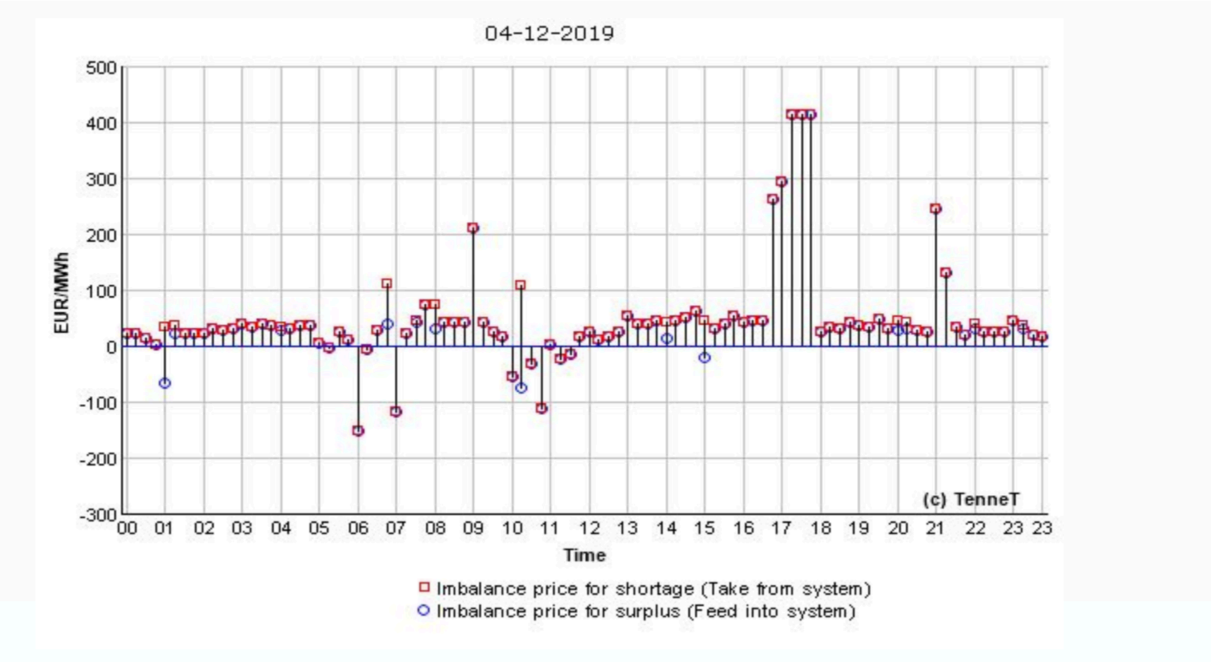

Figure 1.1: TenneT imbalance

The figure shows that the imbalance price difference between the lowest and the highest price point is over 500€/MWh, while the average price lies around 50€/MWh. These negative prices and extreme price peaks could be a result of a period when a high dependency on inflexible power generation happens at the same time as low electricity demand (Clean energy wire, 2018).

2.2. Imbalance markets and reserves

In the Netherlands, TenneT is the main transmission system operator. To better understand where the price of electricity comes from, this section focusses on the role of TenneT, it's requirements and restrictions.

2.2.1 Balancing the imbalance market

As stated in section 2.1, electricity production must be equal to the electricity consumption at all times. To balance supply and demand, a controlling mechanism has been put in place, called the TenneT imbalance market. During the day, there are constant fluctuations both to the production and to the consumption of electricity. This primarily results from the substantial, and often hard to precisely forecast, amount of different factors that affect both variables. To balance possible deviations, transmission operators buy energy reserves from different reserve markets (Fingrid, n.d.). These reserves are power plants that can adjust their electricity generation according to the actual demand (Fingrid, n.d.)

Stated in the "Capacity mechanisms for electricity (2017)", the EU is still unclear if the market itself can align production and consumption or if capacity mechanisms are required. By keeping the power supply and demand equal at all times, electricity providers must ensure the power grid is always running stable at a frequency of 50 Hertz (TenneT, 2018). To ensure the security of the electricity supply, there are clear rules and procedures in place. These policies encompass different kinds of capacity mechanisms; volume-based and price-based. Volume-based can again be divided into focused and market-wide mechanisms. The strategic reserve is a volume-based capacity mechanism and is in particular utilized in Belgium, Germany, Poland and Sweden.

2.2.2 How TenneT Operates

In the Netherlands, TenneT is operating as a single buyer. In return for the transmission of their electricity, Dutch energy producers have to offer reserve capacity to TenneT. TenneT defines this capacity as “the capacity they can produce or consume over or under the amount reported in their E-programme” (TenneT, n.d.). To determine how much this reserve capacity should be, regulations have been set by the Grid Code. The Grid Code contains the rules for the power network (TenneT, n.d.).

The bids offered by the participating suppliers are treated like options by TenneT. The company calculates the energy volume, subsequently adjusts the volume consistent with the bid price and eventually corrects the volume in line with the information received from the program responsible parties (PRP). The PRP is a system that informs TenneT daily about transactions that are in anticipation to take place on the following day, as well as the specifications of the grids they are going to use to transport the demanded electricity (TenneT, n.d.).

To avoid extremely high or low prices, TenneT expects its suppliers and extractors to participate in balancing the grid. Parties that do not comply with these rules and participate in under- or oversupplying the grid, can expect fines of €3000,- euro (TenneT, 2018).

2.3 The effect of policy

To increase the market share of renewable energy, various policies have been put in place to promote and incentivize innovation and invention in the field of renewable energy technology. Different policies might have similar wishes but very different results. This section focusses on the different policy effects

2.3.1 Different policy approaches

Literature by Jaffe et al. (2002) explains how different policies could provide an incentive for individual firms to adopt more sustainable technologies. By creating a clear distinction between two environmental policies, two different categories are introduced. One group contains market-based policies. These policies contain subsidies, pollution charges and pollution permits that motivate companies to take action in reducing their total emissions. All policies in this category provide monetary incentives that align their profit-orientated interest with social interest.

The other group of environmental policies is categorized as the command-and-control group (Jaffe et al., 2002). Unlike the first group, these policies don’t incentivize the companies based on monetary benefits. This group is forced to adapt to uniform technology standards, being forced to reduce pollution (Jaffe et al., 2002).

While the command and control approach does set standards for all firms, it’s demanding approach comes at disadvantages. By forcing companies into reducing emissions, the results are not effective for every firm. Their findings are in line with their suggestion, showing that market-based policies are incentivizing not only companies to change, but also do so in an effective way.

Years of financial incentives and subsidies have created a strong transition towards renewable energy, both in the Netherlands and neighbouring countries. To predict the energy price, it is important to pay attention to these policies (Esteves et al., 2015). Long term incentive plans can completely reshape the national energy mix and thereby affect the imbalance price.

2.3.2 Renewable energy policy in the Netherlands

From the year 2003, three different types of renewable energy subsidy schemes have been implemented by the Dutch government. These are called the “Environmental Quality of Electricity Production” (Milieukwaliteit van Elektriciteitsproductie, MEP), the “Stimulation of sustainable energy production” (Stimulering duurzame energieproductie, SDE), the “SDE+” (RVO, n.d.)

The MEP was the first of the three policies to be introduced. Firms that applied for the MEP received a subsidy for up to ten years (RVO, n.d.). Based on the amount of renewable energy that was generated, the MEP allocated it’s subsidies to the different applying companies. Hereby the MEP allowed for a distinction between the subsidy levels that were given to the different forms of renewable energy production (RVO, n.d.). One of the main goals of the MEP was to stimulate the potential of wind energy and during the entire duration of the subsidy period, the MEP had no maximum budget for the number of subsidies that were provided to renewable energy generators (RVO, n.d.).

After five years (in 2008), the MEP was succeeded by the SDE scheme (RVO, 2008). The SDE scheme lasted for two years and had a compensation mechanism in place that based the subsidy amount on the belief that electricity production of fossil fuels was less expensive than the production from renewable energy sources (RVO, 2008). To compensate renewable energy suppliers, their subsidy was dependent on the price of electricity or/and gas and granted for a period of twelve to fifteen years (RVO, 2008).

In 2011, the SDE scheme made way for the SDE+ scheme. The key difference between the SDE and the SDE+ scheme is that the SDE scheme was based on a specific budget for each renewable technology, whereas the SDE+ scheme consisted of a budget for all the renewable technology combined (RVO, 2019). By introducing feed-in tariffs and funding opportunities, the Dutch government sparked renewable energy entrepreneurship, reshaping the Dutch energy mix.

2.4 The Dutch electricity market

Building upon the policy information provided in section 2.3, years of supportive schemes and policies have shaped the Dutch energy mix. Since the national energy mix can be seen as a primary driver of the electricity prices, this section analyses the Dutch energy market.

2.4.1 Energy mix of the Netherlands

In the Netherlands, energy originates primarily from natural gas and coal combustion (van Leeuwen et al., 2017). The amount of coal combustion in the Netherlands has risen significantly in recent years, leading to increased CO2 emissions (van Leeuwen et al., 2017). This increase stems predominantly from the decline in coal prices and the government's decision to radically decrease the dependency on natural gas (van Santen, 2018). The government plans to phase out the use of natural gas completely by 2060 while becoming CO2 neutral in 2050 (CBS, 2019). To achieve this goal, various policy measures have been initiated that support the renewable energy sector. Focused to attract more investments in renewable energy, feed-in tariffs and attractive energy tax policies have been able to realize an increase in renewable energy generation equal to 7.4% in 2018 (CBS, 2019).

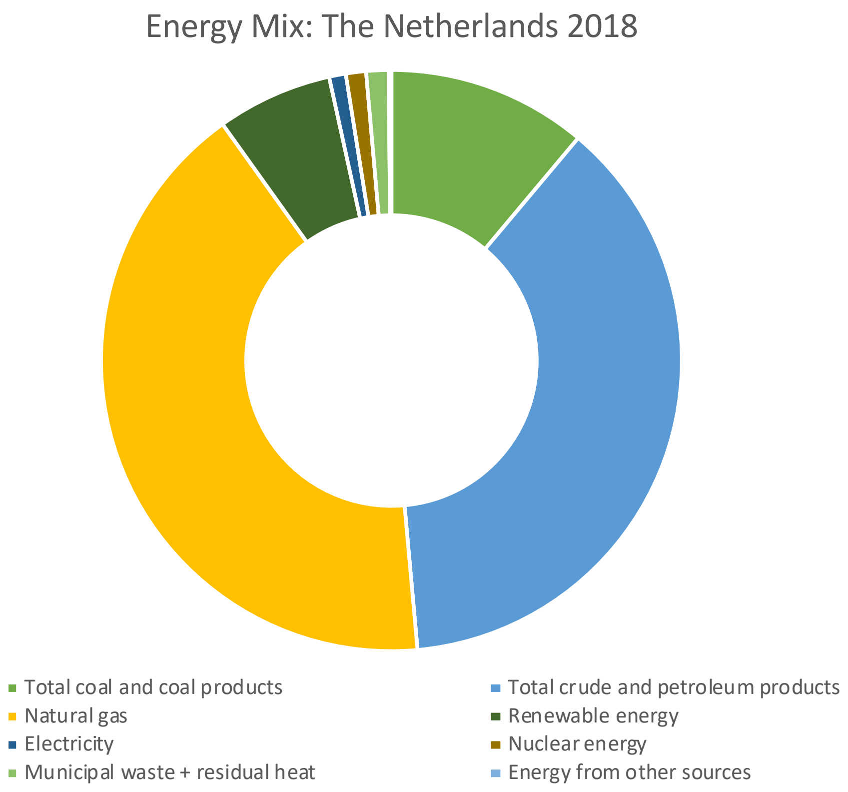

Figure 1.2: Energy Mix, The Netherlands 2018

2.4.2. Adjustment to production

Due to the increasing focus on renewable energy production, it is important to understand the degree of sophistication for fossil fuel-powered electricity plants to adjust their production. As demand and supply need to balance at all times, energy sources have to operate flexibly and profitably. The operational flexibility can be seen as an important influential factor of the electricity price, and hence it has to be taken into consideration (Gonzalez-Salazar et al., 2017).

Although the renewable energy sources solar and wind require a higher capital upfront investment, their operation cost compared to coal and gas are significantly lower. On top of that, they can easily be adjusted according to demand. Although this flexibility would be a key benefit for every other producer, the renewables that find their way into the very beginning of the merit order curve hardly ever need to rely on their flexibility (Gonzalez-Salazar et al., 2017). These plants can be characterized as highly flexible.

Coal and nuclear power plants, on the other hand, find themselves in a highly inflexible and price-sensitive position on the merit order curve. For them, they are constantly adjusting their production to ensure the lowest possible costs and lowest possible (financial) damage to the power plant. These baseload production plants are characterized as inflexible.

Lastly, there are also (moderately) flexible plants. These plants take around three hours to start production, and often use highly flammable sources, such as oil and gas (Gonzalez-Salazar et al., 2017). To balance the energy system, it is of key importance to understand the national energy mix. A country with flexible and highly flexible energy sources would be far less difficult than a country that consists of highly flexible and highly inflexible energy sources (Gonzalez-Salazar et al., 2017). Unfortunate for TenneT, the Netherlands is relying on the aferementioned "inflexible and highly flexible" energy mix (CBS, 2019). To determine whether this combination indeed results in amplified results, hypothesis III is proposed:

Ho_3: *The effect of flexible energy sources on the imbalance price of electricity, with renewable energy in particular, is amplified when forecasted incorrectly.*

Ha_3: *Flexible energy sources, with renewable energy in particular, have the ability to correct output sufficiently enough to prevent extreme price effects on the imbalance price.*

To determine which factors affect the price of energy in the Dutch imbalance market, it is important to determine the factors that cause the price spikes. To determine these spikes, a quantile regression analysis will be performed.

3. Methodology

The basic principle of a regression analysis is to determine the relationship between a dependent variable and predictor variables. A limitation to the traditional least squares regression models, however, is that the model only allows an interpretation of the results located at the centre of the distribution (Hung et al., 2010). Since this research focuses on the peaks of the energy prices, be it the extreme lows and extreme highs, a quantile regression analysis is applied.

3.1 The quantile regression

The quantile regression analysis was first introduced by Koenker and Baset (1978) and commonly finds its way into many financial and economic applications. Thanks to the quantile distribution characteristic, the quantile regression analysis is commonly used to determine the extreme highs and extreme lows of the dependent variable. Using the quantile regression analysis has various advantages. First, the model uses a linear programming representation that allows a straightforward (simplified) examination. Second, estimators of the quantile regression analysis may be of greater efficiency than OLS estimators using if an error term is used that is non-nominal (Hung et al., 2010). Last, the estimated coefficient vector is characterized to be not sensitive to outliers, since the objective function of the quantile regression is a weighted sum of absolute deviations (Buchinsky, 1998).

In this research, the imbalance price of electricity is used as our dependent variable, with the actual generation of renewable energy and the forecasted generation of renewable energy both being the independent variables.

3.2 The generation of renewable energy

In the Netherlands, renewable energy has a priority dispatch into the electricity grid, which is specified in article 16 of the Renewable Energy Directive (Chaves et al., 2015). With limited storage options available, the effect of renewable energy on the energy price is commonly considered to be diverging, suggesting an amplifying effect on the electricity price peaks (Fischer, 2010). Although renewable energy covers a wide set of energy sources, this research focuses on solar and wind generation. For solar generation, personal energy generation is excluded and the total wind energy factor is a combination of both onshore and offshore wind generation.

Furthermore, a distinction is made between two independent variables; the actual generation of renewable energy and the forecasted generation of renewable energy. Comparing both methods allows for a wider interpretation of the direct (actual generation) and possible speculative (forecasted generation) effect on the electricity price in the imbalance market.

3.3 The model

To determine the effect of the share of renewables on the price of electricity in the Dutch imbalance market, the period between 01-01-2015 to 20-09-2019 will be used. In the last years, the share of renewables has increased at a substantially high pace (Niesten et al., 2018). By defining recent observations – thus the underlying factors – the current market is best represented. After the data was formatted the model in this research interprets the lower 5% quantile and the higher 95% quantile using the statistical software named Gretl. To capture the full effect of renewable energy on the imbalance price, three different models have been created. All models use "imbalance electricity price" as a dependent variable, the constant (a) and "total load" (b) as an independent variable.

3.3.1 Model I

In Model I, the "actual generation solar energy" (c) and "the actual generation of total wind energy" (d) are included as independent variables. These two independent variables allow an interpretation of the price effect in the 5th and 95th quantile. Model I can be formulated as follows:

<u>Model I:</u>

Quantile 5%:

$$q(5\%, t) = a + b \times Load(t) + c \times shareSolar(t) + d \times shareWind(t) + e(t)$$

Quantile 50%:

$$q(50\%, t) = a + b \times Load(t) + c \times shareSolar(t) + d \times shareWind(t) + e(t)$$

Quantile 95%:

$$q(95\%, t) = a + b \times Load(t) + c \times shareSolar(t) + d \times shareWind(t) + e(t)$$

3.3.2 Model II

In Model II, this formula is further expanded by adding "delta total share of renewables", containing independent variables "delta load" (f), "delta solar" (g) and "delta wind (h). These variables capture the difference between the actual and day-ahead forecast of total load, solar and wind energy. Model II can be formulated as follows:

Model II:

Quantile 5%:

$$q(5\%, t) = a + b \times Load(t) + c \times shareSolar(t) + d \times shareWind(t) + e(t) \\ + f \times Load(t) + g \times shareSolar(t) + f \times shareWind(t)$$

Quantile 50%:

$$q(50\%, t) = a + b \times Load(t) + c \times shareSolar(t) + d \times shareWind(t) + e(t) \\ + f \times Load(t) + g \times shareSolar(t) + f \times shareWind(t)$$

Quantile 95%:

$$q(95\%, t) = a + b \times Load(t) + c \times shareSolar(t) + d \times shareWind(t) + e(t) \\ + f \times Load(t) + g \times shareSolar(t) + f \times shareWind(t)$$

3.3.3 Model III

In Model III, the is comparison is made between Model I and Model II. Model III is the most complete model capturing the total effects, both direct and indirect, of renewable energy sources on the imbalance market price. The results from Model I are classified as "coefficient I", the results from Model II are classified as "coefficient II" and the "difference" is calculated by subtracting "coefficient I" from "coefficient II".

Model III:

- Coefficient I

$$q(5\%, t) = a + b \times Load(t) + c \times shareSolar(t) + d \times shareWind(t) + e(t)$$

$$q(50\%, t) = a + b \times Load(t) + c \times shareSolar(t) + d \times shareWind(t) + e(t)$$

$$q(95\%, t) = a + b \times Load(t) + c \times shareSolar(t) + d \times shareWind(t) + e(t)$$

- Coefficient II

$$q(5\%, t) = a + b \times Load(t) + c \times shareSolar(t) + d \times shareWind(t) + e(t) + f \times Load(t) + g \times shareSolar(t) + f \times shareWind(t)$$

$$q(50\%, t) = a + b \times Load(t) + c \times shareSolar(t) + d \times shareWind(t) + e(t) + f \times Load(t) + g \times shareSolar(t) + f \times shareWind(t)$$

$$q(95\%, t) = a + b \times Load(t) + c \times shareSolar(t) + d \times shareWind(t) + e(t) + f \times Load(t) + g \times shareSolar(t) + f \times shareWind(t)$$

- Difference (II – I)

Quantile 5%: $\Delta\, Difference = Coefficient\ II\ q(5\%, t) - Coefficient\ I\ q(5\%, t)$

Quantile 50%: $\Delta\, Difference = Coefficient\ II\ q(50\%, t) - Coefficient\ I\ q(50\%, t)$

Quantile 95%: $\Delta\, Difference = Coefficient\ II\ q(95\%, t) - Coefficient\ I\ q(95\%, t)$

4. Data

The data section provides an in-depth overview of the data described in the methodology, containing the descriptive statistics, data sources and data adjustments. Please note that all data described refers to the Dutch energy market. To avoid repetition, all variables will be shortened like this example: “actual generation of Dutch solar and wind energy” will be referred to as “actual generation of solar and wind energy”.

4.1 Descriptive statistics

The dependent variable is the electricity price in the imbalance market named “imbalance price”. Both electricity on the imbalance market and the day-ahead market are controlled by TenneT. TenneT hereby takes the responsibility to keep the electricity market in balance; matching supply and demand (TenneT, nd). TenneT publishes two electricity prices, one for selling and one for buying electricity. This research investigates the “buying prices”. The reason why the buying prices are used is that this number displays the price that TenneT sells their generated electricity for. The data is retrieved from TenneT’s website, having 15-minute intervals and ranging from 01-01-2015 to 20-09-2019. All electricity measures are determined in MW and Euro.

The share of renewables is divided into two independent variables, explaining the actual and forecasted generation rates of solar and wind energy. The independent variables are named “ solar generation” and “wind generation”. Due to data limitations, this research restricts itself to solar and wind energy as benchmark renewable energy sources. Furthermore, this research hypothesizes the unpredictability effect of renewable energy, in which solar and wind are most significant. The data for the independent variables are retrieved from the ENTSOE database. All measures are shown in Mw and 15-minute intervals.

To capture the full effect of renewable energy production on the imbalance price, the variables “delta total load”, “delta solar” and “delta wind” are added to the model II. This variable “delta load” equals the actual total generated power minus the day-ahead (forecasted) total power generation. Common, the “delta solar” equals the actual total generated solar power minus the day-ahead (forecasted) total solar power generation and “delta wind” equals the actual total generated wind power minus the day-ahead (forecasted) total wind power generation.

Common to the renewable energy variables, the total load, total day-ahead of renewable energy and day-ahead of total load have been retrieved from the ENTSOE database and are shown in Mw and 15-minute intervals.

4.2 Data adjustments

To make the data coherent, all the days in which there was 0 generation for both the wind and solar energy were removed from the data set. To make sure the forecasted and actual generation target the same period, days in which the actual generation for both wind and solar was equal to 0 have also been removed from the forecasted generation model. Please find appendix 8.1 for a full overview of the data set.

As the generation of solar energy is equal to 0 at night, the data set has been adjusted so that only the "day" data is captured. Although the day data varies for each season, the "day data" in this sample is captured as the period between 8:00 - 20:00. In total, these adjustments have provided a data set with 16383 samples.

5. Results

5.1 Model I

I. Quantile regression; 5th quantile

To analyze the effect of renewable energy on the 5% lowest values, a quantile regression on the 5th quantile, or tau 0.05, is performed. From table 1.1 can be concluded that the average price in the 5th quantile equals 30.099. The variable "total load" has an insignificant effect on the imbalance price equal to $6.21329e^{-6}$, whereas both variables "total solar day-ahead/total load day-ahead" and "total wind day-ahead/total load day-ahead" are significant with t values of -19.6968 and -17.3241 respectively. "Total solar day-ahead/total load day-ahead" has a negative and significant (t= -19.6968) effect on the imbalance price equal to -1453.32 and "total wind day-ahead/total load day-ahead" has a negative and significant (t= -17.3241) effect on the imbalance price equal to -463.602.

Based on these results, the 5% quantile price formula can be drafted as follows:

$$q(5\%, t) = 30.099 + 6.21329e^{-6} \times Load(t) - 1453.32 \times shareSolar(t) - 462.602 \times shareWind(t) + e(t)$$

II. Quantile regression; 50th quantile

Table 1.2 shows the results of the quantile regression for the average of the model, named the 50th quantile or tau 0.5. Table 1.2 shows that the average price in the 50th quantile equals 37.41. The variable "total load" has a significant effect (t= 3.49227) on the imbalance price equal to 1.0648e-5. Variable "Total solar day-ahead/total load day-ahead" has a negative and significant (t= -5.847) effect on the imbalance price equal to -51.7348 and "total wind day-ahead/total load day-ahead" has a negative and significant (t= -11.2285) effect on the imbalance price equal to -36.0282.

Based on these results, the 50% quantile price formula can be drafted as follows:

$$q(5\%, t) = 37.41 + 1.0648e^{-5} \times Load(t) - 51.7348 \times shareSolar(t) \\ - 36.0282 \times shareWind(t) + e(t)$$

III. Quantile regression; 95th quantile

The 95th quantile has a significantly higher average price of electricity, equal to 200.983. Furthermore, table 1.3 shows that the total load has an insignificant effect of -1.73910e^{-5}, while both variables "solar" and "wind" are significant with t values of -5.92421 and -3.19646 respectively. Common to the effect of both renewable variables in the 5th quantile, "Total solar day-ahead/total load day-ahead" has a negative and significant (t= -5.92421) effect on the imbalance price equal to -1023.69 and "total wind day-ahead/total load day-ahead" has a negative and significant (t= -3.19646) effect on the imbalance price equal to -200.327.

Based on these results, the 95% quantile price formula can be drafted as follows:

$$q(95\%, t) = 200.983 - 1.73910e^{-5} \times Load(t) - 1023.69 \times shareSolar(t) \\ - 200.327 \times shareWind(t) + e(t)$$

When an interpretation of the results from I, II and III is made, the conclusion can be drawn that in the imbalance price in the 5th quantile and the 95th quantile are both significant and negatively affected by an increase in renewable energy production. Hypothesis $H0_1$ is rejected.

5.2 Model II

Building upon Model I, Model II includes the variables "delta total load", "delta solar" and "delta wind". These variables provide us with the following results:

I. Quantile regression; 5th quantile

Starting with an analysis of the 5th quantile, or tau 0.05, table 1.4 displays an average price of -117.388. The variable "total load" has a positive and significant (t=24.696) effect on the imbalance price equal to 0.00900742. "Total solar day-ahead/total load day-ahead" has a negative and significant (t=24.696) effect of -595.125 on the imbalance price and variable "total wind day-ahead/total load day-ahead" has a similar negative and significant (t=21.0166) effect on the imbalance price equal to -378.778. "Delta Total Load" has a positive and significant (t= 24.8389) effect on the imbalance price equal to -0.00905675, "Delta Total Solar" has a negative and significant (t= -14.5487) effect on the imbalance price equal to -0.175630 and "Delta Total Wind" has a negative and significant (t=-29.1821) effect of -0.0435738 on the imbalance price.

Based on these results, the 5% quantile price formula can be drafted as follows:

$$\begin{aligned} q(5\%, t) = {} & -117.338 + 0.00900742 \times Load(t) - 595.125 \times shareSolar(t) \\ & - 378.778 \times shareWind(t) + e(t) - 0.00905675 \times Load(t) \\ & - 0.175630 \times shareSolar(t) - 0.0435738 \times shareWind(t) \end{aligned}$$

II. Quantile regression; 50th quantile

Starting with an analysis of the 50th quantile, or tau 0.5, table 1.5 displays an average price of -50.9102. The variable "total load" has a negative and significant (t=-12.6466) effect on the imbalance price equal to -0.000859119. "Total solar day-ahead/total load day-ahead" has a negative and significant (t=-13.2614) effect of -129.811 on the imbalance price and variable "total wind day-ahead/total load day-ahead" has a similar negative and significant (t=-15.4201) effect on the imbalance price equal to -51.7625. "Delta Total Load" has a negative and significant (t= -12.6564) effect on the imbalance price equal to -0.000859517, "Delta Total Solar" has a negative and significant (t= -6.52240) effect on the imbalance price equal to -

0.0146651 and “Delta Total Wind” has a negative and significant (t=-23.7846) effect of -0.00661469 on the imbalance price.

Based on these results, the 50% quantile price formula can be drafted as follows:

$$\begin{aligned} q(50\%, t) = {} & -50.9102 - 0.000859119 \times Load(t) - 129.811 \times shareSolar(t) \\ & - 51.7625 \times shareWind(t) + e(t) - 0.000859517 \times Load(t) \\ & - 0.0146651 \times shareSolar(t) - 0.00661469 \times shareWind(t) \end{aligned}$$

III. Quantile regression; 95th quantile

Starting with an analysis of the 95th quantile, or tau 0.95, table 1.6 displays an average price of 150.519. The variable “total load” has a positive and significant (t=2.92052) effect on the imbalance price equal to 0.00434577. “Total solar day-ahead/total load day-ahead” has a negative and significant (t=-4.48254) effect of -961.113 on the imbalance price and variable “total wind day-ahead/total load day-ahead” has a similar negative and significant (t=-6.41630) effect on the imbalance price equal to -471.782. “Delta Total Load” has a positive and significant (t= 2.96634) effect on the imbalance price equal to 0.00441258, “Delta Total Solar” has a negative and significant (t= -1.79279) effect on the imbalance price equal to -0.0882952 and “Delta Total Wind” has a negative and significant (t=-9.85618) effect of -0.0600414 on the imbalance price.

Based on these results, the 95% quantile price formula can be drafted as follows:

$$\begin{aligned} q(95\%, t) = {} & 150.519 + 0.00434577 \times Load(t) - 961.113 \times shareSolar(t) \\ & - 471.782 \times shareWind(t) + e(t) + 0.00441258 \times Load(t) \\ & - 0.0882952 \times shareSolar(t) - 0.0600414 \times shareWind(t) \end{aligned}$$

Based on the findings of quantile regression I, II and III, the conclusion can be drawn that when the Delta Total Renewable is positive, or when the actual generation is larger than the day-ahead forecast, both “Delta Total Solar” and “Delta Total Wind” have a negative and significant effect on the imbalance price in the 5th, 50th and 95th quantile. This additional negative effect can be classified provides evidence for the rejection of $H0_2$.

5.3 Model III

Model III compares both Model I and Model II results, providing a total overview of the expected effects of renewable energy. Table 1.7 shows both the direct effects of "Delta Total Load", "Delta Total Wind" and "Delta Total Solar" as well as the indirect effects. To quantify the indirect effects, the difference between Model II and Model I is analyzed for each quantile and variable.

I. Average price

5th Quantile: $\Delta\, Difference = -117.388 - 30.099$

50th Quantile: $\Delta\, Difference = 50.9102 - 37.41$

95th Quantile: $\Delta\, Difference = 150.519 - 200.983$

The average price in Model II is more extreme compared to Model I. The difference between the average price in the 5th quantile is equal to -147.487. In the 95th quantile, the difference is equal to -50.464. These results show a significant diverging effect on the average price in Model II compared to Model I, providing evidence for an amplifying effect of including the "Actual - Forecasted Deltas".

II. Day-ahead load

5th Quantile: $\Delta\, Difference = 0.00900742 - 6.21329e^{-6}$

50th Quantile: $\Delta\, Difference = -0.000859119 - 1.0648e^{-5}$

95th Quantile: $\Delta\, Difference = 0.00434577 + 1.73910e^{-5}$

The day-ahead load in the 5th quantile is equal to 0.00900742 and in the 95th quantile to 0.00434577. Both results are affected positively by the indirect effects, showing a significant converging effect on both variables.

III. Total solar day-ahead/total load day-ahead

5th Quantile: $\Delta\,Difference = -595.125 + \; 1453.32$

50th Quantile: $\Delta\,Difference = 129.811 + \; 51.7348$

95th Quantile: $\Delta\,Difference = 214.413 + \; 1023.69$

“Total solar day-ahead/total load day-ahead” is positively affected by 858.195 in the 5th quantile. Surprisingly, the 95th quantile is also positively affected by 1238.103. This strong significant effect changes the 95th quantile from a negative to a positive effect. These results provide evidence for the proposed amplifying effect of including the “Actual -Forecasted Deltas”.

IV. Total wind day-ahead/total load day-ahead

5th Quantile: $\Delta\,Difference = -378.778 + \; 463.602$

50th Quantile: $\Delta\,Difference = -51.7625 + \; 36.0282$

95th Quantile: $\Delta\,Difference = -471.782 + \; 200.327$

The variable “Total wind day-ahead/total load day-ahead” is positively affected by 84.824 in the 5th quantile, but significantly affected by -271.455 in the 95th quantile. This significant diverging effect provides evidence for the proposed amplifying effect of including the “Actual -Forecasted Deltas” in Model II.

Although the “Day-ahead load” provided converging effects, the variables “Average price”, “Total solar day-ahead/total load day-ahead” and “Total wind day-ahead/total load day-ahead” have diverged. This diverging effect provides evidence for the amplifying effect of flexible (renewable) energy sources and supports the $H0_3$ hypothesis.

6. Theoretical Implications and discussion

6.1 Research Question

Does the increasing share of renewable energy lead to more "extreme" electricity prices in the Dutch imbalance market? A quantile regression analysis approach to the Dutch imbalance market.

As introduced in the theoretical framework, various theories have given suggestions for the different factors that could lead to more extreme prices in the energy market. First, the merit order theory suggests that introducing an energy production source with low marginal costs would lead to lower energy wholesale prices. However, when this source is highly volatile, it would lead to a radical difference in merit order set up and thus affecting the electricity wholesale prices. In this research, the imbalance price in both the 5th and 95th quantile is indeed highly sensitive to the share of renewable energy production sources.

Connolly added that this can be primarily related to the limited storability of electricity, especially that of decentralized solutions, such as small scale solar plants. Sewalt and Jong (200) used the non-storability discussion to show that grid overpowering and inaccurate forecasting leads to more extreme and even negative prices. The results of this thesis contribute to this research by providing proof for the effect of inaccurate forecast on the imbalance price. Results show that prices indeed become more extreme and that the price peaks (5th and 95th quantile) are more exaggerated in Model II.

By providing evidence on earlier imposed research, this research finds that by providing a quantile regression analysis approach, renewable energy prices do contribute to more extreme energy prices.

Findings suggest that renewable energy, however, affects the national market via a broad way of channels. As policies are key factors that shape the energy mix of a country, implications of this research urge policymakers to become more aware of the effects of introducing green energy alternatives. On the other side, this research contributes to investors and hedge funds who could benefit from the current market situation and exploit the volatility for profit.

6.2 Discussion: The investor & energy policy

To commit to the Paris 2020 climate change rules, governments have introduced various policies to radically change their emission output. Politicians, often under large amounts of pressure from modern-day media and public opinion, tend to become more extreme in their outings. Although sometimes radical changes are needed to reach the new goals, a big challenge lies within the actual methods these results are achieved. The introduction of a new policy is often not confined to the direct effects it ceases to have. Whether a government uses a stimulative "market approach" or a dictatorial "control" approach often is introduced to get to the same results, however, both may encounter completely different outcomes.

In regards to renewable energy, Dutch municipalities have encountered the indirect effects of supportive policy firsthand. Ever since the Dutch government has introduced the latest subsidy scheme for renewable, over a thousand solar farms have been initiated all over the Netherlands(source). These solar farms have been built at locations where the ground is widely available, such as Groningen, Drenthe, Overijssel and Limburg. Although this boost in renewable energy production is a good step into a more sustainable direction, the policymakers failed to include the effect on local governments in their plan. Thanks to the inability to store solar energy, local municipalities have increasing issues with their electricity provision. In a town where there are more solar panels than inhabitants, this local oversupply causes the electricity to either overpower the net or solar panels have to be shut down.

It is therefore of great importance to understand the efficacy of these subsidies and tax reductions, but even more so, to understand the alignment of the policy with the characteristics of the investors. By better understanding the characteristics of the renewable energy investor, governments can not only improve the efficiency of their policies but also get a better insight into the feasibility of the policy targets. Whereas earlier research has focused primarily on the investment, the empirical identification of the actual monetary contributors could spark a whole different discussion. Unlike often assumed, the investors consider are different types, rather than one "profit-maximizing" actor.

6.3 Shortcomings & further research

This research focusses on the effect of current renewable energy sources in the Netherlands and their effect on the prices in the 5th and 95th quantile. It provides valuable information for policymakers and electricity orientated traders, however, to provide a full view of the different effects of electricity generation sources, this research should also consider other, low emission energy sources. To provide a clear recommendation, it would be advisable to include different countries that rely on different renewable energy sources. By including countries such as Norway, which primarily uses hydropower, the implications could be different.

The research has not included the different seasonal aspects in the dataset. As renewable energy sources such as wind and solar depend on weather-related elements, seasonality could be a strong predictive factor. Since renewable energy has an influence on the imbalance price of electricity by directly dispatching energy into the power grid, the ability to predict these power inflows would help an energy trader with forming his trading strategy. When forming a trading strategy based on trading in the imbalance market, knowing these insights would help when trying to predict the market extremes.

From an environmental perspective, this research argues the polluting nature of a flexible and inflexible energy source. Although supported in researches from Henk (2020) and Youri (2020), no actual analysis is made of the environmental impact of the hybrid energy mix. To answer the question, "Is green energy actually green", further research could focus on the inclusion of emissions and power transfer between different countries. By allocating the actual (national) emissions, the national contributions, both directly and indirectly, this thesis could provide insight to European policymakers.

7. Conclusion

With the intensifying global focus to become more sustainable, policies and supportive schemes are impacting national economies both directly and indirectly. Being aware of the challenges and opportunities in these rapidly changing economic environments could create a key competitive advantage for businesses and nations alike.

This research has aimed to analyze the impact of the increasing share of renewable energy on the Dutch imbalance market. Taking a quantile regression approach, the peak prices of the Dutch imbalance market has been analyzed and formulated in three models.

Model I provided an interpretation of the effect that "actual generation solar energy" (c) and "the actual generation of total wind energy" have on the imbalance price in the 5th and the 95th quantile. Based on the results, hypothesis $H0_1$ was rejected. Providing evidence that the imbalance price of electricity is indeed sensitive to the production from renewable energy sources.

Model II built upon Model I by including the variables “delta total load”, “delta solar” and “delta wind”. The differences in actual and forecasted energy production affected the imbalance price of electricity in the 5th and 95th quantile both positively and negatively, resulting in the rejection of hypothesis $H0_2$.

Finally, Model III combined Model I and Model II to determine whether an incorrect forecast of the production of electricity, with renewable energy sources in particular, amplifies the effect of the flexible energy sources. Although the “Day-ahead Load” provided converging effects, the variables “Average price”, “Total solar day-ahead/total load day-ahead” and “Total wind day-ahead/total load day-ahead” diverged. This diverging effect provides evidence for the amplifying effect of flexible (renewable) energy sources and therefore support the $H0_3$ hypothesis.

Based on these findings, this research contributes to policymakers, investors and entrepreneurs who are affected by, or see opportunity in, extreme energy prices.

Appendix

Table 1.1:

Model I: The effect of variables “total load”, “total day-ahead solar” and ”total day-ahead wind” on “imbalance price”				
Dependent variable:	Imbalance price			
Observations:	16383			
Quantile:	5th			
	Tau	Coefficient	Std. Error	T-ratio
constant	0.05	30.099	2.60743	11.5435
Total Day-ahead Load	0.05	$6.21329e^{-6}$	$2.54305e^{-5}$	0.24432
$\frac{\text{Total Day-ahead Solar}}{\text{Total Day-ahead Load}}$	0.05	-1453.32	73.7842	-19.6968
$\frac{\text{Total Day-ahead Wind}}{\text{Total Day-ahead Load}}$	0.05	-463.602	26.7605	-17.3241

Table: 1.2

Model I: The effect of variables “total load”, “total day-ahead solar” and ”total day-ahead wind” on “imbalance price”				
Dependent variable:	Imbalance price			
Observations:	16383			
Quantile	50th			
	Tau	Coefficient	Std. Error	T-ratio
constant	0.5	37.41	0.3126	119.685
Total Day-ahead Load	0.5	$1.0648e^{-5}$	$3.0491e^{-6}$	3.49227
$\frac{\text{Total Day-ahead Solar}}{\text{Total Day-ahead Load}}$	0.5	-51.7348	8.84686	-5.847
$\frac{\text{Total Day-ahead Wind}}{\text{Total Day-ahead load}}$	0.5	-36.0282	3.2086	-11.2285

Tabel 1.3

Model I: The effect of variables “total load”, “total day-ahead solar” and ”total day-ahead wind” on “imbalance price”				
Dependent variable:	Imbalance price			
Observations:	16383			
Quantile:	95th			
	Tau	Coefficient	Std. Error	T-ratio
constant	0.95	200.983	6.10646	32.9131
Total Day-ahead Load	0.95	$-1.73910e^{-5}$	$5.95569e^{-5}$	-0.292006
$\frac{\text{Total Day-ahead Solar}}{\text{Total Day-ahead Load}}$	0.95	-1023.69	172.798	-5.92421
$\frac{\text{Total Day-ahead Wind}}{\text{Total Day-ahead Load}}$	0.95	-200.327	62.6715	-3.19646

Table 1.4

Model II: The effect of variables “total load”, “total day-ahead solar”, ”total day-ahead wind”, “Delta Total Load”, ”Delta Total Solar” and “Delta Total Wind” on the “imbalance price”				
Dependent variable:	Imbalance price			
Observations:	16383			
Quantile:	5th			
	Tau	Coefficient	Std. Error	T-ratio
constant	0.05	-117.388	5.4461	-21.5544
Total Day-ahead Load	0.05	0.00900742	0.0003647	24.696
$\frac{\text{Total Day-ahead Solar}}{\text{Total Day-ahead Load}}$	0.05	-595.125	52.5554	-11.3238
$\frac{\text{Total Day-ahead Wind}}{\text{Total Day-ahead Load}}$	0.05	-378.778	18.0228	-21.0166
Delta Total Load	0.05	0.00905675	0.000364619	24.8389
Delta Total Solar	0.05	-0.175630	0.0120718	-14.5487
Delta Total Wind	0.05	-0.0435738	0.00149317	-29.1821

Table 1.5

Model II: The effect of variables “total load”, “total day-ahead solar”, ”total day-ahead wind”, “Delta Total Load”, ”Delta Total Solar” and “Delta Total Wind” on the “imbalance price”				
Dependent variable:	Imbalance price			
Observations:	16383			
Quantile:	50th			
	Tau	Coefficient	Std. Error	T-ratio
constant	0.5	50.9102	1.01435	50.1897
Total Day-ahead Load	0.5	-0.000859119	6.79325e^{-5}	-12.6466
$\frac{\text{Total Day-ahead Solar}}{\text{Total Day-ahead Load}}$	0.5	-129.811	9.78861	-13.2614
$\frac{\text{Total Day-ahead Wind}}{\text{Total Day-ahead Load}}$	0.5	-51.7625	3.35681	-15.4201
Delta Total Load	0.5	-0.000859517	6.79115e^{-5}	-12,6564
Delta Total Solar	0.5	-0.0146651	0.00224842	-6.52240
Delta Total Wind	0.5	-0.00661469	0.000278108	-23.7846

Table 1.6

Model II: The effect of variables “total load”, “total day-ahead solar”, ”total day-ahead wind”, “Delta Total Load”, ”Delta Total Solar” and “Delta Total Wind” on the “imbalance price”				
Dependent variable:	Imbalance price			
Observations:	16383			
Quantile:	95th			
	Tau	Coefficient	Std. Error	T-ratio
constant	0.95	150.519	22.2187	6.77443
Total Day-ahead Load	0.95	0.00434577	0.00148801	2.92052
$\frac{\text{Total Day-ahead Solar}}{\text{Total Day-ahead Load}}$	0.95	-961.113	214.413	-4.48254
$\frac{\text{Total Day-ahead Wind}}{\text{Total Day-ahead Load}}$	0.95	-471.782	73.5287	-6.41630
Delta Total Load	0.95	0.00441258	0.00148755	2.96634
Delta Total Solar	0.95	-0.0882952	0.0492501	-1.79279
Delta Total Wind	0.95	-0.0600414	0.00609175	-9.85618

Table 1.7

Model III: The effect of variables “total load”, “total day-ahead solar”, ”total day-ahead wind”, “Delta Total Load”, ”Delta Total Solar” and “Delta Total Wind” on the “imbalance price”				
Dependent variable: Observations:	Imbalance price 16383			
	Tau	Coefficient Model I	Coefficient Model II	Difference (II-I)
constant	0.05	30.099***	-117.388***	-147.487
	0.5	37.41***	50.9102***	13.5002
	0.95	200.983***	150.519***	-50.464
Total Day-ahead Load	0.05	6.21329e^{-6}	0.00900742***	-0.0090012067
	0.5	1.0648e^{-5}***	-0.000859119***	-8.69767e^{-4}
	0.95	-1.73910e^{-5}	0.00434577***	0.004363161
$\frac{\text{Total Day-ahead Solar}}{\text{Total Day-ahead Load}}$	0.05	-1453.32***	-595.125***	858.195
	0.5	-51.7348***	-129.811***	-78.5458
	0.95	-1023.69***	214.413***	1238.103
	0.05	-463.602***	-378.778***	84.824

$\frac{\text{Total Day-ahead Wind}}{\text{Total Day-ahead Load}}$	0.5	-36.0282***	-51.7625***	-15.7343
	0.95	-200.327***	-471.782***	-271.455
Delta Total Load	0.05	-	0.00905675***	0.00905675***
	0.5	-	-0.000859517***	-0.000859517***
	0.95	-	0.00441258***	0.00441258***
Delta Total Solar	0.05	-	-0.175630***	-0.175630***
	0.5	-	-0.0146651**	-0.0146651**
	0.95	-	-0.0882952***	-0.0882952***
Delta Total Wind	0.05	-	-0.0435738***	-0.0435738***
	0.5	-	-0.00661469***	-0.00661469***
	0.95	-	-0.0600414***	-0.0600414***

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