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Renewable Energy Systems

Correlation between electricity production of renewable sources and the use of pumped storage hydro power in Austria in the years 2015 – 2017

A Master's Thesis submitted for the degree of
"Master of Science"

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Vienna, 05.10.2018

Affidavit

I, **DIPL.-ING. STEFAN JORTHAN**, hereby declare

1. that I am the sole author of the present Master's Thesis, "CORRELATION BETWEEN ELECTRICITY PRODUCTION OF RENEWABLE SOURCES AND THE USE OF PUMPED STORAGE HYDRO POWER IN AUSTRIA IN THE YEARS 2015 – 2017", 78 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
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ABSTRACT

Energy revolution is a concept that is widely discussed nowadays. One important element therein is a shift towards greenhouse gas free generation of electricity and a renunciation of fossil fuels.

There are many different possibilities to realise such an energy revolution. In the field of electricity generators these are hydroelectric power stations, wind power plants, photovoltaic power plants and many more. Hydroelectric power stations are well established and well known. emerged during the last decades.

These new, volatile energy producers are placing new demands on grid operators and power plant operators. Wind power plants and photovoltaic power plants have relatively low full load hours compared to run-of-river hydro plants or gas power plants. Therefore, it is necessary to install a very high capacity to generate the same amount of energy. This high installed capacity may lead to an overproduction of energy when there are very good wind conditions.

This overproduction can either be stored or the electricity generation has to be reduced to avoid an overproduction. Electricity can be stored in battery systems, power to heat systems, pumped storage hydro plants and many more. Pumped storage hydro plants are the most efficient way to store huge amounts of energy.

In Austria wind power plants and pumped storage hydro plants are located far apart. Thus, the energy has to be transferred over long distances. This factor is of key importance to the grid operator APG.

This thesis analysis the correlation between electricity production of renewable sources and the use of pumped storage hydro power in Austria in the years 2015 to 2017. It examines which influence the wind energy, which mainly occurs in the eastern part of Austria, has on pumped storage hydro plants, which mainly exists in the western part of Austria and whether there is any correlation.

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1 INTRODUCTION

1.1 MOTIVATION

Electricity production from renewable energy sources plays a significant role in contributing to the reduction emissions (especially CO2) and in limiting the use of fossil fuels. As a result, the import dependency of fossil primary energy sources decreases, and domestic added value is increased when using primary energy sources from Austria (Pfemeter, et al., 2015).

Furthermore, the expansion of renewable energy production facilities is being promoted in many countries. In Germany and Austria, this applies in particular to wind energy and photovoltaics. Both wind energy and solar energy have a high fluctuation as they are dependent on the weather and the sunlight. The generation of wind energy depends only on the wind with electricity generation being possible throughout the year in good wind conditions. Photovoltaic power production is only possible with solar radiation and this depends on the time of the day, the season and the cloud cover. However, to produce the same amount of energy per year with volatile energy sources (like wind energy and photovoltaic) requires around three times the installed capacity of a conventional plant (Führer, et al., 2017). This is due to the low full load hours of the volatile energy sources (see also chapter 2.1). However, the grid and the cables must be designed for the installed power.

The use of these renewable sources has been increasing for several years now and will continue to increase in future. This increase impacts on several factors such as capacity of grid and prices for example.

Electricity has no storage life and thus the amount of demand and production must be equal all the time. The high fluctuation and uncertainty in electricity generation make the balancing of generation and consumption difficult and the seasonal differences in consumption and production also constitute to the complexity. The amount of energy consumption and of energy production have different peak times. Energy consumptions reaches its maximum in winter, while the maximum electricity production through renewable forms of energy happens in summer. Due to this increased volatility the existing power plant fleet will have to adopt.

If renewable energy capacity will increase beyond the network load, it can happen that renewable energy needs to be throttled without sufficient storage and grid.

Electricity can be stored in different ways such as pumped storage hydro power, battery systems, heat storage systems and others.

Austria has numerous pumped storage hydro plants that are used for storage of electricity.

Austria´s wind turbines are mostly located in eastern Austria whereas the pumped storage hydro plants are located in the Alps in western Austria. Generators and storage facilities are thus far apart and any storage resulting from an overproduction of wind energy would have to be transmitted over long distances. If there is a lack of electricity generation from wind energy the energy supply must be provided from other sources in order to meet the electricity demand. Generation from pumped storage hydro plants also has to be transmitted over long distances. Balancing the feed-in fluctuations of wind energy must go beyond far distances to the pumped hydro storage plants (Wolter, et al., 2011). This location dependency represents a challenge regard to the evaluation of necessary steps.

1.2 CORE OBJECTIVE

This master thesis deals with the question of whether there is a correlation between generation from wind energy and the use of pumped storage hydro plants in Austria. It also deals with the question whether there is a relationship between the price of electricity and the generation from wind energy and possible impacts on the modes of operation of pumped storage hydro plants. Subsequently, the strength of the correlation will be examined.

A very high negative correlation between generation of wind energy and storage capacity of pumped storage hydro plants would mean that the generated wind energy is stored in pumped storage hydro plants. Therefore, the energy has to be transferred via the grid.

This question is of interest to the grid operator APG. If there is a very high negative correlation this has an impact on the grid because the energy is transmitted between wind turbines and pumped storage hydro plants. The amount of energy that will be transmitted may lead to an overload of the grid. Wind power plants are among the volatile energy producers. In order to ensure energy security, there must be appropriate compensation options (for example controllable power plants). This compensation then takes place via the grid.

There are already some cases where redispatch activities have been necessary to guarantee the security of energy supply. This redispatch activities could have been reduced by sufficient transmission networks (Weixelbraun, 2017). To ensure supply and system security, it it important to drive grid expansion as needed. The necessary expansion measures must be initiated timely because it takes a long time due to extensive approval procedures and many involved parties. (Führer, et al., 2017)

In contrast, a high positive correlation means that both wind power plants and pumped storage hydro plants generate energy at the same time. This means that the wind energy is not stored in pumped storage hydro plants. The energy goes directly to the grid and is consumed.

In the case of increasing wind energy generation and decreasing price of electricity one speaks of a negative correlation. The more energy is available, the lower the price will be. If there is no generation of wind energy other power plants must cover the demand and therefore price of electricity will increase. The opposite case, a positive correlation between generation of wind energy and the price, is a high generation of wind energy and a high price.

From an economic point of view, pumped storage hydro plants will generate energy at high electricity prices and will operate in pumping mode at low electricity prices. This case illustrates a positive correlation between price and pumped storage hydro plants.

1.3 MAJOR LITERATUR

Data from the Austrian Power Grid (APG), the ENTSO-E platform and the Energy Exchange Austria (EXAA) are used for the research. This paper analyses the period from 2015 to 2017 and is based on the 15-minute data of APG, ENTSO-E and EXAA. The data is publicly available on the web pages.

The data offered by above mentioned organisations represent the essential literature for this master thesis. Reports and articles from the internet and library of Vienna University of Technology were used for further research.

APG operates most of the high-voltage grid in Austria. It is the Transmission System Operator (TSO) in Austria. The transmission system operators have following tasks :

- They operate the infrastructure of countrywide power grids for electricity transmission
- They provide access to these power grids for electricity traders, electricity suppliers and generating companies, distributors and directly connected customers in a transparent and non-discriminating way.
- They must keep fluctuations in the grid as low as possible. For this purpose, balancing power must be procured. This balancing power is used to compensate differences between energy production and energy consumption.

APG belongs to Verbund AG and was founded in 1999 (Wik182). They operate high voltage lines (110 kV, 220 kV and 380 kV) with 6 700 km length as well as substations and grid switchgears.

Parts of the high voltage grid in Vorarlberg belong to the „Vorarlberger Übertragungsnetz GmbH“ (Wik182).

TSO´s in Europe are members of the European Network of Transmission System Operators for Electricity (ENTSO-E). The ENTSO-E represents 43 transmission system operators from 36 European countries and was established in 2008 by the European Union (Wik183). The network codes are rules that specifies how the network operators may regulate power plants to keep the grid stable. In order to keep the grid stable, the voltage and the frequency may fluctuate only slightly. Interconnecting the grids of almost all transmission system operators provides a large system with many compensation options and common reserves. There are several grids which cannot be connected directly because the run asynchronous. The largest grid is the continental European grid. All transmission system operators provide fundamental data on their electricity grids. These can be accessed via the ENTSO-E transparency platform.

The Energy Exchange Austria is an electronic marketplace for electricity trade. The EXAA is dealing with the control area of APG and all four control areas in Germany

(Ampiron, TenneT, 50Hertz and Transnet BW). All 24 h or 96 quarter hours per day can be traded. At least 0,1 MWh must be traded (EXAA). The exchange is a day-ahead spot market. There is an auction every day (Monday to Friday) where participants can submit their bids and offers. The traded energy must be physically delivered the following day (Trades on Friday are for Saturday, Sunday and Monday). The price is set automatically with an algorithm. This evaluates the orders. Around 70 companies are trading at the EXAA electricity spot market (WikEXAA).

1.4 STRUCTURE OF THE THESIS

This thesis is divided into 6 chapters. The first chapter summarises the research area, describes the core objective and question addressed and lists the major literature used. The second chapter describes the basics of electricity generation in Austria with a special focus on wind energy and pumped storage hydro plants. The locations and fundamental power data as well as historical development are described. Furthermore, it gives a historical view on electricity generation in Austria.

The third chapter looks at the data that is being used for analysis in more detail as well as the method of analysing these data.

The fourth chapter describes the forms of analysis and the subsequent chapter explains the evaluations. Several methods of analysis and statistical methods of testing are used.

The results are shown and described in the fifth chapter. Several different records are compared.

The last chapter summarises the research results. The core question will be answered.

2 DESCRIPTION OF ELECTRICITY GENERATION IN AUSTRIA

This chapter describes general facts about electricity generation in Austria, beginning with a historical review. The years 2015 to 2018 are described in more detail. It starts with an analysis of the maximum production capacity and power generation and then focuses in more detail on wind power and pumped storage hydro plants.

Austria´s power plant park have always been largely hydroelectric power plants. These include run-of-river, pumped storage hydro and storage hydro plants. Most of the run-of-river plants are located at the danube as well as on smaller rivers like Inn, Salzach and many more. The second largest group of power plants are thermal power plants, such as natural gas, coal and oil. Since 1997 renewable energy power plants are starting to rise. This are wind power plants, photovoltaic panels and geothermal power plants. Table 1 shows the historical development of installed power plant capacity in Austria since 1950.

Table 1: Installed Power Plant Capacity in Austria 1950 to 2017 (own graph, data from (E-Control, 2018)

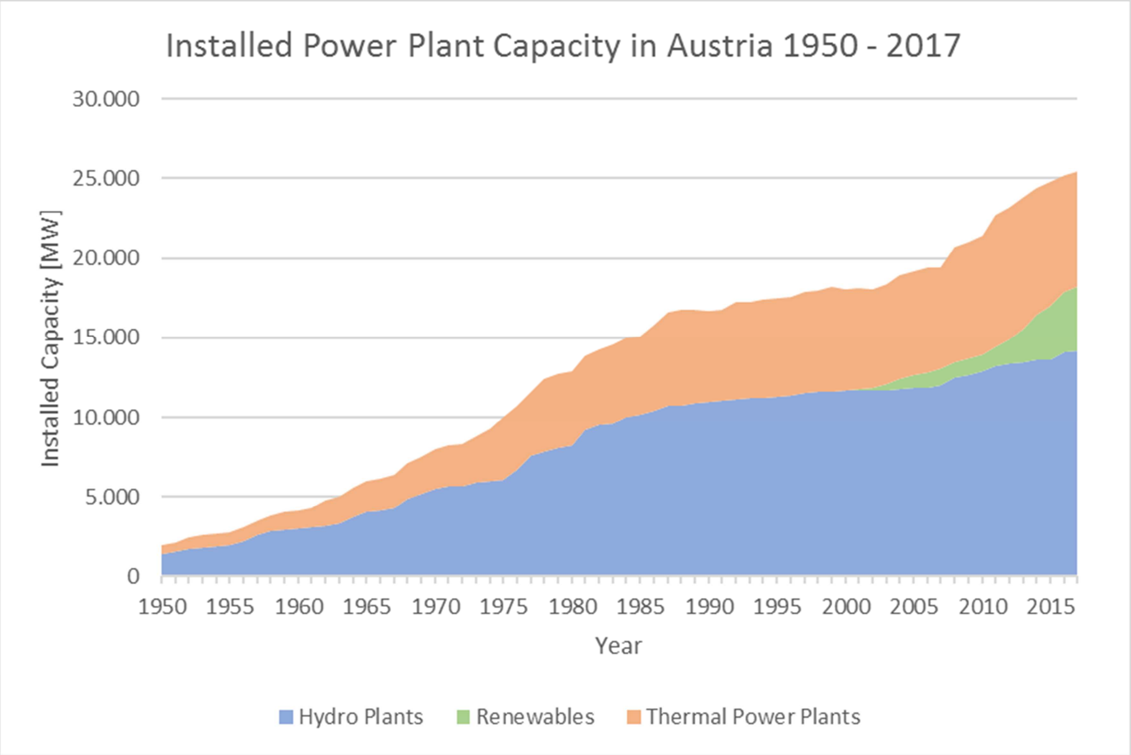

Table 2: Installed Power Plant Capacity in the control zone of APG in Austria (own table, data from (APG18))

	2018		2017		2016		2015	
Power Plant Type	[MW]		[MW]		[MW]		[MW]	
Biomass	491,00	2%	473,80	2%	473,60	2%	464,20	2%
Natural Gas	4.467,70	20%	4.465,80	21%	4.465,80	21%	4.501,20	22%
Black coal	598,00	3%	598,00	3%	766,00	4%	1.171,00	6%
Oil	177,90	1%	177,90	1%	177,90	1%	177,90	1%
Geothermal	0,90	0%	0,90	0%	0,90	0%	0,90	0%
Pumped storage hydro	3.401,10	16%	3.401,10	16%	2.971,10	14%	2.971,10	14%
Run-of-river	5.604,70	26%	5.580,80	26%	5.574,70	27%	5.542,70	27%
Storage hydro	2.984,60	14%	2.964,90	14%	2.964,90	14%	2.964,90	14%
Other renewables	42,30	0%	32,50	0%	32,50	0%	31,30	0%
Photovoltaic	1.031,00	5%	1.031,00	5%	723,00	3%	587,00	3%
Waste	149,80	1%	144,10	1%	144,10	1%	144,10	1%
Wind	2.841,60	13%	2.696,00	12%	2.497,40	12%	2.120,90	10%
Miscellaneous	22,80	0%	22,80	0%	22,80	0%	22,80	0%
Total	**21.813,40**	**100%**	**21.589,60**	**100%**	**20.814,70**	**100%**	**20.700,00**	**100%**

[1]

Table 2 shows the installed power plant capacity per power plant type in the years from 2015 to 2018. It shows the figures for the control zone of the APG. The largest generation capacitiy is provided by run-of-river plants followed by gas-fired power stations. This is followed by pumped storage plants and storage power plants. Wind power plants currently account for only 13 % of the installed capacity. But there has been an increase of 34 % in the last 4 years. Photovoltaic has also experienced a high level of increase of 75 %. However, the installed capacity only accounts for 5 % of the total installed capacity in Austria.

Austrias power plant fleet largely consists of renewable energy sources and specifically of hydropower.

[1] APG listed wind power plant capacity of 2.696 MW in 2017. OeMAG listed 2.320,3 MW for the same year. The OeMAG ist only listing power plants with feed-in-tariff.

Table 3: Generation of electricity in Austria (own table, data from (APG18))

	2017		2016		2015	
Power Plant Type	[GWh]		[GWh]		[GWh]	
Biomass	2.600,13	4%	2.535,48	4%	2.618,61	5%
Natural Gas	9.729,25	15%	7.863,76	12%	8.315,27	15%
Black coal	1.406,83	2%	1.465,86	2%	1.839,47	3%
Oil	-	0%	-	0%	-	0%
Geothermal	0,63	0%	0,62	0%	0,63	0%
Pumped storage hydro	1.578,67	2%	2.953,90	5%	1.754,90	3%
PSHP comsumption	- 3.087,37		- 2.130,80		- 2.400,27	
PSHP generation	4.666,04		5.084,70		4.155,17	
Run-of-river	26.855,42	42%	28.215,32	44%	19.353,27	36%
Storage hydro	4.607,44	7%	4.544,81	7%	3.020,42	6%
Other renewables	-	0%	-	0%	-	0%
Photovoltaic	1.144,30	2%	939,15	1%	819,78	2%
Waste	876,00	1%	878,40	1%	-	0%
Wind	6.726,18	11%	5.323,48	8%	4.911,21	9%
Miscellaneous	192,72	0%	193,25	0%	2.418,40	4%
Delta Import/Export	7.728,22	12%	8.743,04	14%	8.743,04	16%
Import	26.753,29		23.676,82		23.676,82	
Export	- 19.025,06		-14.933,78		- 14.933,78	
Total	**63.445,80**	100%	**63.657,06**	100%	**53.795,00**	100%

[2]

Table 3 shows the generated energy in Austria. The main energy is generated by run-of-river plants. This is followed by gas-fired power plants, imports and wind power plants which contribute roughly the same energy supply. Wind power and photovoltaics provide about 37 % respectively 39 % more energy in 2017 compared to 2015. Pumped storage hydro plants consume and generates energy. In total they only generate only 2 % to 5 % of the energy in Austria, but they buffer energy and generate about 7 % to 10 % of the yearly used energy in Austria.

There is a big difference between installed capacity and generated energy. The run-of-river power plants account for 26 % of the installed capacity but generates 42 % of the electrical energy. This is shown in Figure 1. The outer ring shows the generated energy while the inner ring shows the installed capacity. The difference for the run-of-river power plants is clearly visible.

[2] There is a difference on Import and Export energy data between APG and E-Control. E-Control includes the whole area of Austria while APG only include their control zone. (Mantler, 2018). This difference does not have any influence on the analysation done in this thesis.

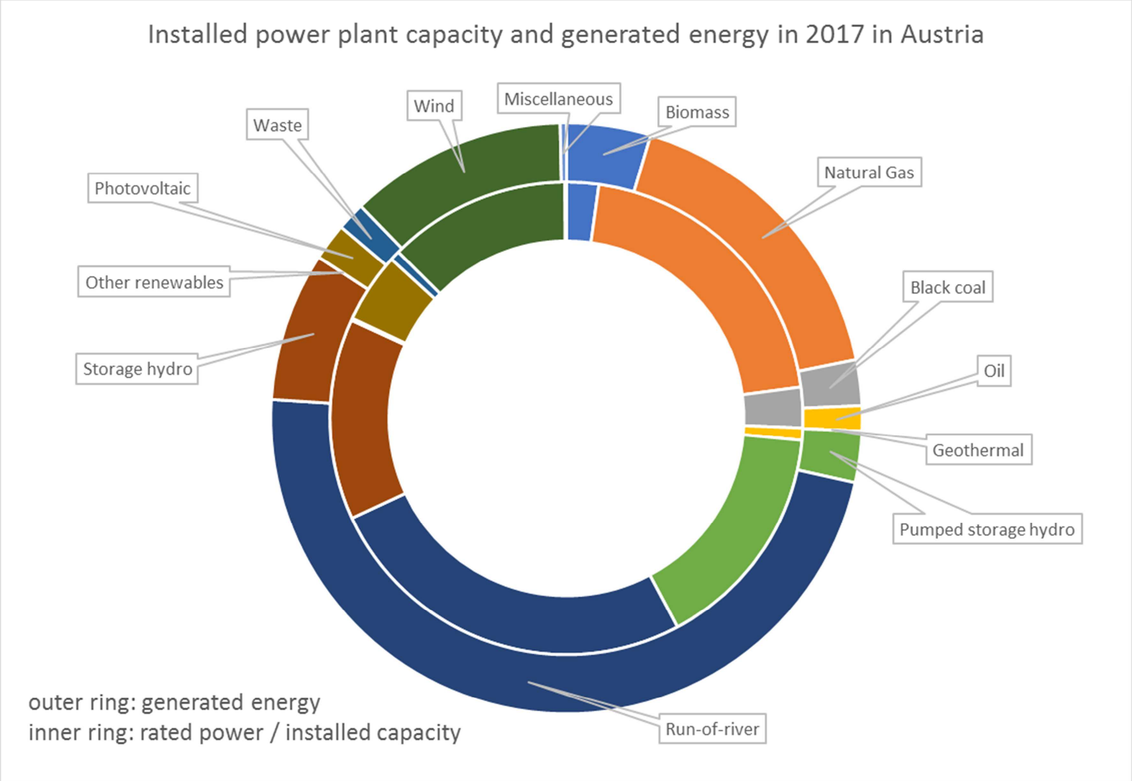

Figure 1: Installed power plant capacity and generated energy in 2017 in Austria (own graph, data from (APG18))

2.1 WIND

This chapter delves into wind power generation. It shows the installed capacity and yearly generation in Austria and federal states and provides a brief view on future developments.

In Austria, the north east of the country is best suitable for wind power generation. The high yield areas are in lower Austria (especially "Weinviertel" and eastwards of Vienna provide good conditions) and Burgenland (see also Figure 2 and Figure 3). The full load hours are around 2000 FLH (Wolter, et al., 2011) to 2150 FLH (Winkelmeier, et al., 2014). Half of the wind power plants that are operating all year round have 2380 FLH (Wolter, et al., 2011). The FLH calculated of the data of APG ranges from 2132 to 2495 h which matches with the data described in above literature. [3]

[3] For comparison: around 7 000 FLH for nuclear energy, 6 500 FLH lignite, 3 500 FLH hard coal, 3 500 run-of-river, 900 FLH photovoltaics (Bun18)

Alpine areas with high wind speeds can either be only used to a very limited extent or not be used at all. This is mainly due to difficulties of economic and ecological development such as infrastructure, sites, installation and maintenance.

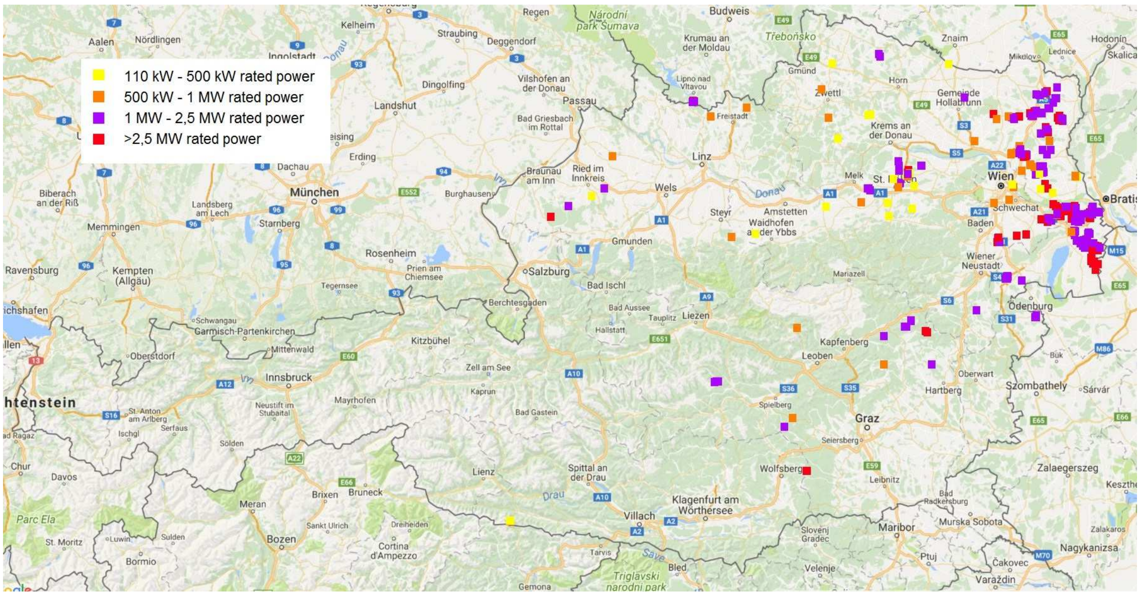

Figure 2: Location of wind power plants in Austria (IGW18)

Figure 2 illustrates the location of wind power plants in Austria. Most plants are located in the eastern part of Austria. Most of the plants have a rated power from 1 MW to 2,5 MW (shown on violet dots squares). There are no wind power plants in Vorarlberg and Tirol.

Figure 3 shows the analysis of the installed wind capacity of the federal states. Federal states that are not listed do not have wind power plants in a size of significant importance. 90 % of the installed wind power capacity can be found in Lower Austria and Burgenland.

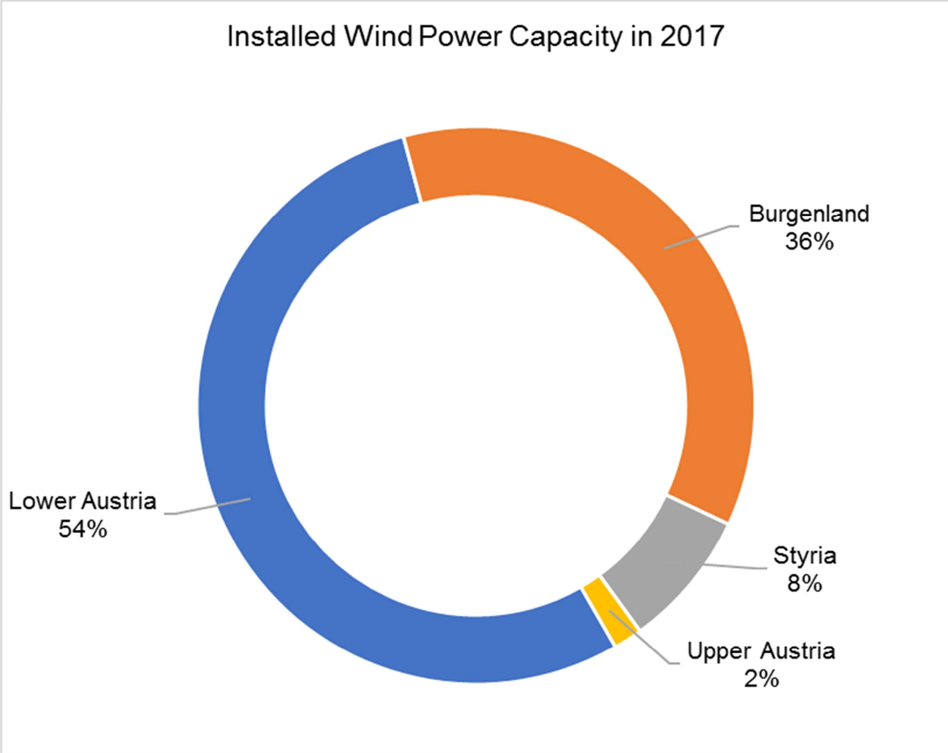

Figure 3: Installed wind power capacity split up to federal states in 2017 (own graph, data from (IGW18))

In 2013, as much wind energy was produced in Burgenland as the entire state consumed (IGW18).

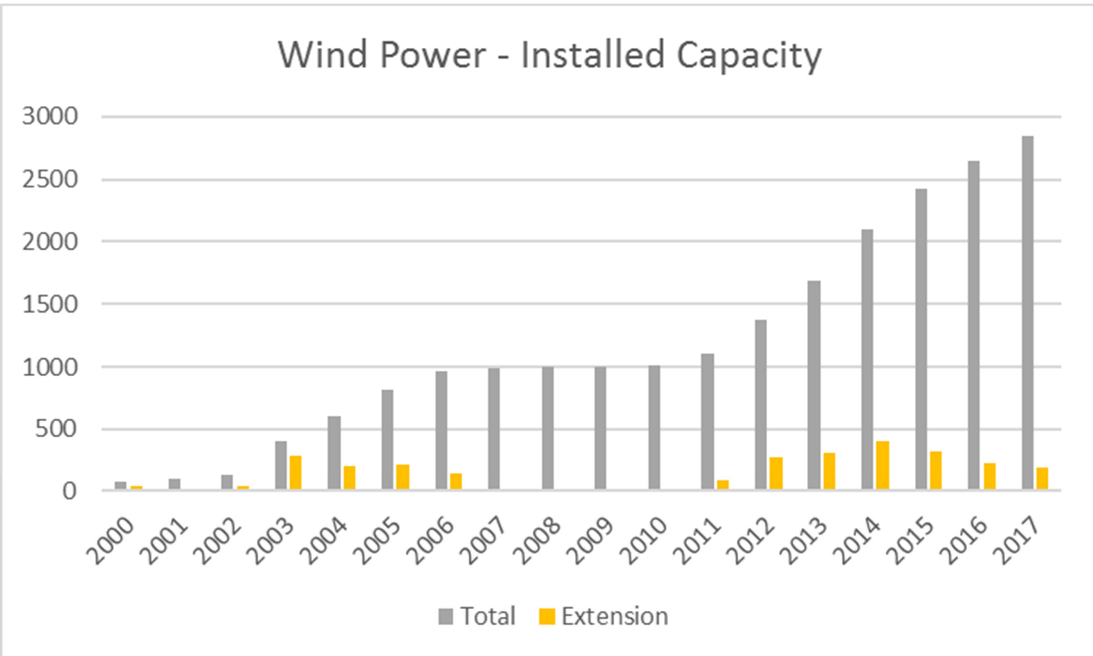

Figure 4: Installed Capacity of Wind Power Plants in Austria from 2000 to 2017 (own graph, data from (Win18))

Figure 4 shows the annual construction of wind turbines (yellow) and the cumulated total rated power (grey) from 2000 to 2017. The rated power is in MW. The graph also illustrates that almost no new plants were erected from 2007 to 2010. A new eco electricity act in Austria that came into forced in 2012 changed the situation (IGW18) and after 2012 an increase in capacity can be seen again.

In 2017 nearly 7 TWh of wind energy were generated which makes up 11 % of the domestic generation (own calculation) (Win18). This figure is higher than according to OeMAG who announced 5,7 TWh in 2017 (OeMAG). This is because OeMAG only counts the funded power plants (Reittinger-Hubmer, 2018). About 20 % of the wind power plants do not get a feed in tariff because they are not in the OeMAG regime anymore (Amatschek, 2017).

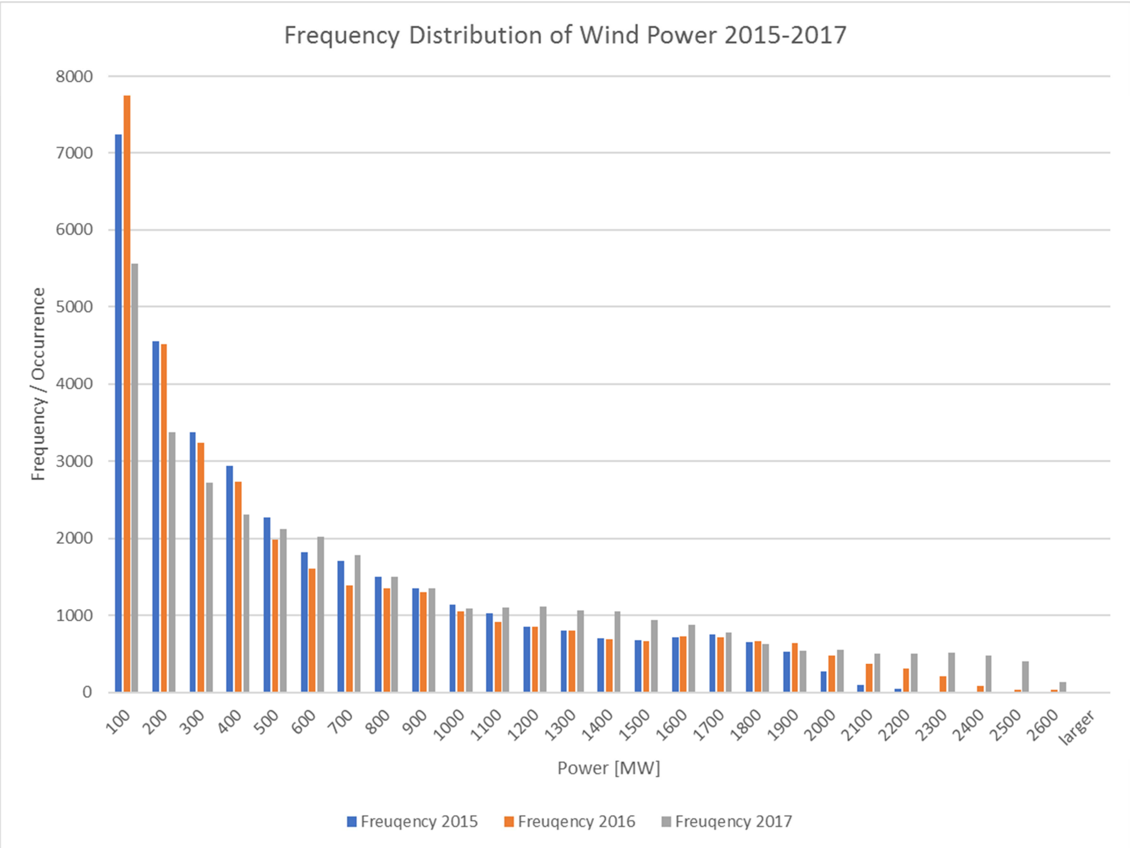

Figure 5: Frequency distribution of wind power in 2015 to 2017 (own graph, data from (APG18))

Figure 5 illustrates the frequency distribution of wind power with the x-axis giving the categorised rated power (in 100 MW steps) and the y-axis the frequency of occurrence. Even though there is more than 2 800 MW of installed power, it hardly happens that this full power is also used at the same time. Most of the time it is only a fraction of the total installed power that is used to generate energy. Similar figures are stated in (Wolter, et al., 2011). The wind regime is not the same everywhere.

Figure 6 is a similar graph to the graph in Figure 5 but uses percentage and an inverted axis. The graph shows that for only 10 % of the time in 2017 about 70 % of the installed capacity was used to generate electricity. This also means that for 100 % of the time only 70 kW were available.

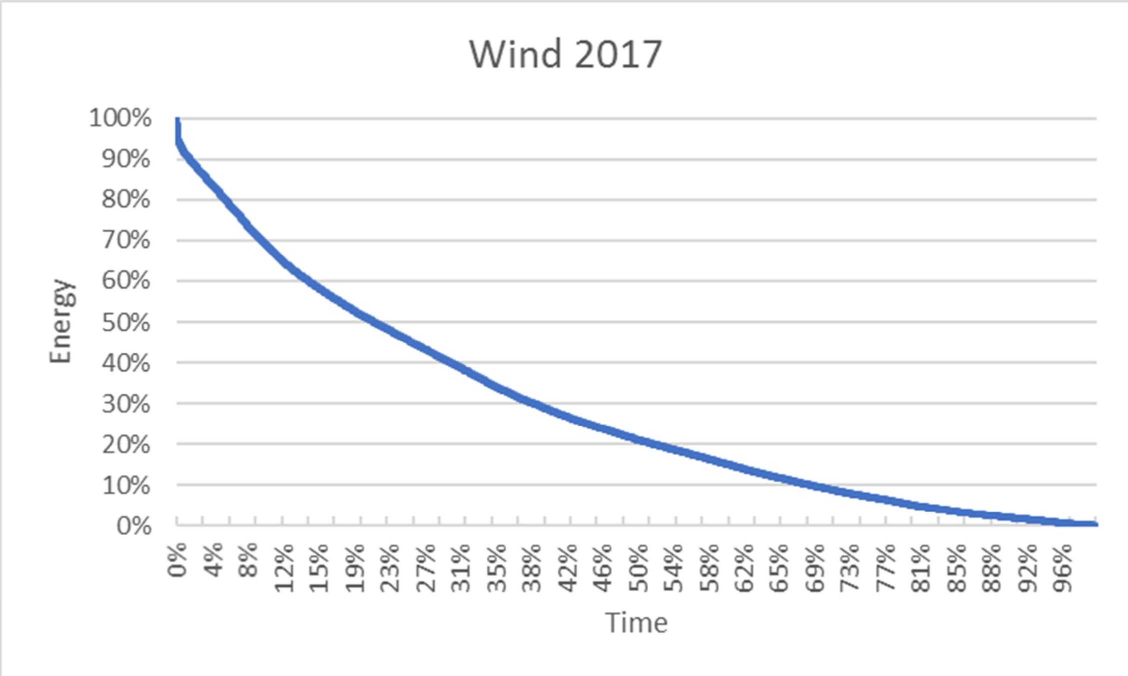

Figure 6: load curve of wind power generation in 2017 (own graph, data from (APG18))

There is a high potential for wind power plants in Austria. With continuing construction activity 3 800 MW could be installed by 2020. This could lead to a generation of 8,9 TWh. The scenario 2030 in the study assumes an installed capacity of 6 649 MW with an electricity production of 17,7 TWh (Winkelmeier, et al., 2014). This prediction is also found in (Haas, et al., 2017). In this scenario Burgenland could cover their electricity needs required for one year 2,8 times. Another study forecasts 5 000 to 8 000 MW installed wind power in 2030 (Nghiem, et al., 2017). The Austrian government´s goal for electricity generation is to be 100 % renewable in 2030. Wind power should generate 22,5 TWh in 2030 (Kronberger, 2018).

Wind power is a volatile form of energy. To ensure security of supply, appropriate control reserves must be planned. A good forecast of wind is an important tool to plan the control reserves more accurately (Wolter, et al., 2011).One study dealt with the modelling of the feed-in of wind energy into the grid. The exemplary model provides good results between reality and prediction (Lück, et al., 2017). A wind power plant off-grid operation does not make sense as the security of supply cannot be guaranteed unless a large amount of storage options were available.

2.2 PUMPED STORAGE HYDRO PLANT

This chapter deals with pumped storage hydro plants (PSHP) and describes how they work, their power and capacity.

PSHP is one possibility to store electricity through converting it to potential energy by using water. Water is pumped from a lower basin up to a higher basin where it is temporarily stored. This storage is possible for a long time period and hardly sees any losses. Losses during storage occur only through evaporation. Therefore, the energy can theoretically be stored for an unlimited period of time. If electricity is needed the water is released back to the lower basin through a turbine. The energy efficiency is about 75% to 80% (Manwaring, et al.), (Krzikalla, et al., 2013). During high energy demand the stored energy is released to the grid to cover the peak load. PSHP are suitable for covering peak loads within minutes due to their fast controllability. PSHPs can switch their operation mode within few minutes (Krzikalla, et al., 2013) and constitute a valuable addition to the less adjustable basic load power plants. Many basic load power plants need hours for starting or stopping energy production (Aus18) which is far too slow to react on variations in demand or production. Another advantage of PSHPs is their capability of a black start which means no energy is required to start the generation of the turbines.

At the moment PSHPs are the most economical solution for storing huge amounts of energy (Juranitsch, 2011). They have high efficiency, a long life span (about 100 years) and have moderate investment costs (Haas, et al., 2013). The investment costs are between 1 700 to 2 200 Euro/kW (Haas, et al., 2013), 1 000 to 2 000 Euro/kW (Ess, et al., 2012) respectively 500 to 2 500 Euro/kW (Brauner, 2013).

During periods of low energy prices or periods of overproduction the water is pumped up to the upper basin and stored.

Figure 7 shows a schematic diagram of a pumped storage hydro plant. It shows the upper and lower basin that are connected with pipes. The lower basin can either be a lake (artificial or natural) or a river. The power house is located close to the lower basin. In the power house the turbine and the pump are installed. Furthermore, there is the entire controller. The feed into the grid or the energy supply from the grid takes place form the power house building.

PSHP needs large basins with a maximum height difference. The alps offer the best terrain for them because large basins are easy to erect, and the height difference is given by the natural environment. Therefore, the number of possible locations is limited which will increase the investment costs for future projects.

The amount of energy that can be generated depends on the height difference between upper and lower basin and the amount of water which can be stored. The amount of power depends on the turbine/generator and the water flow rate.

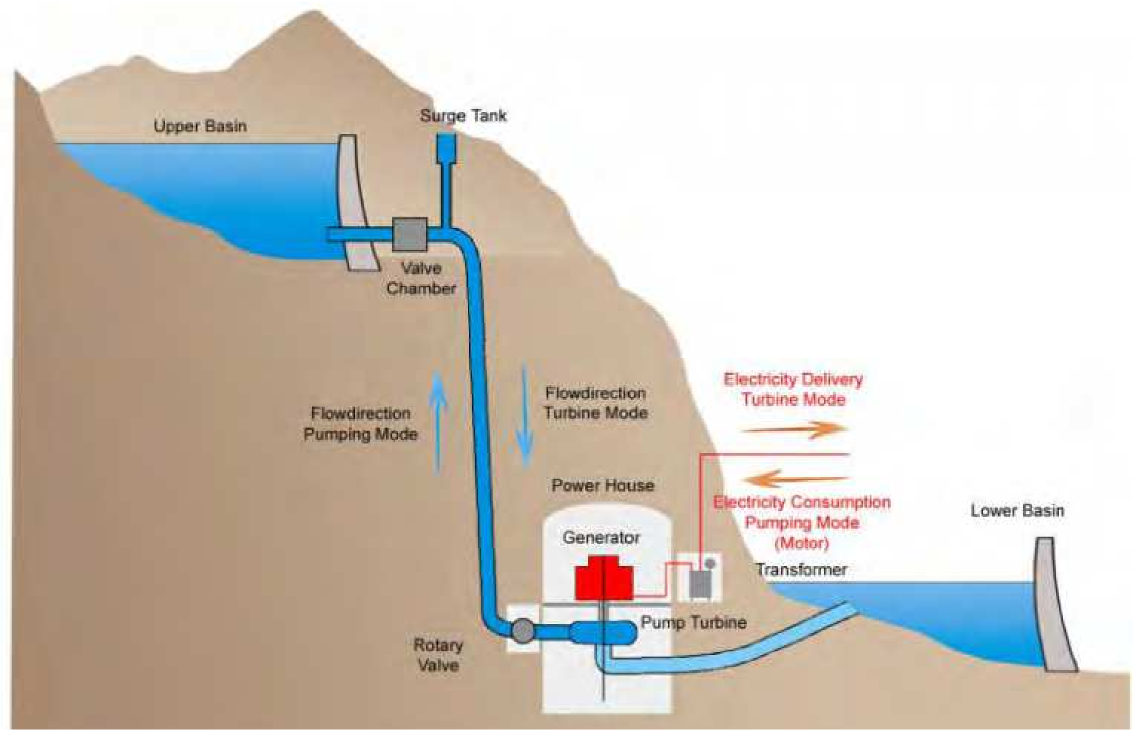

Figure 7: Schematic diagram of a PSHP (Manwaring, et al.)

Most PSHPs are located in western and southwestern Austria, mainly in the federal states Tirol, Vorarlberg, Salzburg and Kärnten.

The maximum capacity of all PSHP and storage plants in Austria is 3,27 TWh (Aus18), (ECo181). The capacity of a PSHP is about 2 TWh[4] (ent18). The filling rate of all storages was between 16,5 % and 85,5 % in 2017 (ECo181). The lowest rates

[4] According (Weixelbraun, 2017) the PSHPs have an energy capacity of about 5 TWh.

are in March and April (see Figure 8) because of winter time. This is because there is nearly no precipitation that fills immediately the basins and a lot of stored water is used to generate electricity. In spring time during the snowmelt and a lower energy demand the reservoirs are refilled.

Figure 8 shows the stored energy value of water reservoirs and hydro storage plants in Austria for the years 2015 to 2017. The maximum amount of stored energy occurs in the summer and autumn months. In winter a lot of energy is needed which in turn leads a minimum filling value in March.

The more often PSHPs are used the more profitable they are. Volatile renewable energy like wind power and PV will increase the operation hours (operating grade) of PSHPs (Zach, et al., 2013). In Austria pumped storage hydro plants store energy mainly for short time periods. That means during high demand peaks during the day PSHPs generate electricity whilst low demand periods during night they pump the water up to the higher basin. This effect is illustrated in chapter 5.2.

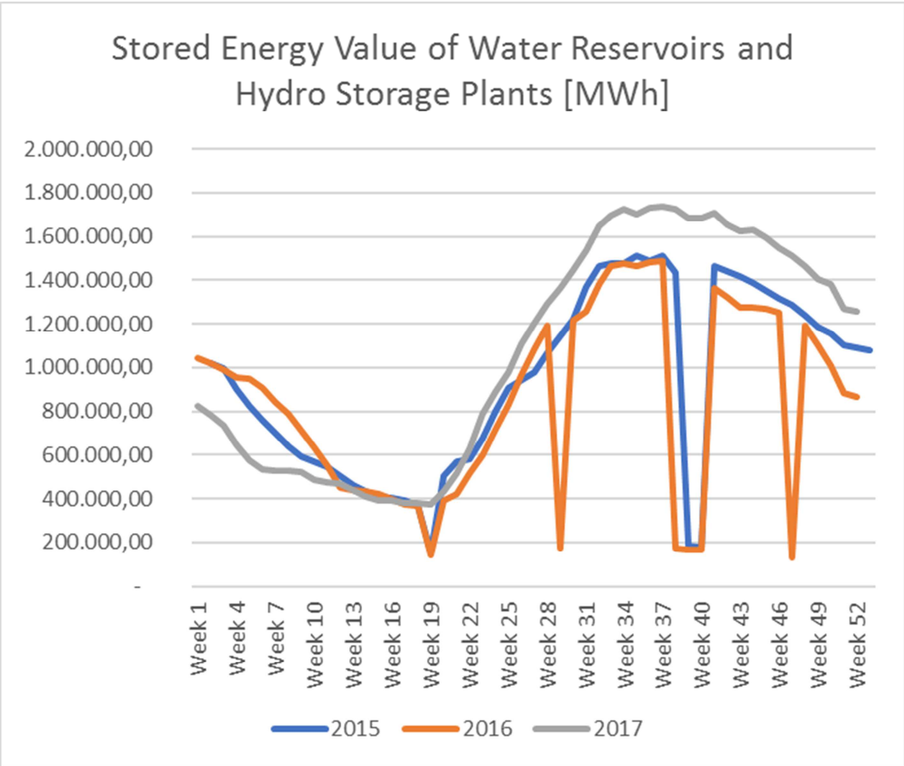

Figure 8: Stored Energy Value of Water Reservoirs and Hydro Storage Plants in Austria (own graph, data from (ent18))

Most of the time PSHPs are generating electricity (Figure 9). On the x-axis a whole year (shown in hours) is illustrated. The y-axis shows the generation of energy (positive values) and demand of energy (negative values) of the PSHPs in Austria. The values are sorted with the greatest generation shown on the left side and the greatest demand of energy on the right side. Overall more energy is generated than consumed because there is a natural inflow given by rivers or rainfall.

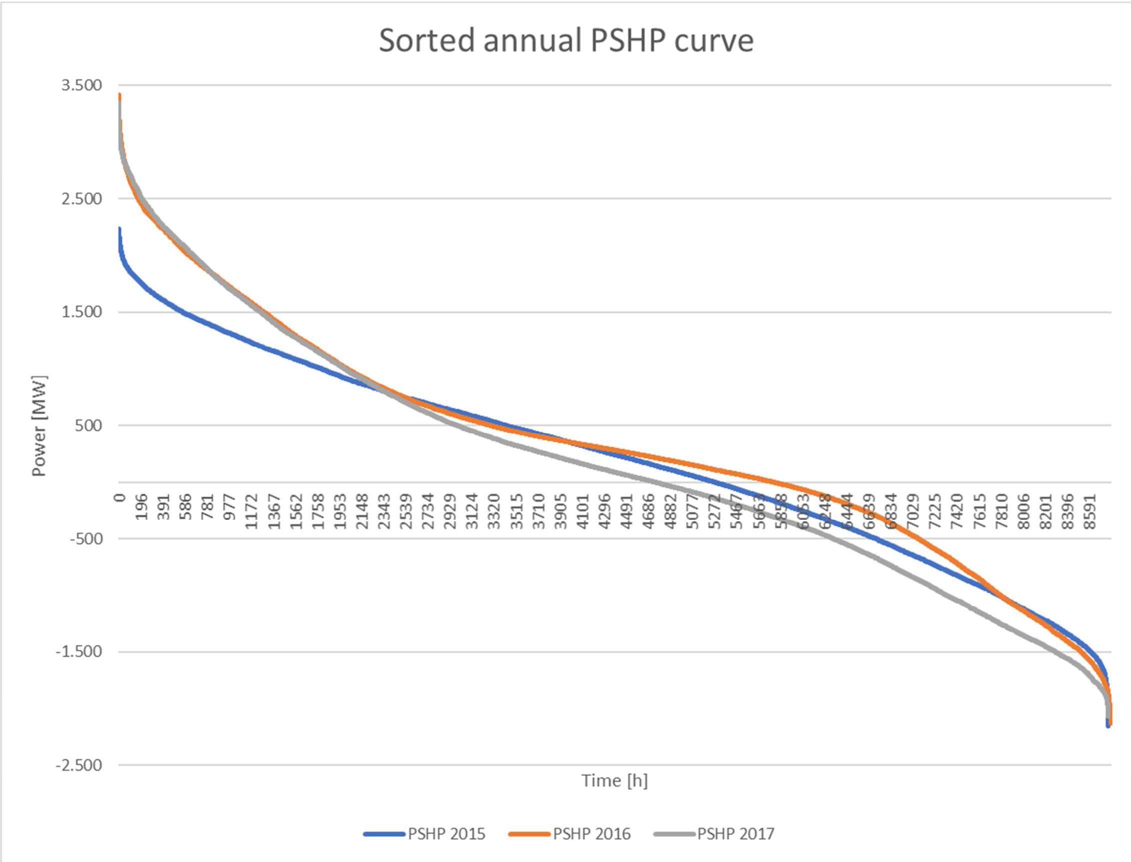

Figure 9: Sorted annual PSHP curve (own graph, data from (APG18))

Figure 10 shows the frequency distribution of PHSPs in the years 2015 to 2017. The y-axis gives the frequency of occurrence, the x-axis gives the categorised power (100 MW steps). Negative values mean that the PSHP is consuming energy (for pumping up the water), positive values show that the PSHP is generating electricity. It rarely happens that the full power is used at the same time.

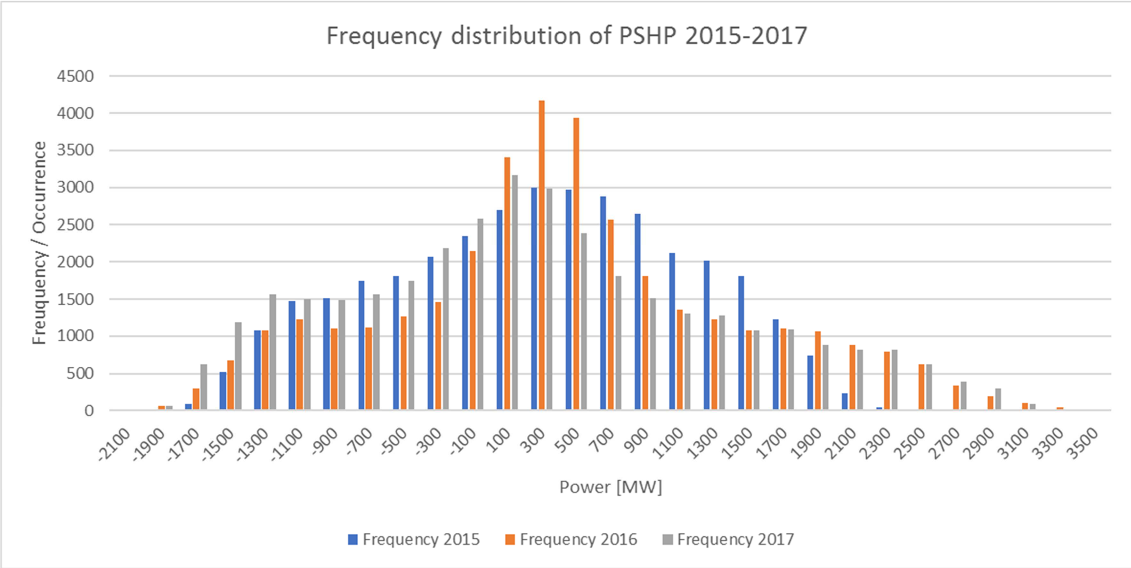

Figure 10: Frequency distribution of PSHP in the years 2015 to 2017 (own graph, data from (APG18))

Table 4: List of existing PSHP in Austria ((Eur18), (ent18), (Wik18), (Oes18), (Ver18), (kel18), (Ill18), (Neuner, 2018))

No.	Name	Power	Energy	operating grade	head of water	water quantity	year of completion	federal state	Owner
		[MW]	[GWh / a]	[%]	[m]	[m³/s]			
1	Malta-Hauptstufe	730	618	11	1106	80	1979	Carinthia	Verbund
2	Kopswerk II	525			818	80	2008	Vorarlberg	Vorarlberger Illwerke AG
3	Limberg II	480			346	144	2012	Salzburg	Verbund
4	Reißeck II	430			595	80	2015	Carinthia	Verbund
5	Häusling	360	188	6	696	65	1988	Tyrol	Verbund
6	Kühtai	289	55,5	4		80	1981	Tyrol	Tiroler Wasserkraft AG
7	Rodundwerk II	295	486	20	354	98	1976/2011	Vorarlberg	Vorarlberger Illwerke AG
8	Lünerseewerk	232	371	18	974	27,6	1958	Vorarlberg	Vorarlberger Illwerke AG
9	Roßhag	231	328	15	630	52	1972	Tyrol	Verbund
10	Rodundwerk I	198	322	19	780	36	1952	Vorarlberg	Vorarlberger Illwerke AG
11	Feldsee	140	300		524		2011	Carinthia	kelag
12	Malta Oberstufe	120	37	7	198	70	1979	Carinthia	Verbund
13	Limberg I / Kaprun Oberstufe	113	152 - 166,1					Salzburg	Verbund
14	Fragant (Innerfragant I)	108	82	9	1185	10,1		Carinthia	kelag
15	Hintermuhr	104	180		497		2009	Salzburg	Salzburg AG
16	Fragant (Innerfragant II)	100	93	11	409	15,9		Carinthia	kelag
17	Koralpe	50	160				2011	Carinthia	kelag
18	Nassfeld	31,5	51,6		317	11,6	2006	Salzburg	Salzburg AG
19	Ranna	19					1925	Upper Austria	Energie AG Oberösterreich
20	Heiterwang	2,9					2009		Elektrizitätswerke Reutte

Table 4 shows installed and operating PSHPs in Austria. The rated power adds up to 4,5 GW (and is comparable to (Zach, et al., 2013)), but differs to the data of APG in Table 2. The reason for this is that PSHPs in Vorarlberg are not in the control area of APG but in the German control area (Mantler, 2018). Vorarlberg has an installed capacity of 1,25 GW.

The list is ordered by the rated power. The largest PSHP is Malta-Hauptstufe with 730 MW power and an electricity generation of 618 GWh / a. Most of the PSHPs are only operating at less than 20 % of the time per year.

There are plans for installing new and upgrading existing PSHPs within the next decades. A study claims that this will mean an increase of installed capacity of about 5 GW (Wolter, et al., 2011), (Zach, et al., 2013). Planned PSHPs are listed in Table 5.

Table 5: List of planned PSHPs ((Eur18), (ent18), (Wik18), (Oes18), (Ver18), (kel18), (Ill18))

No.	Name	Power	Energy	operating grade	head of water	water quantity	year of completion	federal state	Owner
		[MW]	[GWh / a]	[%]	[m]	[m³/s]			
1	Ausbau KW Kaunertal	900	620				2034		Tiroler Wasserkraft AG
2	Limberg III	480					tbd		Verbund
3	Obervermuntwerk II	360					2018		Illwerke AG - VKV
4	Rotholz Erweiterung	320					tbd		Verbund
5	Energiespeicher Riedl	300			350	100	tbd		Grenzkraftwerke GmbH / Ve
6	Ebensee	170					2020		Energie AG Öberösterreich
7	Tauernmoos	130					2025		ÖBB
8	Ausbau Sellrain-Silz / Kühtai	130	216				2026		Tiroler Wasserkraft AG
9	Dießbach	32					2018	Salzburg	Salzburg AG

3 DESCRIPTION OF DATA AND METHOD

3.1 DESCRIPTION OF DATA

This research for Austria uses date from January 1st, 2015 till December 31st, 2017. The data was provided by APG ((APG18) and (APG181)), Energy Exchange Austria (EXAA) and ENTSO-E transparency (ent18) platform.

The following generation types are listed:

- Wind
- Solar (electricity production of Photovoltaic)
- Biomass
- Gas
- Coal
- Oil
- Geothermal
- Pumped storage hydro plant
- Hydro run-of-river and poundage
- Hydro water reservoir
- Other renewable
- Waste
- Other

The following data was used for research:

- Generation of wind energy
- Generation of photovoltaic
- Load
- Generation / consumption by pumped storage hydro power
- Spot market prices of electricity in Austria

All data is given in a 15 minutes interval. The generation of electricity and the load is shown in power in Watt. In order to arrive at Watthours, the figures must be multiplied by 0,25 to get the energy in Watthours.

Table 6 shows an extract of the data as an example. In the first two columns date and time are shown. The penultimate column shows the load. The load is the total final consumption in in the APG area (APG181). The load is not measured but it is calculated of the sums of production (production plus imports) minus exports and PSHP consumption. The last column in Table 6 shows the spot price of electricity in MWh / €.

The first row in Table 6 shows the energy generation and consumption on January 1st, 2017 from 0:00 to 0:15. In this time 23,502 MWh was gained from wind energy. The bulk of the energy at that time was generated from gas-fired power plants. The pumped storage power plants were in pumping mode.

Table 6: extract of the data table for the year 2015 (own table, data from (APG18), (APG181) and (EXAA))

From	To	Wind [MW]	Solar [MW]	Biomass [MW]	Gas [MW]	Coal [MW]	Oil [MW]	Geothermal [MW]	PSHP [MW]	run-of-river [MW]	Storage [MW]	other REN [MW]	Waste [MW]	other [MW]	Load [MW]	Price [€ / MWh]
01.01.2017 00:00	01.01.2017 00:15	94,008	0	300	2.462,80	158,8	0	0,072	-871,6	1.469,60	518,4	0	100	22	6.654,00	33,70
01.01.2017 00:15	01.01.2017 00:30	94,029	0	300	2.235,20	160,4	0	0,072	-869,2	1.499,60	618,8	0	100	22	6.628,00	27,10
01.01.2017 00:30	01.01.2017 00:45	94,27	0	300	2.086,80	160,8	0	0,072	-918,8	1.502,40	643,2	0	100	22	6.575,60	25,19
01.01.2017 00:45	01.01.2017 01:00	88,888	0	300	1.928,80	159,2	0	0,072	-960,4	1.512,40	634,8	0	100	22	6.430,40	14,00
01.01.2017 01:00	01.01.2017 01:15	86,582	0	300	1.638,80	159,2	0	0,072	-970	1.533,20	587,2	0	100	22	6.438,00	36,60
01.01.2017 01:15	01.01.2017 01:30	88,738	0	300	1.488,00	160	0	0,072	-920,8	1.522,80	599,6	0	100	22	6.344,40	31,43
01.01.2017 01:30	01.01.2017 01:45	85,968	0	300	1.482,80	160,8	0	0,072	-1.008,40	1.518,40	581,2	0	100	22	6.286,80	21,29
01.01.2017 01:45	01.01.2017 02:00	83,101	0	300	1.477,60	158,8	0	0,072	-1.033,60	1.508,40	432,4	0	100	22	6.192,40	15,70
01.01.2017 02:00	01.01.2017 02:15	75,597	0	300	1.404,80	160	0	0,072	-1.043,20	1.528,00	476	0	100	22	6.220,40	36,30
01.01.2017 02:15	01.01.2017 02:30	73,93	0	300	1.374,80	160,8	0	0,072	-1.058,40	1.523,60	349,6	0	100	22	6.149,20	30,00
01.01.2017 02:30	01.01.2017 02:45	67,929	0	300	1.372,40	159,2	0	0,072	-1.065,20	1.520,00	292	0	100	22	6.051,20	19,69
01.01.2017 02:45	01.01.2017 03:00	70,792	0	300	1.382,00	160,8	0	0,072	-1.100,80	1.479,60	84,8	0	100	22	5.985,20	12,00
01.01.2017 03:00	01.01.2017 03:15	73,228	0	300	1.368,00	159,6	0	0,072	-1.270,00	1.492,40	201,6	0	100	22	5.921,60	24,90
01.01.2017 03:15	01.01.2017 03:30	77,877	0	300	1.354,40	160	0	0,072	-1.324,00	1.463,60	210,8	0	100	22	5.856,80	24,78
01.01.2017 03:30	01.01.2017 03:45	73,103	0	300	1.343,20	159,6	0	0,072	-1.349,20	1.471,60	243,2	0	100	22	5.791,20	19,40
01.01.2017 03:45	01.01.2017 04:00	69,296	0	300	1.343,60	159,6	0	0,072	-1.358,80	1.441,20	188,8	0	100	22	5.752,40	12,91
01.01.2017 04:00	01.01.2017 04:15	69,606	0	300	1.338,40	160,8	0	0,072	-972	1.486,00	285,6	0	100	22	5.708,80	24,94
01.01.2017 04:15	01.01.2017 04:30	67,502	0	300	1.334,00	159,2	0	0,072	-984	1.483,60	237,6	0	100	22	5.720,00	21,01
01.01.2017 04:30	01.01.2017 04:45	66,664	0	300	1.342,80	160	0	0,072	-1.000,80	1.470,80	78,8	0	100	22	5.703,60	20,70
01.01.2017 04:45	01.01.2017 05:00	72,208	0	300	1.348,00	158,8	0	0,072	-1.016,00	1.450,80	77,2	0	100	22	5.727,20	15,34
01.01.2017 05:00	01.01.2017 05:15	75,456	0	300	1.323,60	160	0	0,072	-960	1.422,40	197,2	0	100	22	5.796,00	16,45
01.01.2017 05:15	01.01.2017 05:30	78,868	0	300	1.312,80	159,6	0	0,072	-957,2	1.424,40	190,8	0	100	22	5.813,60	21,92
01.01.2017 05:30	01.01.2017 05:45	78,789	0	300	1.306,00	160	0	0,072	-947,2	1.412,80	225,6	0	100	22	5.833,20	13,34
01.01.2017 05:45	01.01.2017 06:00	75,855	0	300	1.306,80	160,4	0	0,072	-958,4	1.410,80	217,6	0	100	22	5.830,00	23,61
01.01.2017 06:00	01.01.2017 06:15	75,772	0	300	1.297,60	159,6	0	0,072	-1.251,20	1.420,40	254	0	100	22	5.724,00	12,00

3.2 METHOD

Potential correlations are examined by using chronological evaluations and regression analyses. The results are presented graphically, in formulas and in tables.

The transmission capacities of the grid are not taken into account in the analysis.

Calculations and graphs were created with Microsoft Excel and Matlab. All data from the various sources is brought to a consistent, comparable format. Mathematical functions are used to perform the calculations. The presentation of individual rows is done graphically in two- and three-dimensional images.

For further editing the residual load was calculated for every 15 minutes interval.

The residual load is the share of the consumption that is independent of volatile energy sources, e.g. wind and sun.

$$P_{residual\ load} = P_{load\ total} - P_{wind\ generation} - P_{solar\ generation} \tag{1}$$

A negative residual load indicates a surplus of energy generation. This surplus has either to be stored or power plants have to be throttled down. Studies forecast time periods with negative residual load for Germany in 2050 (Ess, et al., 2012).

4 ANALYSIS OF DATA

This chapter describes the methods for analyzing the data.

The following methods are applied for data analysis:

- Chronological analysis
- Regression analysis
    - Linear regression model
    - Coefficient of determination analysis
    - Correlation analysis
    - F-Test and T-Test analysis

4.1 CHRONOLOGICAL ANALYSIS

In this chapter the chronological plots of residual load, generation of wind and solar energy, the generation respectively consumption of PSHPs as well as the price for electricity are investigated. The chronological plot is shown for each year (2015 until 2017). Within this 3-year time span particular periods will be viewed in more detail. These are characterized by a high generation of wind with a quasi-simultaneous demand of PSHPs (“high wind production – pumping mode of PSHPs“) on the one hand and by a high generation of wind with a quasi-simultaneous high generation out of PSHPs (“high wind production – high generation of PSHPs”) on the other hand. High wind production and pumping mode of PSHPs means that there is a negative correlation whereas high wind production and high generation of PSHPs means that there is a positive correlation.

4.2 REGRESSION ANALYSIS

4.2.1 LINEAR REGRESSION MODEL

Regression analysis is used for estimating the relationship between a dependent variable and one or more independent variables. They can be used to create a prediction model by using the functional relationship of independent variables or to quantify the heaviness of the relationship. There are several techniques for a regression analysis. The most frequently technique is the linear regression analysis.

Following equation shows the relationship between several independent variables x_i and the dependent variable y, b is the error term. $f(.)$ is the function for the model.

$$y = f(x_1, x_2, x_3, \dots, x_n) + b \tag{2}$$

Equation (3) shows the one-dimensional case for a linear regression analysis. their factor / parameter m and the error term. It is a simple straight line.

$$y = m_1 x_1 + b \tag{3}$$

Following equation shows the linear relationship between two independent variables x and their factors m and the dependent variable y, b is the error term.

$$y = m_1 x_1 + m_2 x_2 + b \tag{4}$$

To calculate $f(.)$ or the parameters m the ordinary least squares method is used. It is the way to find the best matching straight line. This method yields parameters whose sum of square deviations is minimized. The deviations are called residuals and the latter are the difference between the true value y and the value $\hat{y}$ predicted by the model.

$$e_i = y_i - \widehat{y_i} \tag{5}$$

Research will be done between the generation / consumption of pumped storage hydro plants, the production of wind power, the residual load and the prices in several variations:

$$P_{PSHP,single\ regression} = m_1 P_{wind} + b \tag{6}$$

$$P_{PSHP,single\ regression} = m_1 P_{residual\ load} + b \tag{7}$$

$$P_{PSHP,multiple\ regression} = m_1 P_{wind} + m_2 P_{residual\ load} + b \tag{8}$$

$$P_{PSHP,multiple\ regression} = m_1 P_{wind} + m_2 P_{price} + b \tag{9}$$

$$P_{Price,single\ regression} = m_1 P_{wind} + b \tag{10}$$

$$P_{PSHP,single\ regression} = m_1 P_{Price} + b \tag{11}$$

The linear regression analysis is done for each year.

There are methods to prove the regression model which are described in the chapter 4.2.4.

4.2.2 COEFFICIENT OF DETERMINATION ANALYSIS

To compare the estimated (calculated by the regression analysis) and actual values the coefficient of determination r^2 or R^2 is used. The coefficient ranges between 0 .. 1. Where 0 means that the regression line is not appropriate. 1 means a perfect correlation which means the regression equation can predict the y-value. The coefficient of determination is calculated by using the residual sum of squares SS_{res} and the total sum of squares SS_{tot}.

$$R^2 = r^2 = 1 - \frac{SS_{res}}{SS_{tot}} = 1 - \frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)}{\sum_{i=1}^{n}(y_i - \bar{y})} \tag{12}$$

4.2.3 CORRELATION ANALYSIS

The correlation coefficient shows the linear relationship between two values x and y. It ranges between -1 .. 0 .. +1. If the correlation coefficient is 0 then there is no relationship between these two values. 1 shows a total positive, -1 a negative correlation.

$$r_{xy} = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2 \sum_{i=1}^{n}(y_i - \bar{y})^2}} \tag{13}$$

Below equation is used to calculate the correlation coefficient between three values y, x_1, x_2 (Kiel, 2008). In this case the correlation coefficient ranges between 0 .. +1.

$$r_{y,x1,x2} = \sqrt{\frac{r_{x1y}^2 + r_{x2y}^2 - 2r_{x1x2}r_{x1y}r_{x2y}}{1 - r_{x1x2}^2}} \tag{14}$$

Table 7: Meaning of the correlation coefficient between three values (own table, interpretation from (Rumsey))

Value	Meaning
-1	Perfect negative linear relationship
-0,7	Strong negative linear relationship
-0,5	Moderate negative relationship
-0,3	Weak negative association
0	No linear relationship
+0,3	Weak positive association
+0,5	Moderate positive relationship
+0,7	Strong positive linear relationship
1	Perfect positive linear relationship

The interpretation as shown in Table 7 is not standardized and other interpretations can be found in literature.

4.2.4 F-TEST AND T-TEST ANALYSIS

To calculate a regression model does not prove that the investigated correlation is significant. This means that it is not proven that the correlation is also valid for other values than those that were used to calculate it. There are test methods to validate the regression model beyond the variables. This proves if the observed correlation between the dependent variables and independent variable is random or not. These test methods are called F-Test and T-Test.

The F-Test gives information if the correlation is valid for the entity, the T-Test checks every independent variable for its significance.

When testing a model with the F-test it is checked whether at least one independent variable provides an explanation for the model and that the model is therefore significant. Therefore, a null hypothesis is deployed. The null hypothesis declares that none of the independent variables have any influence on the dependent variable. It asserts $H_0: \sigma_A = \sigma_B$ (Pernerstorfer). That also means $m_1 = m_2 = \cdots = m_i = 0$. The model is significant, if it the significance level α_0 is smaller than the probability value p. Then the null hypothesis will be rejected. The significance level is chosen in advance, most common are values 5 % (significant result), 1 % (very significant result) or 0,1 % (very high significant result) (Wikipedia). Furthermore, the null hypothesis model will be rejected if the F-Value is larger than the critical F-Value. F is the quotient of the variances. If the null hypothesis is rejected it can be claimed that the coefficient of determination is high enough and at least one independent variable determines the dependent variable.

$$F = \frac{S_B^2}{S_A^2} = \frac{\sigma_B^2}{\sigma_A^2} = \frac{\frac{1}{n_B-1}\sum_{i=1}^{n_B}(x_{B,i}-\bar{x}_B)^2}{\frac{1}{n_A-1}\sum_{i=1}^{n_A}(x_{A,i}-\bar{x}_A)^2} \tag{15}$$

$$H_0 \; will \; be \; rejected \; if \; F \; > \; F_{critical} \; and \; p < \propto_0 \tag{16}$$

Equation (15) shows how to calculate the F Factor.

If the null hypothesis is not rejected, then there is no correlation between the real values and the calculated values of the model.

A t-Statistics describes the significance of a coefficient estimated by means of an econometric approach (Haas, 2018). The t-test values depend on the significance level and the sample size. The sample size is 35 040 for 2015 and 2017, and 35 137 for 2016. A t-distribution level of 1,96 was chosen. That means 95 % (which equals a significance level of 5 %) of the values lies within 1,96 standard deviations of the mean. If the t-value is larger than 1,96 it has a significant impact.

5 RESULTS

In this chapter the results of the data analysis as described in chapter 4 will be illustrated and explained. The results will be discussed at the end of each chapter.

5.1 CHRONOLOGICAL ANALYSIS I

The time courses show the days of January 1st to December 31st on the X-axis. The Y-axis shows the course of the day from 0 o'clock to 24 o'clock from top to bottom. The intensity of the colour indicates the values. For each year (2015 to 2017) three diagrams are shown. These indicate the generation of wind energy, the generation or consumption of the pumped storage power plants and the energy price.

The top diagram shows the generation of wind energy. The lighter the shade of gray, the less energy was produced, the darker the more energy was produced. The values in the legend have the unit MW.

The middle diagram shows the generation or the consumption of pumped storage power plants. Brown tones indicate the consumption, i.e. the pumped storage power plant is in pump mode. The blue colour indicates the energy production. The darker the colour, the higher the values. The values in the legend have the unit MW.

The bottom diagram shows the energy price in Euro / MWh. Green tones indicate negative prices, yellows and reds a positive price.

The top diagram in Figure 11 shows the production of wind energy. This shows up as irregular with peaks in spring and autumn as well as in the beginning of the year. The middle diagram shows the energy flow of the pumped storage power plants. The energy demand peaks in the morning and in the evening can be clearly recognized. These are closer together in the winter months than in the summer months. The pumped storage power plants deliver the most energy at these peak times. The pumping takes place mainly in the night and morning hours. In spring it is also pumped at lunchtime. The Christmas holidays, and thus the lack of morning and evening peaks is also recognizable. There are no clear production peaks here. The bottom diagram shows the price history of electricity. Negative prices are rare, mostly in the night. The energy demand peaks in the morning and in the evening are also evident here (clearly indicated by the red colours). The two lowest diagrams show a correlation. If the price rises, energy production by pumped storage power plants also increases. If the price is low (or even negative) then more water will be pumped. Obviously, a connection between the pumped storage power plants is difficult to detect. Only in the spring where a production peak occurs can be seen a lower energy production by pumped storage power plants.

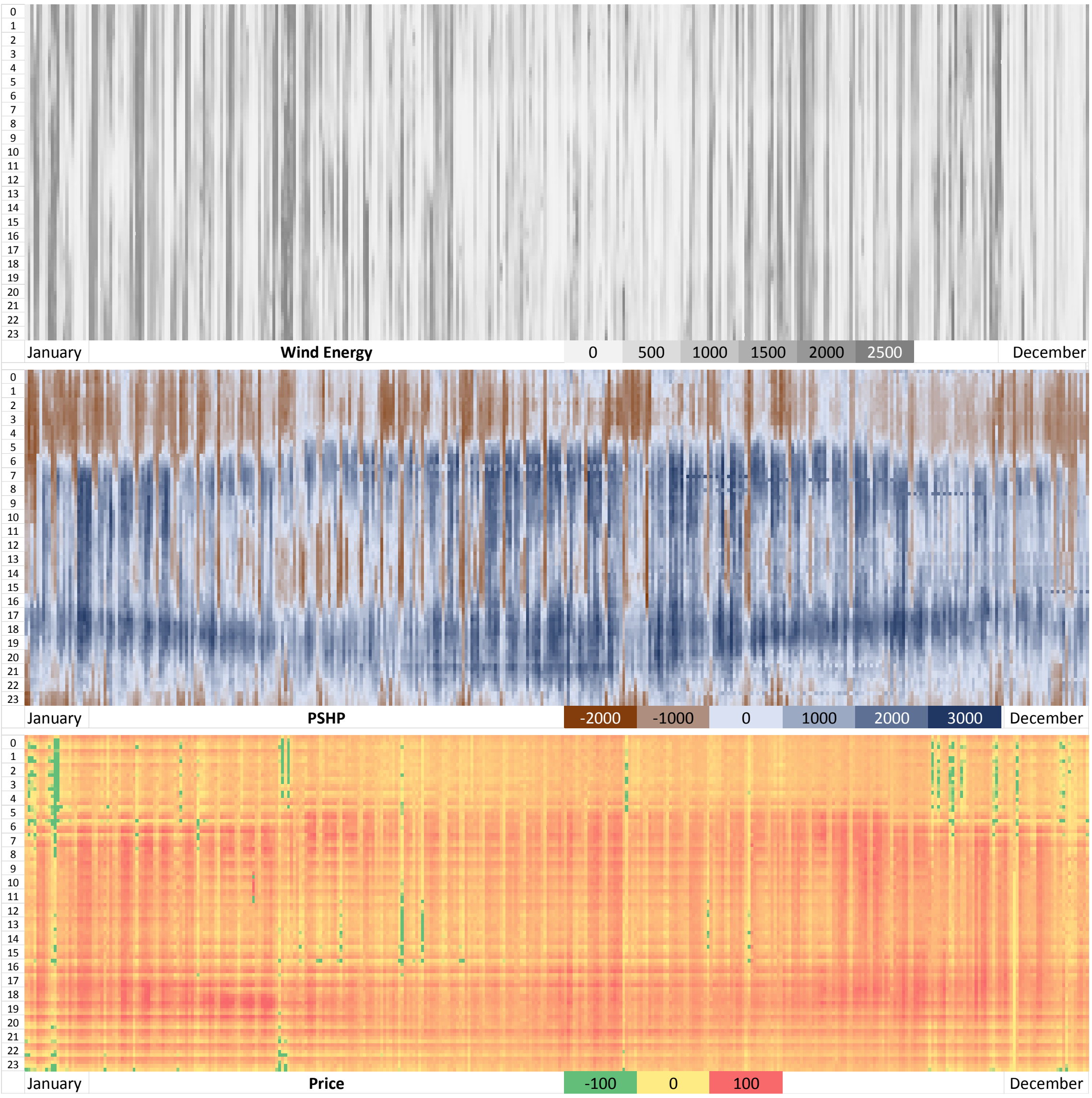

Figure 11: Time history over the year and hour of wind power generation, pumped storage power plants and price for year 2015 (own graph, data from (APG18), (APG181) and (EXAA))

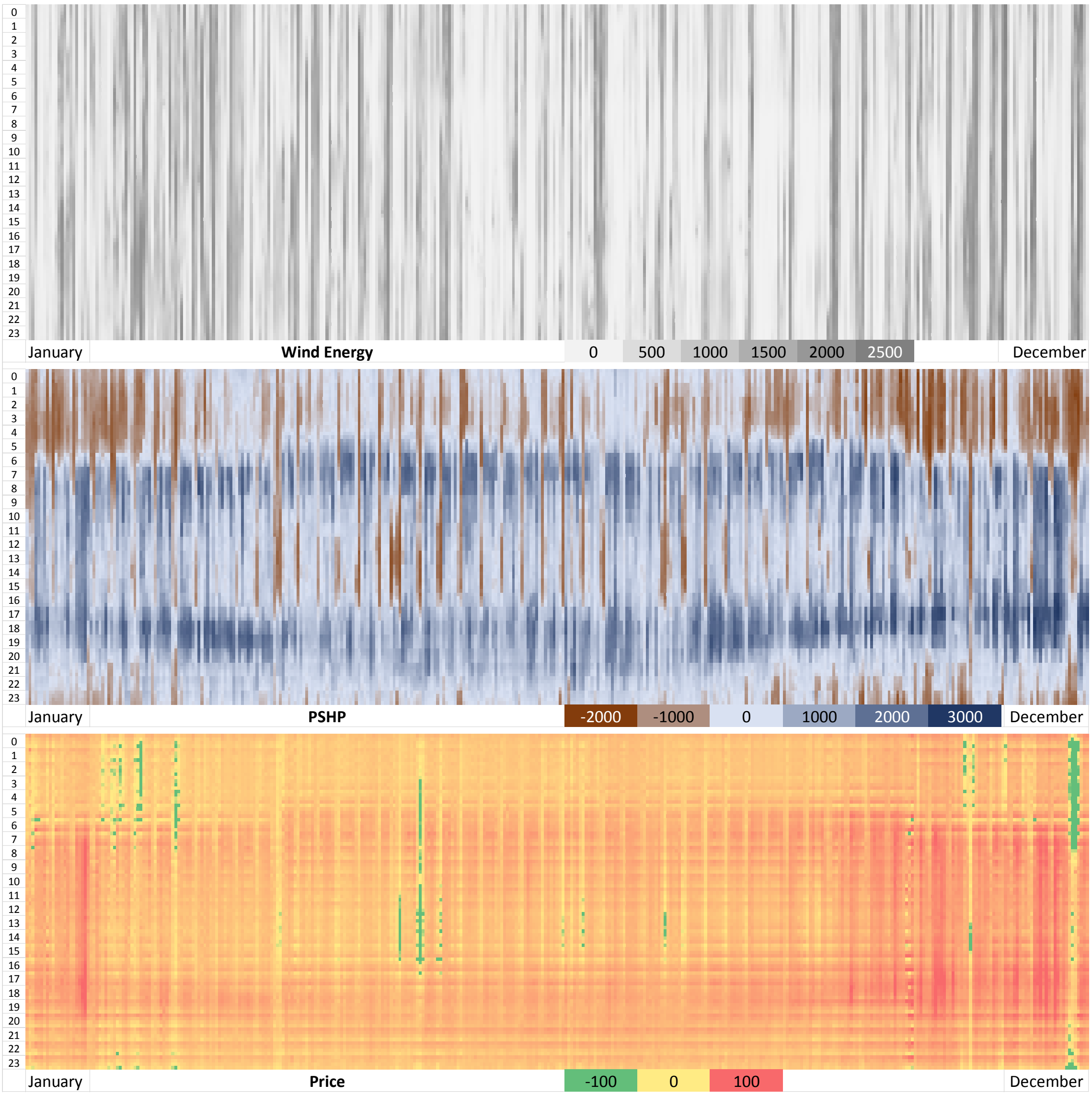

Figure 12: Time history over the year and hour of wind power generation, pumped storage power plants and price for year 2016 (own graph, data from (APG18), (APG181) and (EXAA))

Figure 12 shows the production of wind energy, the load flows of the pumped storage hydro plants and the price for 2016. Wind power has very high electricity generation for a few days. Based on the load flows of the pumped storage power plants, one can again clearly see the course of the day with its morning and evening peaks. Remarkable is the low pumping operation in the summer months. At the end of December, presumably due to the high energy yield from wind energy, there is a negative price that is noticeable even with a high pumping rate of the pumped storage hydro plants. The prices are higher in the winter months than in the summer months.

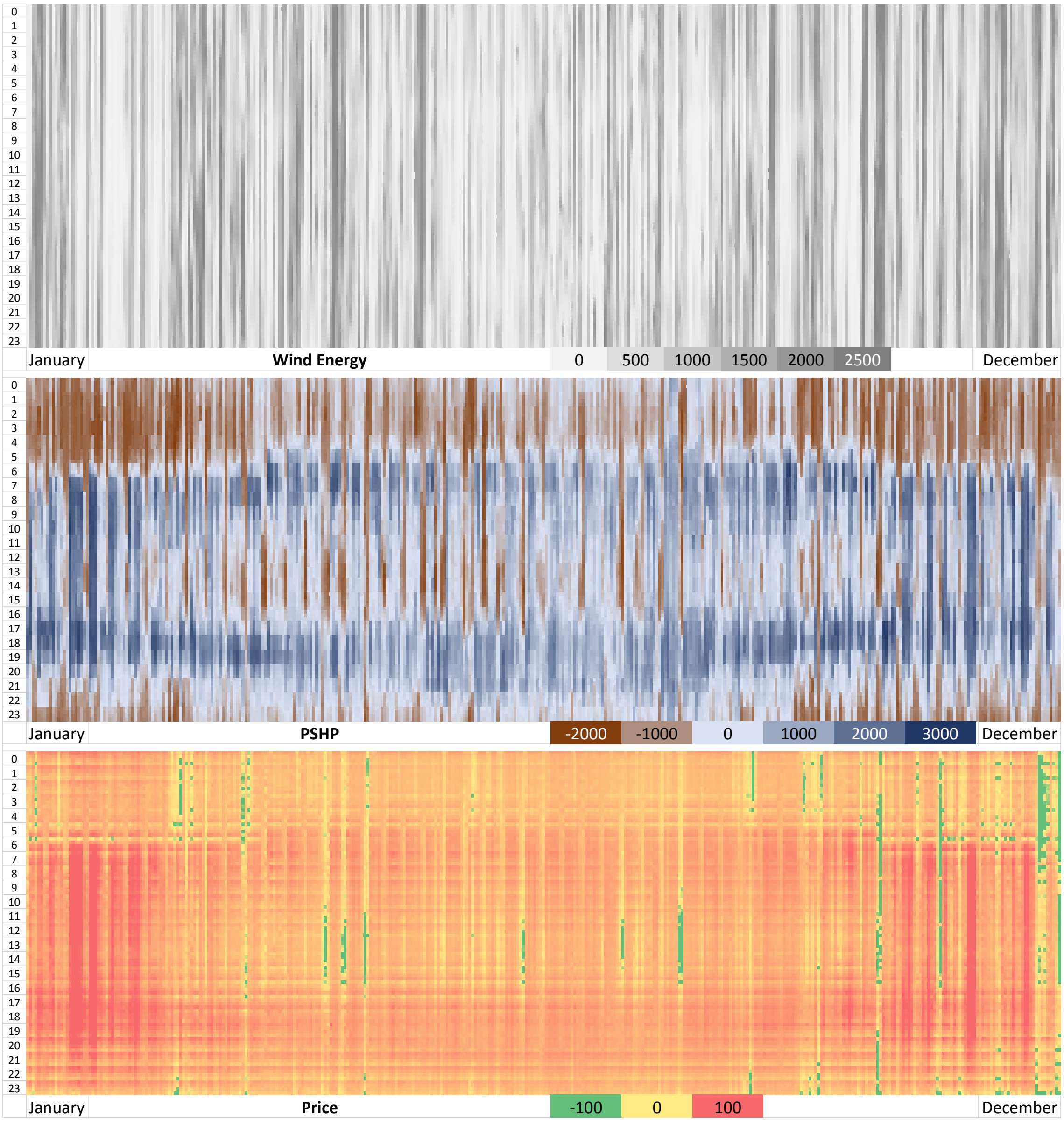

Figure 13: Time history over the year and hour of wind power generation, pumped storage power plants and price for year 2017 (own graph, data from (APG18), (APG181) and (EXAA))

There was more wind production in 2017 than in 2015 and 2016 (see also Table 3). Pumped-storage power plants produce the most electricity at the morning and peak peaks. Pumping is used during the night, and sometimes at midday when a lot of wind energy is produced. However, there are also days when pumping takes place at very low wind energy production (see month of June). The Christmas holidays show a similar picture as in the years 2015 and 2016. At these times, increasingly negative electricity prices occur.

5.2 CHRONOLOGICAL ANALYSIS II

All the graphs show the chronological sequence of wind generation (dark blue line), PV generation (orange line), generation / demand of PSHP (grey line) and the residual load (yellow line). The values are on the left y-axis in MW. On the right y-axis there are the values for the spot price of electricity (dotted light blue line) in € / MWh.

Figure 14 shows the chronological sequence for the year 2015. The energy production from pumped storage hydro plants fluctuates between – 2 000 and + 2 000 MW (grey line). The generation from wind energy (dark blue line) also shows a fluctuating course and extends up to + 2 000 MW. The generation peaks are visible in January, March and November. Photovoltaic generation is much smaller in comparison with the maximum value of + 492 MW. Residual load fluctuates between 2 000 and 10 000 MW. On three days (November 29th, December 25th and December 29th) there is a very low or even negative residual load. The reason is a very low load (about 2.000 to 2.500 MW). The days before and after have a normal load of around 6.000 MW. Obviously, this is an error[5] in the data because such a load step within 15 minutes of more than 2/3 of the whole load in Austria is implausible.

The electricity price is around 30 € / MWh.

[5] Confirmed by APG (Mantler, 2018)

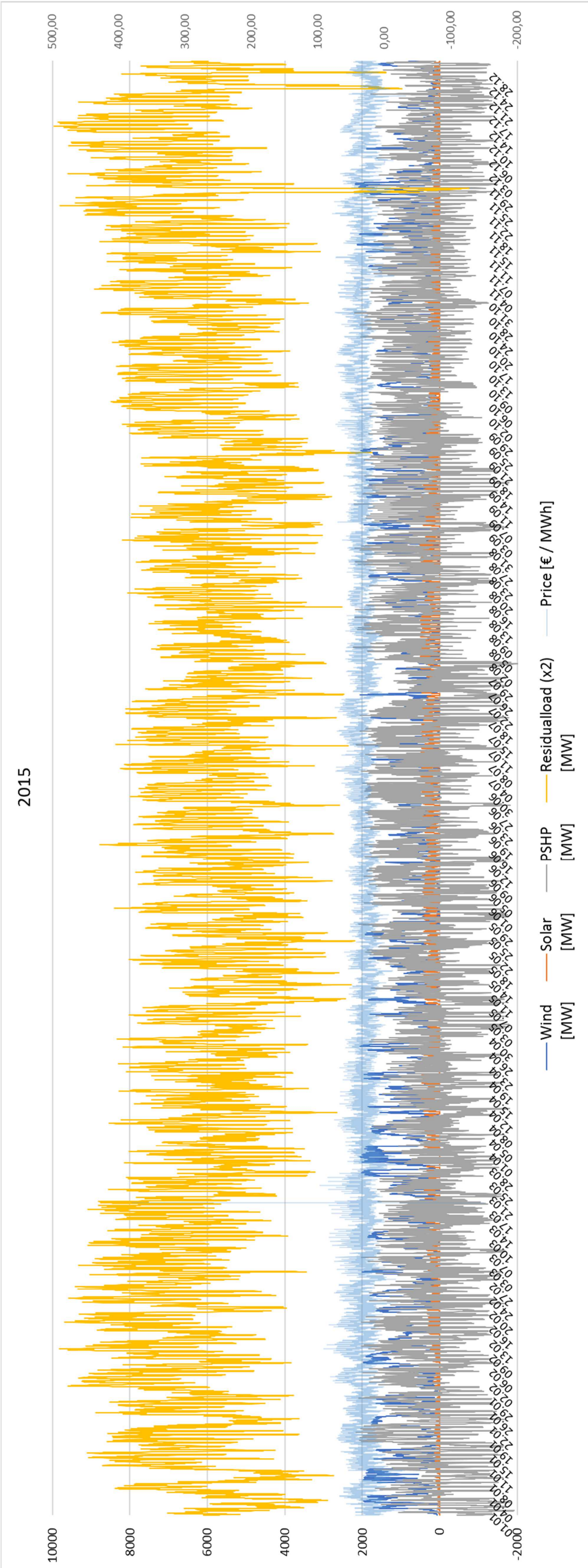

Figure 14: chronological sequence of residual load, production of Wind and Solar and PSHP in 2015 (own graph, data from (APG18), (APG181) and (EXAA))

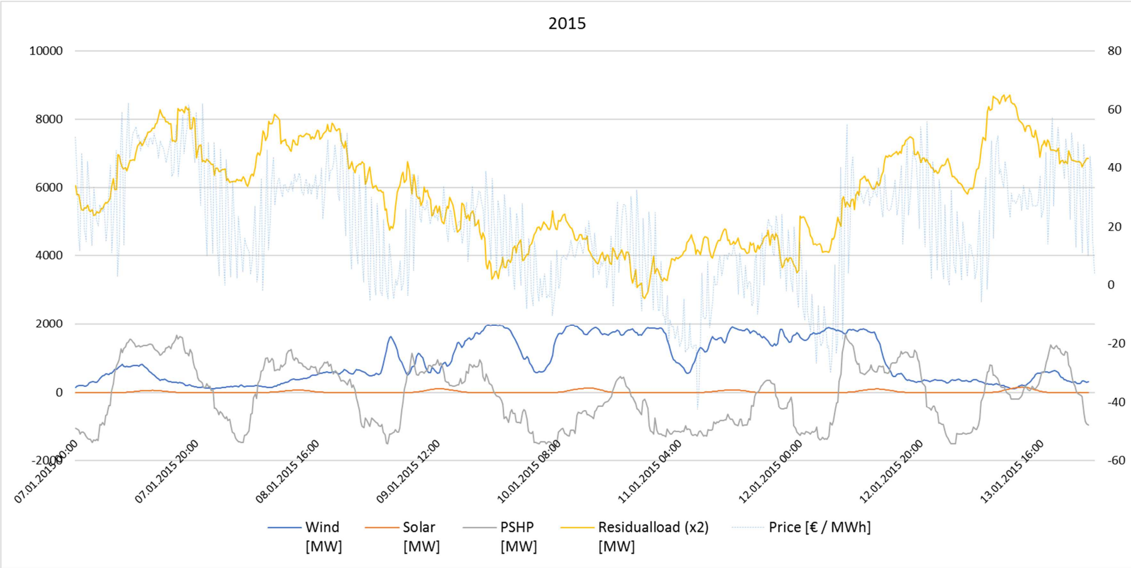

Figure 15: detailed chronological sequence of Figure 14, January 7th till January 13th, “high wind production – pumping mode”

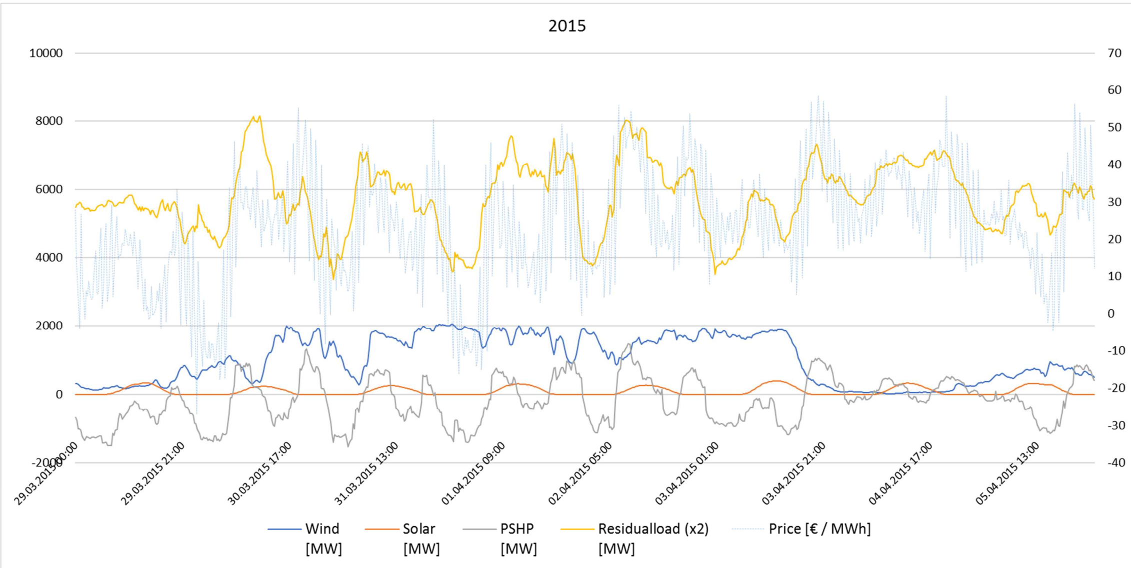

Figure 16: detailed chronological sequence of Figure 14, March 29th till April 5th, “high wind production – pumping mode”

Figure 15 and Figure 16 show details of the chronological year 2015 where the PSHPs go (mostly of the time) to pump mode when there is a high generation of wind energy. During midday, which can be recognized by high solar electricity generation, a higher load occurs. The higher load has to be covered by additional electricity generation of PSHPs. The price correlates with the residual load and has an influence on the operating mode of the PSHPs. If the price increases or is high the PSHPs goes to generation mode.

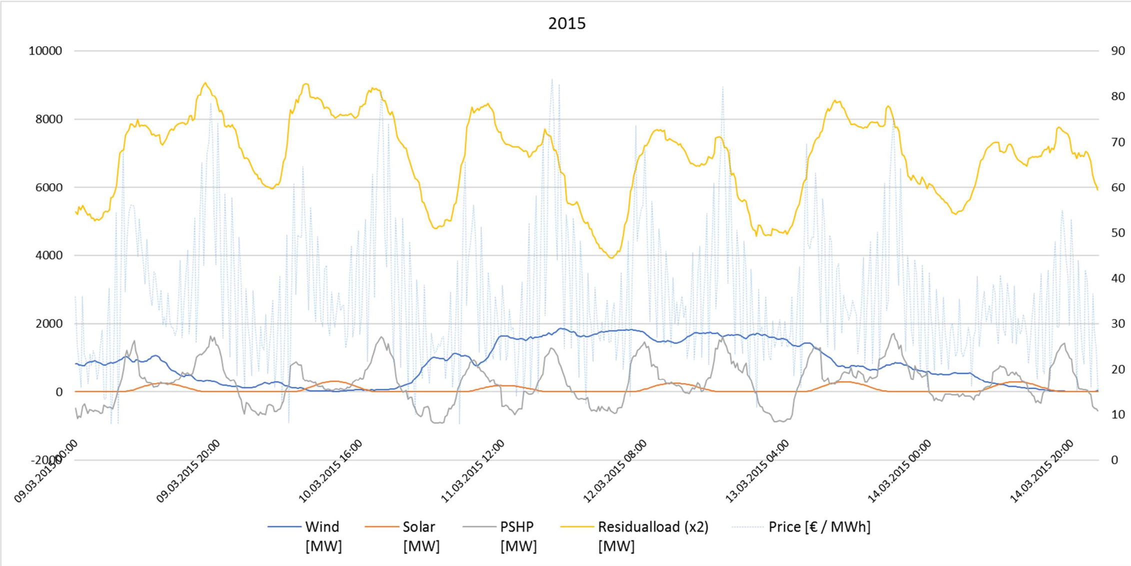

Figure 17: Detailed chronological sequence of Figure 14, March 9th till March 14th, “high wind production – high generation of PSHPs”

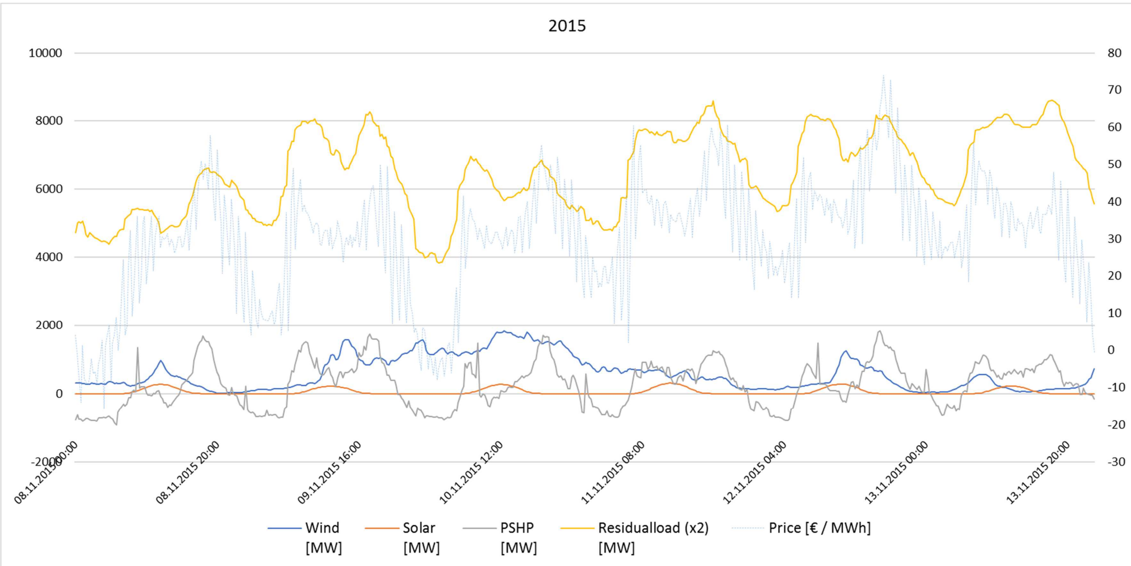

Figure 18: Detailed chronological sequence of Figure 14, November 8th till November 13th, “high wind production – high generation of PSHPs”

Figure 17 and Figure 18 show cases of high energy production of wind and high generation of PSHPs. The price again follows the residual load and the PSHP mode. The price does not have any visible relationship with the generation of wind energy. If the energy generated by wind is increasing there is no observable correlation to the price.

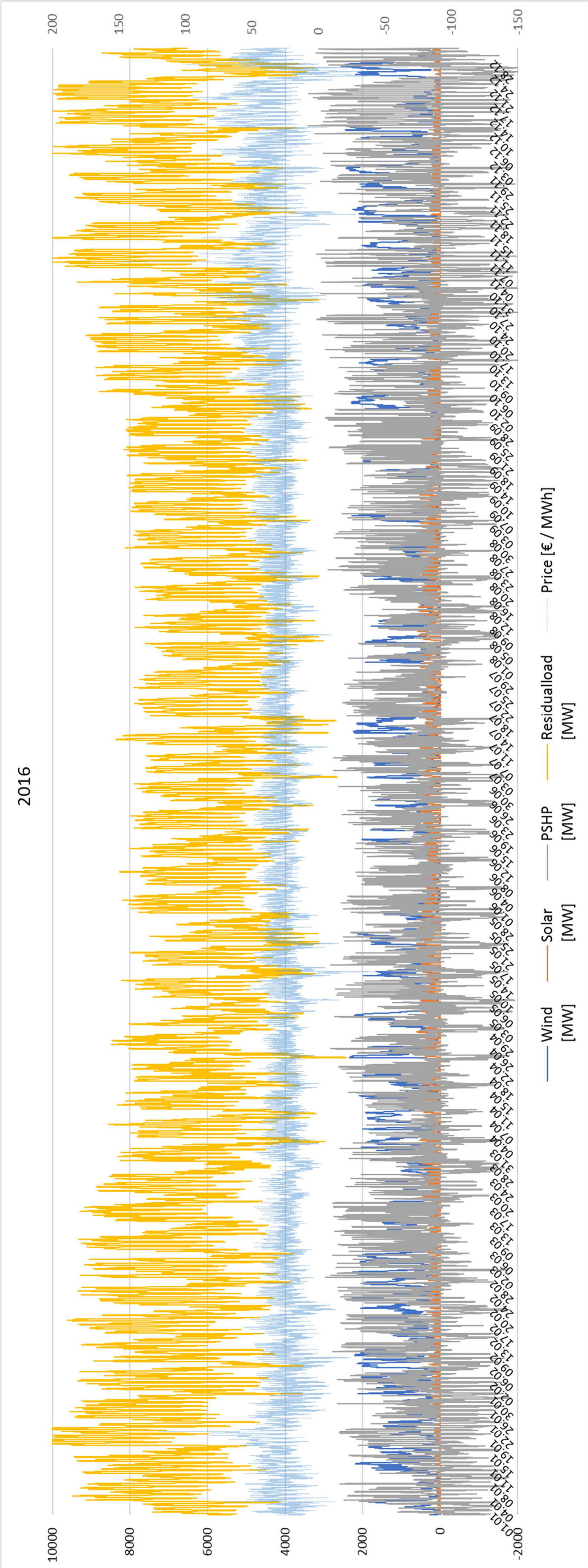

Figure 19: Chronological sequence of residual load, production of Wind and Solar and PSHP in 2016 (own graph, data from (APG18), (APG181) and (EXAA))

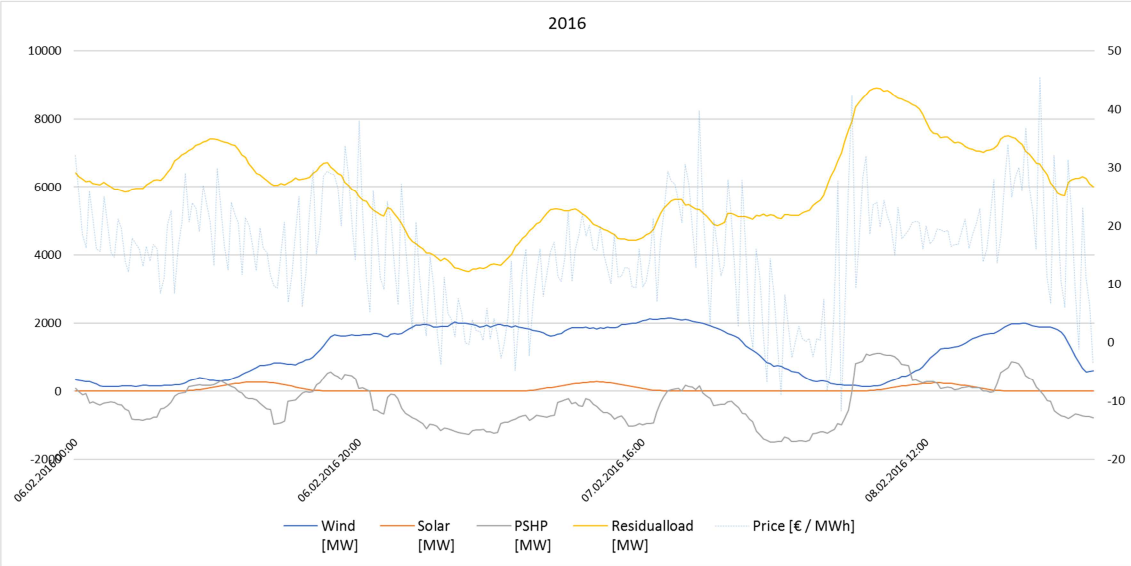

Figure 20: Detailed chronological sequence of Figure 19, February 6th till February 12th, “high wind production – pumping mode”

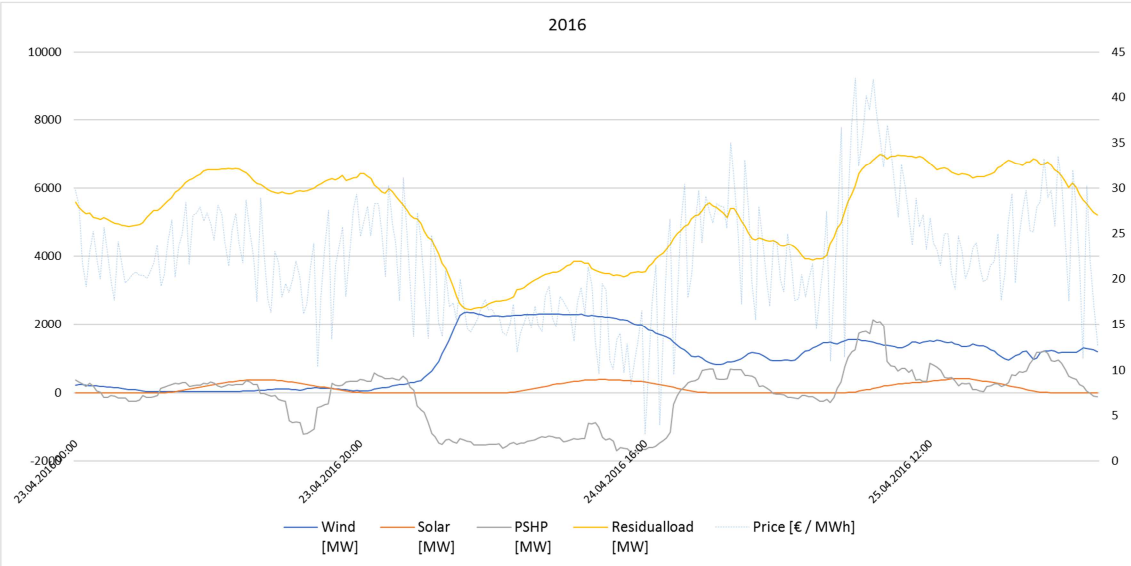

Figure 21: Detailed chronological sequence of Figure 19, April 23rd till April 25th, “high wind production – pumping mode”

Figure 20 and Figure 21 show the “high wind production – pumping mode” for two detailed time periods in 2016. The figures show a negative correlation between generation of wind and PSHPs. This negative relationship is nearly perfect on April 23rd in Figure 21. If there is a strong increase of the electricity price, the PSHP starts to generate electricity (see Figure 20 February 8th and Figure 21 April 25th) and after a time the price levels off. The reason for this might be that other (cheaper but slower starting) plants starts to generate.

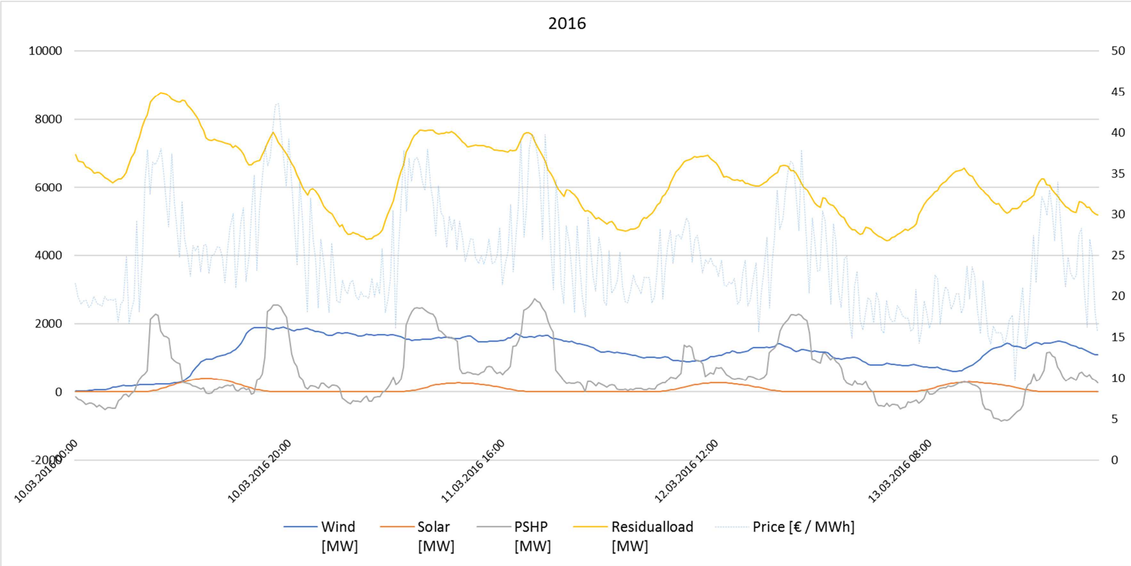

Figure 22: Detailed chronological sequence of Figure 19, March 10th till March 13th, “high wind production – high generation of PSHPs”

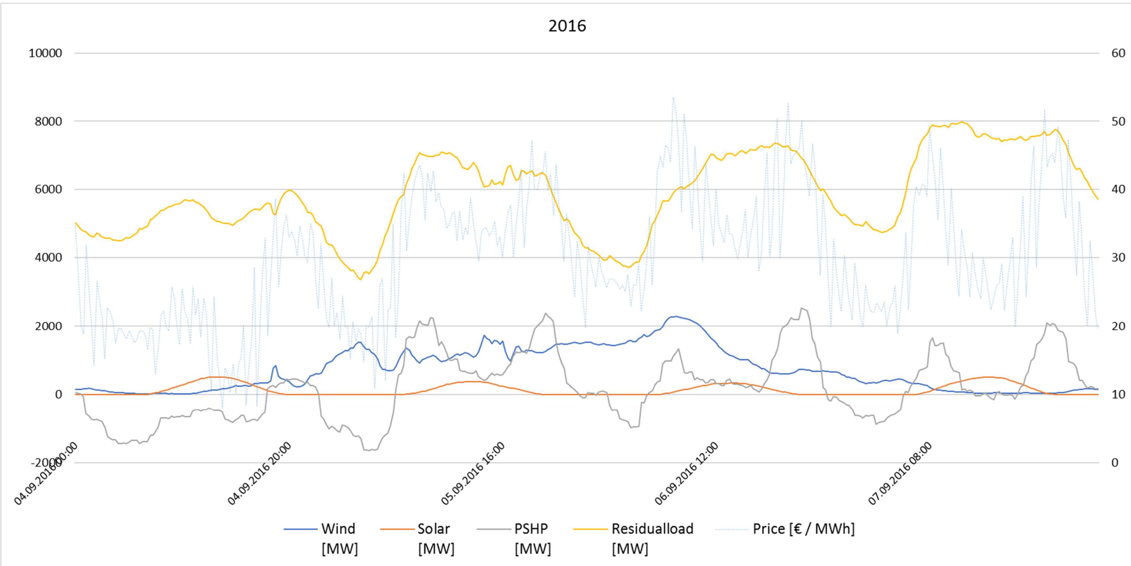

Figure 23: Detailed chronological sequence of Figure 19, March 10th till March 13th, “high wind production – high generation of PSHPs”

Both figures show a simultaneous energy generation of PSHPs and of wind energy. In Figure 22 the load demand during the day is visible, PSHPs are generating energy during the day peak time (morning and afternoon). This is visible through the peaks before and after noon (noon is shown with the small peak of the solar generation line).

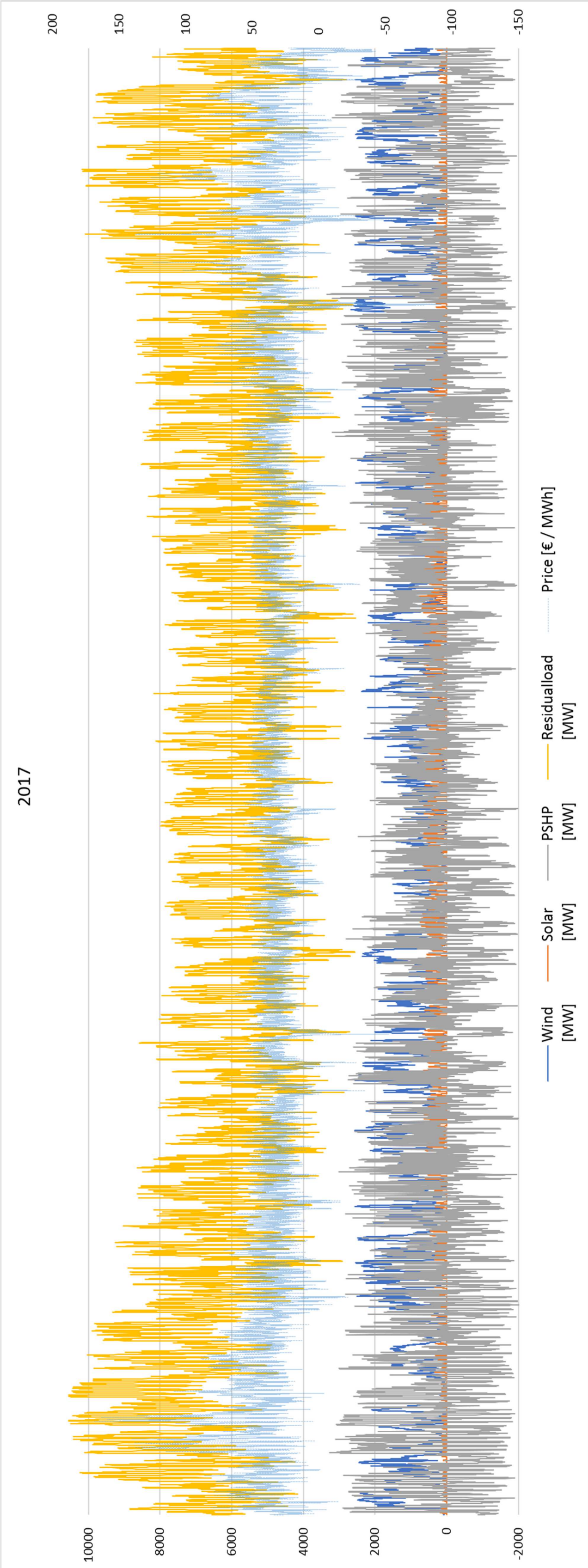

Figure 24: Chronological sequence of residual load, production of Wind and Solar and PSHP in 2017 (own graph, data from (APG18), (APG181) and (EXAA))

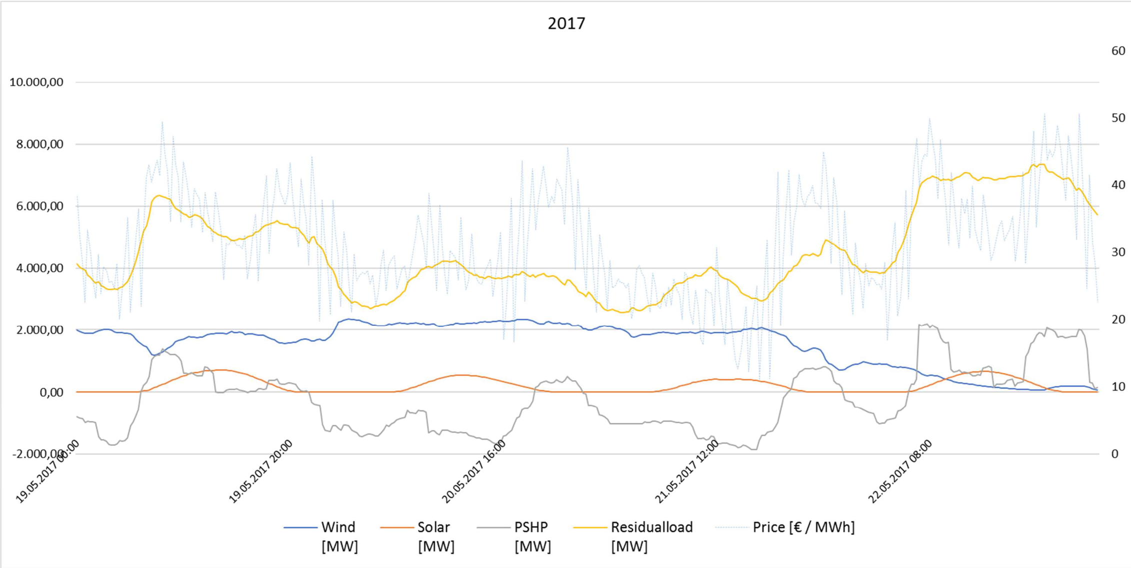

Figure 25: Detailed chronological sequence of Figure 24, May 19th till May 25th, "high wind production – pumping mode"

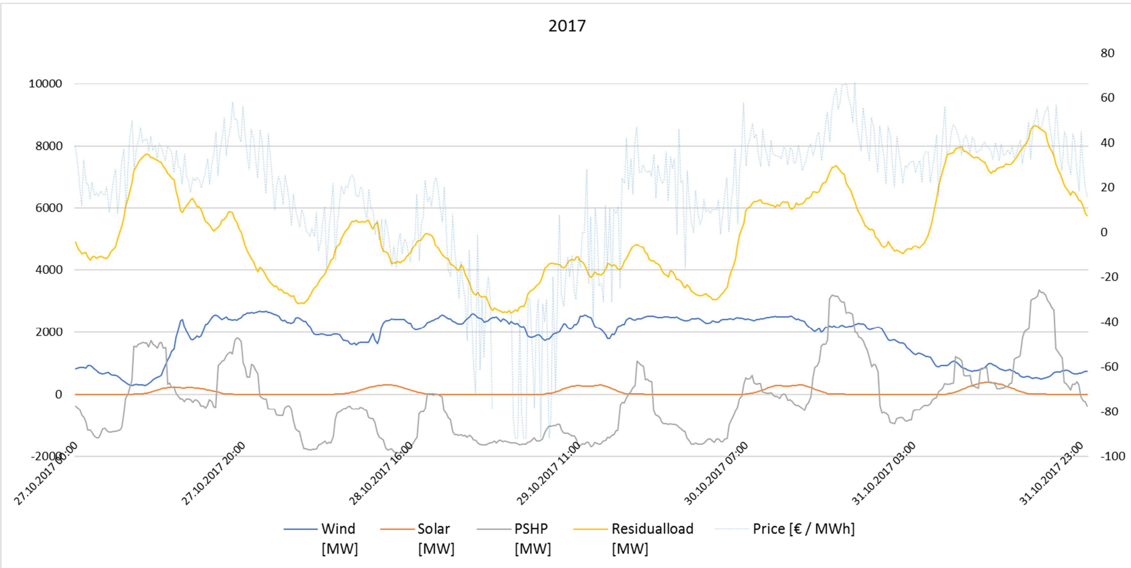

Figure 26: Detailed chronological sequence of Figure 24, October 27th till October 31st, "high wind production – pumping mode"

On these days high energy generation of wind correlates with energy demand of PSHPs. In Figure 25 the PSHP is in pumping mode even if the price of energy is positive in contrast to Figure 26 where the price is also negative. The price correlates very closely with the residual load.

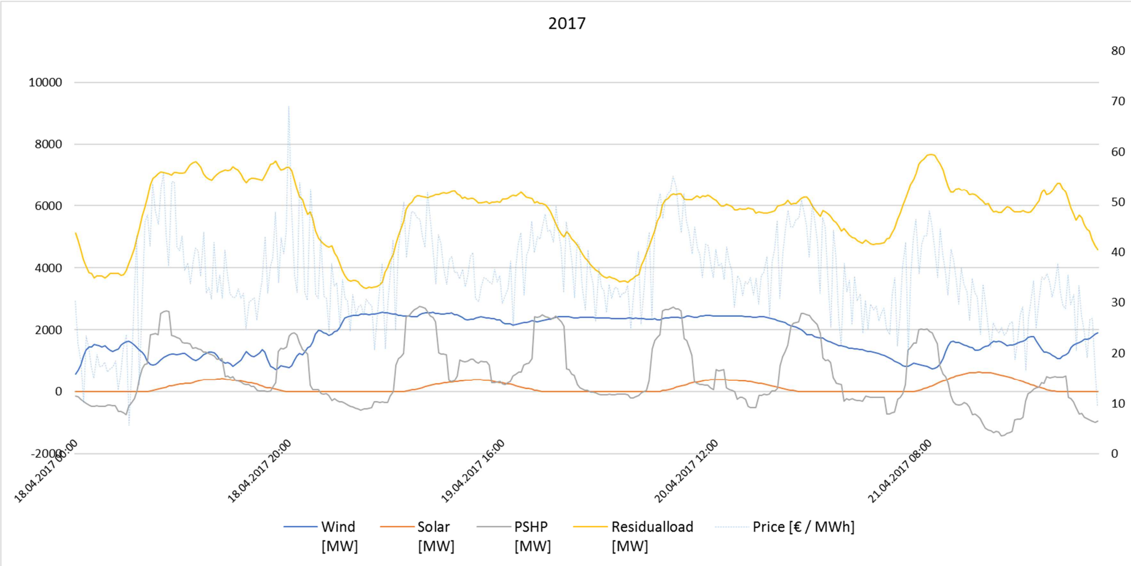

Figure 27: Detailed chronological sequence of Figure 24, April 18th till April 21st, “high wind production – high generation of PSHPs”

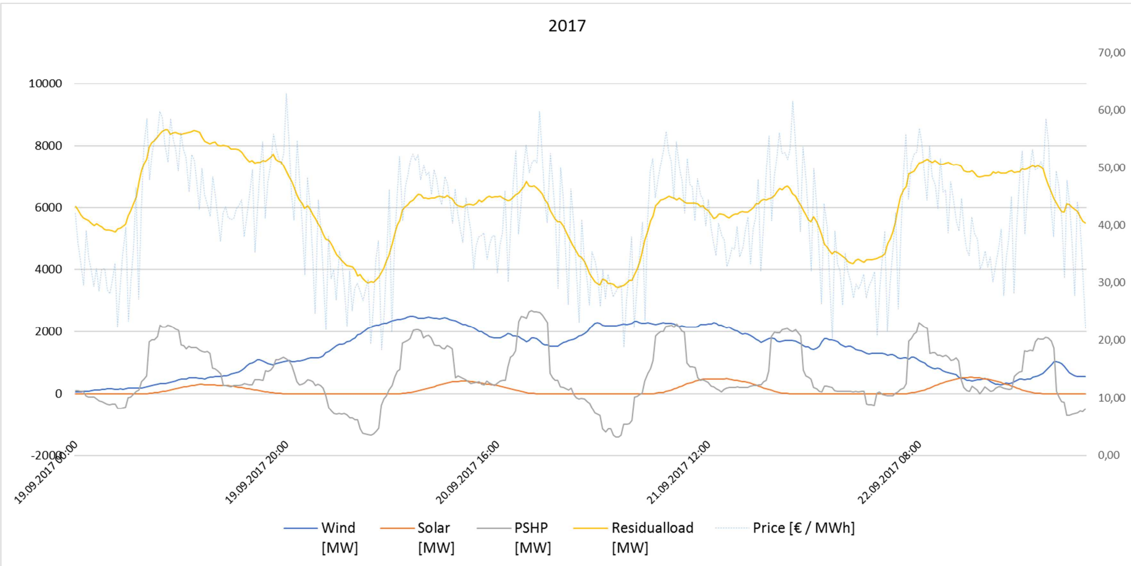

Figure 28: Detailed chronological sequence of Figure 24, September 19th till September 22nd, “high wind production – high generation of PSHPs”

In 2017 there are periods with high wind power generation and high generation of PSHPs. In Figure 28 shows the daily load curve. During morning and afternoon the load increased and therefore the PSPHs are generating energy. During noon the PSHPs nearly stopped generating electricity. In the morning and afternoon, the price decreased. This drop in price might be a possible reason for PSPHs to stop generating energy. During nighttime the price decreased to about 30 € / MWh and the PSPHs used this time for pumping up the water. During daytime the price increased to about 50 € / MWh.

None of the analysed years show a distinct correlation between generation of wind energy and generation / consumption of PSHPs. There are days where a lot of wind energy is generated and PSHPs consume energy (“pump mode”) as well as days with lot of wind energy generation while PSHPs also generates energy.

Furthermore, there is no negative residual load during all three years. The amount of generated solar energy is little compared to wind energy or PSHP energy. Solar energy is only produced during daytime. This is shown in the graphs by the small peaks on the orange.

Table 8: Minimum, maximum and average values of analysed years (own graph, data from (APG18), (APG181) and (EXAA))

		2015	2016	2017
Wind [MW]	min	0,57	0,30	0,07
	max	2181	2557	2677
	average	561	606	768
PV [MW]	min	0	0	0
	max	513	615	756
	average	94	107	131
PSHP [MW]	min	-2153	-2132	-2074
	max	2235	3416	3349
	average	200	336	180
	pump average	-689	-714	-769
	generate average	788	877	983
Price [€ / MWh]	min	-149	-103	-102
	max	381	150	169
	average	32	29	35

Table 8 shows the minimum, maximum and average values of generated wind energy, photovoltaic energy, pumped storage hydro plants and the prices for the years 2015 to 2017. For wind energy, the maximum energy generated, and average energy generated over the three years was calculated increases. The maximum values close to the installed power (see Table 2). In photovoltaics, there are also large increases in both the average energy produced and the maximum generated energy.

The pumped storage power plants show that there are times when the maximum installed power is fully utilized for electricity generation. The average energy requirement for the pumping operation has increased as well as the average energy generated. This is also shown by the graphics in chapter 5.3.

The prices are on average between 29 € / MWh and 35 € / MWh.

5.3 REGRESSION ANALYSIS

This chapter shows the results by using linear regression analysis as well as the correlation analysis, coefficient of determination analysis and F-Test analysis.

5.3.1 ANALYSIS BETWEEN PSHP AND RESIDUAL LOAD + WIND

Regression analysis was done according to quotation (8) for each year. The following equations show the relationship between wind energy and residual load to the generation / consumption of PSHPs. Furthermore, the coefficient of determination was calculated according quotation (12) and the correlation coefficient according quotation (14). In addition, an F-Test and T-Test was done.

$$P_{PSHP,2015} = 0{,}1313 P_{wind} + 0{,}3622 P_{residual\ load} - 2107 \quad (17)$$

$$Coefficient\ of\ determination_{2015} = 0{,}33$$

$$Correlation\ coefficient\ _{2015} = 0{,}58$$

$$F = 2{,}98, p = 0, F_{critical} = 1{,}0177 => \ H_0\ has\ to\ be\ rejected$$

$$P_{PSHP,2016} = 0{,}2035 P_{wind} + 0{,}4864 P_{residual\ load} - 2916{,}25 \quad (18)$$

$$Coefficient\ of\ determination_{2016} = 0{,}429$$

$$Correlation\ coefficient\ _{2016} = 0{,}65$$

$$F = 2{,}33, p = 0, F_{critical} = 1{,}0177 => \ H_0\ has\ to\ be\ rejected$$

$$P_{PSHP,2017} = 0{,}1652 P_{wind} + 0{,}485 P_{residual\ load} - 3029{,}29 \quad (19)$$

$$Coefficient\ of\ determination_{2017} = 0{,}394$$

$$Correlation\ coefficient\ _{2017} = 0{,}63$$

$$F = 2{,}539, p = 0, F_{critical} = 1{,}0177 => \ H_0\ has\ to\ be\ rejected$$

Table 9 gives an overview about the figures and relations.

Table 9: Overview over parameters for PSHP as a function of Wind and Residual Load (own table). T-values are in brackets.

	P_{Wind} m_1 t-value	$P_{residual\ load}$ m_2 t-value	b	r^2	$r_{y,x1,x2}$	F	p	$F_{critical}$	Model
2015	0,1313 (16,8)	0,3622 (128,4)	-2107 (-106,2)	0,33	0,58	2,98	0	1,0177	Valid
2016	0,2035 (27,9)	0,486 (159,1)	-2916,25 (-132,3)	0,429	0,65	2,33	0	1,0177	Valid
2017	0,1652 (22,1)	0,485 (145,2)	-3029,29 (-123,2)	0,394	0,63	2,54	0	1,0177	valid

The coefficient of determination is always below 0,5, which shows that this relationship cannot be mapped adequately with the regression line. According to the F-Test the null hypothesis be rejected. This means that the model is valid but because of the small coefficient of determination not very accurate. Furthermore, al t-values are bigger than 1,96, which means that they do have a significant impact.

The correlation factor is higher than 0,5. This means a positive relationship. The more wind is generated and the higher the residual load is, the more energy will be generated by PSHPs. This result is surprising as it was expected that the more wind energy is in the grid, the less energy has to be generated by PSHPs. The next two chapters provide additional research on the factors that influence the PSHPs.

Figure 29 to Figure 31 show the relationship between PSHP, wind power and residual load for the year 2015 to 2017. The power of the PSHP in MW is plotted on the z-axis. Wind and residual load are displayed on the x- and y-axes. Each blue dot of the scatter plot represents a value from the 15-minute data series (see chapter 3 and Table 6). The dimensions and axis scaling are the same for all three graphics so that an optical comparison is possible. Over the three years, the scatter plot is increasing in all dimensions. As a result of the 37 % increase in installed wind power from 2015 to 2017 (see chapter 2), the annual energy generated has increased as well. As a result, there is an expansion of the scatter plot both on the x-axis and on the y-axis. Although the installed capacity of the pumped storage hydro power did not change significantly between 2015 and 2017, there is also an expansion on the z-axis. This means that in 2017 the PSHP´s occasionally produced or consumend more energy than in previous years. The scatter plot shows a slight slope, the higher the residual load, the more energy is generated by PSHPs, the lower the residual load the less energy is generated. The wind energy has less influence on the pumped storage hydro plants, even with little wind, the PSHPs are almost active at maximum. This is also visible in the formulas (17) to (19), the factor for the residual load is higher than for the wind power. In the Figure 32 to Figure 34 and Figure 35 to Figure 37 this effect is also visible in two dimensional graphs. There you can see that the higher the residual load, the more energy is produced by PSHPs. There is no clear relationship between PSHP and wind power plants. Pumped storage hydro plants are almost independent of the generated wind energy as well as in generator or pumping mode.

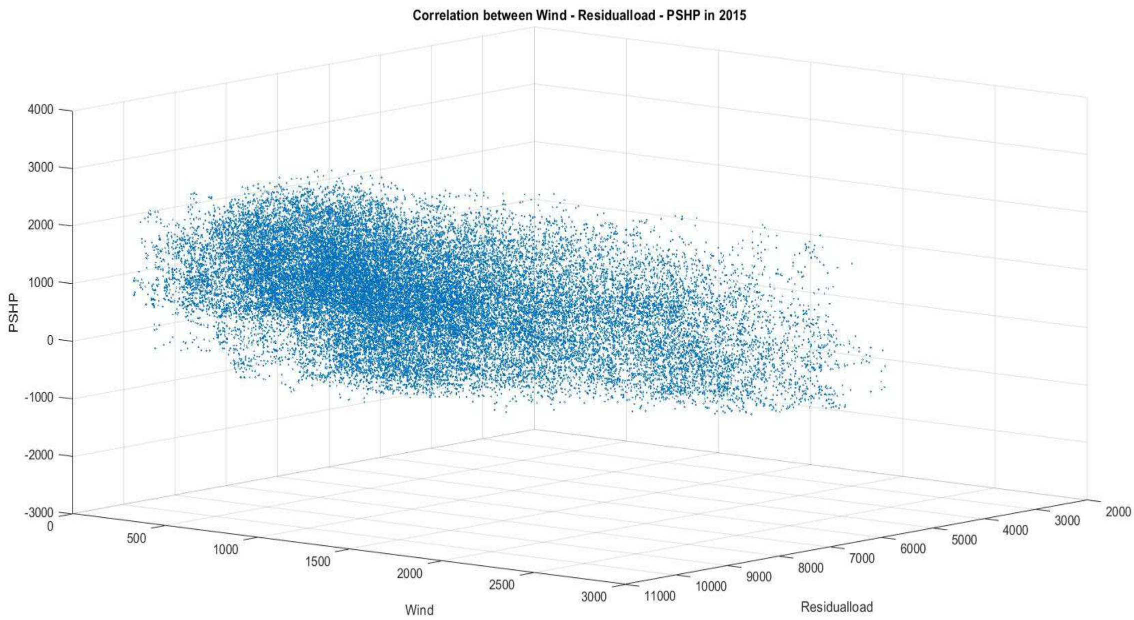

Figure 29: Correlation between PSHP, Wind and residual load in 2015 (own graph, data from (APG18) and (APG181))

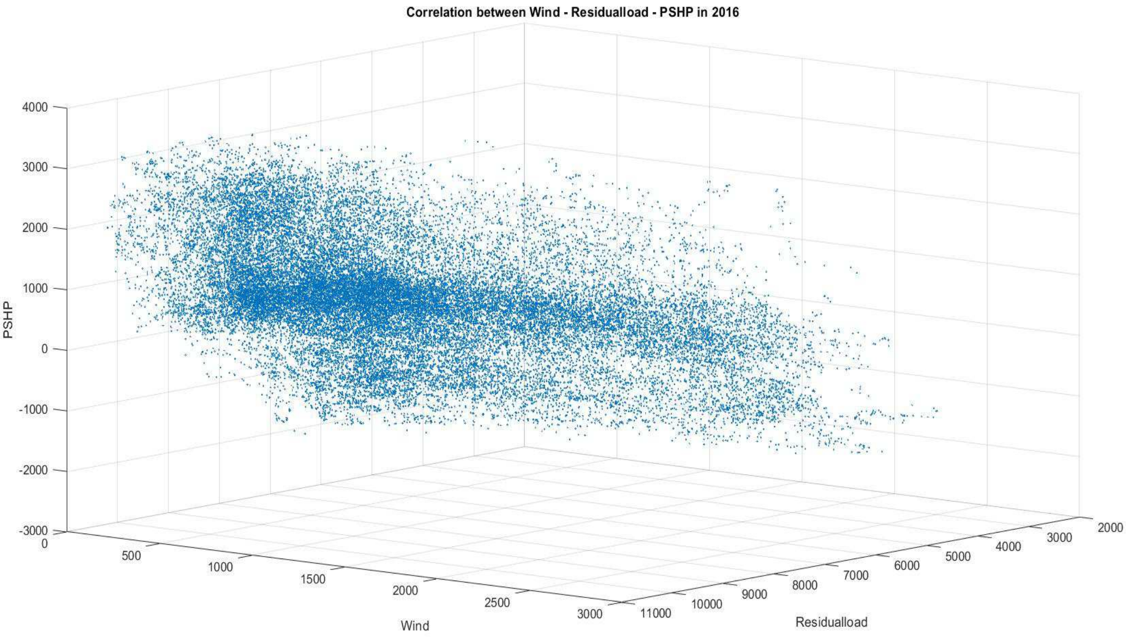

Figure 30: Correlation between PSHP and residual load in 2016 (own graph, data from (APG18) and (APG181))

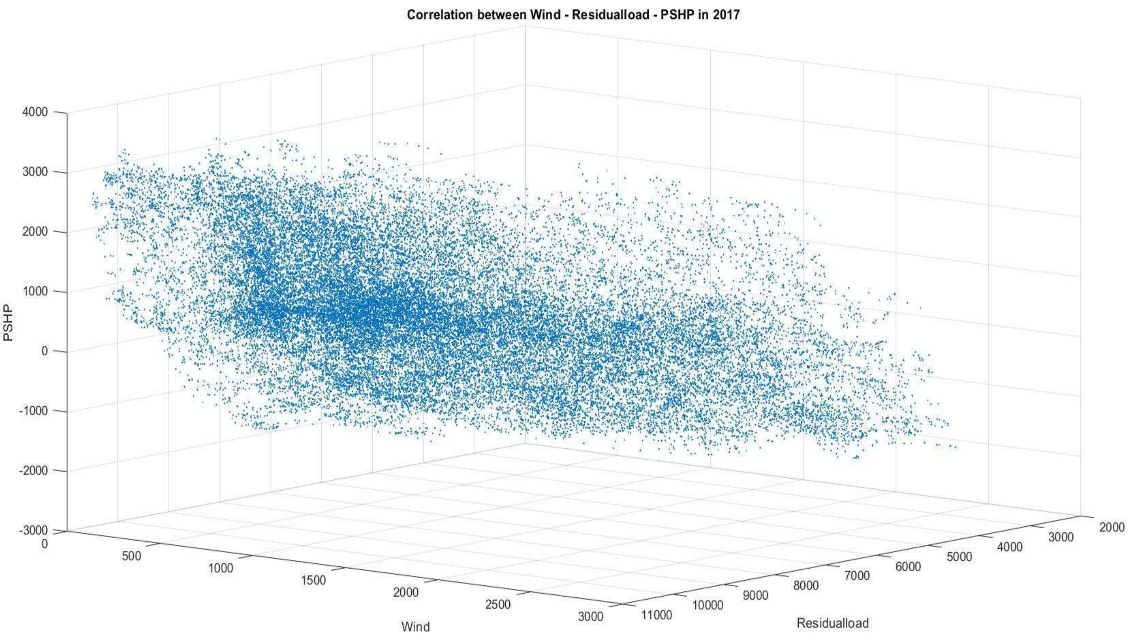

Figure 31: Correlation between PSHP and residual load in 2017 (own graph, data from (APG18) and (APG181))

5.3.2 ANALYSIS BETWEEN PSHP AND RESIDUAL LOAD

The regression analysis was done according to quotation (7).

$$P_{PSHP,2015} = 0{,}348 P_{residual\ load} - 1923{,}1 \quad (20)$$

$$Coefficient\ of\ determination_{2015} = 0{,}33$$

$$Correlation\ coefficient\ _{2015} = 0{,}57$$

$$F = 3{,}03, p = 0, F_{critical} = 1{,}0177 => \ H_0\ has\ to\ be\ rejected$$

$$P_{PSHP,2016} = 0{,}455 P_{residual\ load} - 2593 \quad (21)$$

$$Coefficient\ of\ determination_{2016} = 0{,}42$$

$$Correlation\ coefficient\ _{2016} = 0{,}65$$

$$F = 2{,}4, p = 0, F_{critical} = 1{,}0177 => \ H_0\ has\ to\ be\ rejected$$

$$P_{PSHP,2016} = 0{,}455 P_{residual\ load} - 2710 \quad (22)$$

$$Coefficient\ of\ determination_{2017} = 0{,}39$$

$$Correlation\ coefficient\ _{2017} = 0{,}62$$

$$F = 2{,}6, p = 0, F_{critical} = 1{,}0177 => \ H_0\ has\ to\ be\ rejected$$

Table 10: Overview over parameters for PSHP as a function of Residual Load (own table). T-values are in brackets.

	$P_{residual\ load}$ m_1 t-value	b t-value	r^2	$r_{y,x1}$	F	p	$F_{critical}$	Model
2015	0,348 (131,3)	-1923,1 (-115,8)	0,33	0,57	3,03	0	1,0177	Valid
2016	0,455 (158,2)	-2593 (-136,7)	0,42	0,65	2,4	0	1,0177	Valid
2017	0,455 (148,2)	-2710 (-135,2)	0,39	0,62	2,6	0	1,0177	Valid

There is a more or less distinct correlation between the residual load and the pumped storage hydro plants. This is also shown in the correlation coefficient that is between 0,57 and 0,65 which means a positive correlation.

The higher the residual load, the more energy generation of PSHP is necessary. The reason for this is a higher load and/or less energy production by renewables. Figure 32 to Figure 34 show the strong correlation.

Nevertheless, the coefficient of determination is below 0,5 which is an indication that the calculated regression line does not map the reality even though the model is valid which was proven by the F-Test. The result of the t-test shows that all coefficients are significant.

In the following figures blue dots show the measured data, orange dots show the calculated correlation from equation (17) to (19). The black line shows the regression line from equation (20) to (22). The x-axis shows the residual load in MW, the y-axis the pumped hydro storage in MW.

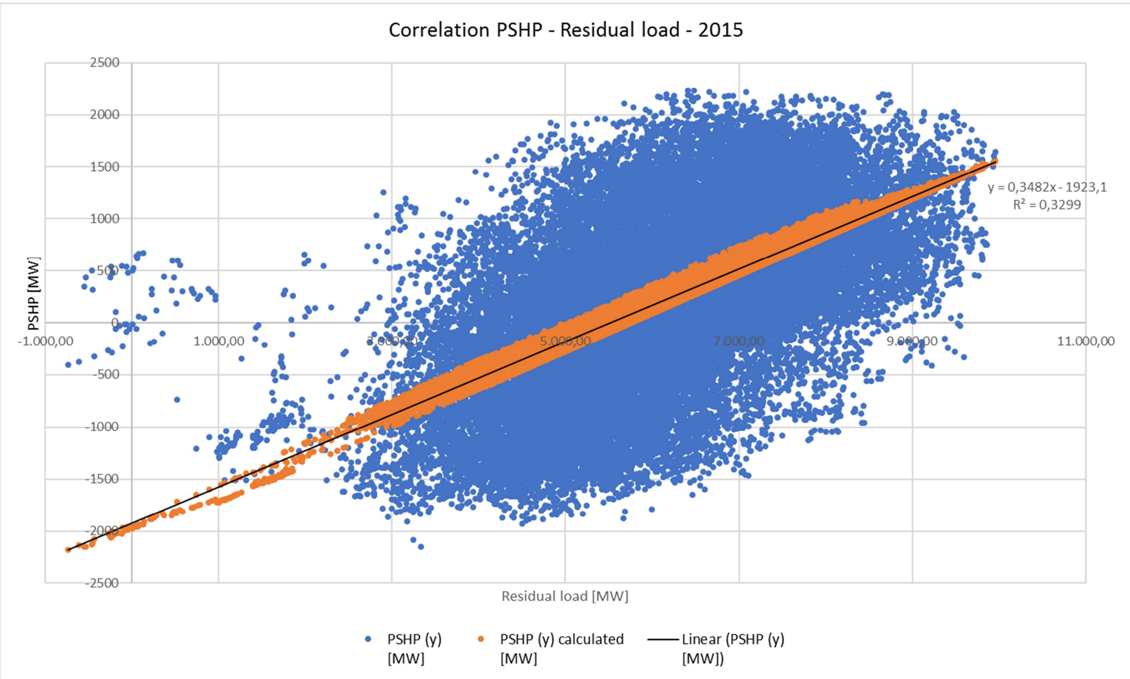

Figure 32: Correlation between PSHP and residual load in 2015 (own graph, data from (APG18) and (APG181))

Figure 32 shows the few wrong values (values with negative residual load). This was described in chapter 5.2.

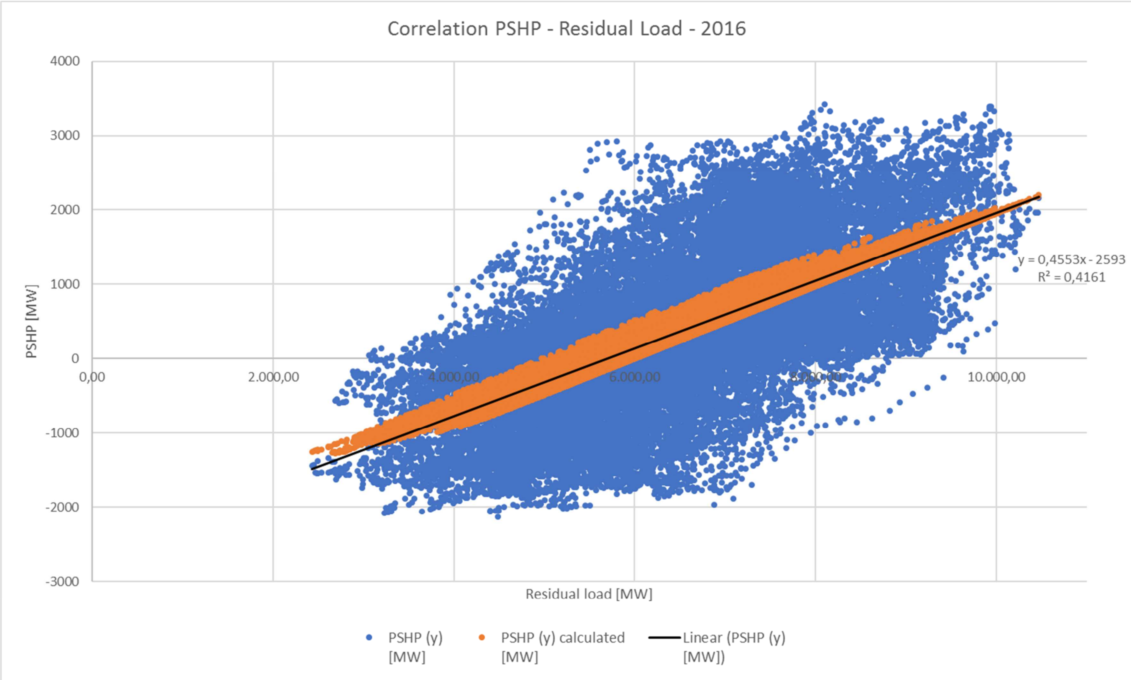

Figure 33: Correlation between PSHP and residual load in 2016 (own graph, data from (APG18) and (APG181))

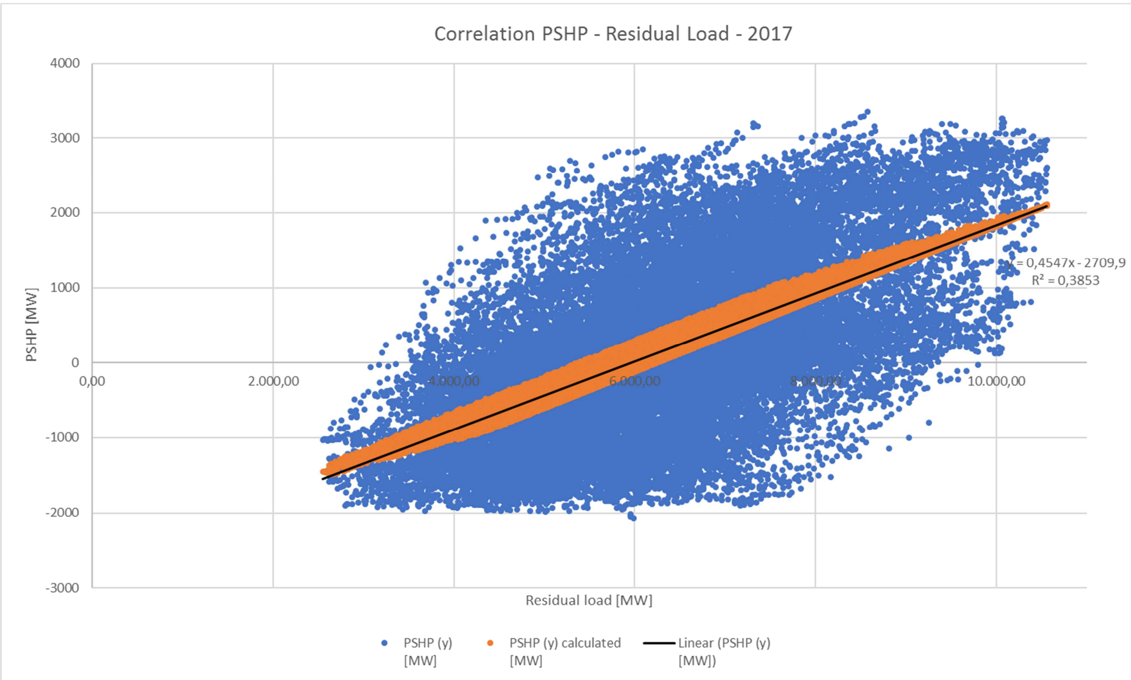

Figure 34: Correlation between PSHP and residual load in 2017 (own graph, data from (APG18) and (APG181))

5.3.3 ANALYSIS BETWEEN PSHP AND GENERATION OF WIND POWER

The regression analysis was done according to quotation (6).

$$P_{PSHP,2015} = -0{,}247 P_{Wind} + 338{,}7 \quad (23)$$

$$Coefficient\ of\ determination_{2015} = 0{,}02$$

$$Correlation\ coefficient\ _{2015} = -0{,}15$$

$$F = 45{,}2, p = 0, F_{critical} = 1{,}0177 => \ H_0\ has\ to\ be\ rejected$$

$$P_{PSHP,2016} = -0{,}22 P_{Wind} + 470 \quad (24)$$

$$Coefficient\ of\ determination_{2016} = 0{,}02$$

$$Correlation\ coefficient\ _{2016} = -0{,}13$$

$$F = 58{,}6, p = 0, F_{critical} = 1{,}0177 => \ H_0\ has\ to\ be\ rejected$$

$$P_{PSHP,2017} = -0{,}28 P_{Wind} + 395 \quad (25)$$

$$Coefficient\ of\ determination_{2016} = 0{,}03$$

$$Correlation\ coefficient\ _{2017} = -0{,}17$$

$$F = 34{,}2, p = 0, F_{critical} = 1{,}0177 => \ H_0\ has\ to\ be\ rejected$$

Table 11: Overview over parameters for PSHP as a function of wind generation (own table). T-values are in brackets.

	P_{wind} m_1 t-value	b t-value	r^2	$r_{y,x1}$	F	p	$F_{critical}$	Model
2015	-0,247 (-28,1)	338,7 (50,2)	0,02	-0,15	45,2	0	1,0177	Valid
2016	-0,22 (-24,6)	470 (61,7)	0,02	-0,13	58,6	0	1,0177	Valid
2017	-0,28 (-32,4)	395 (44,8)	0,03	-0,17	34,2	0	1,0177	Valid

As $r_{y,x1}$ in Table 11 indicates there is no correlation between the generation of wind power and the pumped storage hydro plants. The correlation coefficients are close to zero, the range is from -0,13 to -0,17. The negative value can be explained by the fact that the more wind energy is generated, the less energy is generated by the pumped hydro storage plants (or the pumped hydro storage plants are consuming energy for pump mode).

The coefficient of determination is close to zero, it is not possible to replicate the values with the equations. This is also clearly visible in the Figure 35 to Figure 37. The PSHP is either generating or consuming energy independently of the amount of generated wind energy.

The F-test shows that the model is still valid. The T-Test shows a significance of the independent variables.

In the following figures blue dots show the measured data, orange dots show the calculated correlation from equation (17) to (19). The black line shows the regression line from equation (23) to (25). The x-axis shows the residual load in MW, the y-axis the energy generated of wind power plants in MW.

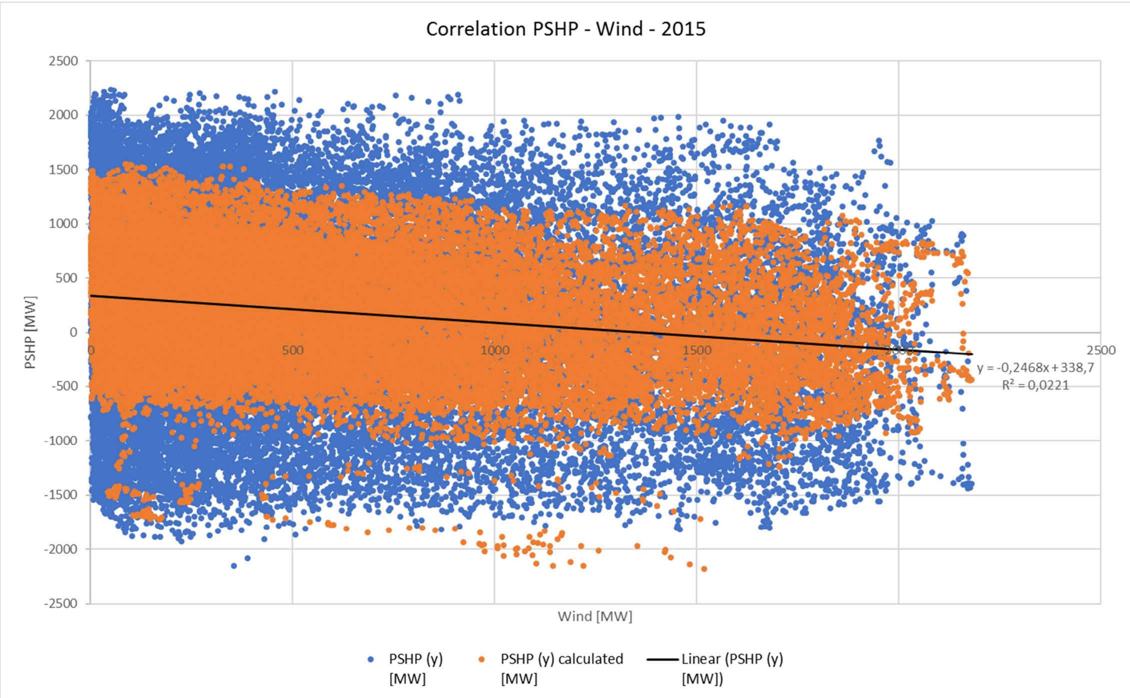

Figure 35: Correlation between PSHP and wind power in 2015 (own graph, data from (APG18) and (APG181))

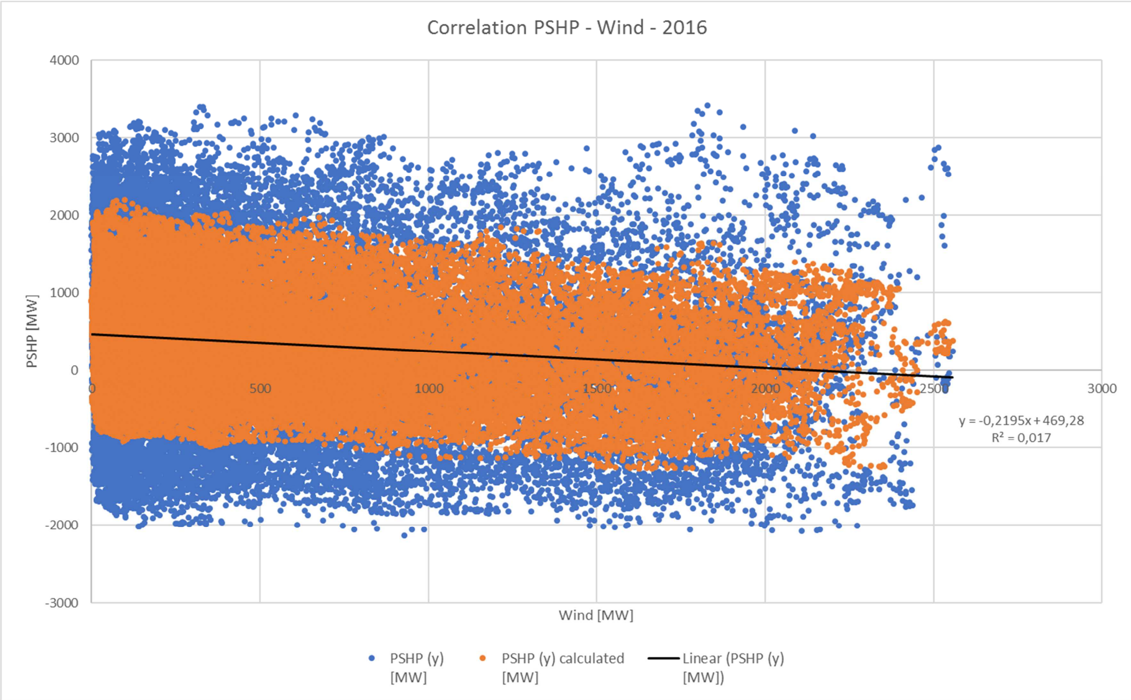

Figure 36: Correlation between PSHP and wind power in 2016 (own graph, data from (APG18) and (APG181))

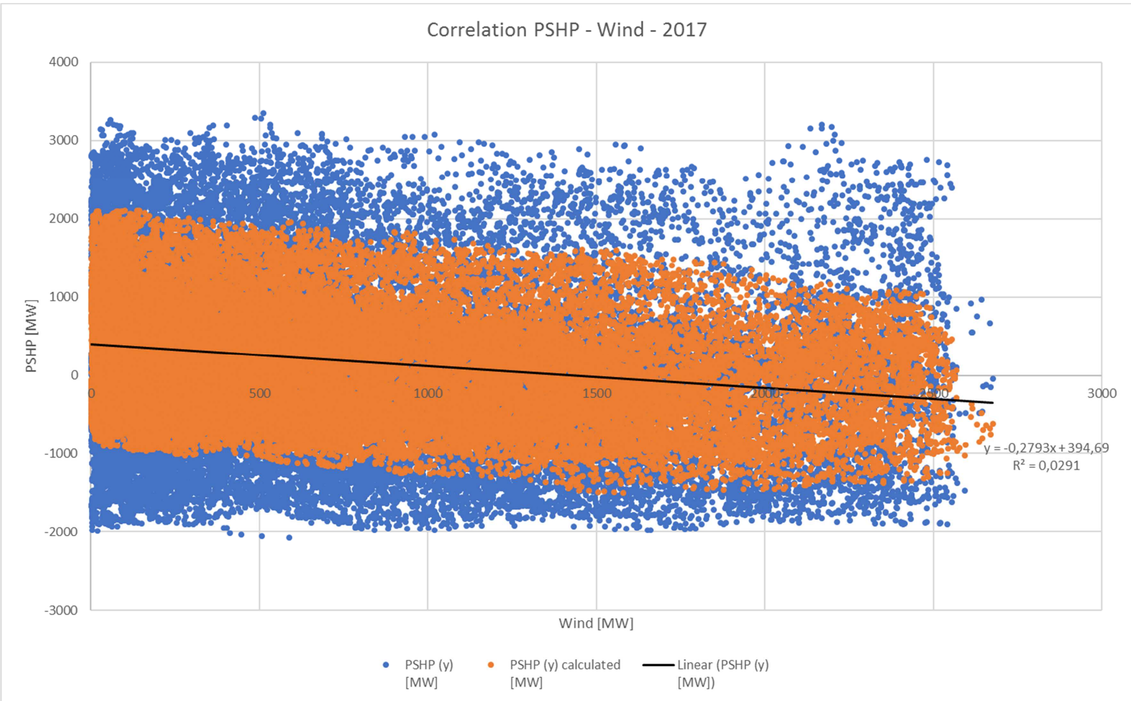

Figure 37: Correlation between PSHP and wind power in 2017 (own graph, data from (APG18) and (APG181))

5.3.4 ANALYSIS BETWEEN PSHP AND PRICE + WIND

The regression analysis was done according to quotation (9). The following equations show the relationship between wind energy and price and the generation / consumption of PSHPs. The coefficient of determination was calculated according to quotation (12) and the correlation coefficient was calculated according to quotation (14). Moreover, an F-Test and T-Test was carried out.

$$P_{PSHP,2015} = -0{,}138 P_{wind} + 41 P_{Price} - 1040{,}5 \tag{26}$$

$$Coefficient\ of\ determination_{2015} = 0{,}48$$

$$Correlation\ coefficient\ _{2015} = 0{,}69$$

$$F = 2{,}064, p = 0, F_{critical} = 1{,}0177 => \ H_0\ has\ to\ be\ rejected$$

$$P_{PSHP,2016} = -0{,}11 P_{wind} + 49 P_{Price} - 1036{,}8 \tag{27}$$

$$Coefficient\ of\ determination_{2016} = 0{,}41$$

$$Correlation\ coefficient\ _{2016} = 0{,}64$$

$$F = 2{,}414, p = 0, F_{critical} = 1{,}0177 => \ H_0\ has\ to\ be\ rejected$$

$$P_{PSHP,2017} = -0{,}121 P_{wind} + 41 P_{Price} - 1141{,}9 \tag{28}$$

$$Coefficient\ of\ determination_{2017} = 0{,}45$$

$$Correlation\ coefficient\ _{2017} = 0{,}67$$

$$F = 2{,}22, p = 0, F_{critical} = 1{,}0177 => \ H_0\ has\ to\ be\ rejected$$

Table 12: Overview over parameters for PSHP as a function of Wind and Price (own table). T-values are in brackets.

	P_{Wind} m_1 t-value	P_{Price} m_2 t-value	b	r^2	$r_{y,x1,x2}$	F	p	$F_{critical}$	Model
2015	-0,138 (-21,5)	41,7 (177,3)	-1040,5 (-113,2)	0,48	0,7	2,1	0	1,0177	Valid

	P_{Wind} m_1 t-value	P_{Price} m_2 t-value	b	r^2	$r_{y,x1,x2}$	F	p	$F_{critical}$	Model
2016	-0,11 (-16)	49,4 (154)	-1036,8 (-91)	0,41	0,64	2,4	0	1,0177	Valid
2017	-0,121 (-18)	41 (164)	-1141,9 (-99,5)	0,45	0,67	2,22	0	1,0177	valid

There is a strong positive correlation that mainly derives from the price (the t-value shows a much higher significance than the wind).

The value of the determination coefficient is around 0,41 to 0,48.

Figure 38 to Figure 40 show the relationship between PSHP, wind power and price for the year 2015 to 2017. The power of PSHP in MW is plotted on the z-axis. Wind power (in MW) and price (in Euro / MWh) are displayed on the x- and y-axes. Each blue dot of the scatter plot represents a value from the 15-minute data series (see chapter 3 and Table 6). The dimensions and axis scaling are the same for all three graphics so that an optical comparison is possible. As the year progresses, the scatter plot expands and becomes larger. Clearly visible is the inclination of the scatter plot a a function of the price. The higher the price, the sooner the pumped storage hydro plants will generate electricity. In 2017, the cap can be seen by the maximum output of the pumped storage hydro plants. Despite the rising price, electricity is produced with the maximum power. This hysteresis-like shape can also be seen in Figure 45 and Figure 46 in particular. Electricity generation form wind energy has little impact on the price (see also Table 13).

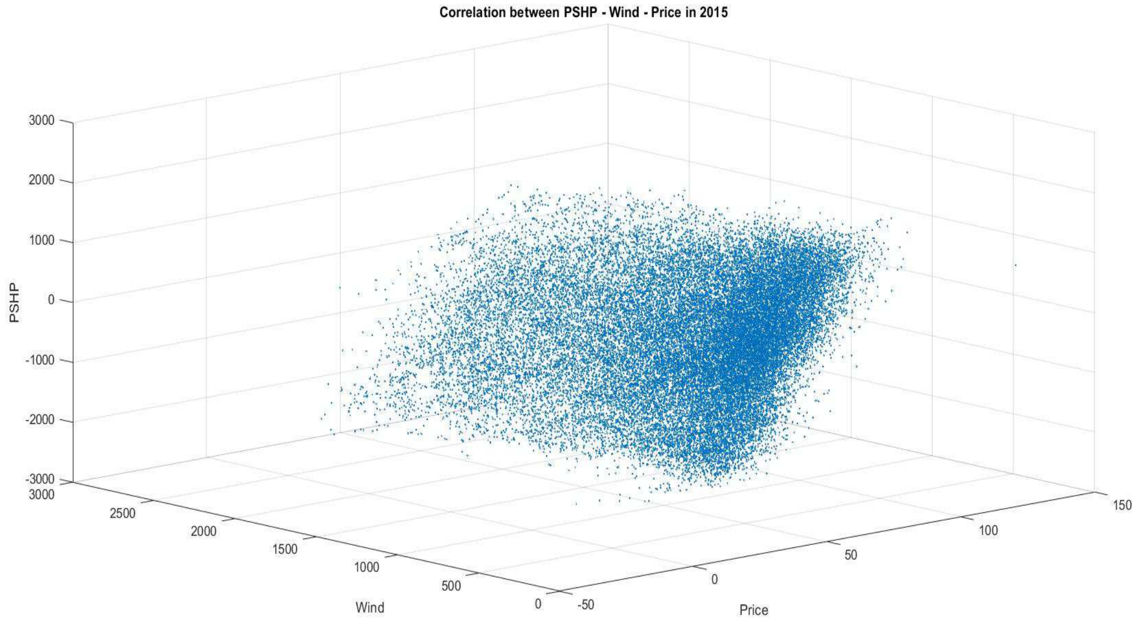

Figure 38: Correlation between PSHP, price and wind power in 2015 (own graph, data from (APG18) and (EXAA))

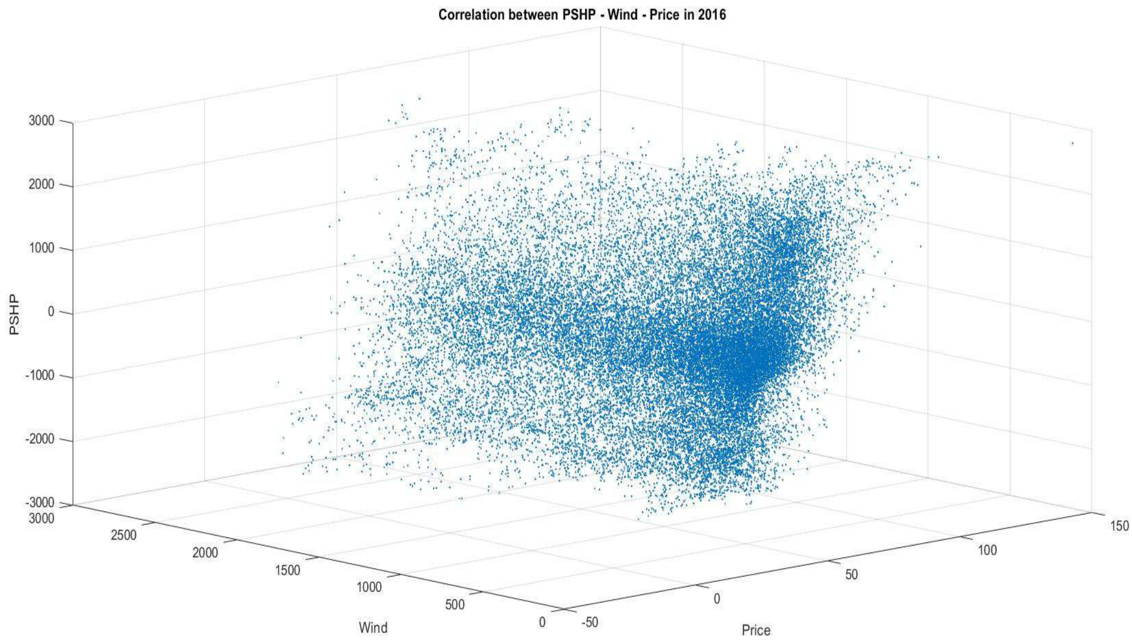

Figure 39: Correlation between PSHP, price and wind power in 2016 (own graph, data from (APG18) and (EXAA))

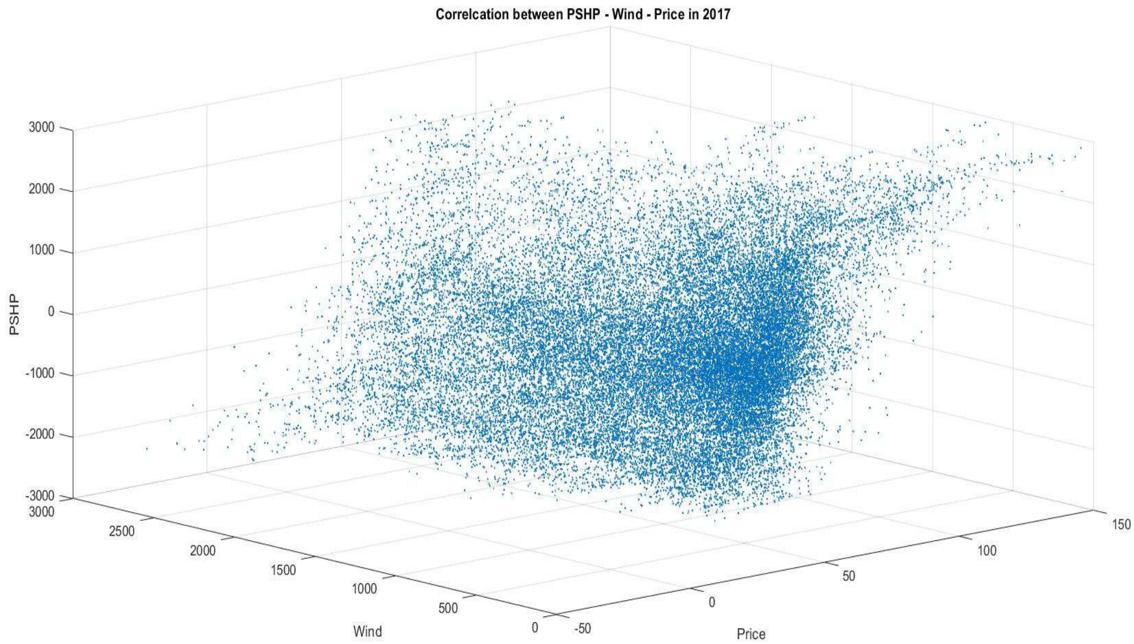

Figure 40: Correlation between PSHP, price and wind power in 2017 (own graph, data from (APG18) and (EXAA))

5.3.5 ANALYSIS BETWEEN PRICE AND GENERATION OF WIND POWER

The regression analysis was done according to quotation (10).

$$P_{Price,2015} = -0{,}0026 P_{Wind} + 33{,}065 \tag{29}$$

$$Coefficient\ of\ determination_{2015} = 0{,}01$$

$$Correlation\ coefficient\ _{2015} = -0{,}1$$

$$F = 109, p = 0, F_{critical} = 1{,}0177 => \ H_0\ has\ to\ be\ rejected$$

$$P_{Price,2016} = -0{,}0022 P_{Wind} + 30{,}46 \tag{30}$$

$$Coefficient\ of\ determination_{2016} = 0{,}01$$

$$Correlation\ coefficient\ _{2016} = -0{,}1$$

$$F = 96, p = 0, F_{critical} = 1{,}0177 => \ H_0\ has\ to\ be\ rejected$$

$$P_{Price,2017} = -0{,}004 P_{Wind} + 37{,}47 \quad (31)$$

$$Coefficient\ of\ determination_{2017} = 0{,}02$$

$$Correlation\ coefficient\ _{2016} = -0{,}15$$

$$F = 45{,}2, p = 0, F_{critical} = 1{,}0177 => \ H_0\ has\ to\ be\ rejected$$

Table 13: Overview over parameters for Price as a function of wind generation (own table). T-values are in brackets.

	P_{wind} m_1 t-value	b t-value	r^2	$r_{y,x1}$	F	p	$F_{critical}$	Model
2015	-0,0026 (-18,1)	33,065 (297,4)	0,01	-0,1	109	0	1,0177	Valid
2016	-0,0022 (-19)	30,46 (311)	0,01	-0,1	96	0	1,0177	Valid
2017	-0,004 (-27,9)	37,47 (264,6)	0,02	-0,15	45,2	0	1,0177	Valid

As illustrated in Figure 41 to Figure 43 and in the equations (29) to (31) there is no correlation between the generation of wind power and the spot price of electricity. This is also shown in the correlation coefficients that are nearly 0. It is evident that the model is not suitable to calculate prices based on wind generation only. This is because the coefficient of determination is 0. The generation of wind power does not have any effect on the electricity price. The factor m_1 is very small, and therfore the sum of the multiplication has nearly no influence.

The F-test shows that the model is still valid. The T-Test shows a significance of the independent variables. The significance of the factor b is far larger than of m_1.

It is only in 2017 (see Figure 46) that some instances show that the price goes down with increasing generation of wind power and vice versa. The reasons for this could be the increasing electricity generation by wind power. From 2015 to 2017 the energy production of wind increased by 36 % (see Table 3). Many more wind power plants produced electricity at the same time in 2017. This can be seen in the frequency distribution (see Figure 5).

Because the installed capacity increased from 2015 to 2017 the x-axis covers a wider range in 2017 than in 2015 and 2016.

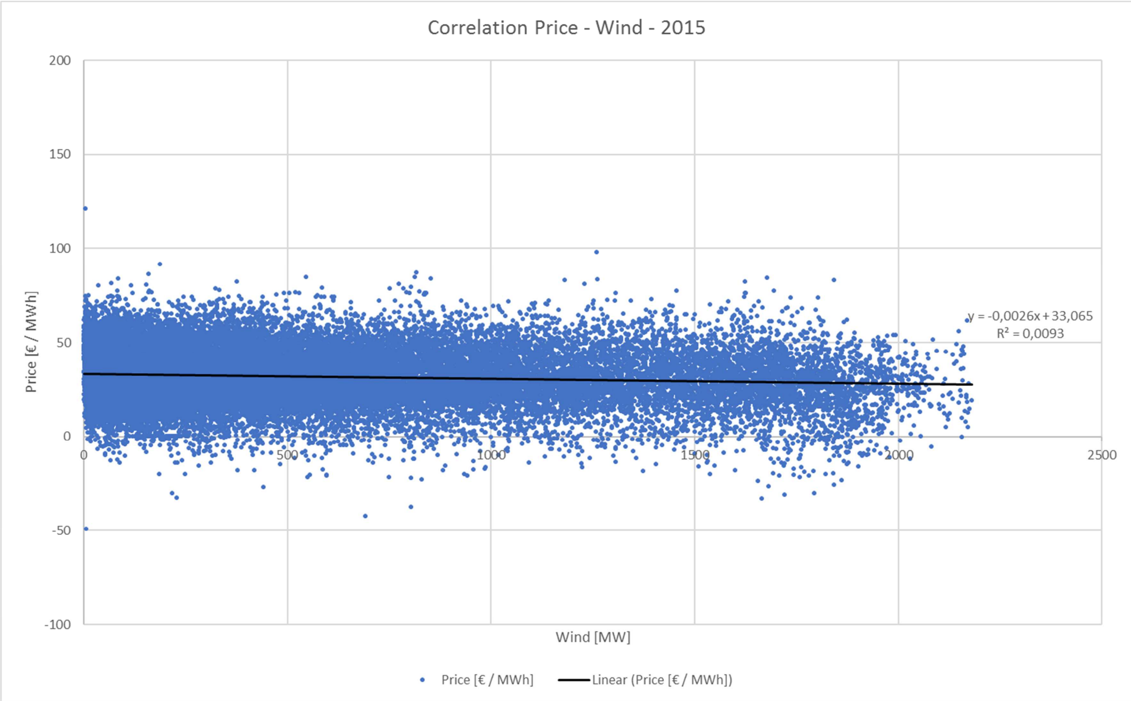

Figure 41: Correlation between price and wind power in 2015 (own graph, data from (APG18) and (EXAA))

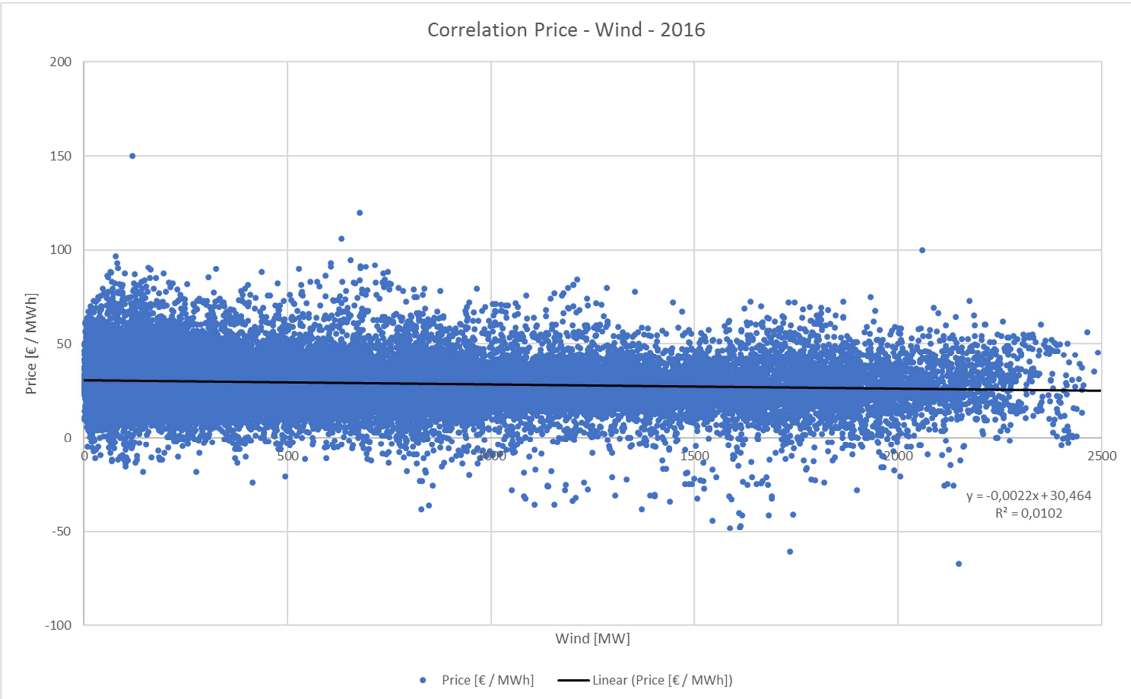

Figure 42: Correlation between price and wind power in 2016 (own graph, data from (APG18) and (EXAA))

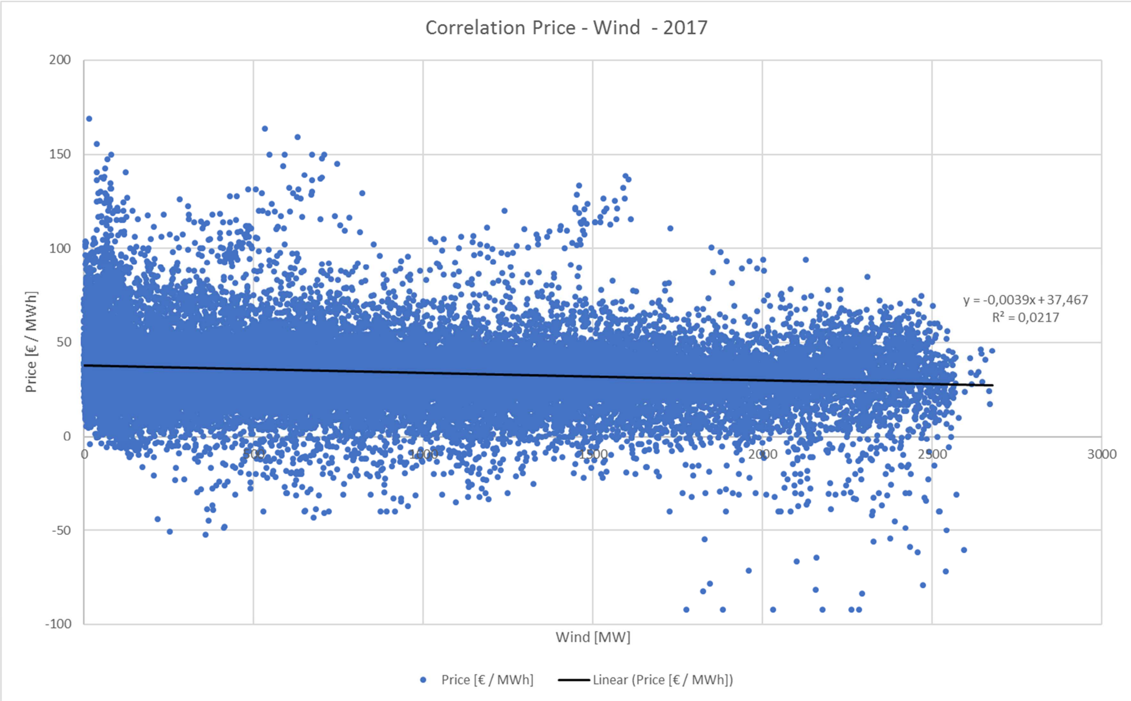

Figure 43: Correlation between price and wind power in 2017 (own graph, data from (APG18) and (EXAA))

5.3.6 ANALYSIS BETWEEN PSHP AND PRICE

The regression analysis was done according to quotation (11).

$$P_{PSHP,2015} = 42{,}2P_{Price} - 1133 \tag{32}$$

$$Coefficient\ of\ determination_{2015} = 0{,}4777$$

$$Correlation\ coefficient\ _{2015} = 0{,}69$$

$$F = 2{,}09, p = 0, F_{critical} = 1{,}0177 => \ H_0\ has\ to\ be\ rejected$$

$$P_{PSHP,2016} = 49{,}96P_{Price} - 1119{,}9 \tag{33}$$

$$Coefficient\ of\ determination_{2016} = 0{,}41$$

$$Correlation\ coefficient\ _{2016} = 0{,}64$$

$$F = 2{,}44, p = 0, F_{critical} = 1{,}0177 => \ H_0\ has\ to\ be\ rejected$$

$$P_{PSHP,2017} = 41{,}7P_{Price} - 1258 \tag{34}$$

$$Coefficient\ of\ determination_{2017} = 0{,}45$$

$$Correlation\ coefficient\ _{2017} = 0{,}67$$

$$F = 2{,}24, p = 0, F_{critical} = 1{,}0177 => \ H_0\ has\ to\ be\ rejected$$

Table 14: Overview over parameters for PSHP as a function of Price (own table). T-values are in brackets.

	P_{Price} m_1 t-value	b t-value	r^2	$r_{y,x1}$	F	p	$F_{critical}$	Model
2015	42,2 (179)	-1133 (-138)	0,477	0,69	2,09	0	1,0177	Valid
2016	49,9 (156,2)	-1119 (-109)	0,41	0,64	2,44	0	1,0177	Valid
2017	41,7 (167,8)	-1258 (-130)	0,45	0,67	2,24	0	1,0177	Valid

There is a correlation between the price of electricity and pumped storage hydro plants (the correlation coefficient is above 0,64). This can be explained by the fact that the higher the electricity price is the more profitable it is to generate electricity using PSHPs. The lower the price (especially if the price is negative) the more reasonable it is to use electricity to pump water up to the storage basins. As described in chapter 5.3.5 the year 2017 shows some cases illustrate the above.

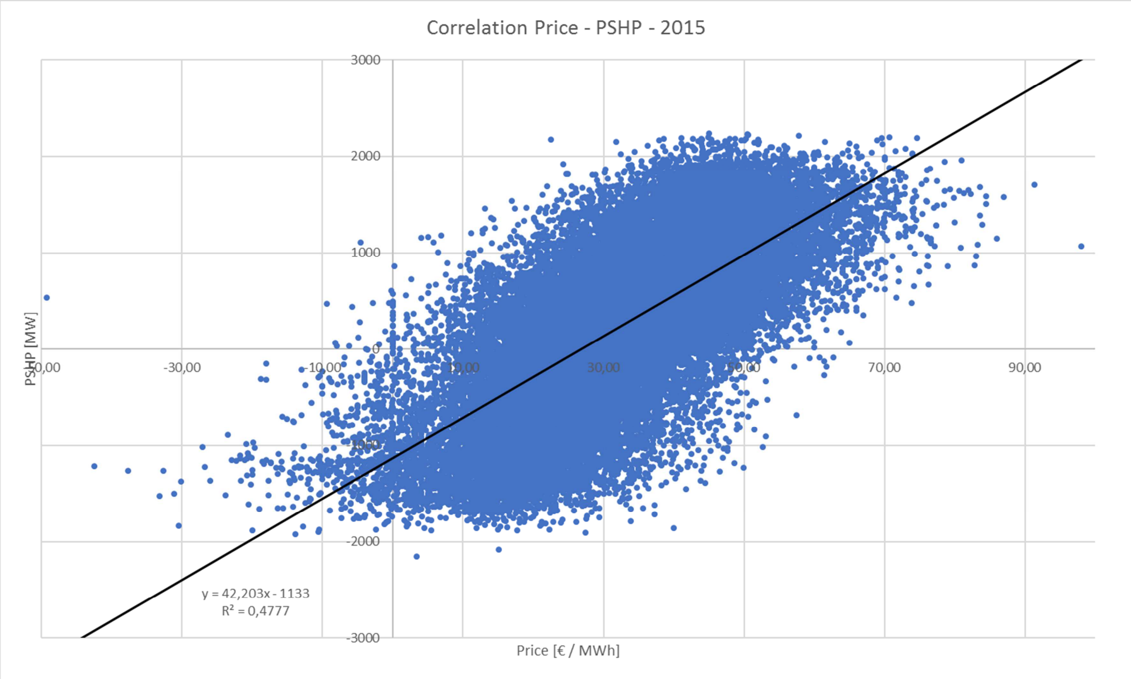

Figure 44: Correlation between price and PSHP in 2015 (own graph, data from (APG18) and (EXAA))

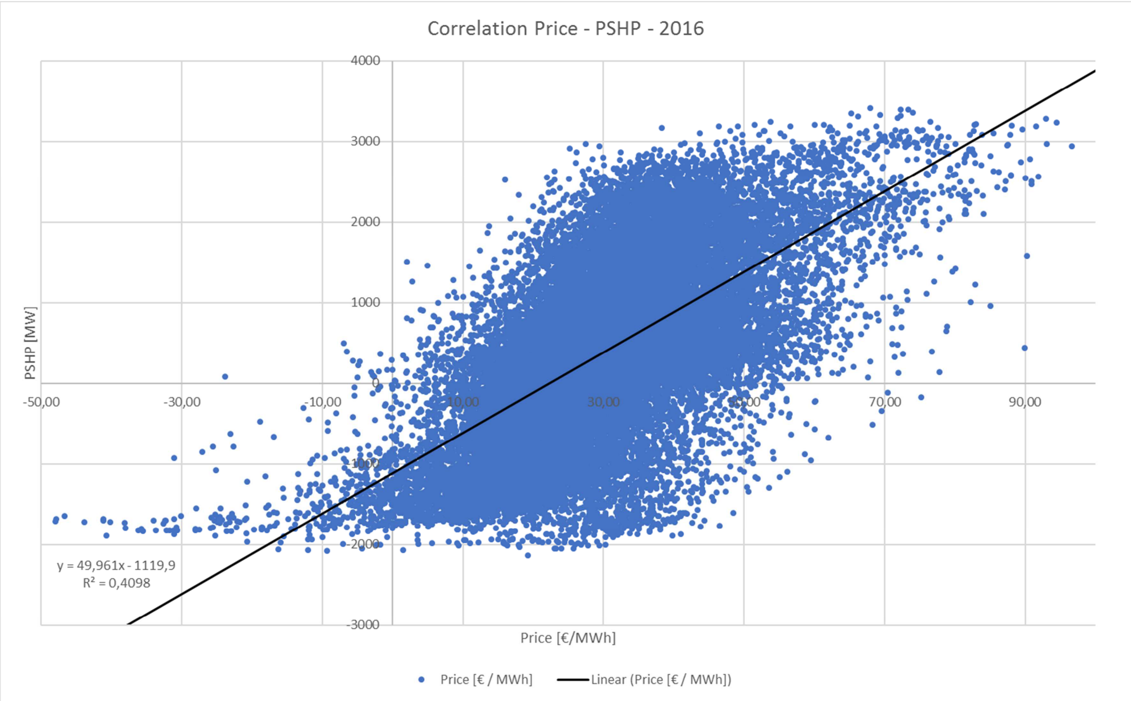

Figure 45: Correlation between price and PSHP in 2016 (own graph, data from (APG18) and (EXAA))

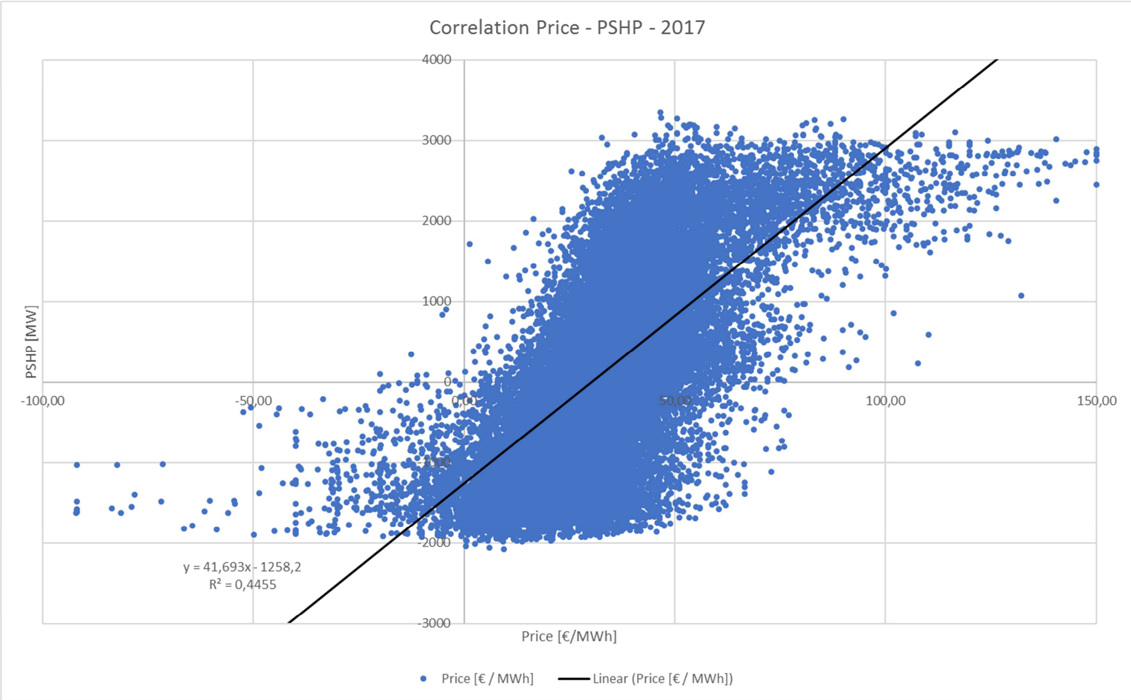

Figure 46: Correlation between price and PSHP in 2017 (own graph, data from (APG18) and (EXAA))

In 2016 and 2017 there is the upper limit of PSHP generation visible. This is because there are only 3 401 MW installed capacity available (see Table 2). The limit in pumping mode lies at about 2 000 MW. The installed pumping capacity is smaller (e.g. Limberg II has 480 MW installed generation capacity but only 144 MW installed pumping capacity (Mantler, 2018)).

6 CONCLUSION

There is nearly no correlation between the generation of wind power and the pumped storage hydro plants. However, the prefix of the correlation coefficient shows the expected direction (the more wind energy, the more energy is consumed by PSHPs) A visible correlation between the generation of wind energy and the consumption of PSHPs can only be found on some days (see chapter 5.2). One study (Wolter, et al., 2011) claimed that there is a correlation, however this is not proven in the study.

A correlation between the generation of wind power and the price could not be found. The prefix, however again shows the expected direction (the more electricity is generated by wind power, the lower the price becomes).

There is a correlation between residual load and PSHP and between price and PSHP. The higher the price, the more energy is produced by PSHPs.

Table 15: Summary of the correlation coefficients (own table)

		Wind	Residual load	Wind + Residual load	Price	Price + Wind
PSHP	2015	-0,15	0,57	0,58	0,69	0,69
	2016	-0,13	0,65	0,65	0,64	0,64
	2017	-0,17	0,62	0,63	0,67	0,67

Table 16: Summary of the correlation coefficients (own table)

		Wind
Price	2015	-0,1
	2016	-0,1
	2017	-0,15

Given the trend seen in the figures there might be a change in future in the correlation between wind power and price and wind power and PSHP (in case the generation of wind power continuous to increase).

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APG	Austrian Power Grid
CO2	Carbon dioxide
ENTSO-E	European Network of Transmission System Operators for Electricity
EXAA	Energy Exchange Austria
h	h
FLH	Full Load Hours
PSHP	Pumped storage hydro plant
MW	Megawatt
GW	Gigawatt
MWh	Megawatt hours
GWh	Gigawatt hours
OeMAG	Abwicklungsstelle für Ökostrom AG
PV	Photovoltaic
TSO	Transmission System Operator