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Electric Storage Possibilities in the Future Power System

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Abstract

In recent years, the amount of renewable energy sources in Europe has increased substantially. During the work on this thesis, wind and solar energy is added to the simulating tool, PSST. Where wind and solar energy are added the generation mix and the electricity prices are influenced. This is especially seen in Germany which has a lot of wind and solar energy at the present time, and are planning to increase an expansion in the future. In Germany this leads to a decrease in the use of lignite and hard coal, which then reduces the CO_2 emissions. As result of the increased amount of renewable energy sources that can not be controlled to a great extent, there will be more unstable electricity production in the power system. An electric storage can be used as a buffer and create more stability. The storage possibilities PHS and CAES were modeled in PSST as well. However, the results from modeling these storages proved them to be unprofitable, which does not corresponds to reality. The main reason is for this flaw is the modeling of the marginal costs, which needs to be done differently. The marginal cost needs to be base on an yearly or weekly optimization in the use of respectively PHS and CAES. Even though this was done, CAES seldom proved to be beneficial, due to low efficiency and the fact that CAES uses gas as a fuel. However, if the modeling where done with a newer CAES in mind, with higher efficiency and compressor capacities CAES might be profitable, especially if in addition the gas prices can be lowered as well.

Sammendrag

I de siste årene har det blitt en storstilt økning i energiproduksjon fra vind og sol. Gjennom arbeidet på masteroppgaven har vind- og solenergi blitt implementert i et simuleringsprogram, PSST. Der disse energikildene er lagt til har produksjonfordelingen og strømprisen endret seg. Dette er spesielt synlig i Tyskland, som har mye vind- og solenergi i dag, og som også planlegger å bygge ut mer. I Tyskland fører dette til en nedgang i bruken av brun- og steinkull i kraftproduksjonen, noe som minker CO_2-utslippene. En av resultatene av å øke andelen fornybar energi er mer ustabil produksjon, da de fornybare kildene vanskelig lar seg kontrollere. Dette kan løses ved å lagre den elektriske energien. Lagring kan gjøre på forskjellige måter, og under dette arbeidet har PHS og CAES blitt modellert i PSST. Imidlertid har resultatene vist at lagringsenhetene ikke er lønnsomme, noe som ikke stemmer med virkeligheten. Årsaken til feilen er modelleringen av marginalkostnadene. Marginalkostnadene må basere seg på en årlig eller ukentlig optimering i bruken av henholdsvis PHS og CAES. CAES viser seg å være lite lønnsomt på grunn av den lave virkningsgraden og bruken av gass som brensel. Det antas at dette vil gjelde selv ved simulering med en bedre modell. Det er kun hvis CAES blir modelert med verdier som kan representere en nyere type CAES, med høyere virkningdgrad og kompressor kapasitet at CAES kan vise seg å være lønnsom. Spesielt hvis gass prisen kan modeleres lavere i tillegg.

Acknowledgments

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3 Abbreviations

General abbreviations

RES	Renewable Energy Sources
ENTSO-E	European Network of Transmission System Operators for Electricity
TSO	Transmission System Operator
PHS	Pumped Hydro energy Storage
CAES	Compressed Air Energy Storage
EMPS	EFI's Multi-area Power market Simulator

Country abbreviations

Country code	Country	Country code	Country
AT	Austria	IT	Italy
BA	Bosnia-Herzegovina	LT	Lithuania
BE	Belgium	LU	Luxembourg
BG	Bulgaria	LV	Latvia
CH	Switzerland	MK	Macedonia
CZ	Czech Republic	NI	United Kingdom
DE	Germany	NL	Netherlands
DK	Denmark	NO	Norway
EE	Estonia	PL	Poland
ES	Spain	PT	Portugal
FI	Finland	RO	Romania
FR	France	RS	Serbia
GB	Great Britain	RU	Russia
GR	Greece	SE	Sweden
HR	Croatia	SI	Slovenia
HU	Hungary	SK	Slovak Republic
IE	Ireland	UA	Ukraine

1 Introduction

1.1 Research Motivation

The climate changes has been addressed with great concern in EU the last years, and they are willing to change their energy production to generators that emit less greenhouse gases. This willingness is presented in the "Energy Roadmap 2050" written in 2009, with obliged targets for all member states. This has led to a significant increase in the use of renewable energy sources, especially in Germany [1]. The increase is expected to continue for the whole EU, and will affect the transmission planning and system operation significantly. Solar and wind energy are two renewable energy sources which have had an increase in Europe. However, solar and wind energy are hardly controllable and predictable, and the need for flexible energy sources is growing proportionally with the expansion of renewable energy. Electric storage might be part of the solution, but electricity can not be stored as it is and need to be converted to another energy form instantaneously. Different ways of storing energy exist today, but in order to benefit from the storages, the optimal storage technology for each location and how to use it must be defined.

1.2 Scope Of The Thesis

The scope of the thesis is to implement wind and solar energy in the Power System Simulation Tool, PSST, developed by SINTEF Energy, and look at the impact these energy sources have on the European power system. Additionally electric storage possibilities are modeled in PSST, based on present and future projects in Europe. The objective is to give suggestions on how the storage possibilities should be modeled and used to increase optimization of the power grid.

1.3 Outline

The motivation and the main scope of this research is given in the previous sections. In **chapter 2** the background is compiled with elaborations of the relevant properties in the European power market, together with the general structure of electric storages and their attributes and drawbacks.

Chapter 3 explains the general approach for modeling the European power marked in PSST. The modeling of the storage possibilities PHS and CAES are thoroughly demonstrated.

Chapter 4, section 4.1 presents the results from adding renewable energy in PSST by looking at both 2010 and 2020.
Chapter 4, section 4.2 gives a overview of the results from including electric storages in PSST, PHS and CAES.

Chapter 5 is a discussion about the results presented in chapter 4, both the impacts from wind and solar energy, and a critique of the modeling of electric storage.

Chapter 6 finalizes the thesis. It sums up the main points from chapter 4 and gives recommendations for further research and modulations.

2 Background

2.1 ENTSO-E

The European Network of Transmission System Operators for Electricity, ENTSO-E, was established in 2008, representing 41 of the Transmission System Operators, TSOs, in Europe from 34 countries, see figure 2.1. The main idea behind ENTSO-E is to optimize the power production and flow throughout the European countries, with cross-border exchange and trade. Each TSO is in control over their own transmission lines, but with ENTSO-E it is easier to buy and sell electricity from other countries/TSO-areas. In total the ENTSO-E has 532 million customers with an electricity consumption of 3200 TWh. [2].

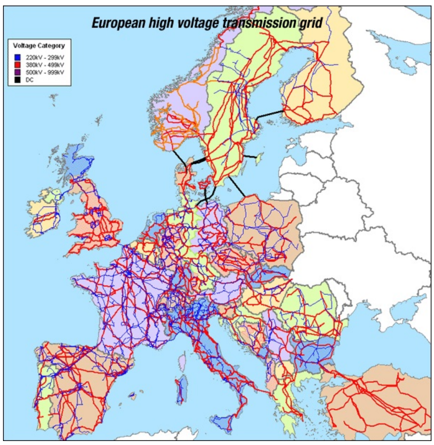

Figure 2.1: The European power system [3].

2.2 Demand and Production

The demand of electricity changes throughout the day, day of week, season and weather conditions, and the TSOs uses previous experience and market analyses to predict the future demand. Knowing the demand, the TSOs buy the electricity from the power producers at the lowest price possible. The power producers inform the TSOs about their price for every possible power output at each hour. For the

TSOs the optimal solution is based on the unit commitment and economic dispatch, where the *unit commitment* is which generators should be used, and when. The *economic dispatch* is the output power from these generators [4]. In Europe, there are many different energy sources such as fossil fuel, renewable- and nuclear power. Nuclear power can not start production right away and it is not profitable to turn the generators off and on a lot, but it is cheaper and have a high power capacity compared to other energy sources. Therefore, the nuclear power plants are often set with the same power output for the whole year. The same accounts for coal power plants. These power plants are called base generators, since they can cover the basic demand in the system. More expensive generators like oil and gas generators, but are easily turned off and on, are used to cover the peak demand. This is the demand that exceeds the power output from the base generators. Hydropower can also be turned off and on easily and is used as a peak load generator, but in countries with a lot of hydropower, this can due to its low marginal cost, also be used as a base generator. Some of the renewable energy sources like solar and wind can not be controlled and their electricity production need to be used when produced. However in some cases, when the load is to low, or there is congestion, there can be necessary to turn the solar and wind plants completely off. The power producers needs to let the TSOs know how much power they can produce in the future. This is among other factors based on fuel cost, production cost and stops due to maintenance. For wind and solar producers it is harder to find their future production, and they need to use prediction models and weather forecasts when predicting their future production. Due to the impossibility to forecast the demand and production accurate for every producers and customers, there is a need for energy reserves.

2.3 Balancing the Power System

The TSOs are responsible for an efficient and secure electricity distribution in their power system, considering both public and private interests. In order to have an efficient power system there must be a balance between production and consumption, creating a system frequency at 50 Hz. Higher production than consumption leads to a higher frequency, and vice versa. A deviation from this frequency reduces the voltage quality and can in severe cases lead to total blackouts in some part of the power grid. Knowing the importance of keeping the frequency stable, there exist different methods for balancing the power system and the frequency. First of all planning and communication is important, and the TSOs have good communication routines with the relevant power actors. If there are a deviation from the planned production or consumption, there are three regulation reserves; primary, secondary and tertiary regulation reserves, that can be used in order to maintain a balanced power system [5] .

Primary regulation
Primary regulation are automatically used for maintaining the momentary balance between the production and consumption. In case of line or production outages, the TSOs need to have an alternative power production that can react momentary,

these are called primary reserves [5].

Secondary regulation
The secondary reserves are used when the primary reserves are not enough to keep up the frequency balance. This type of regulation can almost momentary be set off, but are not as fast as the primary reserves [5].

Tertiary regulation
Tertiary regulation is used to free up the secondary reserves when the power system is in balance, or when there are larger outages in the system than the primary and secondary reserves can handle [5] [6].

2.4 Energy Storage

In Europe, there has been an expansion of the electricity production from renewable energy sources, like solar and wind. These energy sources have little or no marginal costs, but they are hard to regulate and predict. For an optimized power production with low costs, the solar and wind generation should be used as much as possible regardless of the load in the power grid. In some cases, the possible production will exceed the load, and if there is no possibilities to increase the load, the production needs to be down-regulated, or completely turned off, which leads to surplus energy in the system. One way to increase the load is to use this energy and stored it, but since electricity as a form can not be stored as it is, it must be converted into other energy forms. Today, there exist several methods to store energy, with different degree of production capacity, storage capacity and ramp-up time, see figure 2.2 on the following page. The idea behind storages is to store energy when the load is low and use it when the load is high, lowering the total electricity price. In this report the focus will be on pumped hydro energy storage, PHS, and compressed air energy storage, CAES.

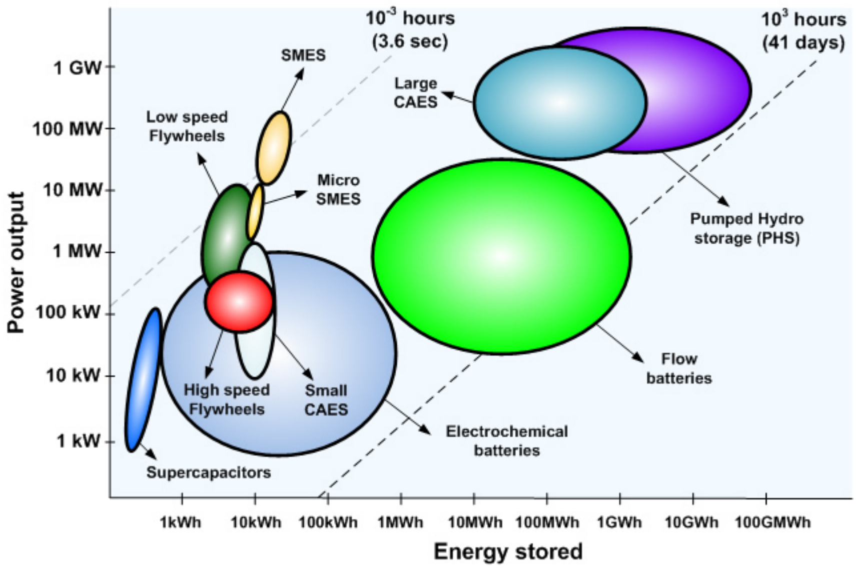

Figure 2.2: Overview of the storage possibilities and their advantages

2.4.1 Pumped Hydro Storage

The pumped hydro energy storage is a well-known technology and can store a high amount of energy. It is based on hydro power with reservoirs, which can in some cases store water for whole seasons. In high load periods the water from the upper reservoir is led down to a turbine connected to a generator, creating electricity like normal hydro power plants. However, in low-load periods when the marginal cost in the system is lower than the water value, the pumps will start and move the water from the lower reservoir to the upper reservoir back again, which is shown in figure 2.3. In this way there is more energy in the reservoir than before the pumping, which can be used later in high load periods. When using electricity to pump water in a higher reservoir the electricity is converted to potential energy.

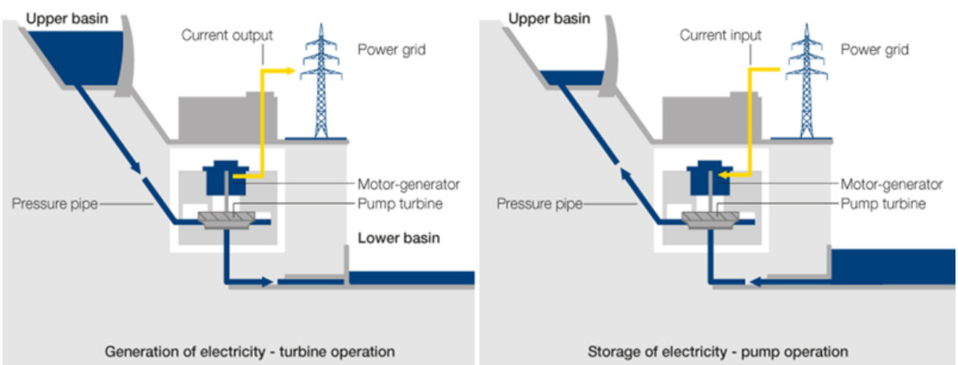

Figure 2.3: Operation of hydro power with a pump [7]

The advantages with pumped hydro storage is that it can recover around 80% of the flow rate, so the efficiency is very high compared to other storage possibilities. A pump can be added to an already existing hydropower plant which will decrease the investment cost substantially, specially if the same tunnels can be used as well. New tunnels can however increase the efficiency of the pumping. When building a hydro pumped storage, one must take the environment into account. If a new reservoir is needed this will have a huge impact on the surroundings. Therefore adding a pumps to an existing plant is easier and cheaper. Regardless if a new reservoir is needed or not, the water from the lower reservoir will be added to the upper reservoir, which can cause troubles regarding the water life and fauna, and this must be taken into account. Additionally a rapid change in the reservoir level can cause drought and death for fiches, and must be avoided. Nevertheless, hydro pump storage is a cheap and easy way of storing energy with no CO_2 emissions [8].

2.4.2 Compressed Air Energy Storage, CAES

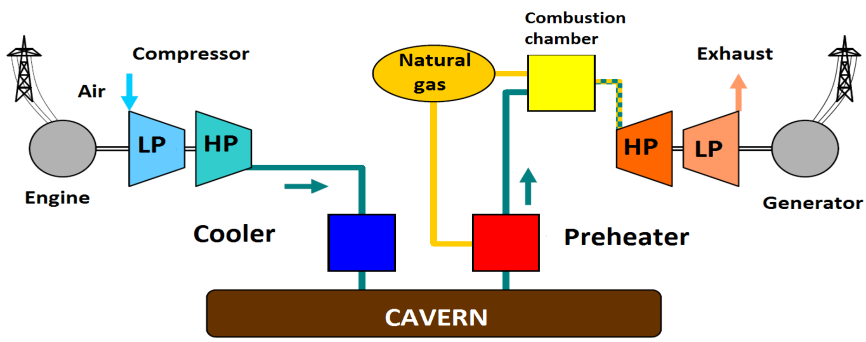

Figure 2.4: Operation of compressed air energy storage

The main principle behind CAES is to compress air with electricity in low-load periods. The compressed air is stored in caverns until the electricity prices are higher/high-load periods. A motor runs a compressor that increases the air pressure in two steps. The air is then stored in one or more caverns. When the energy is needed, the air is lead to a combustion chamber where natural gas ignites the air, which causes an expansion that spins the turbine. The turbine is connected to a generator which will produce electricity to the power grid. When the air is compressed it has a high temperature, $600 - 800\,°C$, which needs to be reduced in order to not destroy the cavern. Furthermore the air needs to be heated before the air is led to the combustion chamber. If this is combined by using a heat exchanger instead of just let the heat out in the air, the efficiency can be raised to 70%. This technology is called Adiabatic Compressed Air storage, AA-CAES, and an ongoing project in Germany called ADELE will use this technology. The existing plant at Huntorf was build in 1987 and have a turbine with a capacity of 290 MW which can operate for maximum 3 hours, and a compressor that have a capacity of 60 MW which needs to be ran for 12 hours to fully charge the cavern to have 720 MWh [9]

[10]. The turbine can run for four hours at 290 MW, after that the cavern pressure is too low to keep up the power output, but will produce at lower effect for about ten more hours. ADELE is planned to be in its test-phase in 2016, with 1000 MWh storage, and a turbine capacity of 360 MW for four hours [11]. The efficiency and storage possibility is much lower for CAES than for hydropower storages. The efficiency can reach 42-52% with CAES, and the cavern used for storage can hold the energy for up to 10 days. However, in places where there is little or no suitable location for hydropower storage, CAES is a good alternative.

2.4.3 Other Types of Storages

Vanadium Redox Flow batteries, VRF

VRF batteries consists of two electrolytes in two different tanks. The electrolytes have different amount of "loose" ions, and when they are pushed together with a pump, some of the electrons will move to the other electrolyte through a membrane, creating electricity. When the batteries are charging electricity is used to move the electrons the other way. The power output is based on the size of the electrode, and the energy capacity is based on the tank size, making it easy to use this technology for different types of applications, also the efficiency is high, 75 % . Smaller batteries is used widely, and there are also some bigger batteries used for output balancer from wind and solar plants. The largest one is in Japan and has a capacity of 1.5 MW [12][13][14].

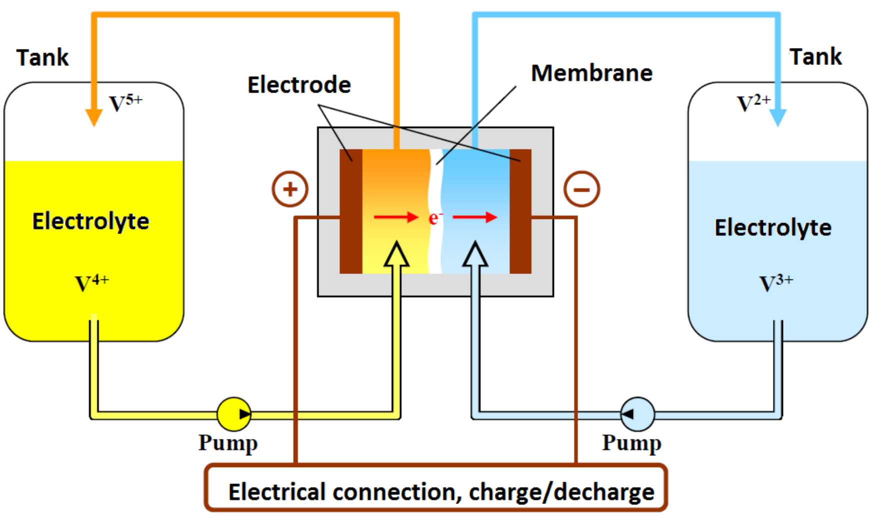

Figure 2.5: Operation of a vanadium redox flow battery, VRF [15].

Hydrogen storage

In hydrogen storage systems, electricity is used to convert either methane or water into H_2 molecules through electrolysis. The hydrogen is stored in tanks or caverns until the electricity is needed, and is then fired in thermal power plants, like gas or steam plants. The efficiency is quite low, only 20-40%. Today there exists no large hydrogen storage plants [13].

2.4.4 Pros and Cons

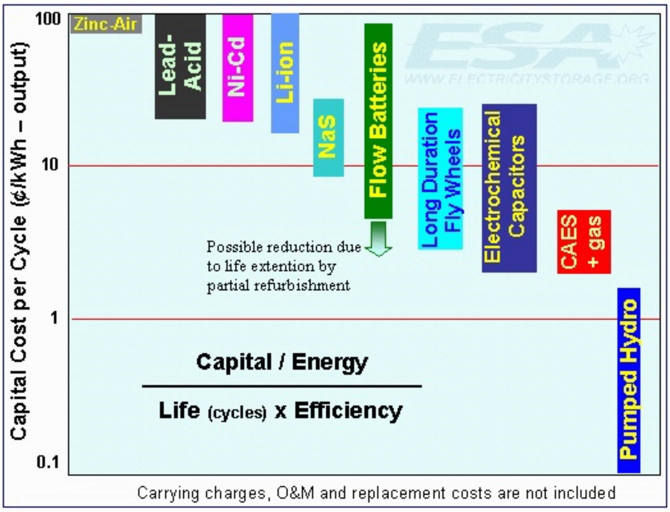

Table 2.1: Pros and cons for the different storage possibilities

	PHS	CAES	Redox	Hydrogen storage
Storage capacity	High	Medium	Low	Low
Power output	High	Medium	Low	Low
Marginal costs	Low	Medium	Medium	Medium
Construction	Hard	Medium	Easy	Easy
Ramping time	Short	Medium	Short	Medium

In this report it is desirable to look at the impact from two different storages, one with long term storage possibility and one with a shorter range. The cheapest storages per kWh is the pumped hydro storages and CAES is a number two. When also looking at figure 2.2 one can see that PHS and CAES is the two options which can store the most energy. Hydropower reservoir has a great impact on the surrounding environment, but it has no emissions. The CAES on the other hand have smaller storages, but uses gas to achieve energy and will has some CO_2 emissions. This is not the case for batteries, but for hydrogen which uses thermal plants there will be CO_2 emissions.

3 Model Description

3.1 PSST

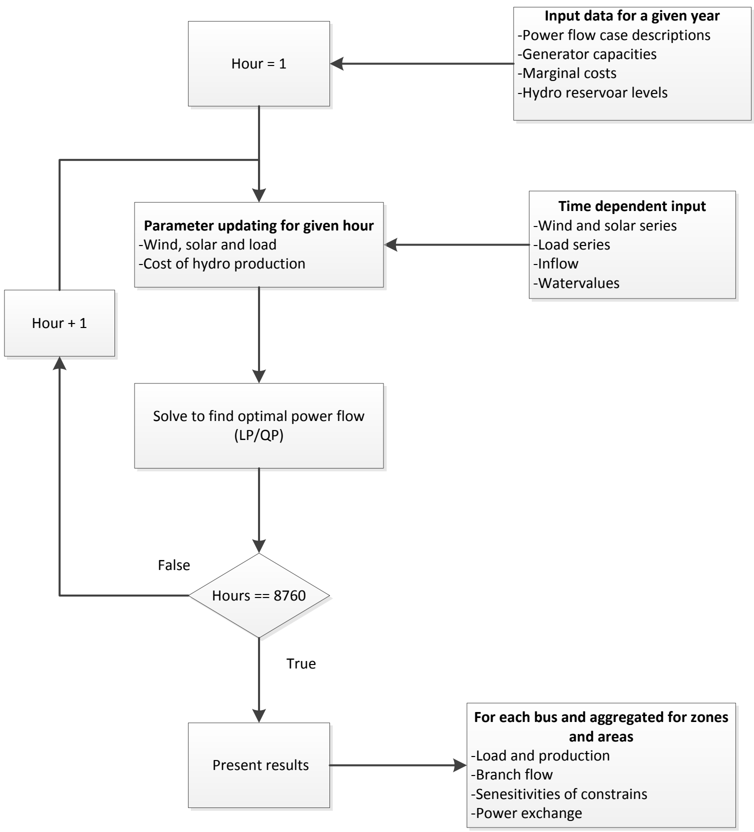

Figure 3.1: The main simulation structure in PSST [16].

Power System Simulation Tool, PSST, is a simulation tool developed by SINTEF Energy Research. The tool contains a model of the existing energy market in Europe, including a simplified model of the power grid. The model is divided into areas (countries), and the areas are further divided into zones which contains several nodes. PSST is based on numerous connected Matlab functions. The input files which are used in these functions contains all gathered information about the power grid - like production, load and transmission constraints for every node in the system at every single hour. The results from the simulation gives the optimal production and energy flow between the buses at every hour. The figure 3.1 presents the main procedure followed by PSST when simulating for one year, 8760 hours.

3.1.1 Load

Load data are collected from Nordpool for the Nordic countries, National grid for Great Britain, Eirgrid for Ireland and UCTE for the rest of the European countries. The data collected are hourly profiles for 2006. These profiles is then scaled to fit future scenarios based on forecasts made by ENTSO-E [17] [18]. Information about how transmission lines and constrains are modeled can be found in [18].

3.1.2 Generation

Each generator has a production maximum and minimum, Pmax and Pmin. Most of the generators can operate from 0 MW, except nuclear generators which has a higher start up production. During the simulation PSST finds the optimal value between Pmax and Pmin for every generator, and which of them should be turned off. To find the optimal solution PSST uses the marginal cost for the generators, except hydro power which uses water values from EMPS.

3.1.3 Wind and Solar Installations

Wind Power

The modeling of the wind power distinguish between onshore and offshore installations. There are around 24000 wind power facilities onshore in Europe, seen in figure 3.2. These are based on installations present in 2010 and are gathered from the data base TheWindpower.net [19] for all the countries except Germany. For Germany the TSOs are obliged to publish their production from renewable energy sources, RES, through the *Erneuerbare Energien Gesetz* and the wind data for Germany is found in [20] and [21]. From the data sets for Germany and the rest of Europe information about installed capacity and the coordinates were found.

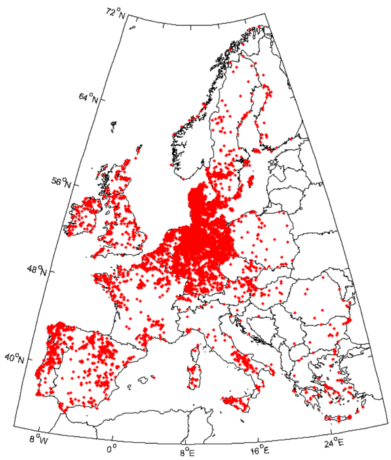

Figure 3.2: Onshore wind installations.

For future scenarios in 2020 and 2030, the wind power installation is based on the European project TradeWind [22], where each wind power organization were questioned about their future wind projects. This data was representative for each region in Europe, and was then distributed proportionally to the 2010 installations in order to find the installed capacity at the specific location representative for 2020 and 2030.

Offshore installation is based on 4coffshore [23] and includes 180 wind farms in 2020 and 320 in 2030. This data set includes wind farms in the North and Baltic Seas and the French Atlantic coast, see figure 3.3. Possible wind farms in Portugal and Spain are not taken into account.

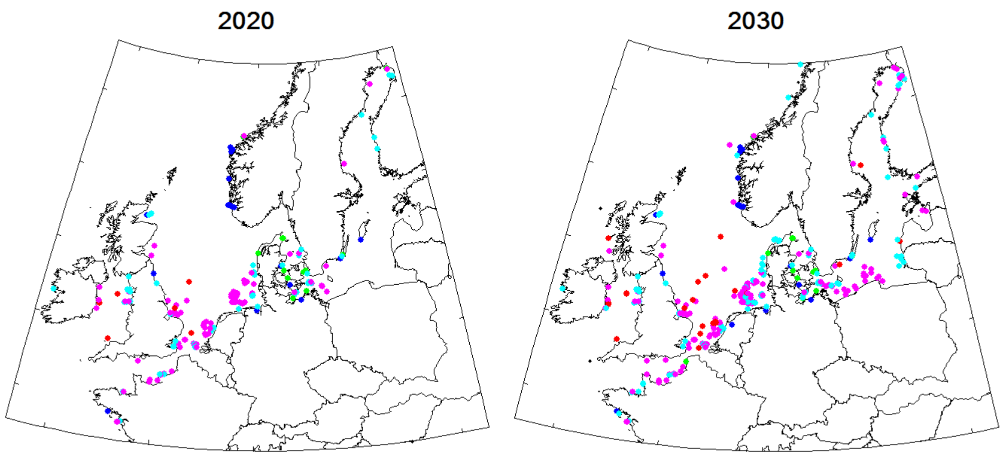

Figure 3.3: Offshore wind installations for 2020 and 2030.

All these data sets give the installed capacity and coordinates for future and present wind farms. However, to achieve the possible production at each installation for each hour, the hourly and locally wind speeds are needed. The wind speed is provided by the numerical weather prediction tool COSMO-EU, developed by Consortium for Small-scale modeling. COSMO-EU includes detailed description of wind speed and solar radiation in Europe with a resolution of $7km \times 7km$, where numerical prediction models are used to achieved wind data between the existing measure devices [24]. The wind data was compared with the real wind production data gathered from TSOs in Germany and Denmark, and a relation between the production and wind speed was found. This relation was assumed to be representative for the other European countries as well, due to the vast topographic variation in Denmark and Germany [25] [26].

Solar power

The solar installations are also based on two different data sets, one for Germany where the TSOs must list their installation of RES, and one for the rest of Europe. For Germany the PV installations are found [21], for the rest of Europe only the total installed capacity in each country is found in [1]. This capacity was then distributed among the buses listed in the PSST model, based on their load. The solar installations for 2010 are seen in figure 3.4.

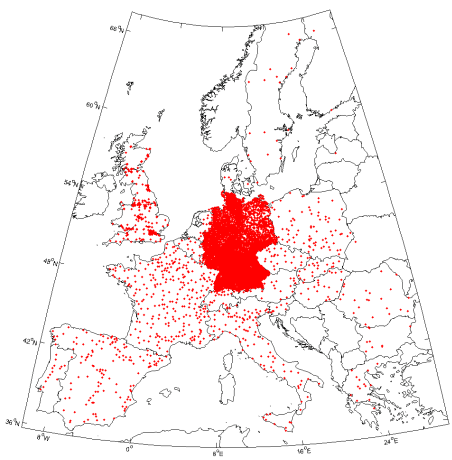

Figure 3.4: Installed solar power in 2010.

Future installation of solar power is also included in [1], and are shown in table 3.1. This is as for 2010 distributed among the future load in the PSST model. For Germany the installation is linearly upscaled to fit the predicted capacity for the whole country, also listed in [1] [26].

Table 3.1: Solar capacity in Europe for 2010 and future scenarios, all numbers are in MW [26].

Country	2010	2020	2030
Austria	66	261	613
Belgium	153	236	277
Bulgaria	3	73	192
Croatia	-	-	-
Czech Republic	99	236	288
Denmark	16	107	156
Finland	8	84	149
France	753	4593	11069
Germany	32500	70582	86243
Greece	76	1602	2485
Hungary	4	80	250
Ireland	5	30	64
Italy	1254	4184	7203
Luxembourg	41	81	108
Netherlands	96	151	241
Norway	-	-	-
Poland	1	18	74
Portugal	156	2147	3044
Romania	5	161	315
Slovakia	4	31	93
Slovenia	3	50	140
Spain	3996	11595	14077
Sweden	15	85	159
Switzerland	-	-	-
United Kingdom	41	204	570
Sum	40020	101504	132177

3.1.4 Cost Function

All the generators in PSST are modeled with a marginal cost found during the Tradewind project[18]. The total cost of the generator is then calculated with either linear, piecewise linear or quadratic functions, based on the type of generator. Finding the total cost from a linear function is done by multiplying the marginal cost in €/MW with the amount of MW used. There is for these generators only one marginal cost for every MW output from the generator. This is not often used, since most generators have a higher marginal cost when the output increases. Piecewise linear and quadratic functions are used to find total cost with different marginal cost. Piecewise linear functions are listed with two or more different marginal cost for different MW output, and the power output in between these are found by interpolation. For generators where a rapid change in the power output from hour to hour is not desired, the quadratic function is used. This so-called Ping-Pong effect will happen when there is small gap between the marginal for the different power outputs. This is especially the case for hydropower where the marginal cost/water value is closely linked to the power production. When the system price is a little higher than the water value it will produce at maximum, causing the water value to increase, which then will cause the hydropower to stop their production, and the water value will decrease again due to inflow. These changes will happen from hour to hour, and will cause an unstable and unwanted use of the hydropower. In order to avoid this the cost function for hydropower is quadratic, as shown in equation 3.1. In the following equations, C_q is total cost from the quadratic function and MC is the marginal cost.

$$C_q = \alpha P^2 + \beta P + \gamma \tag{3.1}$$

where P is the power output, and α and β are cost coefficients. From this equation the marginal cost is derived:

$$MC = 2\alpha P + \beta \tag{3.2}$$

The marginal cost is known, and in order to find α and β the linear cost variation versus production level shown in figure 3.5 is assumed:

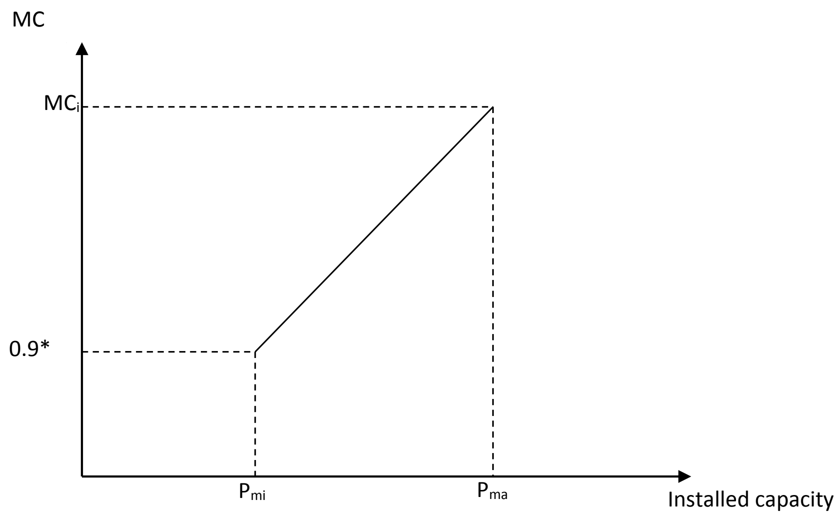

Figure 3.5: Assumed linear cost variation.

From this figure the following equations can be written:

$$MC = 2\alpha P_{max} + \beta \tag{3.3}$$

The marginal cost for P_{min} is 90% of the marginal cost for P_{max}:

$$0.9 \times MC = 2\alpha P_{min} + \beta \tag{3.4}$$

α and β are:

$$\alpha = \frac{MC(1 - 0.9)}{2(P_{max} - P_{min})} \tag{3.5}$$

$$\beta = MC - 2\alpha P_{max} \tag{3.6}$$

Figure 3.6 shows how the total cost varies when using the quadratic cost function.

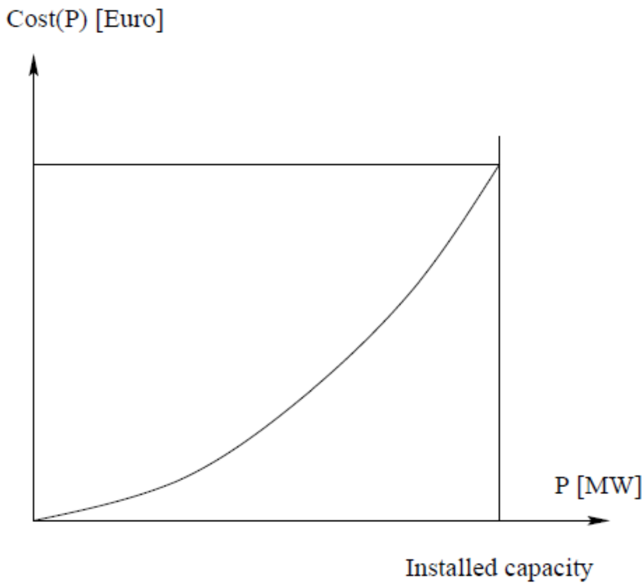

Figure 3.6: Quadratic cost function [18].

3.1.5 Water Values

PSST does not calculate the water values for the hydro reservoirs, this is previously done by another model, EMPS. The water values achieved from EMPS are aggregated values for each area, percentage reservoir level and week number. For Norway and Sweden which have a lot of hydro power, EMPS calculates water values from each zone instead of the whole area. EMPS also returns the inflow to these areas and zones and are in PSST distributed among the hydro generators according to its capacity. The reservoir capacity is only known for the whole country so it is also distributed based on each hydro generators capacity before running the simulation. The reservoir start level is set in advance, either to 0%, 50% or 60% of the capacity. The number depends on assumed reservoir level at the beginning of the year. The water values are listed as a percentage from zero to hundred, based on the reservoir level. In total there is 101 steps where level zero represent an empty reservoir. If the reservoir levels are in between these percentages during simulation, interpolation is used.

When the water value is just a little bit lower than the systems marginal cost, the hydro power is set to produce maximum according to the system preferences. However, when hydro power is producing maximum the reservoir level is rapidly decreasing causing an increase of the water value. In the next hour, the water value will be higher than the systems marginal cost, causing the hydro power to shut down, which then again will decrease the water value. This will make the hydro power jump from shut down to maximum energy input after each hour. This is called the ping-pong effect, after the ping-pongs bouncy movement when put in motion. A quadratic cost function is used to smoothen the jump, forcing hydro power to take smaller step in each hour, and the time between shut down and maximum output is extended. For hydro pumping, the quadratic function is not needed, since the maximum amount of water it can pump is not large enough to affect the reservoir level substantially.

3.1.6 Modeling of PHS

PHS is modeled together with already existing hydro generators and reservoirs in PSST. Hence, only the pump need to be added to the simulation tool. The pump is modeled as a generator, but with Pmax as zero and Pmin as the negative value of the pump's capacity. In this way, the hydro pump can work as a load when needed. The amount of energy stored at every hour is added to the connected reservoir, times an efficiency factor of 80%, resulting in less energy added to the reservoir than the power output from the pump. The idea is that the energy not added to the reservoir is used to run the pump.

Hydropower water values results in use of hydropower when the electricity price in the system is higher than the water value. For the pump, it is desired that it will operate when the marginal cost in the system is lower than the water value. However, due to the efficiency of PHS it is only beneficial to use the pump when the system price is 80% lower than the water value that the energy is later sold for. As an attempt to get the hydro pump to operate beneficial, the marginal cost for the pump is set to be 80% of the water value. Then there will be pumping only when the system price is 80% lower than the water value. Despite this addition to the marginal cost for the pump, there might be unbeneficial use of the pump. This can arise when the electricity used for pumping is higher than the selling price. The problem with this model is that one does not know which price the pumped energy is sold for in the future, and then one does not know at which price it should start pumping. Nevertheless, this model will give an insight of the impact PHS have on the European power grid. There is in PSST added PHS for existing plants for 2010 and planned plants for 2020. This is shown in section 3.2.

3.1.7 Modeling CAES

There is no CAES previously in PSST, and the turbine, compressor and storage need to be modeled with a capacity. The compressor capacity is set to be negatative just like the pump in PHS. For each hour the CAES will compress, produce electricity or do nothing according to the node price and marginal cost of the CAES. The compressed power output is added to the cavern times an efficiency factor of 45 % which is based on the CAES plant in Huntorf. Therefore there is less energy added to the cavern than the power output of the compressor each hour. The production from the turbine will use the energy from the same cavern when the marginal costs at CAES are low enough and as long as there is any energy left in the cavern. The compressor will not compress if the cavern is full.

The CAES has two efficiencies, one that is based on how much gas per MWh it acquires per MWh electricity it produces, gas inn versus electricity out. The second one is how much electricity does the compressor uses versus how much the gas turbine produces, electricity in versus electricity out. These two factors are used to find at which node prices the CAES should compress and produce.

A general gas turbine can convert 51% of the gas to electricity, and a lot of the losses come from compressing air before the ignition chamber. In a CAES cycle the compression is done beforehand and the efficiency increases to 79%. This means that the CAES uses less gas for the same electricity output. In PSST the gas turbine is modeled with a marginal cost of 74.7 €/MWh for Germany, where the emission cost from CO2, with 42 €/MWh is included. The marginal cost for gas is used to find CAES's minimum marginal cost for production,MC_{prod}, based on the efficiency factors. In the equations below the MC_{gas} is the marginal cost for gas, Eff the efficiency factor, and GP is the gas price.

$$GP = MC_{gas} \times Eff = 74.7 \text{ €}/MWh \times 51 = 38.097\text{€}/MWh\% \tag{3.7}$$

$$MC_{prod} > \frac{Gasprice}{Eff} = \frac{38.097 \text{ €}/MWh}{79.4 \text{ \%}} = 48 \text{ €}/MWh \tag{3.8}$$

From equation 3.8 the modeled marginal cost for production of electricity from gas with CAES is found. This cost represent how high the node price must be before it is beneficial to produce electricity from CAES.

The other efficiency factor, *electricity in versus electricity out* is used to find out when it is beneficial to use electricity to compress energy. This factor is modeled to be 54% based on the CAES plant in Huntorf, and shows that almost half of the energy is lost during the CAES cycle. Due to the low efficiency factor, the electricity price when compressing must be almost half the price when producing electricity. It is not possible to find out at which price the electricity from the CAES will be sold for in the next hours. However, as previously modeled, the price must be at least 48 €/MWh to produce electricity from CAES, and the maximum marginal cost,MC_comp for electricity when pumping is:

$$MC_{comp} < 48 \text{ €}/MWh \times 0.46\% = 22.18 \text{ €}/MWh \tag{3.9}$$

It is beneficial to pump for electricity cost lower than this, since the CAES will only produce when the electricity price is high enough to cover the losses in the CAES cycle.

Due to the losses in using CAES the production and compressing limit is far apart compared to hydro, where the efficiency is 80% and only the water values decides when to pump and produce.

From figure 3.7 one can see that the prices seldom are more than 48 €/MWh or less than 22.18 €/MWh. In addition, the periods with low price are too short to allow compression of a significant amount of air.

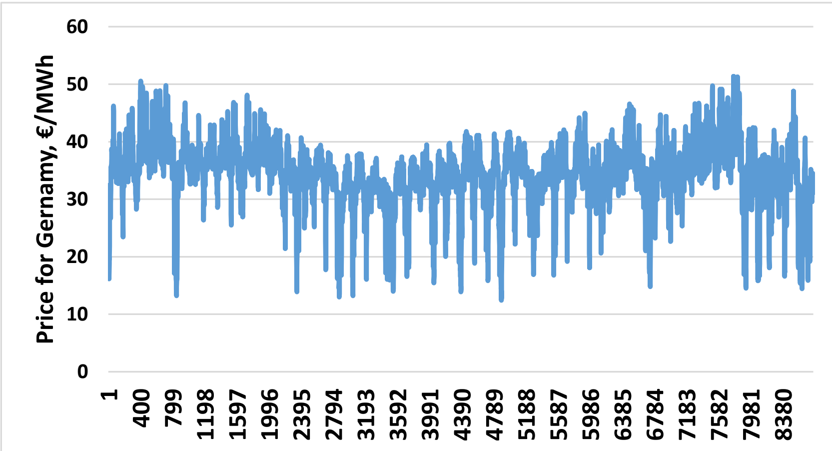

Figure 3.7: Electricity prices in Germany for each hour in 2020.

In order to find the impact of CAES, it was put in a node with varying prices. This node is named *D-19 956* in PSST. The node prices without CAES for whole year are shown in figure 3.8. To get a better overview of the use of CAES the hours with most price fluctuations were examined closer. This is the last 2 weeks, starting on a Monday.

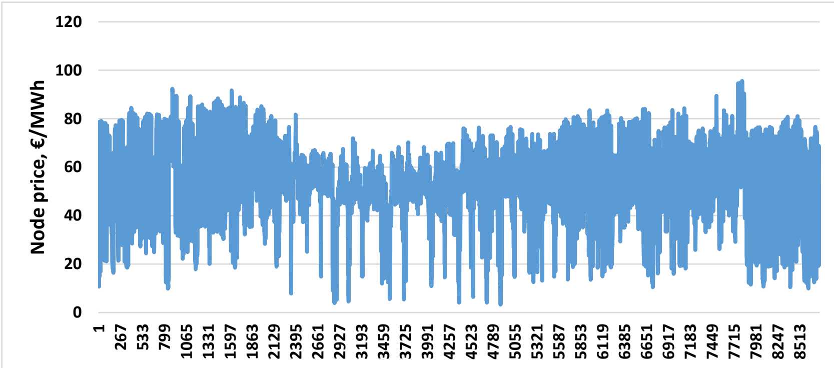

Figure 3.8: Electricity prices in node D-19 956 for each hour in 2020.

3.2 Simulations with Storages

PSST holds scenarios for the year 2010 and 2020, where yhe scenario for 2010 is based on known and existing data. The scenario for 2020 is similar to 2010, but has included the planned development of the power system towards 2020. This is based on roadmaps and known plans, as well as assumed expansion of the system based on previous years. The next tables present the hydropower and CAES which are later simulated. Only the scenario for 2020 is simulated when looking at the impact of storages.

Table 3.2: Scenarios simulated with storages

Scenario	Hydro pumps and CAES
Reference case 2020	Table 3.3, 3.4 and 3.5
Additional pumps	Table 3.6, 3.7
Additional CAES	Table 3.8

The reference case 2020 is without any future storages, only the storages existing today, the amount can be found in the tables listed. This scenario is used for comparing the scenarios with planned storages. The next scenario has added the planned hydro pump storages, and the last has only the extra CAES plant. Due to the lack of use of CAES this is simulated alone. The impact on the rest of the grid is also assumed low due to the relative low cavern and turbine capacity.

3.2.1 Reference Case

For Germany, it was possible to achieve more accurate information about where the pump storage are for 2010, and they are listed in table 3.3. These are the pump storages used in the reference case for 2020.

Table 3.3: Hydro pumps for 2010 in Germany [27].

Bus name	Capacity, MW
D_OB 993	200
D-20 966	266.7
D-12 889	2768
D-11 878	294
D-21 979	317.5
D_KU 991	1308
D-11 886	944
E_TI 990	332
Sum	6430.2

The other countries have known aggregated information about hydro pump storages, and these are shown in table 3.4.

Table 3.4: Hydro pumps for the rest of the countries, 2010 [27]

Country	Capacity, GW	Country	Capacity, GW
AT	0.884	MK	0
BE	1.209	NL	0
BA	0.5	PL	1.3228
BG	0	PT	0.146
HR	0	RO	0
CZ	1.152	RS	0.6394
DK	0	SK	0.954
FI	0	SI	0.185
FR	1.705	ES	1.938
GB	2.488	CH	0
GR	0.735	LT	0.9
HU	0	EE	0
IE	0.292	LV	0
IT	1.28	NO	0
LU	1.15	SE	0
		Sum	17.4802

There exist one CAES already in Huntorf, Germany [9]. This is connected in PSST with bus *D-31 798*, and have the capacities as shown in table 3.5.

Table 3.5: The bus with CAES and its capacity, Huntorf

Bus name	Turbine, MW	Compressor, MW	Storage volume, MWh
D-31 798	290	60	720

3.2.2 Additional PHS 2020

Table 3.6: Hydro pumps for 2020 in Germany and Norway

Bus name	Capacity, MW
Nordel: 9287	1140
Nordel: 9288	260
Nordel: 9124	279
Nordel: 9124	421
Nordel: 9345	980
Nordel: 9344	420
Nordel: 9398	80
Nordel: 9204	59
Nordel: 9208	374
Nordel: 9218	430
Nordel: 9218	57
Nordel: 9353	400
D_OB 993	200
D-20 966	299.5
D-12 889	2692.8
D-11 878	293
D-21 979	685.2
D_KU 991	2565
D-11 886	970
E_TI 990	996
Sum	13601.5

Many PHSs are planned in Norway between 2010 and 2020, and there is also a little increase in Germany. The simulated hydro pumps for 2020 are seen in table 3.6. The rest of the countries have an increase in the number of PHS as well which is seen in table 3.7.

Table 3.7: Hydro pumps for the rest of the countries, 2020 [27]

Country	Capacity, GW	Country	Capacity, GW
AT	2.124	MK	0
BE	1.209	NL	0
BA	0.505	PL	1.3228
BG	0	PT	5.346
HR	0	RO	0
CZ	1.152	RS	0.6394
DK	0	SK	0.954
FI	0	SI	0.185
FR	1.705	ES	1.938
GB	2.488	CH	26.6
GR	0.735	LT	0.9
HU	0	EE	0
IE	0.292	LV	0
IT	1.28	SE	0
LU	1.15	Sum	50.5252

3.2.3 Additional CAES 2020

Table 3.8: Additional CAES at a node with variating prices.

Bus name	Turbine, MW	Compressor, MW	Storage volume, MWh
D-19 799	360	216	1000

During the modeling of CAES the node shown in table 3.8 was used to find the impacts from having CAES. This node was chosen due to its varying node prices. It has the most hours with prices under 22.18 €/MWh and above 48 €/MWh in Germany. The capacities are based on the planned CAES plant named ADELE [11].

4 Results

4.1 Impact from renewable energy

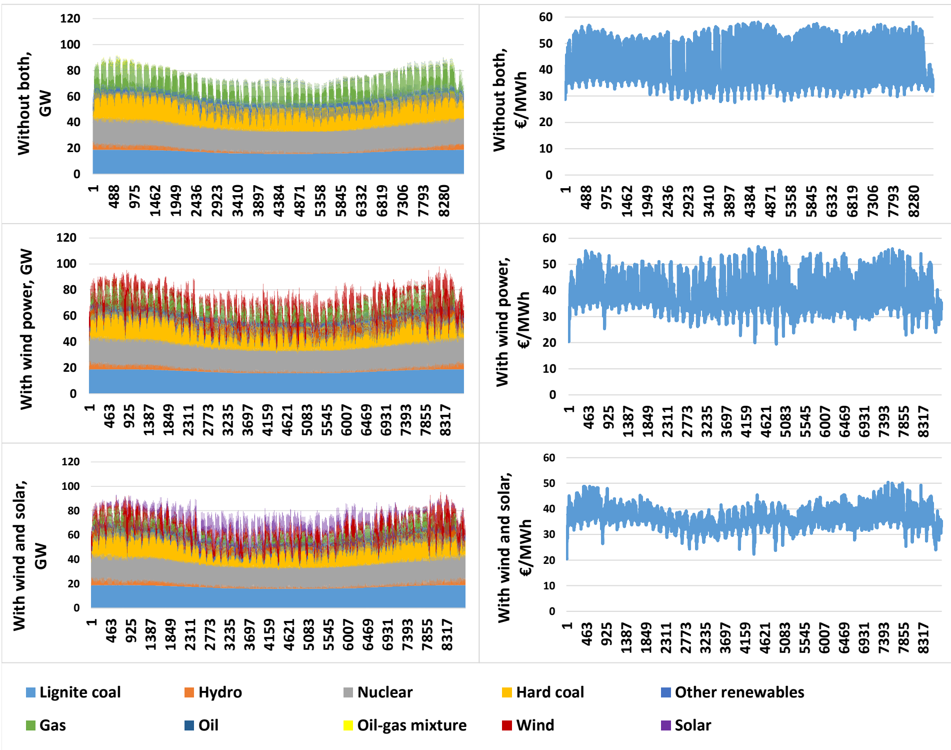

Figure 4.1: The generation to the left and prices to the right in Germany for 2010.

To get an impression of the impact the renewable sources wind and solar have had on the European power grid, three simulations in PSST for 2010 were made. One without any renewable energy, one with only wind, and the last one with wind and solar. None of the simulation had any electric storages included. The impacts on generation and prices for Germany is shown in figure 4.1. From this figure the effect of having wind and solar power in the German power system is seen. The effect is less use of hard coal and gas, gas is almost not used at all when there is both wind and solar in the system. There is also less use of wind, when having solar as well. The prices change due to the renewable energy; they are in general lowered. The mean value goes from 41.79 €$/MWh$ without wind and solar, to 38.8 €$/MWh$ with wind and 36.49 €$/MWh$ with both wind and solar. There is more variation in prices with wind, resembling the wind production. The price flow with solar has less variation and especially during the summer the prices are decreased, when there is more solar power production.

4.1.1 Development from 2010 to 2020

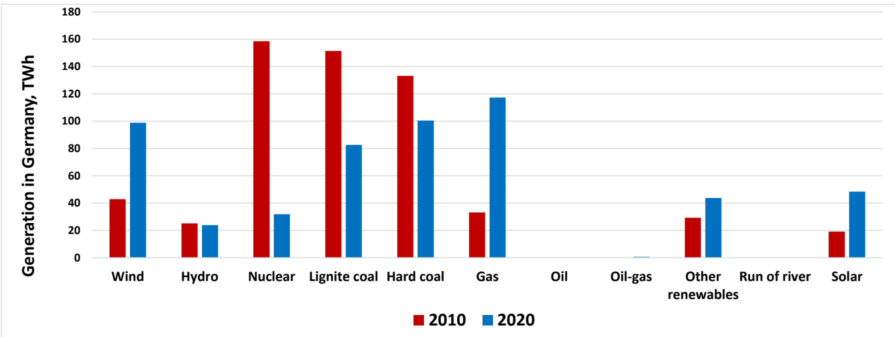

Figure 4.2: Germany's production in 2010 and 2020.

Figure 4.2 present the amount of energy produced from Germany in 2010 and 2020. This is before any storages is added. For 2020 there is less nuclear and coal production in Germany than in 2010, but there is an increase in wind, gas and solar energy production.

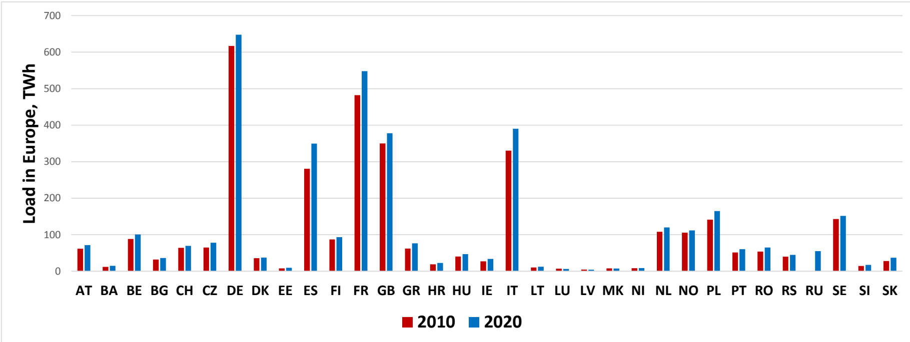

Figure 4.3: EU's change in load from 2010 to 2020.

In figure 4.3 the load in Europe for 2010 and 2020 is presented. There is an increase in load for every country in 2020.

Table 4.1: Number of hours with congestion in the power lines connected to Germany.

From	To	2010 export	2010 import	2020 export	2020 import
DE	NL	13	0	309	-6240
DE	LU	0	0	4	0
DE	FR	0	0	0	-708
DE	CH	824	-364	4259	-2378
DE	AT	4490	-1055	2274	-746
DE	SE	0	0	0	0
DE	CZ	0	0	3	-15
DE	PL	308	-899	1186	-173
DE	DK	63	-7635	61	-8489
	Sum	5698	-9953	8096	-18749

Table 4.1 lists the congestion in and out of Germany for 2010 and 2020. The numbers are representing the amount of hours with congestion. When the congestion is in the export from Germany the numbers are positive, and vice versa for import. In 2010 there is most congestion in the line DE-AT, and DE-DK. For 2020 line DE-CH has also a lot congestion. There is an increase in the amount of hours congested in 2020 in total, but the line DE-AT actually has a lower amount of congestion in 2020 than in 2010.

Table 4.2: Total amount of hours with congestion in all the power lines in Europe

Year	Export hours	Import hours	Total hours	Average lines
2010	42010	-39818	81828	9.34
2020	54488	-42655	97143	11.089

The table 4.2 has the total amount of congestion for the whole of Europe, where a big part of these comes from the lines connected to Germany. The average number shows how many lines which in general are congested at every hour. There is an increase from 2010 to 2020.

4.1.2 Surplus Energy

The next figures present the amount of energy from solar and wind that are not used in 2020 due to lack of load or congestion in the transmission line.

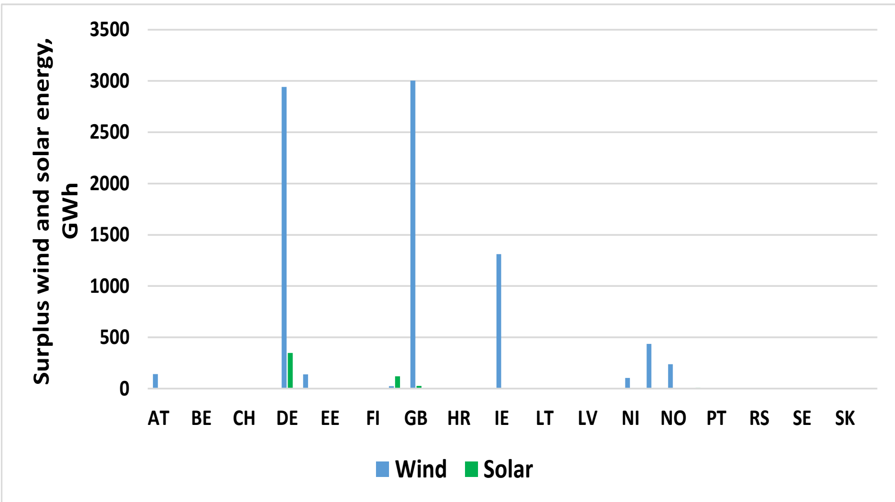

Figure 4.4: Surplus energy from wind and solar for all the countries in Europe in 2020.

From figure 4.4 it is evident that Germany and Great Britain will have the largest amount of surplus wind energy in 2020. Great Britain has and are planning a lot more offshore wind projects, and Germany has in general an increase in renewable energy sources.

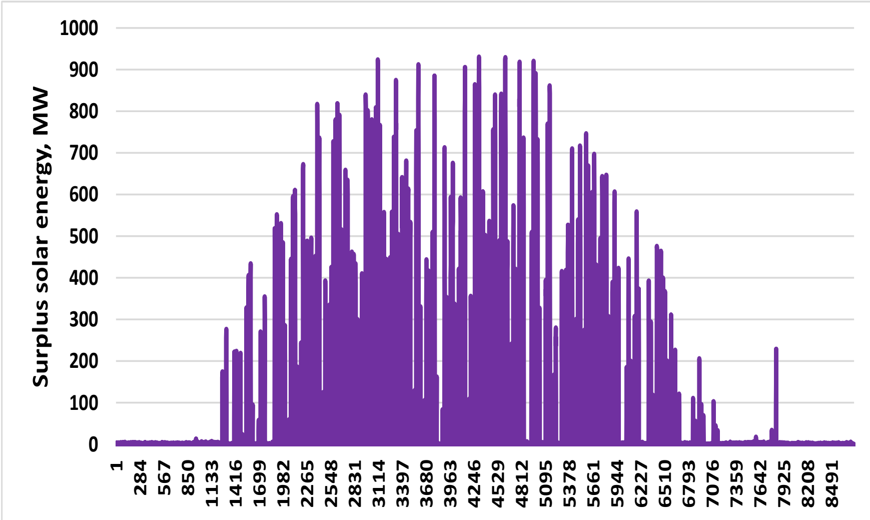

Figure 4.5: Surplus solar energy in Germany for 2020.

As expected there is more unused solar power in the summer, when the potential solar production is higher. The daily variation is also noticeable in figure 4.5. In average the surplus energy is about 1.1% of the produced solar energy, and at the most 3.64%, when solar is around 900 MW.

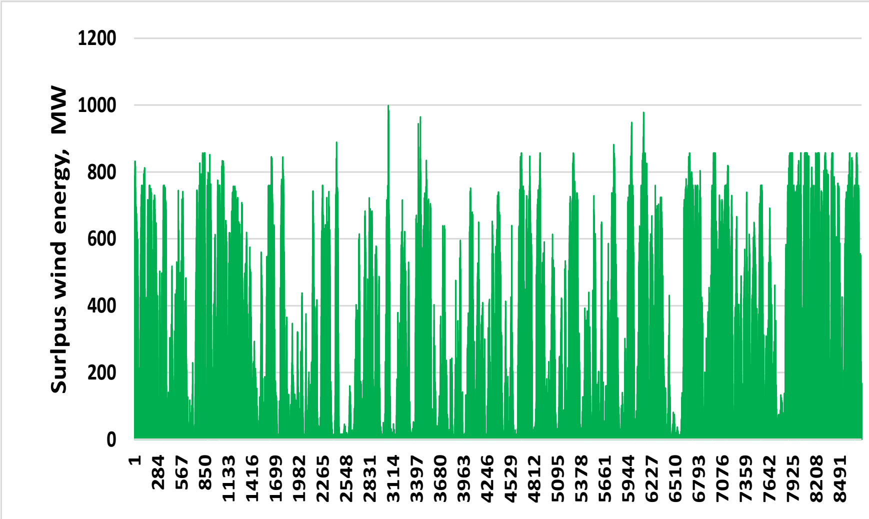

Figure 4.6: Surplus wind energy in Germany for 2020.

Surplus wind production is high throughout the year, as presented in figure 4.6. It has an average on 2.98% compared to produced wind energy, and at the most 4.1%, corresponding to 1000 MW.

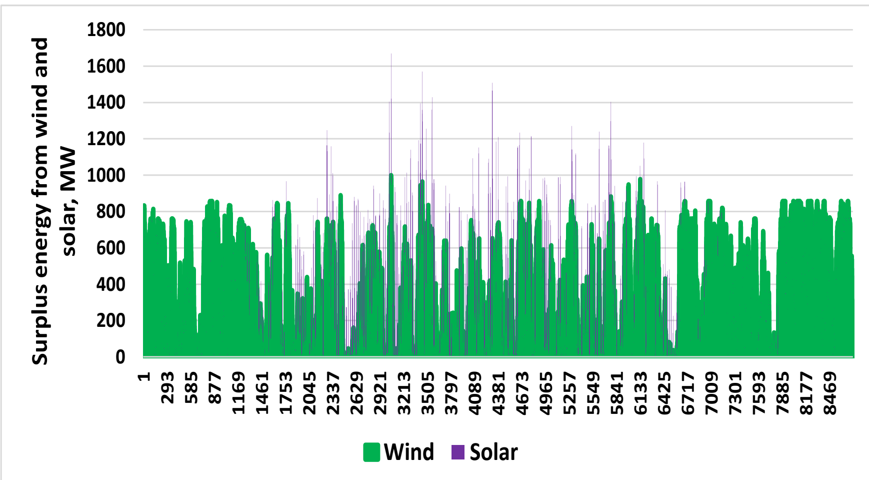

Figure 4.7: Total energy surplus from wind and solar in Germany for 2020.

The result of adding surplus wind and solar energy together is shown in figure 4.7.

The figure reveals that there is most surplus energy in the summer. Surplus wind and solar reaches its peak around 1600 MW, which is about 2.79% of the total production from solar and wind.

4.2 Electric Storages

4.2.1 Impact from PHS

After simulating year 2020 with additional hydro storages, the PHS at Tonstad was examined closer. A node in Norway was chosen, since there were no pumps in Norway in 2010, and the impact would be easier to see. Additionally the node at Tonstad is connected to Germany through a HVDC line, and would give results on how or if the PHS in Norway will impact Germany and rest of Europe.

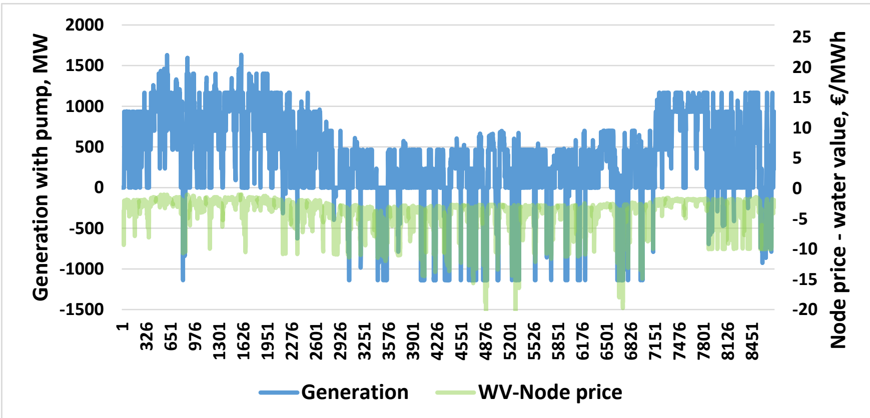

Figure 4.8: Correlation between prices and when the pump is used for 2020.

Figure 4.8 shows when the pump is used at Tonstad compared to the node price minus the water value. When the water value is higher than the node price, the green line is negative, and when the water value is lower than the node price it is positive. The blue line is the generation from Tonstad. Positive means production and negative means pumping. Pumping is done when the price difference is negative, and most during the summer.

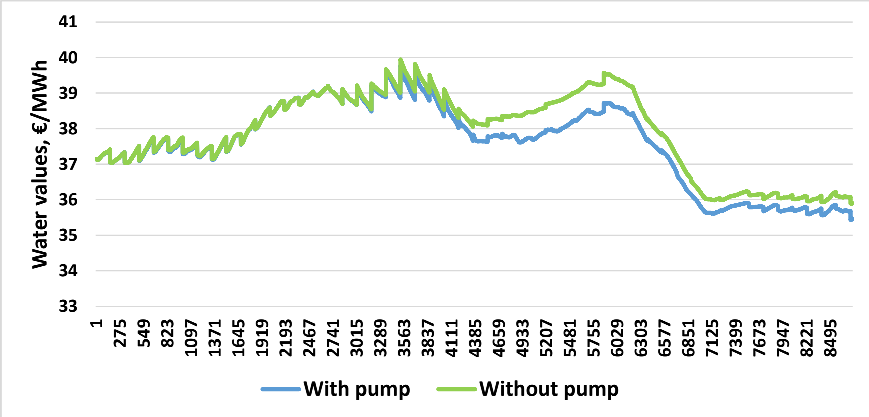

Figure 4.9: Water values for the Tonstad reservoir with and without pump for 2020.

The figure 4.9 present the water values without and with pump storage at Tonstad. They follow the same pattern, but with pump the water values decrease during the summer, and stay lower than the other water values throughout the year.

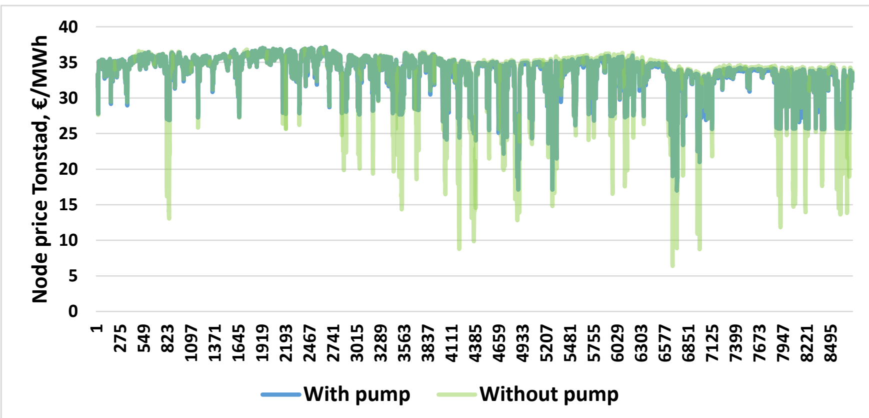

Figure 4.10: Prices at the node at Tonstad with and without pump for 2020.

Figure 4.10 shows the node prices at Tonstad with and without pumps. The prices are almost equal, but when the node price is really low, the node price without pump is much lower than with pump. During and after the summer the node price is a bit higher without pump for almost every hour. There is a little green shade on top of the price curve in this period, where the prices are higher without pump.

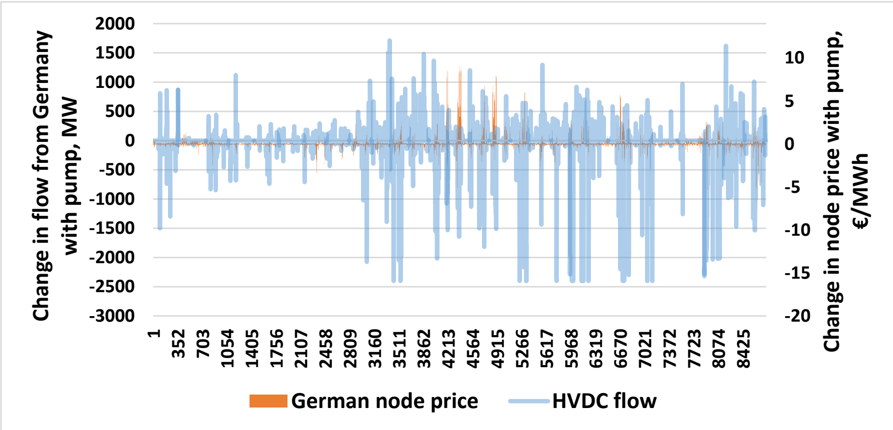

Figure 4.11: Additional flow from Germany and the change in the node price with pump.

Figure 4.11 shows the change in amount of energy going from Germany to Norway. When it is positive there is more flow from Germany with PHS at Tonstad than without. The flow is then compared with the change in node price at the German node. From the figure it can be seen that there is more flow from Germany with PHS at Tonstad, especially in summer, and that increases the node price in Germany.

Table 4.3: Impact from PHS on the node price in the last two weeks.

Scenario	Average price €/MWh	Maximum price €/MWh
Without pump Tonstad	33.31	37.16
With pump Tonstad	33.55	37.16
Without German node	35.15	53.13
With German node	35.22	53.14

Table 4.3 shows the average and maximum node price at Tonstad, and the node connected to Tonstad in Germany. There is a slightly increase of the prices when having PHS at Tonstad.

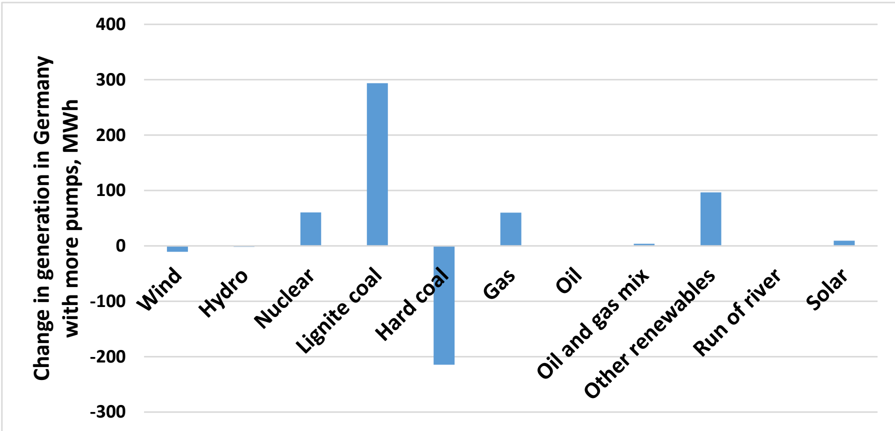

Figure 4.12: Impact of generation in Germany when having additional PHS for 2020.

The impact from PHS on the generation mix in Germany is seen in figure 4.12. When having hydro pump storage in Europe there is less need for hard coal. Additionally there is a little decrease of wind and hydro power when having additional PHS. Thus, it is an increase in the use of nuclear, lignite coal and gas.

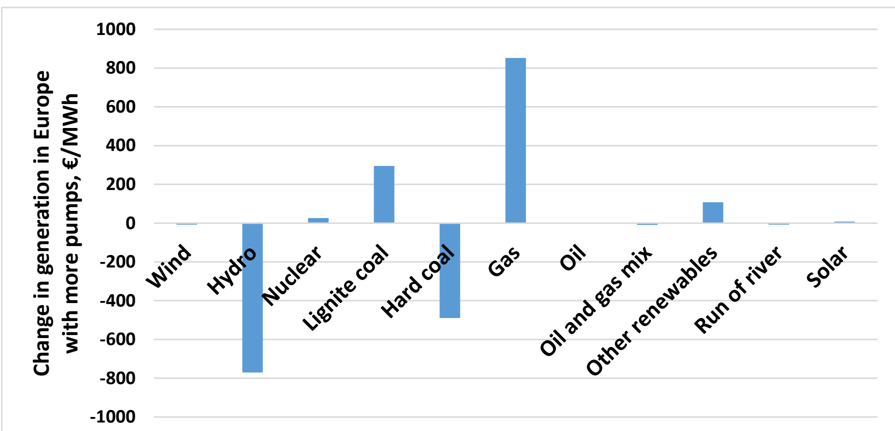

Figure 4.13: Impact of generation in Europe when having additional PHS in 2020.

In figure 4.13 one can see almost the same results as shown for Germany in figure 4.12, the amount is just scaled up. Though hydro power is for the whole Europe, used a lot less with PHS.

4.2.2 Impacts from CAES

After the CAES was implemented in PSST, the two last weeks are studied more closely, while remembering the marginal cost for compressing at 22.18 €/MWh and 48 €/MWh for producing.

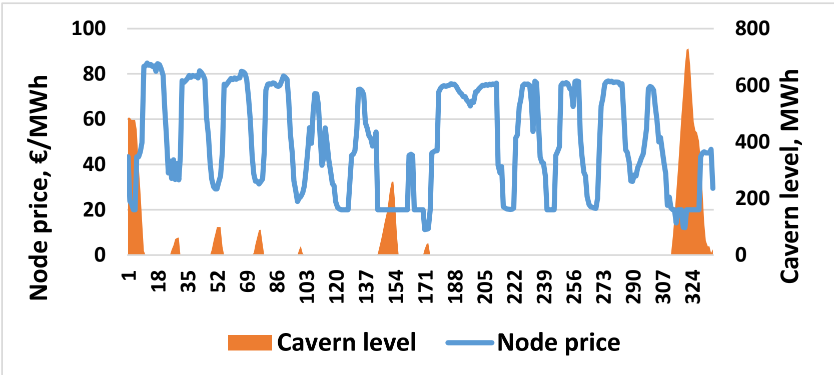

Figure 4.14: Node price and the energy level in the CAES cavern for the last two weeks.

In figure 4.14 the price at the node and the cavern level is presented for the two last weeks in the year. There is an increase of the cavern level when the node price has its troughs. In the weekend of the last week, around hour 324, the cavern is almost completely filled. The maximum capacity of the cavern is 1000 MWh.

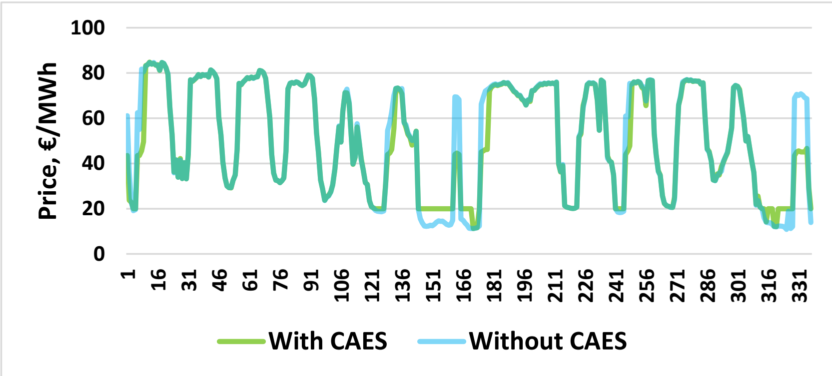

Figure 4.15: Node prices with and without CAES for the last two weeks.

In figure 4.15 the node D-19 956 with and without CAES is compared. The prices are almost the same, but some of the price peeks are lowered with CAES, and some of the troughs are raised. Resulting in a bit more even price curve when having CAES.

Table 4.4: Impact from CAES on the node price in the last two weeks.

Scenario	Average price €/MWh	Maximum price €/MWh
Without CAES	50.60	84.79
With CAES	51.64	84.65

The table 4.4 lists the average price and maximum price without and with CAES at the node. There is an increase of the average price with CAES, but the maximum is lowered.

5 Discussion

5.1 Impact from Wind and Solar Energy

The impact form the renewable energy sources wind and solar are demonstrated well in figure 4.1. These energy sources are decreasing the overall electrical prices in Germany, due to being modeled as having no marginal costs in PSST. The investment and maintenance cost are not included in this model. Wind is a highly variable energy source and the prices in Germany are varying according to this. As shown in the generation overview, the wind energy releases some of the need for gas in Germany. Gas is an expensive fuel, and lowering the use of gas will decrease the prices. The solar power has a similar impact on the generation mix, where even less gas is used. Gas is mostly used as a peak generator, and the load peaks are during the day. An increase of solar power will decrease the use of gas. Some of the solar power is used instead of wind, which is due to congestions in the system. In general, the solar power decreases the electricity price and stables it, mostly due to its production during high load periods. This would not have been the same for other countries with stronger seasonable variations where the high loads are in the wintertime when having little sun. However, this is good news for the German government, since this will encourage the power producers to invest in wind and solar power, and in turn decrease the CO_2 emissions. From this study the expansion of wind and solar power has proven to be beneficial. In Germany, there is money support and tax reduction for building wind and solar generators, which will reduce the investment cost for the private producers and add encouragement for renewable energy. In other words these projections will continue.

Due to the incentives in Germany and in the whole Europe, it is likely that there will be an increase of wind and solar power, and this is included in the 2020 scenario in PSST. This expected development up to 2020 is based on planned projects and road maps, and are assumed reliable and representative for 2020. The development in the generation mix in Germany includes a lot more wind energy, and out-phasing nuclear power. This is in accordance with the government's plans. In 2020, it is expected that wind energy will be a major component of the generation mix, with a doubling of wind production from 2010 to 2020. As seen in figure 4.1, wind is an intermittent power source, and the expansion of this source will lead to a bigger pressure on the other generators. The power system needs to be prepared to cover the wind production in case of little or no wind. Since the lack of wind can happen suddenly, this must be done by a generator with low ramp-up time, and this is the reason why electricity production from gas increases with wind production.

The load profile follows the population growth and people's extensive use of electricity in the last years. A consequence of the increased load is more generation, and in respect to this, the transmission lines needs to do be updated. From the planned development of the transmission lines in 2010 to 2020, there is not enough capacity in the transmission lines to cover the increased electricity flow. There is more congestion in general in Europe. Some of the congestion is due to the increase of wind energy. If there were no constraints in the transmission lines, the wind power does not need to be regulated down in low load periods. From looking at the surplus energy from wind and solar plants in Germany, the amount in percentage is not so large. At the hour with the most surplus energy, the amount reaches 2.79%, so most of the congestions in the export from Germany, does not come from surplus energy. The decrease of hours with congestion in one of the lines connected to Germany, is due to increased transmission capacity.

5.2 Storages

5.2.1 Modeling

The modeling of PHS and CAES is done with the same assumptions. The pumping and compressing capacity is set to be negative, and the production from these are added to their connected reservoirs and caverns. There is pumping and compression when their marginal cost is higher than the system price. This is shown in figure 4.8 for PHS, and figure 4.14 for CAES. The *physical* bit of the modeling works as desired. However, when finding the right marginal cost to set off the pumping/compressing the model has some significant drawbacks. For the pumps, the marginal cost is set to be 80% of the water values used for the hydro generator. The pumps marginal costs follow the reservoir level. For CAES the marginal cost for compressing is constant, 46 % lower than the marginal cost for electricity production from CAES. The idea was to use electricity to pump and compress when the price was low enough to cover the losses. Looking at the results and especially table 4.3 and 4.4, one can see that PHS and CAES is not profitable. There exists PHS and CAES in Europe in reality, which would not be the case if they were not beneficial. Therefore the conclusion is that the model of PHS and CAES is incorrect.

PHS

The marginal cost for pumping take into account the reservoir level, since it follows the same pattern as the water values. The main issue with this is that the pumping can happen at time periods when the electricity is relatively high, and this energy can later be sold for a lower price than desired, due to inflow and/or low hydro production. In this way, the efficiency of the pump is not included in the selling price. This would lead to an unprofitable use of the pump, and higher electricity prices. The main question during the modeling was when the PHS should pump.

To find the best way to use the pump, an optimization of the pumping for a whole year should have been included in the PSST. This should be done beforehand from the same program creating the water values, EMPS.

CAES

The compressor in CAES operates only when the electricity is low enough. However, since the electricity price can be even higher than the set marginal cost for production from CAES, it can be beneficial to compress at even higher electricity prices. In addition, from the result one can see that the energy in the cavern is not used during the most expensive hours, but are used right away when the electricity exceeds 48 €/MWh. One way to change this is to add a cavern level sensitivity to the marginal cost. The sensitivity should have the same pattern as the water values, creating higher cost when the cavern is almost empty and cheaper when it is almost full. Having level sensitivity, the last energy in the cavern could only be used in high load periods. In order to get the most optimal use of CAES, a whole week should be optimized, not just one hour like now. The weekly optimization would reveal the most profitable use of CAES. The profitable use of CAES would be to have a full caverns before a high load, together with cavern level sensitivity that will make the CAES use most of the energy when the system prices are highest. A week is long enough for the optimization model due to the limited cavern capacity.

5.2.2 Results from PHS and CAES

When looking at the water values at Tonstad after the summer, they are lower when pumps are included, due to more pumping during the summer. The fact that the water values does not decrease again means that there is not an increase of hydro production, and there is more water in the reservoir with pumps included. This is an undesired effect, since the cheap hydropower should be used. From figure 4.8 and 4.10 it can be seen that the pump is operating when there is low prices in the node, which increases the electricity price. There is also a little lowering in the node price from the summer to the end of the year. This means that the electricity price in these hours is a bit lower when having pumps, which reflects the lowered water values for the same hours.

Due to the increase of load when having pumps, there is more electricity transmitted from Germany to Tonstad. This increases the node price at the node in Germany. However, the impact from the flow is not substantially. As seen in the figure of the water values the hydropower production has not increased when having pumps, and this is seen in figure 4.13 as well.

From the results, it can be concluded that CAES is quite expensive to use. The main reasons are high fuel price, low efficiency, and low compressor capacity. The gas price in PSST is constant and includes the CO_2 cost. If another gas price was to be used in the model, CAES would be more beneficial. In this model the efficiency of the plant in Huntorf is used. This plant is relatively old, and it is expected that the efficiency is increased in future plants. Improving the CAES with these changes would might prove CAES to be beneficial many other places, and not only in the most varying node in Germany.

6 Conclusion

The inclusion of wind and solar energy in the European power system will decrease the use of lignite and hard coal, and then CO_2 emissions. Electricity prices for the whole Europe are lowered as well. This is even more evident for the future scenario 2020, where there is more wind and solar power. In Germany there is almost a doubling of the wind power production between 2010 and 2020, and has in 2020 a substantially share of the electricity production. When having more wind and solar energy the power market in 2020 there is a larger amount of hours with congestions than for 2010.

Modeling PHS and CAES must be done with respectively yearly or weekly optimization in mind. This is the best way of getting good simulation results from PSST. PHS are nevertheless more efficient and beneficial to use than CAES. Even if CAES was to be modeled better, the fact that it uses gas as a fuel, which is quite expensive energy source, decreases the benefits from having CAES. There must be lower gas prices, better efficiency and a compressor with higher capacity before CAES is profitable.

6.1 Future Work

- Modeling PHS with different marginal cost based on optimization of the whole year.
- Finding better marginal cost for CAES based on a weekly optimization.
- Modeling CAES with cavern level sensitivity.
- Modeling CAES based on a newer CAES plant, with better efficiency and capacities.

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