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Economic Analysis of Arbitrage Values:

A Case of Norwegian Pumped Hydroelectricity Storage Project to Germany

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Abstract

In the face of the rapid growth of electricity which generally comes from renewable sources, intermittent solar and wind power are hindering the sustainability of electricity production. Especially in the absence of sunny and windy weather conditions, storing economic surplus electricity by the PHS method with high energy efficiency, which is a cost-effective solution to improve the security of electricity supply.

In this study, we focus on the evaluation of the potential arbitrage values of the project of Norwegian pumped hydroelectricity storage when connecting with German electricity markets. The time series is within 24 hours of a day or 168 hours of a week in the entire period between 2012 and 2016. The spot price data is collected from the OSL[1] and EEX, and here we observe the price volatility between the peak and off-peak prices by the sever graphs of the daily and weekly patterns made by STATA. We select the electricity price theory in the day-ahead electricity spot markets and the supply-demand model and investigate how price volatility between the peak and off-peak electricity prices affects hourly arbitrage strategies when the Norwegian pumped hydroelectricity storage (PHS) project is expanded to Germany. We employ the daily and weekly patterns of hourly electricity spot prices within 24 hours of a day and 168 hours of a week for the entire period between 2012 and 2016. Each pattern is tested by using the time series data on the historical hourly electricity spot prices on the OSL from the Nord Pool and the EEX. The levels of arbitrage values depend on the estimated daily or weekly patterns of the average hourly electricity spot prices of the OSL and the EEX.

Arbitrage policies by the daily and weekly patterns are estimated through the cost-efficient cycle of pumped hydroelectricity production in the Norwegian PHS, namely (use the cheap electricity from the grids to pump water back into the upper reservoir when electricity prices are low within the off-peak hours of the day, starting at midnight to the next early morning and then pump the water back into the low-level reservoir and convert back into hydroelectricity to be sold when the high prices at the peak hours of the day). Finally, we find that the daily pattern of electricity prices between the buying hours (23-6) and the selling hours (7-22) of the day is statistically significant and more profitable than weekly pattern between the weekend and the five workdays within 168 hours of the week, to achieve optimal arbitrage values in the German electricity market when the Norwegian PHS project connecting with Germany in the short term. Further, we find that Norway has slightly decreased the arbitrage values in the German electricity market when the increasing share of electricity production from solar and wind power.

[1] OSL: Oslo, EEX: European Energy Exchange.

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GWh: Gigawatt-hour

MWh: Megawatt-hour

TWh: Terawatt-hour

KWh: Kilowatt hour

1 GW = 1000 MW= 1000,000 KWh

MWe: Megawatt electricity

1 Introduction

1.1 Low-carbon Economy Transition

Global warming is the result of increasing greenhouse gas (GHG) emissions. The burning of fossil fuels and other pollutant sources is increasing average temperatures on earth, leading to acid rain, and more frequent floods and droughts. Therefore, the Intergovernmental Panel on Climate Change (IPCC) addressed that a framework from the "Paris agreement 2015" regarding controlling the global warming to below 2 °C and pursuing effort to limit it to 1.5°C by 2022 (IPCC, 2016). In the implementation of the target process, the European Union (EU) ambitiously pledged to reduce CO_2 emissions by at least 40% by 2030 (The European Commission, 2016) with the package of "Clean Energy for all Europeans", presented by the Energy Union framework strategy in November of 2016 (REN 21, 2016). It is a key step to transition from fossil fuels to renewables in low-carbon economics.

Renewable energy provides the potentials such as reduction in GHG emissions, reducing dependence on imported fossil fuels, cutting energy costs from oil prices, increasing local employment and promoting local economic growth. Over the past two decades, the increasing energy production from renewables has decreased import dependence on fossil fuels abroad, as well as having developed GDP (Gross domestic product), social welfare and employment (IEA, 2016). So far, burning fossil fuels has phased out step by step and increasing the share of renewable energy in the power market. It is profitable to our ecological environment, health, to increase emerging market competitions and improve the growth of low-carbon economics as well.

1.2 Motivations in the European Electricity Market

With the target, "Clean Energy for All Europeans", the EU takes efforts to reduce at least 40% of GHG emissions by 2030 and an expected share of 50% of renewables by 2030 (European Commission, 2016). The energy package has been in progress for the future European energy markets. The motivations of the package are listed in below:

- Giving priority to the solutions of energy efficiency.
- Increasing the EU's global leadership in renewable energy sector.
- Creating jobs, increasing investments in renewables sectors to low-carbon economic growth.

European Commission (2016) also addressed that the European electricity markets in the next ten years, where the following efforts will be made:

1) Adapting market rules to increase the liquidity of electricity market.
2) Putting consumers at the heart of the energy market

3) Security of electricity supply
4) Expanding cross-regional electricity transaction cooperation

A healthy regional coordination among countries can reduce costs on electricity transmission for European consumers and improve electricity market functioning. Energy grid for electricity integration is an efficient regional solution for interconnection between the individual EU 28-member states. However, the rapidly increasing share of renewables to generate electricity production in large volumes, which brings electricity grids to a big challenge.

1.3 The Growth of Renewable Energy in Europe

1.3.1 The Share of Renewable Energy Consumption

The penetration of renewables is rapidly rising for low-carbon economic growth. In recent years, the growth in renewable energy has higher than the growth of fossil energy (EEA, 2015). The target of 20% renewables in gross final energy consumption by 2020, and should raise it at least 30% by 2030 (WindEurope, 2016). In 2015, the market share of energy consumption from renewables has risen to 16.7% in the EU i.e. double of 8.5% in 2004. In addition to that 11 member states of the EU have already achieved their own 2020 targets, and the highest share of renewables was Sweden (53.9%), next is Finland (39.3%), while Germany (14.6%) and the United Kingdom (8.2%). Although Norway is not the EU 28-member states, the share of renewable energy generation is already highest in Europe, as a large contributor to clean energy, where 69.4% was reached in 2015, which exceeded the 2020 target of 67.5%, (Eurostat, 2017). The perspective for the growth of renewables is optimistic and the share of renewables has increased within 22 of the EU-28 Member States. The entire Europe is making contribution for "Clean energy for all Europeans" from the European Commission (2016) in the future.

1.3.2 The Share of Renewable Energy Generation

In the today's world, renewable energy is playing a key role in the European electricity sector. Electricity production of the EU is expected to reach 34% in 2020 from 19% renewable energy in 2011, and 100% renewables by 2050 (EWEA, 2011). Hence, the security of electricity production is an important factor to balance between supply and demand, as well as the impact on the sustainable growth of low-carbon economic.

Germany has installed new wind power accounted for 44% of the Europe's total new wind capacity (Vaughan, A., 2017). The EU expects to stimulate low-carbon economic growth through increasing renewable energy generations and reducing energy imports (Eurostat, 2016). In Europe, solar and wind power are the major renewables for clean energy generation. Wind Europe (2016) reported that 77% of renewable energy installations in all EU countries and 29% of electricity generation came from renewables in 2015, up from 15% in 2005. Also, 86% of energy in Europe produced by wind, solar, biomass and hydroelectric power is more than that in 2015 at 79% (Marras, C., 2017). It is a good sign for renewable energy transition from fossil fuels and significantly stimulate investment in the renewable energy sector. In the face of the continued growth in global renewable energy consumption, investment in renewable energy has dramatically increased to nearly $286 billion in 2015 which is six times higher than in 2004. However, the total investments in renewables in Europe decreased by 21%, i.e. $48.8 billion (McCrone et al., 2016).

1.4 Intermittent Renewables in Electricity Production Sector in Germany

Germany is a leading country in the low-carbon electricity markets in Europe. Solar and wind power are core renewable sources for Germany. The increasing share of solar and wind power generates large-scale electricity production but aggravates the overall loads of grids. In addition, the intermittency of solar and wind power affects electricity production security for electricity load balancing. It is mainly caused by unpredictable weather conditions such as no sun and wind, and long-term cold weather.

How does Germany maintain the security of electricity production from intermittent solar and wind power?

Facing the ambitious renewables targets in Germany, electricity production has increased since the growth of renewable energy in the power market. But due to lack of favourable weather condition especially in winter time, there is no enough electricity production to meet the high demand for electricity in Germany. Thus, storing large-scale energy is important to maintain the security of electricity production.

Electricity grids can provide high electricity supply but integration costs are high and have no large capacity to store electricity in large volumes in a short term. In this case, pumped hydroelectric storage (PHS) may be a cost-effective solution to store residual electricity and also flexibly adjust electricity supply-demand balancing. In the paper, Norwegian PHS, as a mature storage technology for energy management, may have potential arbitrage values of cross-border electricity trading between Norway and Germany.

1.5 Arbitrage Value and the Hydroelectricity-Production Cycle of PHS

PHS is a cost-effective and sustainable technology, with powerful capacities of energy generation and energy storage, and can flexibly maintain electricity production to meet the relative demand. In the PHS cycle, the pumped electricity production usually occurs: In the off-peak periods, low electricity price leads to a fall in electricity consumption and the electricity is residual in grids. If buying the remaining electricity is purchased at a low cost, pumped water into the upper reservoir for storage, and sell electricity produced by pumping the water back to the lower reservoir from the upper reservoir when the price is high.

Arbitrage values in the economic cycle of pumped electricity production is closely related to electricity prices in the day-ahead electricity spot market and the dynamics in electricity consumption and production in the peak and off-peak time periods. In the peak time, electricity consumption is high at a high cost and electricity production is high at a low cost in the off-peak time. The fluctuated effects of price difference response to the significant utilization of electricity. With the growth of electricity produced from intermittent solar and wind power, producers need to think about how efficiently store cheap surplus electricity to be sold at high-cost and get arbitrage benefits without sunny or windy weather. The purpose of the case study is to test price differences between peak and non-peak electricity prices within the different time periods, which whether affect the levels of arbitrage value of pumped electricity production in the cycle of pumping electricity production in the PHS method.

1.6 Research Questions of This Study

By the end of April 2017, 85% of electricity consumption from renewables, mainly from solar and wind power during the peak hours of a day in Germany (Hanley, S., 2017). It implies that the share proportion of renewables has become lager than before in the electricity sector in Germany. But, intermittency of solar and wind power has impact on the security of electricity supply to match electricity consumption. For example, when the weather is favourable, sufficient electricity supply produced from solar and wind power is to satisfy high electricity consumption. Whereas, in the lack of sunlight and wind, particularly in the winter time, less electricity production from solar and wind leads higher electricity prices and higher electricity demand. As a result, producers increase purchase costs of electricity from abroad and loss large arbitrage values in electricity production cycle.

PHS technology is considered as a supplement solution to improve security of intermittent electricity supply and plays an important role to obtain low-carbon economic benefits in the short term. In the context with the different hourly periods within 24 hours for one day and 168 hours for one week in the entire period (2012-2016), we analyse the electricity price difference in the day-ahead electricity markets for the Norwegian PHS project expanding to the German electricity market, and consider its possibility of large arbitrage values based on daily and weekly patterns of electricity prices in the OSL and the EEX.

The two main research questions in the study, which are presented below:

- Is there an hourly arbitrage value of Norwegian pumped hydropower trading for expansion of Norwegian pumped hydroelectricity storage project to the German electricity market, and will this arbitrage value increase when a connection is made between Norway and Germany?
- Norway has decreased or increased the arbitrage value in that electricity market, when there is increased solar and wind power production in Germany.

To clearly analyse the research question, we follow the given four analysis ideas to estimate the availability of arbitrage values of the Norwegian PHS project connecting with Germany.

1) Analysing electricity price differences in the EEX and the OSL during the peak and off-peak hours of 24 hours in one day and of 168 hours in one week during the entire period from 2012 to 2016.

2) Then we select the daily pattern of electricity price within 24 hours of the day and weekly pattern within 168 hours of the week. The patterns use the time series data on historical hourly electricity prices collected from the OSL (that provided in the Nord Pool) and the EEX market.

3) And we estimate that which pattern between the daily pattern and weekly patterns can create arbitrage strategies in large volume of pumped hydroelectricity trading from the Norwegian PHS project when connecting with Germany.

4) Finally, through investigating the trend of electricity prices in the seven price curves, we assess that Norway has either increased or decreased the arbitrage value from the PHS program, when the rapidly growing share of electricity production from solar and wind power in Germany.

1.7 The Purposes and Structure of This Study

The purposes of this study:

- The main purpose of this study is to estimate if there are large arbitrage values of cross-border electricity trading to make Norwegian pumped hydroelectricity more profitable when expanding Norwegian PHS project to Germany.

- And further objective is that whether the arbitrage value of Norwegian pumped hydroelectricity has been less than before in the German electricity market, when the increased share of electricity production from solar and wind in Germany.

The structure of this study:

- Section 1: The description of renewable energy transition in the electricity markets in Europe.
- Section 2: The background of the electricity markets of Norway and Germany.
- Section 3: Literature review on the relationship between electricity prices and the model of electricity supply and demand, and the relationship between price volatility and arbitrage value. In addition to this we focus to describe energy storage technology and PHS technology which is based on daily pattern of electricity prices. We make the calculation of optimal arbitrage value of pumped hydroelectricity trading, when Norwegian PHS project connecting with Germany.

- Section 4: Following the calculation of optimal arbitrage values from Section 3, we use the time series dataset on electricity prices in the OSL and the EEX, and make seven relevant diagrams for the results of daily pattern and weekly patterns for hourly electricity prices within 24 hours of a day or 168 hours of a week in the five-year period from 2012 to 2016.
- Section 5: We discuss the results of daily and weekly patterns based on the seven graphs and estimate which pattern is the best approach to capture lager arbitrage values of pumped hydroelectricity trading when Norwegian PHS expanding to the German electricity market. Further, we discuss whether Norwegian pumped hydroelectricity has still been valuable during the growing share of electricity generated from solar and wind power in the German electricity sector.
- Section 6: We make a conclusion, that the daily pattern of hourly electricity spot prices may be more profitable to get greater arbitrage values of Norwegian pumped hydroelectricity trading in Germany than in Norway, when investment or expansion Norwegian PHS project to Germany. However, Norway has probably decreased the arbitrage values of pumped hydroelectricity trading with the increased solar and wind production in the German power sector.

2 Background

Electricity is an essential commodity in our daily life, such as commercial workplaces, manufacturing, heating, transportation and households. In the sector, we describe the background of the electricity markets of Germany and Norway and explain the influence of intermittent solar and wind power on electricity supply security in Germany. In this paper, we select the Norwegian PHS technology as a cost-effective solution for intermittent electricity generated from solar and wind power in Germany. Following the research questions of this paper, we use hourly electricity price on the day-ahead electricity spot markets of Norway and Germany, where the OSL market is provide from the Nord Pool and the EEX (European Energy Exchange) market for Germany. The two of electricity exchanges are based on hourly electricity spot prices, €/MWh.

2.1 Norwegian Electricity Market (the OSL) in the Nord Pool

2.1.1 The Nord Pool Market

The Nord Pool market is the first and largest power market in the world, and leading in the power markets in Europe. The four Nordic countries (i.e. Norway, Denmark, Sweden, and Finland) entered the common market, the Nord Pool, from their free markets in the early 1990 (Zafirakis, et al., 2016). Nord Pool has been designated as a nominated electricity market operator (NEMO) for 14 European countries and serves the electricity markets in Poland, Croatia and Bulgaria (Nord Pool, 2016).

The Nord Pool operates the day-ahead and intraday market platforms. Generally, electricity price is higher in early daytimes and lower at nights (Botterud et al., 2010). The frequent volatility of electricity prices in Nord Pool means that the liquidity of the European electricity market can improve energy efficiency and gain returns through a large-scale electricity trading by the daily cycle.

Nord Pool (2016) reported that the Nord Pool market has increased competition for electricity exchange in Europe's electricity trading. In 2016, the average price for the Nordic electricity market was 26.91 €/MWh, and Nord Pool had a total revenue of 505 TWh on electricity transaction. Nord Pool market promotes potential investments in electricity transmission technology in the Nordic and other European regions.

2.1.2 The Norwegian Electricity Market (the OSL)

Norway is a leading low-carbon electricity market in Europe. More than a half of electricity supply in the Nord Pool is provided by hydropower from the Norwegian electricity market, i.e. the OSL (Nord Pool, 2016).

2.1.2.1 The Key Factors of the Current Electricity Market in Norway

Norway is a largest hydroelectricity producer in Europe (Norwegian Ministry of Petroleum Energy, 2016). Norwegian hydroelectric reservoirs and dams are built in the remote mountain areas and hydropower is generated from natural lakes, rivers, streams and waterfalls. Over 96% of electricity production from hydropower is used to almost all of Norway's energy industries (NVE, 2016). There are some key factors of the current Norwegian electricity market are shown as follows (SSB, 2016).

- The large amount of hydroelectricity production guarantees the security of electricity supply. The total electricity production reached 149.5 TWh in 2016, an increase of 3.1% from 2015. The hydropower production accounted for 96.3% of the total electricity production in 2016, compared with 95.8% in 2015.

- The overall tendency of electricity consumption is on the rise. It means that high electricity demand for peak load and high electricity price on the OSL. The total electricity consumption was 133.1 TWh in 2016.

- Norwegian electricity trading in 2014 was about 6100 MW with other European countries, higher than Germany and UK. In 2016, Net electricity export in Norway was 16.5 TWh and 5.7 TWh of electricity import.

2.1.2.2 A Case Example: Electricity Trading between Norway and the UK

Norway is a leading energy interconnector for electricity transmission in the Europe's other electricity markets. For example, Farrell (2015) reported that the agreement is set up by Norway and the UK is to build the world's longest sub-sea electricity interconnector (730 km) between both of the two countries, and Norway will supply about 750,000 MW of the low-carbon electricity to the UK by 2021. "The agreement will benefit the UK homes save up to £3.5bn over 25 years via importing Norwegian cheaper electricity", predicted by Britain's energy regulator. Hence, the agreement will be beneficial to increase security of electricity supply and increase the share of renewables in the UK.

Farrell (2015) addressed it is also beneficial for investors to get returns through exporting surplus electricity to other countries in the short term when lower electricity prices in UK. In return, the interconnection project, NSL (North Sea Link), which brings potential profitability to Norway, which are as follow.

- Increasing Norwegian hydropower share in the European electricity market, based on lower electricity price in the OSL.
- Increasing electricity supply security to meet electricity demands.
- Increasing the electricity market competition in cross-border electricity trading.

2.1.2.3 A Possibility of Cross-border Electricity Trading to Germany

The security of electricity production is crucial to meet the rapid growth of electricity demand for peak load. Norway and Germany are the main electricity markets in Europe. Intermittent electricity production from solar and wind power in Germany makes it possible to affect the security of electricity production. Norwegian PHS is a flexible and efficient method, with high energy input and output efficiency, large energy storage capacity and integration capacity. Hence, the Norwegian PHS approach might be a cost-effective solution to improve the security of intermittent electricity production in Germany.

We know that electricity price difference determines arbitrage opportunities in the short time. Electricity spot prices in the OSL is lower than that in Germany. It implies the price differences between the high and low prices in Germany is greater than in Norway. Thus, it is a possibility to create the arbitrage values of cross-border electricity trading if the Norwegian PHS project connecting with Germany.

As mentioned as the former part, the project of an undersea electricity interconnection between Norway and the UK which is beneficial to not only increase the security of electricity output in the UK, but also investors can achieve the short-term arbitrage revenues. Thereby, the Norwegian PHS project may be an efficient solution to get arbitrage values of the cross-border electricity trade though expanding the Norwegian PHS project to the German electricity market.

2.2 The German Electricity Market

Germany is the core of connecting with the entire European electricity system. To get large arbitrage values and other returns, investors and producers need to consider not only the security of electricity supply is a key element for load balancing, but electricity spot prices in the electricity exchange markets is also an import factor for the cross-border electricity transaction in the German electricity market.

2.2.1 The European Energy Exchange (EEX)

The European Energy Exchange (EEX), as an independent market of electricity trading, was built by the merger of two Germany's energy exchanges in Frankfurt and Leipzig in 2002, and is the leading energy exchange in Europe (EEX, 2017). The EEX holds 50% share of the European Power Exchange (EPEX SPOT) (Zafirakis et al., 2016). On the EEX's spot and derivatives markets, market liquidity and transparent pricing can reduce the financial losses in the process of buying and selling electricity in the short time. In addition, cross-regional electricity integration can increase the interconnection opportunities with other neighbours to strengthen the security of electricity supply. The establishment of EEX aims Germany to become a liberalized electricity market to increase market competition and improve the liquidly of electricity market for the low-carbon electricity trading.

2.2.2 Renewable Transition in the German Electricity Market

Germany's Energiewende (2017), the German Energy Transition, addresses the motivation of energy transformation, "By the year 2020, Germany's GHG emissions shall be reduced by 40% compared to 1990, until 2050 by 80 to 95%." BMWi (2017) addresses that "By 2025, 40-45% of electricity consumption is to derive from renewables in Germany. The total volume of electricity consumption provided from renewables has reached to 31.7% in 2016 compared to 6% in 2000, and electricity exports in 2016 reached 80.7 billion kWh while 27 billion kWh of electricity imports". During the recent three decades, solar and wind power are viewed as major renewable contributors to generate electricity production in Germany. The expansion of shares of solar and wind power has rapidly increased in the electricity system. In 2016, electricity production from solar and wind power accounted for 33.9%, slightly over than 32.9% in 2015 (Burger, B., 2017).

In the face of the increase in low-carbon economic growth in Germany, plants from nuclear power and coals have to shut down by 2022 (Chow, L. 2017). Low-cost renewables lead to the fall in electricity spot prices in the day-ahead electricity market. EU (2016) reported in the EEX, the price of electricity was 30 €/MWh in February 2016 and was the lowest since March 2007 in the wholesale electricity market. BMWi (2017) addresses that the future liberalized electricity market in Germany can provide a large proportion of electricity production from renewables, but also improve the security of energy supply for load balancing. Therefore, it is significantly fundamental to transform renewables from fossil fuels in the electricity market.

At present, German electricity grids cannot have the high capacity of energy storage and electricity transformation for large-scale electricity produced by solar and wind power. The German Energiewende announced that cutting investment of electricity generated from fossil fuels into grids and investment in energy technology regarding energy generation capacity and energy storage capacity to increase the security of intermittent electricity production in the short time (Bräutigam, A. 2015).

2.2.3 Intermittent Electricity Production in Germany

It is vital to develop a cost-effective method to store intermittent electricity for load balancing. German grids are powerful and adjust between electricity supply and demand (Martinot, E., 2015). However, the greater share of intermittent electricity in Germany leads to transmission and storage capacity from grids cannot adapt to store and integrate large-scale intermittent electricity production from solar and wind power. Currently, energy storage technology for intermittent electricity becomes a hot topic (Zafirakis, et al., 2016), because of energy storage performance not only improves the security of intermittent electricity supply and also captures a range of short-term arbitrage values of electricity trading. Therefore, designing an efficient energy storage solution is a significant economic approach for intermittent electricity to improve the security of electricity supply in the electricity production sector in Germany.

2.3 Expansion the Norwegian PHS Project to Germany

Due to the unstable weather, solar and wind power is unable to continuously produce electricity. Intermittent electricity affects the volume of electricity production to meet the peak electricity consumption in the short time. Thus, it is necessary to store surplus intermittent electricity from solar and wind power by applying energy storage method in the short time, when the rapidly growing share of renewables in the Germany electricity market.

Norway is Germany's neighbouring country and has a beneficial platform, the pumped hydroelectric storage (PHS) system, which contains high energy capacity and energy storage capacity. Geographical advantage in Norway makes it possible to expand the PHS project that hydroelectricity timely integrated into the German electricity market. Perhaps PHS figures out the intermittent electricity issue and flexibly balance the electricity supply and demand in the short time. In addition, profitability of PHS is mainly associated with the dynamics of electricity prices in the electricity exchange markets and the price gaps between the peak and non-peak electricity prices by time patterns. High price variability creates the large arbitrage values.

PHS technology is viewed as an electricity interconnector. There are two basic conditions for the cost-effective interconnection between Norway and Germany, the economic profitability and electricity supply security. When expanding the Norwegian PHS program to Germany, it might bring the potential arbitrage values of electricity trading in terms of the round-trip cycle of pumped hydroelectricity production in PHS. As a result, it is important to make a cross-border cooperation regarding renewable electricity interconnection with neighbours. Norwegian PHS investment to Germany may be a cost-effective method to maintain the security electricity production, improve the liquidity of electricity trade market and achieve large arbitrage values of electricity trading.

3 PHS Technology and Arbitrage Values

In this section, we focus not only on energy storage and PHS technology, but also the relevant economic concepts. Firstly, we introduce the special features of electricity and introduce the dynamics in electricity supply and demand. Then, we describe how some major elements affect the electricity price volatility between the peak and off-peak spot prices on the day ahead of electricity market. Furthermore, we introduce the basic technical and economic knowledge of PHS and the calculation of hourly arbitrage values by daily cycle in the different hour periods, considering that the Norwegian PHS project when investing or expanding to the German electricity market, there are large arbitrage values of Norwegian pumped hydroelectricity transaction.

3.1 Special Characteristics of Electricity

A liberalization of electricity markets is profitable for cross-border electricity trading throughout the analysis of price volatility between the maximum price and the minimum price in the day-ahead electricity spot markets. With the increasing demand for electricity, generating and storing electricity are very important to keep the security of electricity production and meet the electricity consumption. However, electricity is an ineffective commodity in the long run (Parail, V., 2010). Wangensteen (2012) showed that the unique commodity of characteristics to explain the question regarding why electricity cannot make electricity trading in the long time? The special features are shown below.

- A short-run product that is produced and immediately sold.
- Non-storability.
- Consumption variability.
- Breakdown possibility.

As a result, these factors are important to improve the capacity of electricity generations and storage when existing surplus or insufficient electricity produced by intermittent renewables. Meanwhile, strengthen the balance between electricity supply and demand is also important for electricity trading including cross-border trading over time. In fact, it is not easy to keep the balance, as the volatility of electricity spot prices is a fundamental economic element to affect the balanced flow of electricity production and consumption.

3.2 Major Factors Affecting Electricity Prices Volatility

3.2.1 The Relationship between Electricity Prices and Electricity Production and Consumption

In the paper, electricity prices we used are usually volatile in the day-ahead electricity spot markets. In the short run, when electricity spot prices are low, low electricity consumption leads electricity production residual during the off-peak periods. When electricity spot prices are high, producers have to produce enough electricity output to meet electricity consumption during the peak periods. In turn, the dynamic electricity consumption and production also has an impact on electricity spot prices on the electricity spot market in the short time. For example, lower electricity production especially generated from intermittent solar and wind power during the peak time, high electricity demand for peak load leads to increase electricity spot prices. As a result, the differences in electricity spot prices between the high and low spot prices, which reflect the dynamics of electricity production and consumption, but also determine arbitrage values of electricity trading in the short run. Also, electricity prices are affected by the following other factors in the current electricity market, for instance, low-cost renewables, costs of power plants, weather conditions (Chamberlain, H., 2015).

3.2.2 Electricity Price Volatility

The dynamic electricity system determines the volatility of electricity prices in the day-ahead electricity spot market (Wangensteen, 2012). Price volatility plays an important role to vary arbitrage values and the balance of electricity production and consumption in the short term. High electricity price volatility for electricity trading is mainly caused by the lack of cost-effective energy storage system in the electricity markets (Werner, D., 2014), but can create large arbitrage values through the process of buying and selling electricity during the peak and off-peak short periods.

What factors affect the electricity prices volatility for the Norwegian PHS project?

In the study, Norwegian PHS, as an interconnector for electricity trading between Norway and Germany. There are main elements affect electricity volatility for the Norwegian PHS project, which are as follow.

i. The model of electricity supply-demand about electricity production and consumption has an immediate impact on the volatility of electricity prices in the electricity day-ahead markets during the short-term periods. Load balance, namely, the balance of electricity supply and demand is one of the major applications from PHS system, which is interacted with electricity spot prices in the electricity markets.

ii. Time pattern of electricity spot prices is an important factor to affect the volatility of electricity prices, because electricity price volatility between the high and low prices, which takes place during the peak and off-peak periods of electricity delivery. In the paper, we selected the short-term periods, which are within 24 hours of a day and 168 hours of a week during the 5-year period from 2012 to 2016. During the peak and off-peak hourly periods, we investigate which period of a day or a week makes it possible to create large arbitrage values of Norwegian pumped hydroelectricity trading for expansion Norwegian PHS to Germany.

iii. Additionally, the factor transmission electricity losses affect the volatility of electricity prices between the peak and off-peak spot prices during the periods of electricity delivery. Grid owners or producers buy electricity to offset for transmission losses from the input node to the market, while consumers pay for the transmission loss from the market to the output node. Therefore, the transmission tariffs in grids system determines the variability of spot prices which between electricity input and output. High spot price for the losses leads to increase transmission cost. Wangensteen (2012) concluded that there will be no economic losses for producers, grid operators and consumers. Thus, the transmission loss costs are neglected in the paper.

Therefore, in the following sections we will describe each factor which affect electricity price volatility and understand clearly that arbitrage value levels are determined by the electricity price differences in the peak and off-peak electricity prices based on time patterns for hourly electricity prices in the OSL and the EEX markets.

3.3 The Electricity Supply-Demand Model and Electricity Prices

The basic mission for the healthy electricity market is to adjust the balance between electricity supply and demand over times (Newbery, D., 2016). The dynamics between electricity supply and demand have an impact on electricity price changes in the electricity exchange markets. Further, the volatility of electricity prices between the high and low prices affects to the equilibrium of supply and demand for electricity (Whelan, et al., 2001). During a peak and non-peak time series, we emphasis on the interaction behaviours between the electricity supply-demand model and the volatility of electricity prices in the day-ahead electricity market.

3.3.1 The Shifting Electricity Demand

Theoretically, high demand for a product defines that the large quantity of the product is bought by end consumers are willing to buy and producers are willing to sell during the peak periods. But, in the electricity markets, costly electricity is not beneficial for end consumers, but for investors and producers to get more arbitrage values during the peak periods. However, during the off-peak periods, low electricity demand and low electricity prices make it possible electricity is residual in the markets. It is not profitable for investors and producers, but for end consumers to save electricity expenditures. Wangensteen (2012) stated that it is the marginal utility of electricity consumption and production.

Apart from electricity price changes affect electricity demand for peak load, end consumers' income also has an impact on the demand for electricity. Whelan et al., (2001) explained that high prices of a product means that the demand goes down, because consumers need to consider their own income levels. In addition, economic growth of a country influences the shifting electricity demand. Increase in economic growth for a country means that increase in incomes for end consumers, high income increases electricity consumption and demand during the peak periods, while low income decreases electricity demand. In the past two decades, the increasing share of renewables in the electricity generations, which has increased low-carbon economic growth and has decreased electricity prices. It is significant to raise the demand for low-carbon electricity.

Therefore, in the competitive electricity markets, the shifting electricity demand mostly relies on electricity price variability in the peak and off-peak periods, end-consumers' income and national economic growth. In this paper, peak electricity demand represents that there are peak electricity prices, which are profitable for investors and producers to get arbitrage value opportunities depending on the volatility of electricity prices for the Norwegian PHS expanding to Germany.

3.3.2 Electricity Production

The dynamic supply-demand model affects electricity prices, in turn, electricity prices determine the equilibrium of electricity supply and demand over time. Low electricity price occurs during the off-peak periods, at the same time, electricity demand is low and electricity production is surplus in the markets. Investors and producers can buy the cheap electricity to pump water to be stored as hydropower in the reservoirs of PHS during the off-peak periods. When electricity price rises during the peak times, electricity production is required to be sufficient to meet the high electricity demand. Investors and producers can convert the stored hydropower back into hydroelectricity for sale. Generally, arbitrage values are created in the cycle of pumped hydroelectricity production in PHS, based on the electricity demand and supply and electricity spot price changes. Thus, electricity production is significantly correlated by the fluctuating electricity prices in the electricity day-ahead markets and the balance of electricity supply and demand during the peak and off-peak periods.

3.4 Energy Storage Technology

Usually, power plants with high energy efficiency can produce enough electricity to meet end consumers' needs within 24 hours of a day. But electricity is non-storable and high electricity generation from intermittent renewable energy over times of a day have become more attractive in the electricity sector. Wood (2017) reported that the installed capacity of Energy storage will reach 8.13 Gigawatt and the returns of the global energy system will rise by 30% by the end of 2017, because of the fall in energy storage costs and the increased electricity consumption. In the European electricity system, investment in cost-effective energy storages is increasing under the rapid increase in renewables (Carbon Brief, 2015).

To be a liberalized and a low-carbon electricity market in Europe, EAC (2014) addressed energy storage technologies have become alternative economic methods to deal with the peak and non-peak load constraints from intermittent electricity across Europe. Table 1 shows that the main energy storage technologies, which come with their own characteristics and applications (Italiana, F., 2012).

Table 1: Main characteristics and applications of Energy storage technologies

Storage device	Storage medium	Power Capacity	Storage capacity	Remarks
Pumped-Hydroelectric Energy Storage (PHS)	Mechanical	Large	Large	Load levelling, frequency regulation, peak generation
Compressed Air Energy Storage (CAES)	Mechanical	Large	Large	Load following, frequency regulation, voltage control
Lead-Acid Battery (LAB)	Chemical	Medium	Medium	Backup power, USP system. Life: 5 y, 250-1,000 cycles
Nickel-Cadmium Battery (NCB)	Chemical	Medium	Medium	storage for solar gen., engine start. Life: 10-15 y, 1,000-3,500 cycles
Sodium-Sulphur Battery (SSB)	Chemical	Medium	Medium	Load management, Power quality Life: > than others; 2,500 cycles
Vanadium Redox Flow Battery (VRFB)	Chemical	Medium	Medium	Integration of renewable resources. Life: 7-15 y, 10,000 cycles
Flywheels	Mechanical	Small	Small	USP system, Integration of wind farms
Supercapacitor Energy Storage (SES)	Electrical	Small	Small	Power quality
Superconducting Magnetic Energy Storage (SMES)	Magnetic	Small	Small	Integration of renewable resources, Transmission upgrade deferral

Source: Operating flexibility of power plants with CCS, 2012.

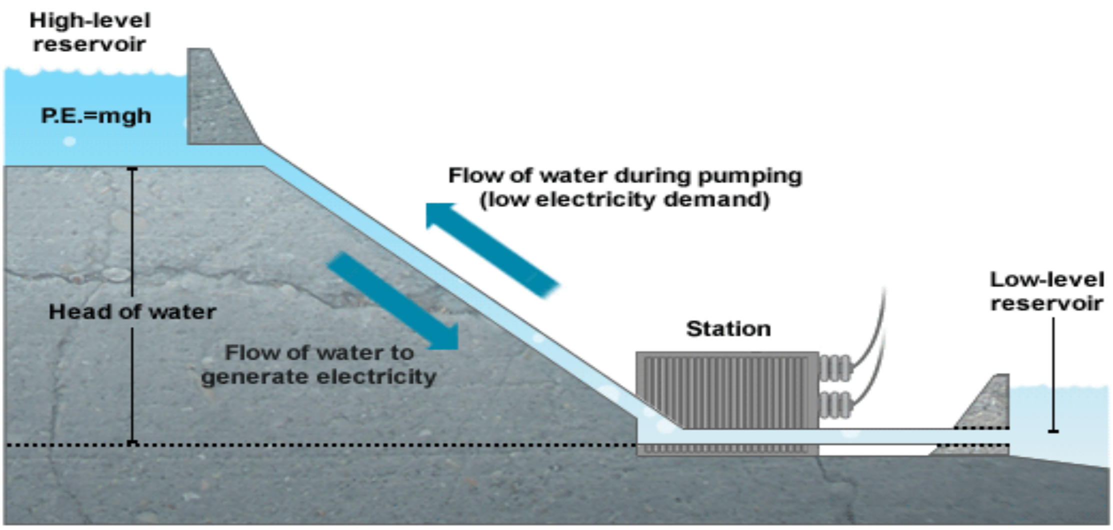
As shown on Table 1, PHS and CAES have similar features and applications for energy management and other technologies such as Sodium-Sulphur Battery (SSB) and Supercapacitor Energy Storage (SES) adapt to applications for power quality (Zafirakis, et al., 2016). PHS and CAES are efficient approaches to achieve revenues in the short term. However, CAES generates electricity through burning natural gas to store energy in an underground storage reservoirs, while PHS generate hydroelectricity by pumping the water back into the reservoirs (IEAGHG, 2012). Also, CAES applications use about 55% of fuel consumption and is conflict with the ambitious clean energy targets by 2030. CAES is not an independent electricity system, but need to cooperate with a gas turbine plant for energy management. So, it leads to high costs of investment in a CAES plant (Chen, et al., 2009). Compared with CAES, PHS is the most low-carbon and cheapest energy storage technology (Gurzu, A., 2017). PHS technology is a cost-effective method, which independently operate energy management and quickly adjust electricity production to match a shifting demand in the peak periods. It is beneficial to improve the security of electricity supply, but also achieve arbitrage strategies in the short term.

3.5 PHS Technology

3.5.1 The Pumped-Hydroelectricity-Production Cycle in PHS

Because of low cost and high energy efficiency of PHS, Norway with 937 hydropower plants could become "Europe's green battery" (Haugan, I. 2015). It is possibly beneficial to store large-scale intermittent electricity generated from solar and wind power and get short-term arbitrage values of electricity trading if Norwegian PHS connecting with the German electricity market. Operating PHS aims to increase electricity production security and flexibly adjust the equilibrium in supply and demand for peak and non-peak load by day and night. The technique principle of PHS system is shown in Figure 1 (Newbery, D., 2016).

Figure 1: The hydroelectricity-production cycle of pumped hydroelectricity storage



Source: Image is taken from BBC bitesize.

During the non-peak periods, i.e. at nights and weekends, low electricity price not only represents low electricity demand or consumption, but also electricity production is residual in the grids. PHS method is significant for energy management to figure out the issue of surplus electricity in grids and to earn more arbitrage revenues in the short term.

According to Figure 1, the cost-effective cycle of pumped hydroelectricity production in PHS, which is shown as follow.

i. When electricity price is low, electricity demand is low and electricity supply is excess during the off-peak periods. Grid operators, electricity producers and investors are willing to buy the cheap electricity from grids and use it to pump water back into the upper reservoir and then is stored in the upper reservoir.

ii. And when electricity price is high, it means electricity consumption for peak load is high during the peak periods. In the cycle of PHS, the stored water from the upper reservoir is pumped back to the lower reservoir and converted into hydroelectricity to be sold. At this moment, arbitrage value may be captured from this PHS's cycle based on electricity price volatility between the peak and off-peak prices in the electricity exchange markets in the short term.

Electricity generation duration in the cycle of PHS is only a few minutes, up to 40 times for a day, and produce 70% of electricity output and 40% of electricity production stored in PHS (IEAGHG, 2012). The flexibility of PHS makes it possible for electricity to be pumped back into hydropower in the off-peak periods and then be quickly converted into hydroelectricity to be sold with peak prices. Thus, the flexibility of pumped hydroelectricity production in PHS is significant to bring more profits. For instance, increasing electricity efficiency, strengthening electricity production supply, the efficient adjustment between electricity demand and supply in the competitive electricity markets, and use minimum costs to achieve optimal arbitrage strategies. There is no denying that PHS is a cost-effective method to figure out large-scale storage of intermittent electricity and has opportunities to get short-term arbitrage values.

3.5.2 Costs of PHS

PHS technology is currently the most commonly utilized and commercially feasible technology of electricity storage. Compared with CAES, the facilities of PHS can utilize electricity price difference to provide cost-effective ancillary grid services. (Ma, et al., 2014). However, investment in installation of facilities in PHS is costly IEAGHG (2012), for example, component costs of facilities in PHS plants are ranged between 600 $ / KWh and 2,000 $/ KWh, while the component costs of other energy storage plants are relatively cheap, about 10 $/KWh. Further, the total costs of a PHS plant cannot be decided by individual owners, but are controlled by monopoly enterprises and the relevant national energy institutions. Therefore, in the case study, it might not be a good idea for German individual owners to invest in building new large-scale PHS plants in location and even in remote areas in Germany.

3.5.3 Main Characteristics of PHS

The applications of PHS in the world are close to 99% of conventional energy storage system, and the rest is supplemented by batteries (Newbery, D., 2016). PHS plant are generally used to adjust the load balancing and the peak shaving by pumping a certain level of water into the upper or lower reservoirs (Rahman, et al., 2012). The major factors such as energy efficiency, transmission capacity and storage capacity, have an economic impact on PHS performance.

The Energy Storage Association (ESA) reported that the transmission losses happen when pumping water to reservoirs in the round-trip cycle of pumped hydroelectricity from PHS system. To minimize the costs of transmission losses, energy efficiency (the ratio of energy output and energy input) is a key element to improve capacities of energy generation and storage, and also to adjust electricity production and the shifting electricity demand. PHS system needs at least 80% energy efficiency for the maximum arbitrage values (Flatley, et al., 2016). Today, the energy efficiency of PHS system varies between 70% and 80 %, and can even reach to 87% (Rehman, et al., 2015). Thus, high energy efficiency is not only more beneficial in minimizing transmission loss costs and guarantee electricity supply security but is also vital to achieve large arbitrage revenues of electricity trading from the pumped hydroelectricity production cycle of PHS when connecting with remote areas and cross-border countries. Generally, large-scale PHS is set between 2000 and 3000 MW, compared to the normal size of PHS (1,000 - and 1,500 MW) (Rehman, et al., 2015). Energy generation capacity of over 240 facilities of PHS system has more than 90 GW (which is 90,000 MW), is equivalent to roughly 3% of the global electricity generation. Electricity storage capacity for a single facility of PHS can be varied between 30MW and 4,000MW of (IEAGHG, 2012). Therefore, investors and electricity producers expect the minimum investment to obtain higher short-term arbitrage values of pumped hydroelectricity transaction through Norwegian cost-effective PHS when connecting with Norway and Germany.

3.5.4 Electricity in the Pumped Hydroelectricity Production Cycle of PHS

We employ the two equations made from the Zafirakis (2016) to analyse the factors of pumped hydroelectricity production cycle in PHS plants. Other factors related of energy efficiency are viewed constant and ignored in this paper. Equation (1) represents the real electricity to buy from electricity grids to the PHS system, which is shown below.

$$E_t^{buy} = \frac{E_{in}}{\eta_{in}} = \frac{E_{storage}}{\eta_{in}} = \frac{N_{in}\Delta t_{ch}}{\eta_{in}} \qquad (1)$$

Where,

E_t^{buy}: Real electricity to buy in the buying hours.

E_{in}: Nominal electricity from grids in the buying hours.

η_{in}: Electricity input efficiency of PHS system.

N_{in} : Volume of the nominal electricity E_{in}.

$E_{Storage}$: Energy storage capacity of the PHS system.
$\frac{E_{storage}}{\eta_{in}}$: The rate of energy storage capacity to input energy efficiency.
Δt_{ch}: The off-peak time period of pumping the water to the upper reservoir.

Where, E_t^{buy} indicates how much actual electricity can be stored in the upper reservoir by pumping water during the buying hours, and is determined by the nominal electricity purchased from grids and input efficiency. Energy efficiency of PHS system include input efficiency η_{in} and output efficiency η_{out} (Zafirakis, et al., 2016), we use η_{in} (85%) and η_{out} (90%) to estimate the optimal arbitrage value in the study.

According to Zafirakis, (2016), $E_{out} = E_{Storage}$, is used to the real electricity for sale in the selling hours, E_t^{sell}, is written by Equation (2), then

$$E_t^{sell} = E_{Storage} * \eta_{out} = E_{out} * \eta_{out} = N_{out} * \Delta t_{dis} \tag{2}$$

Where,
E_t^{sell}: Real pumped hydroelectricity for sale in the selling hours.
η_{out}: Electricity output efficiency of PHS system.
E_{out}: Nominal pumped hydroelectricity in the selling hours.
N_{out} : Nominal volume of pumped hydroelectricity to be sold.
Δt_{dis}: The peak time series of pumping the water back into electricity.

In Equation (2), E_t^{sell} is determined by PHS's energy storage capacity and the output efficiency. Large storage capacity and high output efficiency of PHS can provide sufficient the actual electricity output and achieve large arbitrage values in the cross-border electricity trading.

Through analysing Equation (1) and (2), energy efficiency of PHS system within the short-term signals are significantly correlated with the real quantities of electricity input and output and short-term arbitrage values of electricity trading.

3.6 Arbitrage Values in the Short Term

Short-term arbitrage value is basically determined by electricity price differences between the peak and off-peak spot prices in the day-ahead electricity spot markets in the short term. In this paper, hourly arbitrage values rely on the time series of daily and weekly patterns within 24 hours of a day or 168 hours of a week during the entire period from 2012 to 2016. Different hourly periods determine how much hourly arbitrage values can be achieved from a corresponding pattern of hourly electricity prices on the OSL and the EEX.

3.6.1 Definition and Main Factors of Arbitrage Values

Definition

Generally, hourly arbitrage value is captured by hourly price differences between the high and low spot prices by buying a cheap product and selling it at a high price (Macpherson, T., 2014). Due to the dynamic electricity price fluctuations in the electricity markets, investors or producers would like to buy cheap electricity in large volumes during an off-peak period and selling it when electricity price is high in a peak period, then the arbitrage value could be captured in the process. Actually, arbitrage values are captured through applying the classic economic concept, “buy low and sell high” (Hagstrom, R.G., 1997).

Main Factors

Hourly arbitrage values of electricity trading are mainly determined by hourly electricity price volatility between the peak and off-peak spot prices in the day-ahead electricity exchange markets during the short periods. Whereas on the other hand, hourly arbitrage value is also determined by electricity delivery time patterns in a short period. We select daily and weekly patterns within each of 24 hours a day or 168 hours of a week between 2012 and 2016 to estimate arbitrage values of pumped hydroelectricity trading from Norwegian PHS when expanding to the German electricity market.

In addition, in the process of pumping water back to reservoirs or converting back to electricity in the PHS, there are transformation losses, the maximum quantities of electricity production and electricity storage, which all of these affect electricity price changes in the day-ahead electricity spot markets. Then, it is inevitable to have an impact on the levels of arbitrage values of electricity trading in the cycle of PHS, because of hourly arbitrage values is determined by hourly price differences between the peak and off-peak prices. In this paper, transmission losses, electricity production and electricity storage are constant and their costs are covered into the hourly electricity spot prices in the OSL and the EEX.

3.6.2 Calculation of Arbitrage Values

Usually gird operators and producers manage electricity supply and increase prices to get arbitrage opportunities in a short time series (Birge, et al, 2017). It means that arbitrage values are closely related to electricity prices, electricity supply and demand during the peak and non-peak periods. Thus, we investigate electricity price volatility from daily or weekly pattern of electricity prices to estimate how it affects arbitrage values of electricity trading when the Norwegian PHS expanding to Germany.

In the PHS method, producers or investors are willing to buy a lot of cheaper electricity that pumped the water into the high-level reservoir within the off-peak hours. In case when the electricity price is high, the stored water is pumped back into the low-level reservoir and converted into electricity for sale. Thus, the potential arbitrage values could be created in the round-trip cycle of pumping water to generate electricity in the PHS system.

In the following part, we use the relevant formulas for arbitrage values to evaluate how much arbitrage values can be achieved in the round-trip cycle of PHS system. Zafirakis et al., (2016) addressed that the real electricity to buy E_t^{buy} is not equal to the real electricity for sale, E_t^{sell} in the round-trip cycle of pumped electricity production in PHS system, because energy transmission losses usually occurs in the process of pumping water back into reservoirs. As a result, the real electricity to buy is much than the real electricity for sale, namely, $E_t^{buy} > E_t^{sell}$. In the paper, we set transmission loss costs and electricity production costs in PHS method, which are already included in the electricity spot prices on the day-ahead electricity markets. They can be neglected in the paper.

We use price volatility between the peak and off-peak prices within each of 24 hours for a day or each of hours of 168 for a week, in terms of the spot prices dataset collected from the Nord Pool and EEX markets, and estimate optimal arbitrage values from the round-trip cycle of pumped electricity production in the Norwegian PHS. Though investigating the average hourly electricity prices in the OSL and the EEX from 2012 to 2016, we calculate the average hourly electricity prices gaps happened during the peak and non-peak hours within 24 hours of one day or 168 hours of one week, i.e., the off-peak buying hours is h_t^{buy} and the peak selling hours is h_t^{sell}.

There is an alternative specification of the paper compared to Zafirakis et al., (2016), which is to consider an arbitrage value (ARV) policy of storing one unit of energy per hour (1 MWh) in the Norwegian PHS system, which is based on the basic arbitrage value concept of buying in hours with low electricity prices and selling in hours within high electricity prices.

Thus, we set the time restriction for the alternative arbitrage policy, which is hours of T hours for buying or selling electricity, that is, T = 24 for a day or T = 168 for a week, respectively. Electricity spot price C_{spot} is presented within each hours of 24 hours or 168 hours, i.e., hour t = 1,…., T. In the arbitrage value process of buying and selling electricity trading, if the peak selling hours h_t^{sell}=1 in the hours of selling, which is equal to the off-peak buying hours h_t^{buy} =1 in the hours of buying, i.e., $h_t^{sell} = h_t^{buy}$=1, it is statistically significant to get an optimal arbitrage value of pumped hydroelectricity trading through the round-trip cycle of the Norwegian PHS project. Otherwise, there is no arbitrage value opportunities if $h_t^{sell} = h_t^{buy}$=0.

The storage balance requires that $\sum_{t=1}^{T} h_t^{sell} = \sum_{t=1}^{T} h_t^{buy}, \leq E_{max}^{storage}$ that is, the sum of all the selling hours should be equivalent to the sum of all the buying hours, then the real electricity storage capacity for the buying and selling electricity trading during the same hours should be less than $E_{max}^{storage}$,where $E_{max}^{storage}$ is the maximum available storage capacity.

Usually, energy efficiency determines the level of losses of electricity transmission and also determines energy production capacity and storage capacity. In the study, the transmission losses and its loss costs are ignored in the arbitrage value calculation. But we have to consider the parameters of energy efficiency of PHS, which are energy input efficiency η_{in} (85%) and energy output efficiency η_{out} (90%). As a result, the total hourly arbitrage value (ARV) over T hours within 24 hours by the daily pattern is written by Equation (3), then

$$ARV = \sum_{t=1}^{T} h_t^{sell}(C_{spot}\ \eta_{out}) - \sum_{t=1}^{T} h_t^{buy}\ (C_{spot}\ \frac{1}{\eta_{in}}) \tag{3}$$

Where ARV is calculated on the basis of the difference between the total revenues in the sum of selling hours $\sum_{t=1}^{T} h_t^{sell}(C_{spot}\ \eta_{out})$ and the total costs in the sum of buying hours $\sum_{t=1}^{T} h_t^{buy}\ (C_{spot}\ \frac{1}{\eta_{in}})$. C_{spot} is for hourly electricity prices in the EEX and the OSL, respectively. $C_{spot} h_t^{sell}$ represents that the sum of revenues received from electricity sale during the total selling hours, $\sum_{t=1}^{T} h_t^{sell}$ and $C_{spot}\ h_t^{buy}$ means that the sum of buying cost during the total buying hours $\sum_{t=1}^{T} h_t^{buy}$.

To get an optimal hourly arbitrage strategy based on the daily pattern, we buy cheap electricity in some hours and selling it with high prices in other hours of the day in the EEX, we consider the calculation process of Equation (3), which is as follow.

- The sum of selling revenues for the total selling hours is: electricity price C_{spot} multiply with in the total selling hours $\sum_{t=1}^{T} h_t^{sell}$ with the output efficiency parameter η_{out} . If h_t^{sell} =1in the total hours of selling electricity, otherwise h_t^{sell} =0 that means there is no arbitrage value of the Norwegian PHS expanded to Germany.
- The sum of buying cost for the total buying hours is to multiply with C_{spot} in the total buying hours $\sum_{t=1}^{T} h_t^{buy}$, with input efficiency parameter $\frac{1}{\eta_{in}}$. If h_t^{buy}=1 in the hours of buying, i.e., in buying hours of 24 hours, h_t^{buy} =0 otherwise.
- We note that: h_t^{sell} is not equal to h_t^{buy}, but the sum of h_t^{sell} is equal to the sum of h_t^{buy} , i.e., $\sum_{t=1}^{T} h_t^{sell} = \sum_{t=1}^{T} h_t^{buy}$.
- Then we take the sum of all of the selling hours results in the day and subtract it with the sum of all the buying hours results.
- Finally, we can estimate whether there is the arbitrage value created between the sum of buying hours and the sum of selling hours in the 24-hour day.

We consider explore two alternative arbitrage strategies by buying off-peak electricity in some hours of the day, i.e., $h_t^{buy} = 1$, and selling pumped hydroelectricity in other hours, i.e., $h_t^{sell} = 1$. Note that the sum of h_t^{buy} within T hours of the day has to be equivalent to the sum of h_t^{sell} within (24-T) hours, that is, the parameter for the sum of h_t^{sell} is equal to the parameter for the sum of h_t^{buy} , i.e., $\sum_{t=1}^{T} h_t^{sell} = \sum_{t=1}^{T} h_t^{buy}$. The relevant results of arbitrage strategy A and B will be shown in Chapter 4.2.2.

4 Data and Results

4.1 Data

The purpose of the paper is to estimate large hourly arbitrage values of cross-border pumped hydroelectricity transaction from the Norwegian PHS when connecting with Germany. We have access to the time series dataset [2] on the historical hourly electricity prices, price _hourly.dta, collected from the OSL (which is provided from the Nord Pool) and the EEX. We investigate the dataset on the historical hourly electricity spot prices in each of 24 hours a day and 168 hours a week during the five-year period from 2012 to 2016. The dataset is used to estimate the daily or weekly patterns whether it is statistically significant for optimal arbitrage value of electricity trading when Norwegian PHS connecting with in the German electricity market. The patterns depend on price fluctuations between the peak and off-peak prices of the OSL and EEX, and are exhibited in each of the following seven curves.
On the dataset, there are main seven variables, which are year, week, day, h, hid, and price_osl and price_eex, respectively. From Equation (1), C_{spot} is for the empirical hourly electricity spot prices, price_osl from the OSL and price_eex from the EEX. And price differences between the peak and off-peak prices in the EEX is larger than in the OSL, which determines arbitrages values for cross-border electricity trading between Norway and Germany. In addition, the variable, hid, means that the low electricity prices occur at midnight Sunday to early Monday morning within 168 hours for a week. And the variable, h, the buying hours or selling hours within 24 hours for one day.

The following results of the daily pattern and weekly patterns are displayed in the next part, which explain whether large arbitrage value by the daily pattern in the 24 hours of a day is the optimal method, compared with weekly patterns within 168 hours of a week from 2012 and 2016. Further, we evaluate which electricity markets between Norway and Germany is more valuable to create larger arbitrage of cross-border pumped hydroelectricity trading by investing or expanding Norwegian PHS Germany, especially the rapidly increasing share of solar and wind production in the German electricity production sector.

4.2 Results of Arbitrage Values from Daily and Weekly Patterns

Arbitrage value is determined by the variability of electricity spot prices during the peak and non-peak hours in the short term. By investigating price volatility between the peak and off-peak prices in the 24-hour day or the 168-hour week in Germany and Norway, we can see that different time patterns of electricity prices on the EEX and OSL, which affect the value of hourly arbitrage strategies for cross-border pumped hydroelectricity trading, when expanding Norwegian PHS to the German electricity market.

[2] The dataset is acquired by Assistant Professor Olvar Bergland, PHD, NMBU.

4.2.1 Daily and Weekly Patterns of Electricity Prices

Norwegian PHS technology is a cost-effective method to get the optimal arbitrage values for electricity trading in the short term. Not only its advanced characteristics such as large energy input and output efficiency capacity, high energy storage capacity for the short time, and flexibility of adjusting electricity supply and demand, but also improving the security of intermittent electricity supply and promote low-carbon economic growth.

Lucia and Schwartz (2002) identified that time patterns of spot prices can efficiently evaluate large arbitrage values by analysing the variability of electricity spot prices in the electricity exchange markets. In the study, time pattern of electricity spot prices is an important factor to affect the value of arbitrage for electricity trading by the pump cycle of hydroelectricity production from the Norwegian PHS when connecting with Germany. Based on cheap electricity which is bought in the off-peak periods, and electricity for sale is happened in the peak periods, arbitrage values of the electricity trading is in the process of buying and selling periods. We focus on the analysis of daily pattern and weekly pattern of the volatility of electricity spot prices between the peak and off-peak prices within 24 hours of a day and 168 hours of a week during the five years from 2012 to 2016.

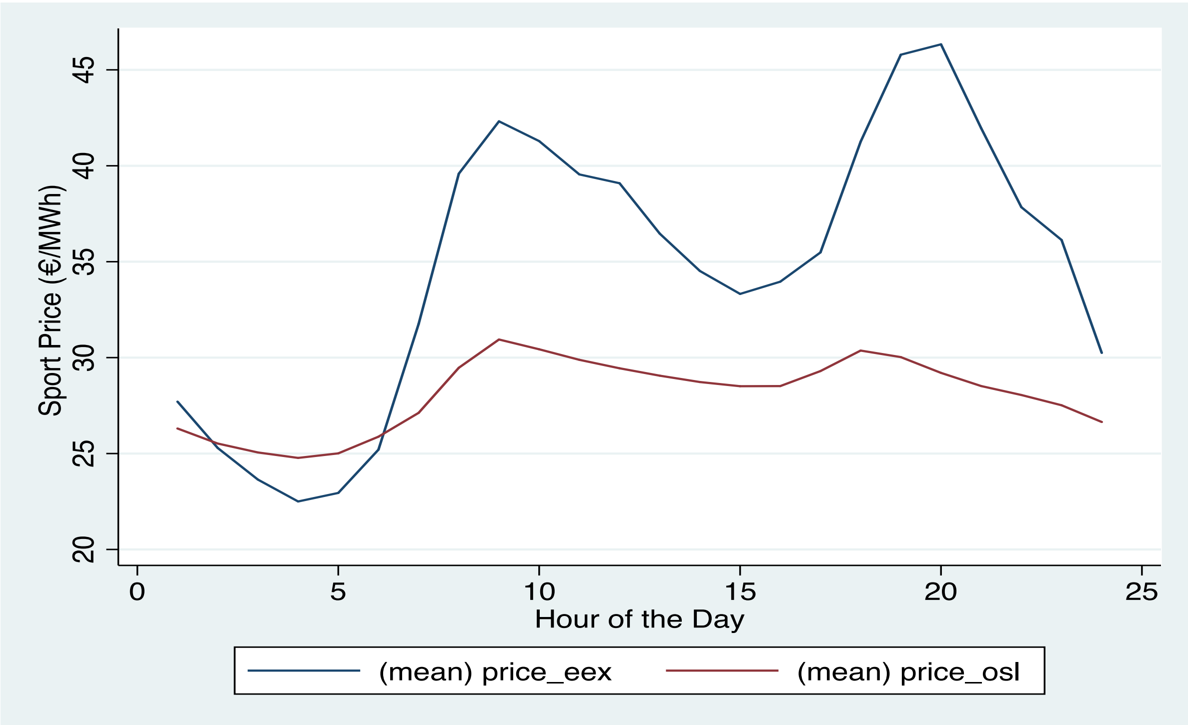
Next, we will investigate the following seven diagrams concerning the daily and weekly patterns of hourly electricity spot price behaviours on the OSL and the EEX, which show that the prices gaps between the peak and off-peak prices and the dynamics in electricity production and consumption during the peak and non-peak hours of a day and a week from 2012 to 2016. It potentially implies that the off-peak hours for buying electricity to achieve large arbitrage opportunities within the peak hours for sale. Then we estimate which of the patterns can create large arbitrage values for electricity trading by the application of Norwegian PHS project to the German electricity market.

4.2.2 Arbitrage Value Results of Daily and Weekly Patterns

Perhaps the arbitrage values of daily or weekly patterns take place the application of the pump cycle of hydroelectricity production in Norwegian PHS, in terms of price differences on the OSL and the EEX. Now, let’s estimating the strengthen and weakness of each of the relevant patterns shown in the following seven curves.

4.2.2.1 Arbitrage values by daily pattern of electricity prices

Figure 2: Daily pattern of the average hourly electricity prices within 24 hours of one day (2012-2016)



In Figure 2, the daily pattern illustrated that the price fluctuation between the highest and lowest hourly electricity prices on the OSL and the EEX in the 24-hour day from 2012 to 2016. We find that the price fluctuations on the EEX is larger than in the OSL during the peak hours and off-peak hours in 24 hours of the day. The peak electricity prices occur at 9 and at 19 in the day for Norway, and at 9 and at 21 in the day for Germany. The off-peak prices occur at 4 in the day for Norway and Germany.

For the EEX market, in the selling hours of the day, i.e. 7-22, where the maximum electricity price, about 46 €/MWh at 20 in the evening. And the second maximum price in EEX, 43 €/MWh at 9 the morning. While, in the buying hours of the day, i.e. 23-6, the minimum spot price in the EEX, about 23 €/MWh at 4 in the early morning. Also, the price differences in the maximum prices and the minimum prices was 23 €/MWh in the EEX during the buying and selling hours within 24 hours for the whole day. Further speaking, the hourly signal at 9 and at 20 of the day presented that electricity demand for peak load serves as households, business workplaces and manufacturers, while the demand for electricity off-peak load occurred the hourly signal at 4 the earlier morning. It indicates that the lowest electricity consumption happens during the buying hours (23-6) in the EEX and leads to low electricity prices and socio-economic surplus electricity in Germany. It is a possibility for investors and hydroelectricity producers from Norway and Germany to buy and store surplus electricity by pumping water to the reservoirs and sell it when peak prices, achieve arbitrage values of electricity trading from the cycle of electricity production from PHS.

Comparing to spot prices in EEX, hourly electricity prices of the OSL looks less volatile within 24 hours for the day. The maximum price was 31 €/MWh at 9 in the morning while the minimum price was 25 €/MWh at 4 in the early morning. Obviously, the price difference in Norway was less than in in Germany; not fluctuated, but tends to be relatively smooth during the peak and off-peak hours of the day. Further, the Norwegian electricity market illustrates that there is sufficient electricity in Norway to guarantee the security of electricity supply and flexibly adjust the balance between the electricity demand and supply during the peak and off-peak hours of the day. Also, the value of arbitrage of pumped hydroelectricity trading in Norway is less than in Germany through expanding Norwegian PHS project when connecting with Germany.

To get optimal the hourly arbitrage values of pumped hydroelectricity trading from Norwegian PHS when expanding to Germany, the profitable hours within 24 hours of the day are important for buying and selling the pumped hydroelectricity. Base on Equation (3), we explore two different arbitrage policies depending on the different hour periods of buying and selling electricity.

- **Arbitrage strategy A**: The daily pattern of hourly electricity prices in the selling hour (7-22) and the buying hour (23-6)

We assume h_t^{sell} =1 in the selling hours (7-22) for the pumped hydroelectricity, and h_t^{sell} = 0 otherwise; and h_t^{buy} = 1 in the buying hour (23-6) of the day to buy cheap electricity, and h_t^{buy} = 0 otherwise. Then the results of the hourly arbitrage value by daily pattern are shown in Table 2.

Table 2: The overall arbitrage value in Norway and Germany by daily pattern across the buying hours (23-6) and the selling hours (7-22) for 2012-2016

Variable	Observation	Mean	Std. Dev	Min	Max
hourly_avr_osl	43848	-.8015413	22.38211	-78.18823	210.942
hourly_avr_eex	43843	1.715945	27.21257	-117.081	261.1647

As shown in Table 2, we find that the parameter of the hourly maximum arbitrage value in Germany is 261.1647 larger than 210.942 in Norway in 2016. The standard deviation of the hour arbitrage value in the EEX is 27.212 larger than 22.382 in Norway. It means that the electricity prices in Germany are still higher than in Norway and the price differences in Germany are greater than in Norway. And the parameter of the mean of the hourly arbitrage value in Germany is almost 1.716 very larger than about -0.802 in Norway within the 24-hour of the day during the entire period between 2012 and 2016. The parameter of the mean of hourly arbitrage value in Norway, -0.802, is negative in the hours of buying electricity, because the pumped hydroelectricity trading in the arbitrage strategy, in total, is nothing to earn returns from pumping back the water into the reservoir.

- **Arbitrage strategy B**: The daily pattern of hourly electricity prices in the selling hour (8-22) and the buying hour (23-7)

Where we change the daily pattern during h_t^{sell} and h_t^{buy}, assume h_t^{buy} = 1 in the buying hours (23-7), otherwise h_t^{buy} =0, and set h_t^{sell} =1in the selling hours (8-22) and h_t^{sell} =0 otherwise, to see Table 3.

Table 3: The overall arbitrage value in Norway and Germany by daily pattern between the buying hours (23-7) and the selling hours (8-22) for 2012-2016

Variable	Observation	Mean	Std. Dev	Min	Max
avr_osl	43848	-2.176618	21.68995	-78.18823	210.942
avr_eex	43843	-.1392319	26.39242	-117.081	261.1647

And Table 4 for the summary of variables across the two periods above is shown in the Appendix A.

Where we look at the standard deviations for hourly arbitrage value in Germany is higher than in Norway. It illustrates price volatility of the hourly arbitrage value in Germany is more volatile than in Norway between the buying hours (23-7) and selling hours (8-22). The maximum arbitrage value in the EEX is greater than in the OSL, the minimum arbitrage value in the EEX is lower than in the OSL. Also, the mean of hourly arbitrage values in Germany is greater than in Norway, but they are negative. This implies that as both Norway and Germany has negative mean of hourly arbitrage values, both of the nations are not profitable to pump hydroelectricity trading with arbitrage strategy B.

As a result, we find arbitrage strategy A is the best to get greater arbitrage values of pumped hydroelectricity trading in the German electricity market during the buying hours (23-6) and the selling hours (7-22) of the day. Norwegian investors and electricity producers would like to buy cheap electricity in Germany and store in the reservoirs in the buying hours (23-6) of the day. When hourly prices are higher in the EEX during the selling hours (7-22), Norwegian investors and producers sell the pumped hydroelectricity back to the German electricity market, then the large hourly arbitrage value is probably captured from the cycle of pumped hydroelectricity production through the Norwegian PHS project when connecting with Germany. Consequently, the daily pattern of hourly electricity prices within 24 hours of a day, which is a profitable method for Norway and Germany to achieve large arbitrage values from the Norwegian PHS project expansion to Germany in the short term.

We use arbitrage strategy A in the selling hours (7-22) and the buying hours (23-6) and analyse the variability of arbitrage value each year between 2012-2016.

Table 5: Arbitrage Strategy A in the selling hours (7-22) and the buying hours (23-6) in 2012

Variable	Observation	Mean	Std. Dev	Min	Max
hourly_avr_osl	8736	-.6263947	23.84228	-78.18823	210.942
hourly_avr_eex	8735	2.268425	33.38259	-60.94118	261.1647

We can see that the mean of ARV in the EEX is positive and much larger than in the OSL. Due to price volatility is estimated by the standard Deviation of AVR, we can see price difference on the EEX is higher than in the OSL. The maximum and minimum arbitrage values in the German electricity market are greater than that in Norway. Arbitrage strategy A is thus more profitable in Germany than in Norway in the cycle of pumping water back into the reservoirs of PHS.

Table 6: Arbitrage Strategy A in the selling hours (7-22) and the buying hours (23-6) in 2013

Variable	Observation	Mean	Std. Dev	Min	Max
hourly_avr_osl	8736	-1.345856	28.59885	-77.27059	88.659
hourly_avr_eex	8735	2.29117	29.09628	-90.027	108.144

Table 6 shows that Germany and Norway have almost same numbers of observation. The mean of hourly arbitrage values in Germany is positive and greater than in Norway. The maximum arbitrage values in Germany is 108.144 larger than 88.659 in Norway. Interestingly, the standard deviation of AVR in the EEX is closer to that of the OSL. It means that the variability of electricity prices is smoothly volatile on the EEX and OSL. Comparing to Table 5, we find that electricity price on the OSL is higher in 2013, while falls in the EEX. Totally, Norwegian producers and investors use arbitrage strategy A to make Norwegian pumped hydroelectricity profitable for expansion the Norwegian PHS project to Germany.

Table 7: Arbitrage Strategy B in the selling hours (7-22) and the buying hours (23-6) in 2014

Variable	Observation	Mean	Std. Dev	Min	Max
hourly_avr_osl	8736	-1.036533	21.00694	-40.12941	63.612
hourly_avr_eex	8735	1.649339	25.00993	-58.527	79.173

The decreased standard deviation of arbitrage values in the EEX indicates that the share of renewable energy production has increased in the German electricity market. Price gaps in the EEX estimated by standard deviation is slightly lower than that of in 2013, but higher than in the OSL. The positive mean of AVR in Germany is greater than the negative mean of AVR in

Norway. It means Arbitrage Strategy A can create large arbitrage values of electricity trading during the buying hours (23-6) and the selling hours (7-22).

Table 8: Arbitrage Strategy B in the selling hours (7-22) and the buying hours (23-6) in 2015

Variable	Observation	Mean	Std. Dev	Min	Max
hourly_avr_osl	8904	-.4217701	15.86331	-36.5647	61.695
hourly_avr_eex	8903	1.47211	24.41853	24.41853	89.793

There are no negative parameters for arbitrage values in the EEX. The mean of AVR on the EEX is greater than that of the OSL in 2015. Negative mean of the arbitrage value in Norway means that Arbitrage Strategy A is not profitable to make pumped hydroelectricity trading in the Norwegian electricity market. The higher standard deviation of AVR on the EEX implies that higher price differences in the EEX create larger arbitrage value opportunity in Germany. Arbitrage Strategy A makes the German electricity market is more market valuable than Norway to the Norwegian pumped hydroelectricity transaction.

Table 9: Arbitrage Strategy B in the selling hours (7-22) and the buying hours (23-6) in 2016

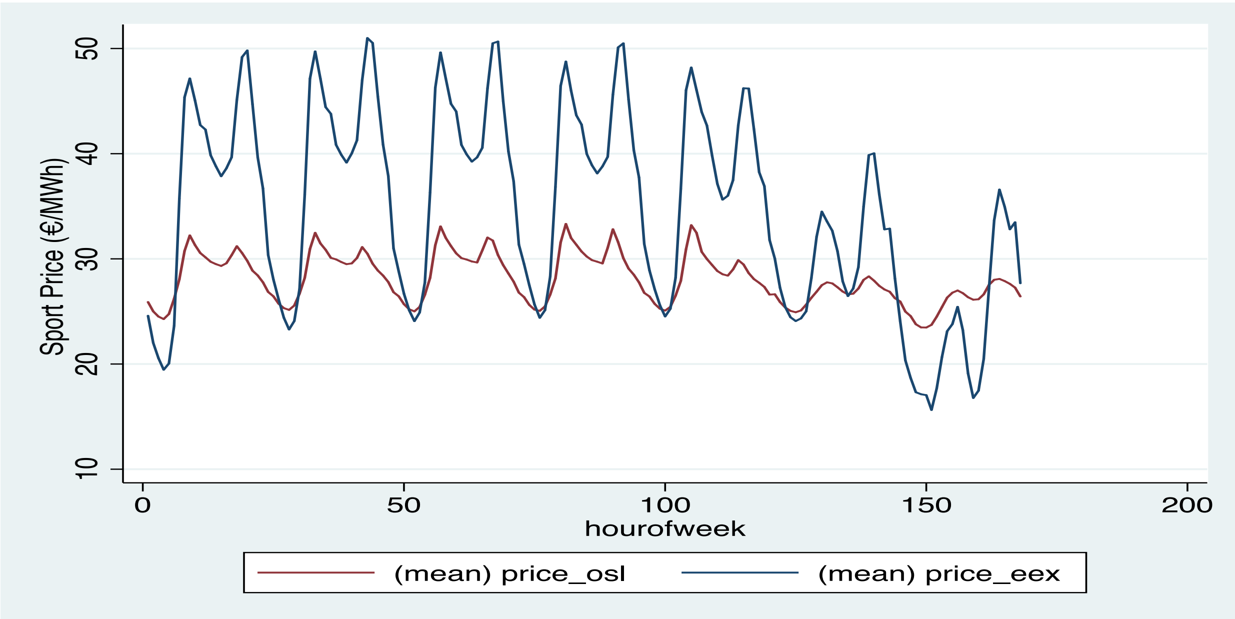
Variable	Observation	Mean	Std. Dev	Min	Max
hourly_avr_osl	8736	-.5844552	20.73543	-59.23382	180.081
hourly_avr_eex	8735	.9033702	22.83902	-117.081	94.464

The negative mean and negative standard deviation of arbitrage value in the OSL mean that there is less arbitrage value in the Norwegian electricity market. Arbitrage Strategy A is not the profitable way of pumping water and generate hydroelectricity to be sold in the Norwegian electricity market when Norwegian PHS investing to Germany, but it is beneficial for the pumped hydroelectricity trading in the German electricity market.

4.2.2.2 Arbitrage value by weekly pattern of electricity prices

Weekly pattern of electricity prices in the entire period from 2012 to 2016:

Figure 3: Weekly pattern of the average hourly electricity prices within 168 hours of one week (2012-2016)



In Figure 3, we use the weekly pattern of the average hourly electricity spot prices of the OSL and the EEX for a 168-hour week (that is equal to 24 hours multiplied by 7 days).

In the spot price curve of the EEX, we observe the peak hourly electricity prices were presented every workday morning and evening, the maximum hourly electricity price was about 51 €/MWh in the evening on Tuesday, Wednesday and Thursday. The second maximum peak price was 50 €/MWh in evening on Monday. The peak hours of each workday for selling electricity occurred during the hour (7-20) each day within 120 hours of the five workdays. The peak hour-time point was at 7 a.m. and at 8 p.m. of each workday, whereas the minimum spot price was 15 €/MWh Saturday midnight and Sunday morning during the off-peak hours of the day, i.e., the hour (1-12) on Sunday. The price volatility between the peak prices and off-peak prices is more volatile during the five workdays and the weekend.

The price curve of the OSL shown in Figure 3, the peak price was 32 €/MWh in the peak hours of the five workdays while 22 €/MWh for the off-peak price in the weekend. Apparently, the hourly spot price gaps in OSL are relatively smooth and smaller than in the EEX between the weekend and the rest days of the week. It means there is less hourly arbitrage value between the weekend and the rest of days within 168 hours of the week in Norway.

We find that there are five larger price differences between the weekend and the other five workdays in Germany than in the Norwegian electricity market. Therefore, there may be some arbitrage values of buying and selling electricity in Germany based on the weekly pattern of hourly spot prices between the five workdays and the weekend.

Weekly pattern of electricity prices in 2012:

Figure 4: Weekly pattern of the average hourly electricity spot prices within 168 hours of one week in 2012

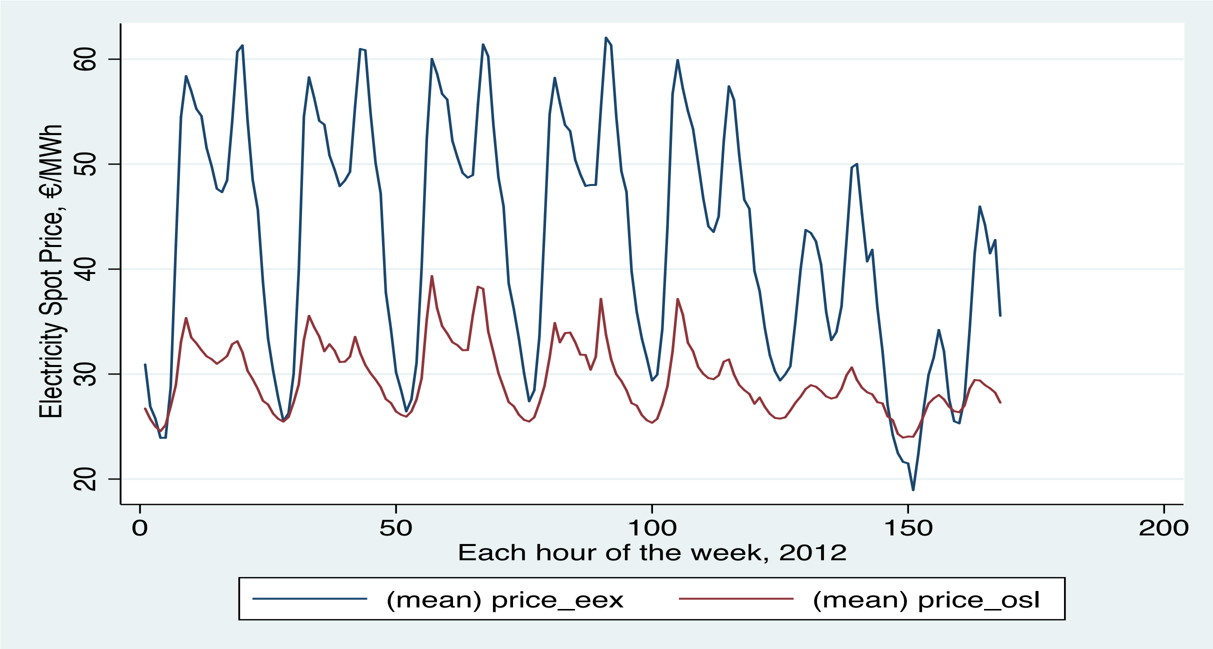


Figure 4 showed the weekly pattern of the hourly electricity spot prices of the OSL and the EEX, which is within 168 hours for a week in 2012. The overall hourly spot price spikes of the OSL and the EEX were presented during the peak hours (7 -20) of the five workdays from Monday to Friday while lower spot prices during the non-peak hours (1- 6) between Saturday midnight and Sunday morning. We can see the peak spot price tendency of the EEX was much higher than in the OSL while the off-peak price of the EEX is lower than in OSL. Thus, larger price differences between the peak and non-peak prices in the EEX than in the OSL.

In the EEX market, the maximum price reached to 60 €/MWh at around 6 pm in every evening of the five workdays for the week, while the minimum prices, 18 €/MWh, occurred during the midnight of Saturday and Sunday morning. High hourly electricity prices in the EEX indicated that Germany still used high-cost fossil fuels to generate electricity, while the share of electricity generated from renewable energy was very small in 2012. The price fluctuations between the peak and non-peak prices looks very volatile between the week and the rest of the week in 2012.

In the OSL market, the hourly electricity prices were much lower than in EEX, is mainly due to sufficient hydroelectricity smoothly meet the shifting electricity demand for peak load.

In 2012, the minimum hourly spot price of the OSL on Sunday was 25 €/MWh and the maximum price was about 30 €/MWh on Wednesday morning. The price fluctuations between the weekend and the rest of the week were smaller than in the EEX. It demonstrated that there are less hourly arbitrage values in Norway than in Germany.

Large price differences between the weekend and the rest of the other five workdays existed in the German electricity market, there might therefore have some arbitrage values of pumped hydroelectricity trading in Germany than in Norway, based on the weekly pattern of the hourly spot prices of the OSL and the EEX within 168 hours in 2012, when Norwegian PHS connecting with Germany.

Weekly pattern of electricity prices in 2013:

Figure 5: Weekly pattern of average hourly electricity spot prices within 168 hours of one week in 2013

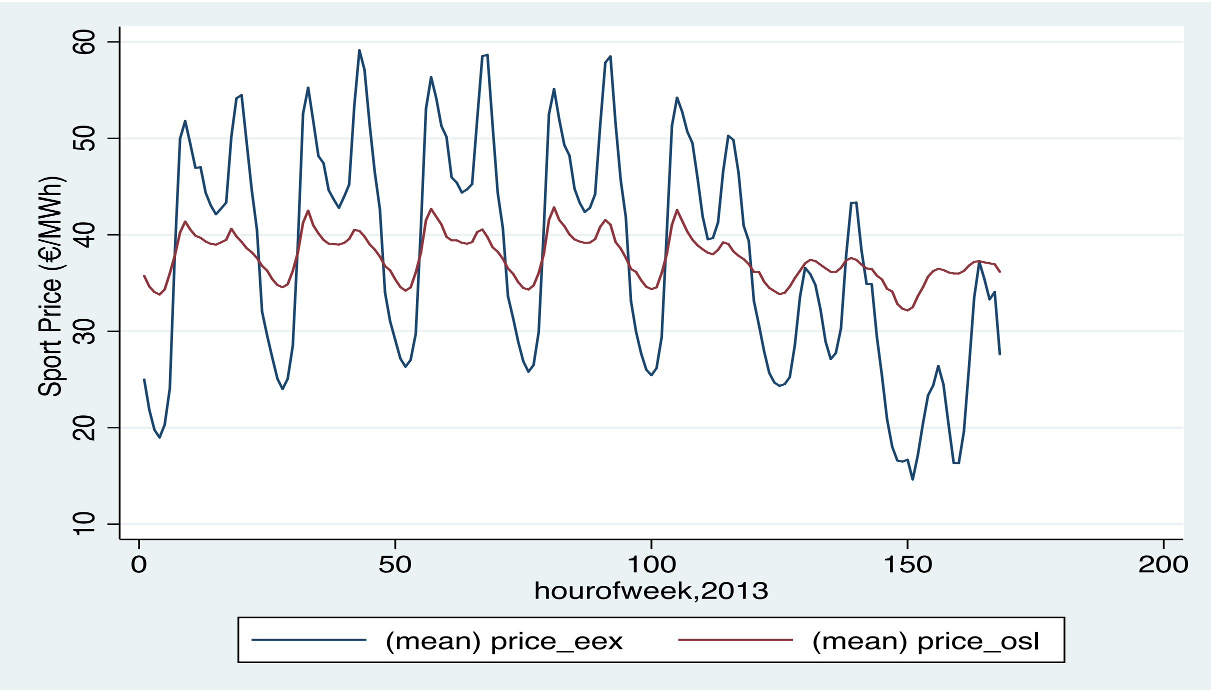


Figure 5 showed that the changes in hourly electricity spot prices in the weekly pattern within 168 hours in the week in 2013 and compared with 2012, the overall spot prices of the OSL increased while the overall spot prices decreased in the EEX. The peak prices of the OSL and the EEX occurred during the peak hours of the five workdays in the week and the off-peak prices occurred at the weekend, especially Saturday midnight and Sunday morning.

In Norway, a large majority of hydroelectricity produced by the cost-effective hydropower is mainly a dominated economic factor to support low-carbon economic growth in Norway. The trend of the spot prices of the OSL were upward, which was probably due to intermittent hydropower not to meet the rise in electricity demand when cold or dry weather.

The peak prices were more than 40 €/MWh on average within workdays from Monday to Friday while the minimum price was 32 €/MWh on weekend. However, there is an interesting thing that the price differences were very small between the weekend and the other five workdays, even though the overall upward tendency of the hourly electricity prices in the OSL in 2013. Also, the hour-time differences between the weekend and the rest of workdays are smaller than in 2012. Further, the smooth price fluctuations implied that the value of electricity supply was close to the peak demand, which leads to less arbitrage values for the pumped hydroelectricity transaction in Norway through Norwegian PHS expanding to Germany. As a result, the weekly pattern of hourly spot prices in Norway is not a profitable method for German investors and grid operators to get optimal arbitrage revenues when Norwegian PHS connecting with Germany.

In the EEX market, the maximum hourly prices were on Tuesday, Wednesday and Thursday, which are almost 60 €/MWh similar with the maximum prices in 2012. The second peak hourly prices were on Monday and Friday, about 50 €/MWh. And the minimum hourly price was about 15 €/MWh in the weekend, slightly less than 19 €/MWh in 2012. It presented that there were some large price gaps between the maximum prices and the minimum prices during the five workdays and the weekend within the 168-hour week in 2013. So, capturing some arbitrage values of pumped hydroelectricity trading in Germany is possible from the weekly pattern when connecting Norwegian PHS with Germany. Additionally, the overall tendency of electricity prices between the weekend and the five workdays of the week, which slightly decreased compared to 2012, is identified that the share of low-cost solar and wind power has been gradually increased in the energy market.

Consequently, there are some arbitrage values captured in Germany instead of in the Norwegian electricity market for the electricity transaction by expansion the Norwegian PHS project to the German electricity market.

Weekly pattern of electricity prices in 2014:

Figure 6: Weekly pattern of average hourly electricity spot prices within 168 hours of one week in 2014

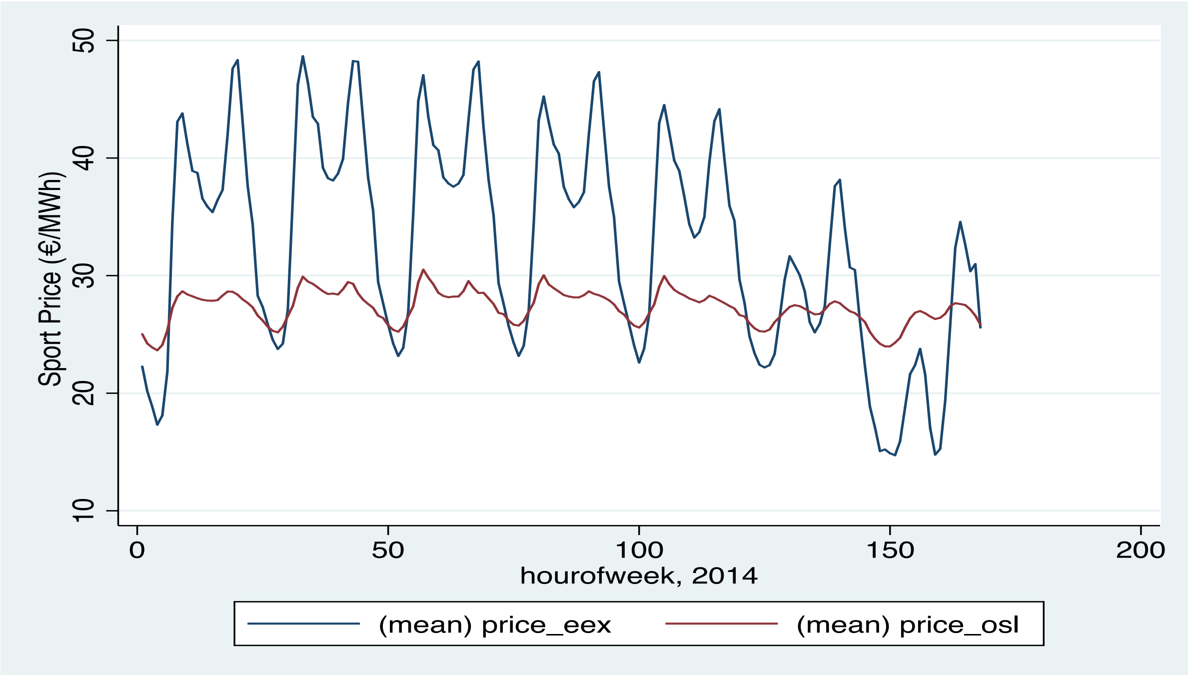


Figure 6 showed that the overall tendency of the average hourly electricity prices of the OSL and the EEX was downward, and the total price differences between the weekend and the rest of the week reduced in Norway and Germany in 2014.

In the spot price curve of the OSL market, the peak prices were almost below 30 €/MWh during the peak and off-peak hours of the five workdays from Monday to Friday in the 168-hour week, and the minimum spot price was 23 €/MWh at midnights in the weekend. We investigated that the hourly price fluctuations between the maximum prices and the minimum prices were less volatile compared to the price curves in the OSL in 2012 and 2013. There is possibly no hourly arbitrage value of Norwegian hydroelectricity trading in the Norwegian electricity market when connecting Norwegian PHS with Germany.

In the EEX market, the continuously downward tendency of spot price in 2014, which demonstrated that the German decreased day-ahead electricity prices was mainly due to the increasing growth of renewable electricity in 2014. The price curve of the EEX showed the peak prices were about 50 €/MWh during the peak hours between Monday and Friday while the non-peak load price was 15 €/MWh during the off-peak hours at midnights in the weekend. The price volatility between the weekend and the other five workdays within 168 hours was higher than in the OSL. The best condition for achieving maximum arbitrage is high price volatility (Salles and Hogan, 2016). As a result, there are some higher price differences between the weekend and the rest of the week in Germany which demonstrate that some arbitrage values may be captured for the Norwegian hydroelectricity transaction when Norwegian PHS connecting with the German electricity market.

In short, the small price volatility between the weekend and the rest of the week in Norway, where less arbitrage values of electricity trade when the Norwegian PHS project connecting with Germany. Oppositely, larger price volatility in the German electricity market possibly capture some arbitrage revenues for Norwegian investors and producers. Consequently, the weekly pattern of hourly spot price in 2014 was not a profitable method for Norwegian electricity market, but is beneficial in the German electricity market to obtain some of arbitrage values.

Weekly pattern of electricity prices in 2015:

Figure 7. Weekly pattern of the average hourly electricity prices within 168 hours of one week in 2015

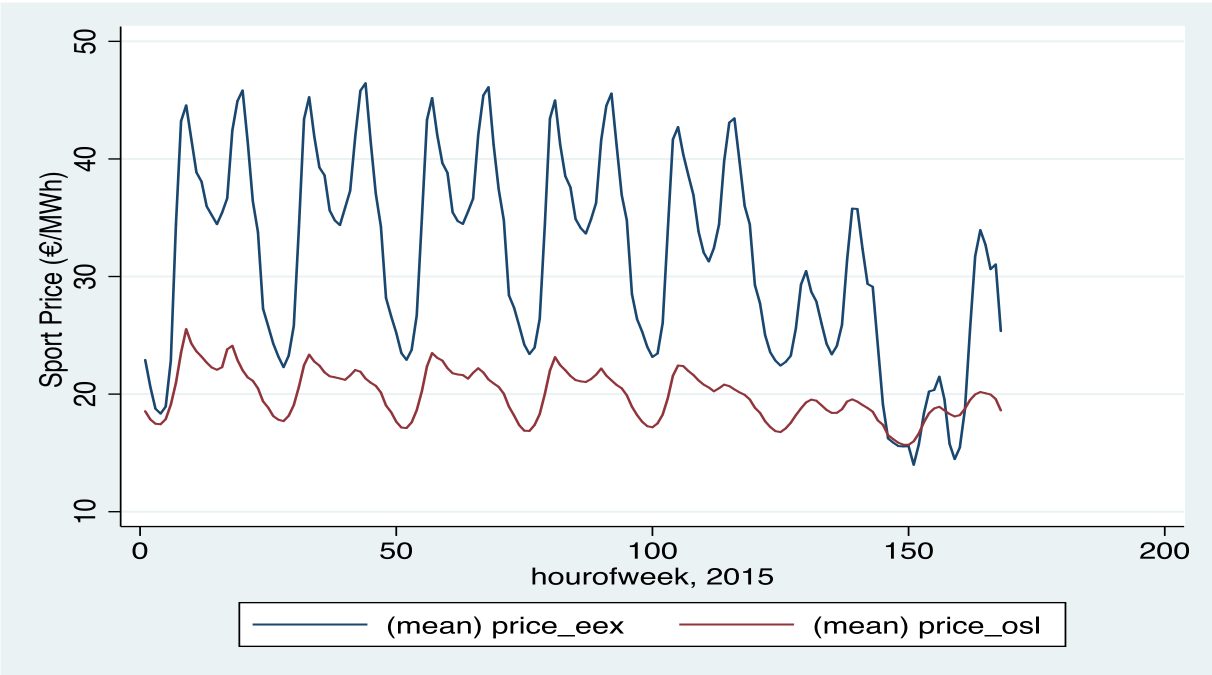


Figure 7 illustrated that the overall tendency of the average hourly electricity spot prices on the OSL and EEX, which are decreased within 168 hours of the week in 2015. And their overall price gaps between the maximum and minimum hourly prices, which reduced during the weekend and the five workdays of the week.

As shown in the price graph of the OSL, the maximum price was 25 €/MWh during peak hours within the 120-hour workdays for the week, while the minimum price was 15 €/MWh within off-peak hours of the 48-hour weekend. The price gaps between the weekend and the rest of the week were very small in the Norwegian electricity market, which illustrated Norway had sufficient electricity production from hydropower in 2015 to meet electricity demand for peak load. Small price differences in Norway lead to less arbitrage values between the weekend and the rest of the week for cross-border electricity trading through the Norwegian PHS expanded to Germany. But, the off-peak electricity prices during the five workdays in

Norway were lower than that in Germany. If German investors or pumped hydroelectricity producers probably buy the cheaper electricity during the off-peak hours within the five workdays in Norway and sell them with peak prices in the German electricity market, there may be some arbitrage values of cross-border electricity trading during the 120-hour workday of the week, through the Norwegian PHS connecting with Germany.

In the EEX, the peak prices within 120 hours of the five workdays from Monday and Friday was 46 €/MWh and the off-peak price was 14 €/MWh within 48 hours of the weekend. We can see that the price fluctuations between the peak prices and the off-peak prices are more volatile compared to in the OSL. In addition, the continuously downward tendency of electricity prices in Germany show that the electricity production from solar and wind power continued to increase in 2015. Large price volatility is respond to large arbitrage values in the short term, thus in the weekly pattern of hours' the electricity price differences between the weekend and the rest of the week achieve some arbitrage values of the pumped hydroelectricity trading in Germany when connecting to the Norwegian PHS project with the German electricity market.

Thereby, the weekly pattern of hourly electricity prices between the weekend and the rest of the week in 2015 is profitable to get some arbitrage values in Germany and in Norway.

Weekly pattern of electricity prices in 2016:

Figure 8: Weekly pattern of the average hourly electricity prices within 168 hours of a week in 2016

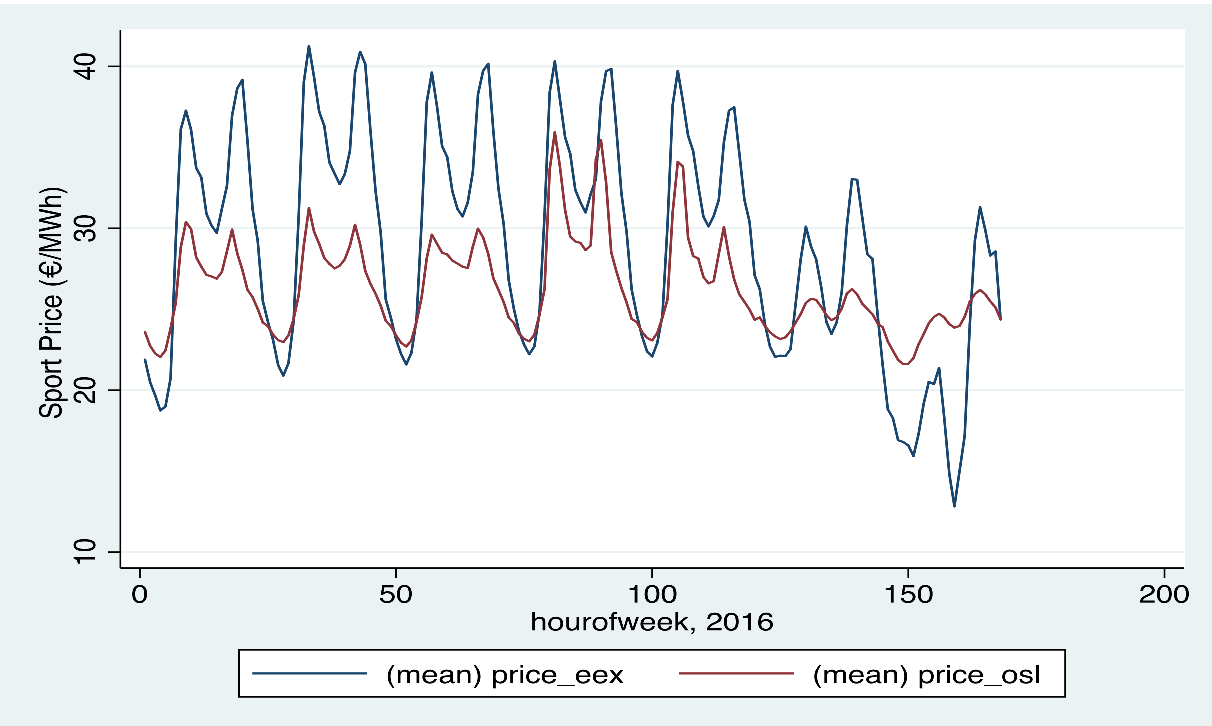


Figure 8 illustrate the weekly spot price patterns within 168 hours of the week in 2016 for Norway and Germany. Significantly, Germany's electricity price continued to fall, whereas Norway's electricity price rose in 2016.

Norway's price curve in 2016 showed that the upward trend in the hourly electricity prices caused the electricity price differences in the OSL which was were higher than before. The peak prices for electricity demand was on Thursday and Friday, similarly the second peak prices were from Monday to Wednesday and the off-peak price was in the weekend. During the peak prices between mornings and evenings within the 120-hour workdays of the week, the maximum price was about 36 €/MWh, while the minimum price was up to 21€/MWh. The price volatility between the weekend and the rest of the week in 2016 was obviously larger than in 2015, which implied that the arbitrage values of pumped hydroelectricity trading might increase when expanding the Norwegian PHS to the German electricity market.

Comparing to the electricity prices in the OSL, the electricity prices of the EEX were still higher than in the OSL. But the hourly electricity prices in 2016 were still on the downward trend, which was mostly caused by the rapidly increasing share from the low-cost solar and wind powers in the German electricity market. The peak price occurred between Monday and Friday of the week, and the off-peak prices was in the 48-hour weekend, especially between Saturday midnight and Sunday morning, and the maximum price was 42 €/MWh on Tuesday while the minimum price was 13 €/MWh on Sunday. We find that the price gaps were still volatile and larger than in Norway. Due to larger price differences between the weekend and the rest of the week in Germany than in Norway, there are probably some arbitrage values of electricity trading in Germany, which is greater than in Norway, when investing Norwegian PHS to Germany.

As a result, the weekly pattern of electricity prices within the 168-hour week was not the best method to achieve optimal arbitrage values of electricity trading in Norway and Germany for expansion or investment Norwegian PHS to the German electricity market.

5 Estimation Results and Discussions

As shown in the above patterns (between Figure 2 and Figure 8), we find that electricity volatility in the EEX is always much higher than in the OSL. It means that electricity prices in Germany are higher than in Norway which also represents that the energy storage system in Norway is more cost-effective than in Germany. Also, we find that both of price gaps and time signals of electricity demand determine how large value the arbitrage can be achieved from the Norwegian PHS project to Germany. We know that the electricity demand usually varies over a short-time series, particularly each period a day affects the peak and peak-bottom spot price level. Clearly, the peak spot prices illustrate that a large amount of electricity production is required to meet high electricity demand for peak load, and the off-peak spot price means the fall in electricity consumption resulting the electricity remaining in the grids.

PHS technology is an economical and flexible method to store and sell electricity in the electricity markets. When the electricity demand for peak load is declining during the non-peak hours, the corresponding electricity prices usually is low, because the dynamics between electricity supply and demand affects the variability of electricity spot prices in the day-ahead market. Thus, in the economic cycle of PHS performance, low electricity demand at the low electricity prices makes electricity production to be residual in the grids. According to the valuable features of PHS and high price differences in the EEX, Norwegian investors are willing to buy cheap electricity from German grids and used it to pump the water back into and be stored in the upper reservoir of the Norwegian PHS plant and then to sell high-cost electricity generated through the stored water pumping back into the bottom reservoir.

Finally, the arbitrage values can be captured from the round-trip cycle of pumped electricity production in the PHS system in the short term. Likewise, German producer are also willing to produce electricity output in the off-peak hours, and store in the Norwegian PHS system for sale when prices are high in the peak hours in Germany. But the different time patterns of electricity prices in the day-ahead electricity spot markets determine the extent of arbitrage value of electricity transaction in the short term.

5.1 Daily Pattern of Electricity Prices

Figure 2 displays the daily pattern which illustrates that the hourly electricity spot prices vary significantly over the 24-hour day and drive price volatility in the day-ahead electricity spot market.

We see that in Norwegian day-ahead electricity spot market, the peak hours occur in the morning and in the evening after work day, while the off-peak time happens at midnight. Within 24 hours for a day, the price differences in the OSL are not sharply fluctuated between the peak and off-peak spot prices, while the price differences of the EEX were apparently much volatile than in the OSL. It demonstrates that electricity demand for peak load in Germany is higher than in Norway, and also the security of electricity supply in Norway is more stable than in Germany.

The minimum electricity price of the EEX was lower than in the OSL in the off-peak hours of the day whereas the maximum price of the EEX was much higher than in the OSL in the peak hours of the day. There is no doubt that, the two important elements for the German electricity market i.e. high price differences between the peak and off-peak prices and the lowest electricity prices at midnight create arbitrage value opportunities for investors and producers from the Norwegian PHS when connecting with Germany. Hereby both of Norwegian and German investors as well as producers may get large arbitrage values of the cross-border electricity transaction.

To get the optimal arbitrage value of the pumped hydroelectricity trading through the Norwegian PHS project expanding to Germany, we set two arbitrage policies and estimate the arbitrage values calculated within 24 hours of a day for each year between 2012 and 2016 and the overall arbitrage values in the entire period. We find that arbitrage strategy A is a profitable arbitrage policy to get large arbitrage values of pumped hydroelectricity trading in Germany within the buying hours (23-6) and the selling hours (7-22) of the day during the past five years. The decline in the mean of arbitrage value in Germany means that the arbitrage values in the German electricity market has reduced for the Norwegian PHS project in the five years. It is mostly due to the growing share of solar and wind power in the German electricity sector. While, the negative mean of arbitrage value in Norway means that the arbitrage strategy A is not beneficial for the Norwegian electricity market. Therefore, arbitrage strategy A is valuable for the daily electricity trading through the Norwegian PHS project connecting with Germany in the short term. Based on electricity price differences on the electricity exchange market and the variability of arbitrage strategies calculated by daily pattern, investors and electricity producers probably would like to invest or expand Norwegian PHS project through the cycle of pumping water back into the reservoirs and sell hydroelectricity to Germany and achieve the optimal arbitrage values with less risks and uncertainties in the short term.

In short, daily pattern of electricity prices in the day-ahead electricity spot market, which is statistically significant for Norway and Germany to achieve arbitrage values in large volume, in terms of the high price volatility during the peak and off-peak hours of the 24-hour day.

5.2 Weekly Patterns of Electricity Prices

In the EEX market, the maximum electricity price within the 168-hour week in the entire period (2012-2016), which decreased to 40 €/MWh in 2016 compared to 60 €/MWh in 2012 and the minimum price was 15 €/MWh in 2016 less than 30 €/MWh in 2012. Apparently, the overall hourly spot price trend of the EEX was downward within 168 hours of a week from 2012 to 2016, led to the tendency of price fluctuations between the peak and off-peak prices was downward as well. And it implies that the fall in electricity consumption and the redundant electricity production left in the grids during the off-peak hours of the 168-hour week, especially happened in the longer off-peak hours of the weekend. The value of arbitrage opportunities is less than before in Germany through trading electricity from the Norwegian PHS project expanding to Germany. However, Norwegian investors still can get large arbitrage value in Germany through the Norwegian PHS project between the five-workdays and the weekend.

As for the electricity spot prices in the OSL within the 168-hour week from 2012 to 2016, there is an overall slight upward trend of hourly electricity spot prices, especially in 2016. Increasing electricity prices during peak hours of the week is correlated to high price volatility between the peak and off-peak prices in the OSL. It means that, adequate electricity production needs to meet the increasing electricity consumption in Norway during the peak hours of the week. Thus, it is statistically significant to increase the arbitrage value of electricity transaction in the Norwegian electricity market in the short term. But, compared to Germany, price fluctuations within 168 hours of the week in Norway are not large, so the arbitrage value of electricity trading in Norway is still lower than in Germany.

Based on the volatile electricity prices differences in the OSL happened during the peak and off-peak hours of the week in 2016, German producers or investors might get less arbitrage value of electricity trading in Norway through the PHS project expanding to the Germany electricity market. As a result, the weekly pattern of electricity prices within 168 hours in a week is not a profitable method in Norway to achieve large arbitrage of electricity trading from the Norwegian PHS when connecting to Germany.

Briefly, the electricity spot price spikes the OSL and the EEX occurred during the peak hours in the mornings and evenings from Monday to Friday of a week, while the off-peak spot prices happened from Saturday midnight to Sunday morning. The EEX's electricity price differences between the five work days and the weekend were much larger than in the OSL. Thus, the large arbitrage value can be achieved in Germany through buying and selling electricity between the weekend and work days from the Norwegian PHS project connecting with Germany.

Compared with Germany, however, less arbitrage value for German investors is in Norway within the 168-hour week, as the price difference between the work days and the weekend is relatively flat. Consequently, weekly patterns of hourly electricity prices between the weekend and the rest of the week (2012-2016) is not statistically significant for Germany to capture large arbitrage revenues in Norway for cross-border electricity trading by the Norwegian PHS project connected with Germany. But it might be beneficial for Norway to get large arbitrage value in the German electricity market.

5.3 Further Research Question

Due to the increased solar and wind power production in Germany, has Norway decreased or increased the arbitrage value in the German electricity market?

By observing the daily and weekly patterns of electricity prices in the day-ahead electricity spot market, we find that the daily pattern is a profitable approach for the estimated PHS program between Norway and Germany can achieve large arbitrage revenues of pumped hydroelectricity transaction from Norwegian PHS when connecting with Germany, based on electricity prices between the peak and non-peak hours within 24 hours of a day in Germany and Norway. Also, through observing the price graphs between Figure 2 and 8, we find that the overall downward tendency of electricity price deficiencies in the EEX between the maximum and minimum spot prices from 2012 to 2016 is mostly due to the increased share of low-cost solar and wind production to smooth electricity supply. It is further beneficial to reduce electricity imports from other cross-border regions. Additionally, we find the hourly electricity prices of the EEX are negative, which is probably because of large share solar and wind production and has gradually reduced electricity production from costly fossil fuel plants in Germany. It makes more benefits to pumped hydroelectricity transaction throughout buying surplus intermittent electricity to pump water back into the reservoirs from the PHS project expanded to Germany.

However, when producing adequate electricity production from solar and wind power in the off-peak hours, electricity is cheaper than in the peak hours and its supply is more than demand, which leads electricity price to go down on the day-ahead electricity spot markets. In such circumstances, electricity consumption is decreasing and price fluctuations between the peak and off-peak prices are falling in the short term. Further speaking, the increased solar and wind production, probably results in lower electricity prices in the German electricity market, and therefore Norway has decreased arbitrage value of pumped hydroelectricity trading in the German electricity market when Norwegian investors and producers expand the Norwegian PHS project to Germany.

As a whole, Norway still may have large arbitrage values of pumped hydroelectricity trading in the German electricity market i.e. sufficient to make Norwegian pumped hydroelectricity more profitable for expansion or investment in PHS to Germany. It is due to price volatility in Germany which is still higher between the peak and off-peak prices in the German electricity market than in the Norwegian electricity market.

While German pumped hydropower producers will probably have less arbitrage value of pumped hydroelectricity transaction when connected to Norway, the smaller price differences in the peak and off-peak prices in the Norwegian electricity market will lower the electricity prices in the peak hours in Norway and are beneficial for German end consumers.

6 Conclusion

Through applying the daily and weekly pattern of electricity prices between the peak and off-peak hours within 24 hours a day and 168 hours of one week from 2012 to 2016, we investigate the fall in price fluctuations in the peak and off-peak prices in the EEX. It shows that the increased share of solar and wind production in the electricity sector is playing important benefit roles to improve low-carbon economic growth in Germany. For instance, accelerate renewable energy transition, improving energy liberalisation market capacity and increase international electricity market competitiveness. However, the decreased price volatility makes it possible to reduce the hourly arbitrage value of electricity trading in the process of buying, storing and selling the pumped hydroelectricity from Norwegian PHS when connecting with the German electricity market. With the decreased share of fossil fuels and nuclear power and the increased share of solar and wind power in Germany, the Norwegian PHS project expanding to Germany may be still valuable for pumped hydroelectricity trading, but Norway has decreased arbitrage values than before.

In the Norwegian electricity market, electricity pricing setting is mainly affected by hydropower supply (Birkedal and Bolkesjø, 2015). By observing the slight upward fluctuations between the peak and off-peak prices in the OSL, the peak electricity price on the OSL is still low and there is probably less arbitrage value of pumped hydroelectricity trading in Norway than in Germany when investment or expansion Norwegian PHS to Germany.

In conclusion, by analysing the calculation of hourly arbitrage value, we find that the daily pattern during the buying hours (23-6) and the selling hours (7-22) is profitable to get greater arbitrage values of cross-border pumped hydroelectricity transaction in Germany throughout expansion Norwegian PHS to Germany. Larger arbitrage values are determined by major factors such as high energy efficiency, high storage capacity and greater price difference (Zafirakis et al., 2016). It illustrates less arbitrage value of pumped hydroelectricity trading in Norway than in Germany, because of the storage capacity and energy efficiency of power plants in Germany are currently still lower than in Norwegian PHS plants. So, it is a possibility to get large arbitrage value in Germany than in Norway by the daily pattern of electricity prices between some hours of buying and other selling hours within 24 hours of one day.

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Appendix A

Table 4: Summary of variables by daily pattern across two periods

Variable	Obs	Mean	Std. Dev.	Min	Max
date	0				
time	0				
year	43848	2014.004	1.412869	2012	2016
week	43848	26.60153	15.06892	1	53
day	43848	4	2.000023	1	7
hour	43848	12.5	6.922265	1	24
hid	43848	84.5	48.49712	1	168
price_osl	43848	28.095	10.97727	.59	234.38
price_eex	43843	34.75801	15.60099	-221.99	210
buy	43848	.6666667	.4714099	0	1
sell	43848	.75	.4330176	0	1
hourly_avr~l	43848	-.8015413	22.38211	-78.18823	210.942
hourly_avr~x	43843	1.715945	27.21257	-117.081	261.1647
avr_osl	43848	-2.176618	21.68995	-78.18823	210.942
avr_eex	43843	-.1392319	26.39242	-117.081	261.1647

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