# Future Perspectives for Hybrid Storage Systems

*- A model-based assessment*


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Synopsis:

As the growth and implementation of European fluctuating RES are increasing, so is the need for storing electricity. Such storage technologies can be operated as either standalone or in joint systems with generators. This thesis therefore tend to determine if utility scaled storage solutions should be implemented and whether these should be operated as standalone or as a part of the hybrid storage system. This will be with focus on operating behind the meter and reducing imbalances generated by the wind farm.
The thesis will compose a feasibility study, comparing Hybrid Storage Systems with stand alone technology, through the use of energyPRO, VBA coding and Excel spreadsheet, designing a Technical Energy Model operating on a hourly basis.
In the light of this approach the thesis concludes, that investments in batteries, whatever they are operated standalone or within a hybrid system, seem to be unprofitable investments in a European context. However, batteries operated as a HSS, seems to have better conditions than batteries operated as standalone.

# Preface

This report is composed by Nikolaj Bjerg Jensen and Thomas Ahrens Nielsen, students at Aalborg University and part of the master thesis programme on 10th semester, Sustainable Energy Planning & Management.
Both Nikolaj and Thomas would like to address a big thanks to Anders Andersen for good supervision throughout the project period, providing with inspiring supervision and constructive criticism.

### Reading guide

Throughout the report, source references are used in the form of the Harvard method, and these are all listed, at the end of the report in the Bibliography. References from books, articles, homepages or the like will appear with the last name of the author and the year of publication in the form of [Author, Year]. If there is no stated year on a source it will be referred to as: [Author, n.d.]. If the author is a company, a homepage or for other reasons not stated, the reference is referred to as: [Name, Year], e.g [Aalborg University, 2015].

Figures and tables in the report are numbered according to the respective chapter. In this way the first figure in chapter 3 has number 3.1, the second number 3.2 and so on. Explanatory text is found under the given figures and tables. Figures without references are composed by the project group. Further a list of figures is to be found straight after the Table of contents.

Nikolaj Bjerg Jensen    Thomas Ahrens Nielsen

# Summary

Energisystemerne i Europa gennemgår i disse år og frem mod 2050 radikale teknologiske ændringer, hvor fossile brændsler såsom kul, olie og gas udfases og erstattes med vedvarende energikilder såsom sol- og vindenergi. Disse energikilder er ofte mere fluktuerende, hvorfor flere aktører påpeger, at lagring af elektricitet i fremtiden vil spille en mere fremtrædende rolle end den gør i dag. Behovet for lagring vil derfor stige i takt med indfasningen af fluktuerende energikilder. Netop kombinationen af de fluktuerende energikilder samt lagringen af el, i såkaldte hybridsystemer, kan være med til at øge implementeringen af begge dele, da samspillet mellem disse teknologier kan bidrage med synergieffekter og dermed optimere driften.

Med baggrund i hybridsystemerne og de mulige synergieffekter tager dette speciale udgangspunkt i følgende problemstilling:

*"Hvordan kan tilføjelsen af et batteri, og dermed dannelsen af hybridt lagringssystem, forbedre driften af en vindmøllepark, og i hvilket omfang bør disse hybride lagringssystemer være en del af fremtidens vedvarende energisystemer?"*

Velvidende, at det kun er muligt at undersøge dele af problemet, retter specialet sit fokus på at undersøge de økonomiske gevinster ved at drifte batteriet bag måleren i kombination med vindmølleparken, og derved undgå tariffer. Ligeledes vil batteriets mulighed for at reducere ubalancer i vindmølleproduktionen blive undersøgt, for derved at se om det er muligt at mindske de potentielle bøder for manglende leveret strøm. Yderligere kombineres dette med en deltagelse på regulerkraftmarkedet, for derved at se om det er muligt at optimere den generelle økonomi.
Specialet tager med inspiration fra Henrik Lunds, ”Choice Awareness Theory” udgangspunkt i en samfundsøkonomisk tilgang til at besvare problemet, hvorfor formålet med specialet er at skabe fokus på brugen af hybride lagringssystemer i en samfundsmæssig kontekst, der kan bruges som informationsgrundlag for fremtidige valg om drift, implementering samt dannelsen af politikker.

Gennem disse rammer, undersøges problemet deduktivt med fokus på gennemførligheden af et hybridt lagringssystem opholdt imod lagring som ”standalone” teknologi. Dette opstilles i en scenariebaseret teknisk energi model, konstrueret gennem samspillet mellem Visual Basic for Applications (VBA) kodning, energyPRO og Excel regneark. Her opstilles Reference scenariet som ”standalone” batteriteknologi, hvor profit generes gennem handel på Day-ahead markedet. Dette holdes op imod 3 uafhængige scenarier, hvoraf Scenarie 1 også handler på Day-ahead markedet, men bag måleren, idet bat-

teriet også har mulighed for opladning direkte fra vindmølleparken, Scenarie 2 reducerer ubalancer i vindmølleproduktionen og Scenarie 3 reducerer ligeledes ubalancer samtidig med en prioriteret deltagelse på regulerkraftmarkedet, som har til formål at generere øget profit samt optimere driften.

For at kunne opstille og forstå afregnings metoder ved handel på de europæiske elmarkeder, gennem den teknisk energi model, udføres en dybdegående og detaljeret beskrivelse og analyse af deltagelse på engros elmarkederne. Denne analyse er baseret på forståelse af såvel primær som sekundær litteratur. Viden omkring elmarkederne og regler på området inkluderes i energimodellen for at kunne inkludere handel og afregning for de forskellige scenarier.
Selve modellen analyseres gennem investeringsteori i form af nutidsværdiberegninger, hvor det forholdsvist hurtigt står klart, at hverken brugen af "standalone" eller hybride systemer er en god investering, forudsat de rammer og præmisser, som er inkluderet i operationsstrategierne for scenarierne. Disse operationsstrategier er dog til dels baseret på baggrund af sparsom forskning på området, hvorfor disse kan detaljeres yderligere.
Endvidere gennemføres en følsomhedsanalyse, hvor det står klart at specielt variablen volatilitet i elpriser samt investeringsomkostningerne er faktorer, som er afgørende for udfaldet af rentabiliteten ved undersøgelse af batteriets deltagelse på engros markederne.

Ligeledes konkluderes det, at der med de inkluderede præmisser og forudsætninger stadig er behov for en del udvikling på området, før hybride lagringsløsninger med ovenstående operationsstrategier bliver rentable. Derfor kan der også være lange udsigter til at disse systemer bliver en integreret del af de fremtidige vedvarende energisystemer i Europa, på højde med andre og lignende teknologier. Variationen indenfor hybride sammensætninger er dog mange, hvor dette speciale blot har undersøgt kombinationen af vindmøller og batterier.

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CHAPTER

# 1 Increasing focus on electricity storage

## 1.1 Electricity storage

> *"Electricity storage will play a crucial role in enabling the next phase of the energy transition. Along with boosting solar and wind power generation, it will allow sharp decarbonisation in key segments of the energy market."*
>
> [IRENA, 2017]

According to this statement from International Renewable Energy Agency and their report called *Electricity Storage and Renewables: Costs and Markets to 2030* [IRENA, 2017] the need for electricity storage is increasing along with the growth and implementation of fluctuating renewable energy sources (RES). Electricity storage is not as widespread as other storage solutions, but the storage of electricity counts several opportunities with different pros and cons. Today, around 4.67 TWh of storage is estimated to exist world wide, where pumped hydro storage dominates the market and counts around 96% of the total storage capacity.[IRENA, 2017] In spite of the high market share for pumped hydro storage, other opportunities for storing electricity exist. These are e.g. compressed air energy storage (CAES), flywheels and several different types of batteries.

Despite the opportunities for integrating energy from fluctuating RES via electricity storage, Lund et al. [2016] states that the best and socioeconomic cheapest way to integrate large amounts of renewable energy (RE) is via the Smart Energy System, which focus on a cross-sectoral approach, where excess electricity is converted into other forms of energy e.g. heat, gas or liquid fuels, which are much cheaper to store compared to electricity. In spite of the fact that electricity storage seems to be more socioeconomic expensive than other storage solutions, the use of electricity storage can potentially provide some services, that cannot be delivered by any of the other storage solutions. The need for electricity storage is emphasised by the growing interest for especially battery solutions and development of different projects around the world.
Such projects, that only a few years ago would have been uneconomic are now in some cases providing enticing returns. These increasing interests for batteries also mean, that the US battery capacity is forecasted to grow 22-fold in the next six years. [Ericson et al., 2018]

The focus on batteries has lead to companies like Vestas Wind Systems and Ørsted engaging them self in several projects about the inclusion of batteries in 2017 and 2018. One of the projects, where Vestas Wind Systems is participating, is the project called Kennedy Energy Park located in Australia. Here, battery storage is combined with wind turbines and photovoltaics (PVs) and is considered *"the world's first utility-scale, on-grid wind, solar and battery energy storage project"* [Vestas Wind Systems, 2017].
Ørsted is participating in several other projects where both stabilization of the grid frequency, as well as balancing the peak demands in the power distribution grid are in focus. [Ørsted, 2017]
The increasing focus on batteries along with the fact that the average price for batteries has declined more than 65% in the period from 2010-2015[1] from 1,000 $/kWh to 350 $/kWh and are expected to decline to prices as low as 50/kWh-60 $/kWh [McKinsey & Company, 2017]. Falling prices on batteries and increased interest for big energy companies has lead to the future focus of this report, which is the batteries and how these can be utilised.

## 1.2 Hybrid storage systems

The wide range of applications for battery storage implies a large market potential for storage projects. Batteries can for example be paired with one or more generators to create a storage system. Such system is also known as a hybrid storage system (HSS). In general a hybrid energy system is the combination of two or more energy sources, that supplies a load of energy [Fulzele and Daigavane, 2018], which is why a HSS is the combination of a generator(s) and an energy storage.
A HSS has several benefits, and according to Ericson et al. [2018] the primary benefits are, that hybrid systems have lower costs and can increase revenue compared to separately built battery- and generator projects.
Lower costs of building a hybrid system is especially linked to the construction costs for instance soft costs as labour and planning as well as hardware e.g. transmission lines, controllers and inverters. Compared to the costs of building the generator and storage separately, these costs are lower when building them as one joint project. This is exemplified by Ardani et al. [2017] as the article concludes that installing a residential PV and battery storage separately, is 18% more costly than simultaneously installation. Secondly an increase in revenue can appear as operational synergies between batteries and generators, which is not possible with standalone technologies.

Also, the Danish Transmission System Operator (TSO), Energinet sees future perspectives in HSS including a lot of different energy storing possibilities, which is very similar to the Smart Energy System approach previously presented by Lund et al. [2016]. The focus in the report from Energinet called *"System Perspectives 2035"* is among other things on hybrid plants, that is able to produce, consume and store energy.

[1] lithium-ion battery packs used in EVs

Batteries are however not in focus in combination with bigger plants, instead Power to Gas and Power to Heat is a consistent part of Energinet's view on the future hybrid plants and ways of storing energy, while batteries are included as a part of the smaller prosumers, which is exemplified by households with PVs. Energinet presumes, that both HSS and batteries will play an important role in the future Danish and European energy systems, but expects the batteries to be installed in the distribution part of the grid and to be used in the combination with smart grids in the households. By installing the batteries at the decentral prosumers, these can deliver services when e.g. electric vehicles are charged and the demand is peaking. [Energinet, 2018]
Energinet does not give up batteries in the central part of the energy system, but they propose the bigger plants in the sector to use the cheaper solutions for storing energy. According to Energinet the combination of central and decentral storage solutions provides a good combination and flexibility in the system. [Energinet, 2018]
Despite Energinet's focus on future batteries located in househoulds and at prosumers, batteries and HSS can also play a role in big scale projects, like Ørsted and Vestas Wind Systems are investigating at the moment, where these can add different value streams to the big scale projects.

Both Joint Institute for Strategic Energy Analysis [2017] and Ericson et al. [2018] focus on the following eight points, concerning the value streams, which are considered important when focusing on the synergy effects of HSS. It is considered that these can be related to both big and small scaled projects, which indicates that HSS can play a potential future role in different parts of the energy system.
The 8 value streams are:

1. Energy arbitrage
2. Frequency regulation
3. Spinning reserves
4. Generation capacity
5. Transmission deferral
6. Demand charge reductions
7. Resilience and reliability
8. Decreased diesel generation

**Energy arbitrage**

The inclusion of a storage provides the flexibility to participate in electricity markets and therefore buy electricity in low price periods and sell it again in periods with higher prices. In such low price periods an opportunity with a HSS is to store the electricity e.g. produced by a combined heat and power (CHP) plant, due to a demand for heat, and save it for periods with higher prices. This opportunity makes it possible to improve the general economy in the hybrid system. For energy arbitrage to be profitable price fluctuations are a necessity to generate sufficient revenue to pay back the investment, this is also due to the loss included in the battery. [Ericson et al., 2018]

**Frequency regulation**

Imbalances between production and demand in the grid can cause problems and in worst case a blackout. The fast response related to batteries makes them well suited for the regulation service in the system. On the other hand these markets are quite small and does not allow numerous participants, but can be profitable for some. [Joint Institute for Strategic Energy Analysis, 2017]

**Spinning reserves**

To maintain the grid stability in cases of unexpected outage from electricity plants or other interruptions in the grid, reserves have to be synchronised to the grid and be able to ramp to full capacity relatively quickly often within 10 minutes. These requirements can result in reserves that must run at part load, which causes a lower efficiency compared to when these units are running at full load. These spinning reserves can be replaced by batteries included in hybrid systems. The fast response and the permanent synchronisation with the grid makes them well suited for this task too, just as the frequency regulation. A problem can be the duration of the deliverance of electricity. Depending on country and region, the requirements to delivering electricity can vary, in the US it can be from minimum 30 minutes to above 2 hours. This is not always suitable for batteries due to the limited amount of energy, but this can be solved by pairing the battery with a gas generator, that during the discharging of the battery starts up and produces for the rest of the required period. Only investing in storage solutions to provide this kind of service, can according to Joint Institute for Strategic Energy Analysis [2017], be unprofitable, because of the relatively high costs for storage solution. Therefore it must me combined with some of the other value streams. [Joint Institute for Strategic Energy Analysis, 2017]

**Generation capacity**

To ensure the grid reliability in the long term, production units are getting payed for generation capacity. This is also a potential revenue for battery storage and battery hybrids. Such capacity is often just required in a few hours a day, mainly when the demand is peaking. This also means, that it can be combined with some of the other value streams and therefore improve the revenue even more. This generation capacity requires relatively large batteries, that are able to deliver electricity for a longer period and with a certain output to reduce the risk of insufficient energy deliverance and thereby penalties. An example from the US market called NYISO contain requirements as *"Energy-limited resources must be able to provide at least 1 MW of grid injection for at least 4 consecutive hours"*. Such requirements sets a natural limit for the size of batteries participating in such markets. [Joint Institute for Strategic Energy Analysis, 2017]

**Transmission deferral**

As the usage of electricity is expected to rise along with the transition from fossil

to renewable energy, the electricity grid is in need of expansion. Along with a changing demand the transmission lines can be overloaded and must therefore be upgraded. Storage sited downstream overloaded nodes can defer or eliminate the need of transmission upgrades. However, maximum loads occur for only a few hours or days per year making storage ideal for such peaks, instead of upgrading the grid. [Ericson et al., 2018]
Along with a deferral of the transmission lines, a battery also makes it possible to dimension the grid a little less than the actual capacity from the production unit e.g. a wind farm. This makes sense because the investment costs for the project will decrease. Curtailment of the wind turbines is a way of solving the problem in periods with restricted grid capacity [Schröder, 2013]. However, batteries can replace this, thus the wind farm can produce full load and export some of the electricity, while the remaining produced electricity is used to charge the battery and eventually dependent on electricity prices can lead to a higher revenue and efficiency for the wind farm.

**Demand charge reductions**

Around the world nearly every commercial and industrial facility faces demand charges, which can account for more than 50% of a commercial customers bill. A demand charge is, unlike energy charge, which is based on the total amount of energy used during a billing period, a charge based on peak electricity usage in a given billing period. Demand charge reduction is one of the most valuable ways of using storage for many behind-the-meter customers, as batteries effectively can reduce the demand charge, by discharging in peak periods, which causes a lower consumption from the grid. HSS offer the same opportunities, and e.g. pairing a PV with a battery system can result in the need for a smaller PV system, as the battery reduces most of the demand peak, exemplified through the PV hybrid where the battery is able to charge when the sun is shining and contrary discharge during periods of cloud cover, where the solar resource is not available. [Ericson et al., 2018]
In relation to this, utility scaled batteries can have the ability, of saving power from one point in time to another and thereby reduce imbalances that a generator might cause when trading on the wholesale electricity markets, due to unforeseen events.

**Resilience and reliability**

Some facilities require that their demand of electricity is met at all times, as a power outage can have critical consequences, whatever the business is private or governmental. Therefore, backup generators are the primary providers of resilience and reliability. Resilience and reliability is the ability to deliver power during a power outage and the delivery of consistent power in an unreliable grid. [Joint Institute for Strategic Energy Analysis, 2017]
*"While diesel generators are traditionally used for backup power, hybridized storage solutions may be a more effective way to provide resilience and reliability."*[Ericson et al., 2018]
In some countries legalisation prohibits backup generators from storing larger shares

of diesel, meaning that they are limited in extended power outages. Also, areas with unreliable grids, can experience higher costs, from maintenance and fuel due to a more frequent use of diesel generators. Lastly, a low reliability of utility power generates stronger drivers for the use of HSS instead of traditional fossil fueled backup generators. [Joint Institute for Strategic Energy Analysis, 2017]

**Decreased diesel generation**

Islands and remote communities also require energy, but usually have no connection to a larger grid. The majority of these areas has diesel generators producing the power, meaning the electricity is more expensive than grid connected sites, as general remote island prices are 3-5 times higher than in larger grids.
HSS is already an alternative to diesel generators in these remote areas, where wind- and solar power removes the need for importing fuel while the battery offers more reliable and resilient power.[Joint Institute for Strategic Energy Analysis, 2017]

Based on the value stream of a HSS, it is clear that hybrids can reduce costs, increase revenue and provide services that a battery and generators cannot provide alone. Such synergy effects also implies that the market potential for battery hybrids may be even bigger than for a stand alone battery storage. Some of the these above mentioned value streams, though, seems to be a little over-thought and optimistic, why these are viewed upon with skeptical eyes. However, some of the value streams, have inspired for further investigation, for which reason the following section will focus on composing a Research question founded on the opportunities of HSS.

## 1.3 Research Question

This wide range of opportunities related to HSS could be the argument for the increasing interest and the recent projects including batteries and different supply units. However, these systems and especially batteries are still in the stage of development, and the question is, if these systems are ready to be integrated in utility scale and ready to create an acceptable revenue, that makes them a good investment. Concurrent with the development of HSS, it is of common interest to assess the different above-mentioned value streams and determine where to put the main focus in this sector, and assess the opportunities for this concept.
HSS can potentially both be RES and fossil based systems, but the focus of this report will be on the renewable energy systems and fluctuating RES, because of global trends and political goals of being less and less dependent on fossil fuels. With that in mind and the possible benefits of including HSS in renewable energy systems, this report will focus on the following research question:

***How can the addition of a battery, and thus the formation of a hybrid storage system, improve the operation of a wind farm, and to what extent should these hybrid storage systems be a part of future renewable energy systems?***

According to the 8 value streams listed above, HSS containing batteries seem to have different opportunities to expand revenues, improve the profit and increase the flexibility of the system, this assessment will however only investigate energy arbitrage and reduction of potential imbalances related to wind farm production. With this in mind the two approaches below will be the focus in the rest of the thesis.

- Compared to standalone technologies, is it then possible for a HSS consisting of a battery and a wind farm to benefit from energy arbitrage by operating behind the meter?
- Compared to standalone technologies, is it then possible for a HSS consisting of a battery and a wind farm to improve the economy by reducing imbalances? And can additional income be generated by simultaneously trading on the regulating power market?

Investigating and analysing these two operational approaches for HSS, will help this thesis to clarify how and if the use of HSS can contribute to the overall renewable energy system. The different approaches will be compared on the basis of their socio-economic costs, to clarify if and how these HSS should be operated, to benefit the society and not just the investors. Therefore, the thesis will construct a feasibility study, by comparing HSS to standalone solutions, with the focus of socio-economy. The approaches will be analysed and compared in the context of the European markets, as these markets is experiencing a radical technological change from fossil fuels to RES of which several are committed to the Paris agreement.[United Nations, 2018]

Also, the thesis can be considered as an initial report for operation of HSS, for which reason the thesis will create a basic focus on the operation of HSS in relation to energy arbitrage and reduction of imbalances and hopefully be an inspiration, ideal for further research in the specific topic as well as a general contribution to the existing knowledge in the field.

CHAPTER

# 2 The operation of HSS

This chapter will elaborate on existing literature within the topic of optimizing the operation of HSS, with the purpose of establishing the most optimal operation strategy for the assessed HSS in this research and to gain insight in existing research done in the field. However, as studies about operation strategies for hybrid solutions is very limited, this literature study will investigate the operation field and the operation strategy for electricity storage in general.

In this master thesis batteries are combined with wind turbines to achieve benefits and maximise the profit. What makes such a system different from standalone generators as a wind farm is the storage part, in this case the batteries. Klausen [2017] has investigated the opportunities for the operation of a standalone battery in Germany and the size of the different markets. When looking at participation in the wholesale markets and the Regulating Power market, Klausen [2017] concludes that participation in the wholesale markets seems to be more profitable than delivering regulation services, when comparing the price per MWh of sold/bought electricity. It has to be said that the numbers in the article are estimations, but the average payment for participating in the wholesale markets is around 31,6 €/MWh, while the price for Primary Control Reserve (FCR) is around 21,7 €/MWh which is the highest price of both primary, secondary and tertiary reserves. There is no focus on the profitability of investing in a battery e.g. in form of Net Present Value (NPV) calculations in the article.

The NPV calculations for lithium-ion battery systems are however been investigated by Fleer et al. [2017] with focus on battery systems participating on the FCR market. The conclusion is, that the investment of a battery system is very sensitive to price changes and two out of four scenarios in the article lead to a negative NPV. Investing in battery systems is therefore associated with a generally high risk. This is supported by another article from Fleer et al. [2018], that emphasises the fragility related to price changes. When it comes to actual hybrid solutions the main part of the research treats a combination of either electricity generators as e.g. wind and PV, or a combination of different storage solution that complement each other, which is investigated by Bocklish [2015].
The research on the topic is mainly about standalone batteries, while research of HSS systems is conducted in a limited extent.

Yet, different studies have investigated the use of optimal operating and bidding strategies for storage units, all of them with slightly different approaches. However, most of them are focusing on arbitrage, which is the utilisation of the price variations on the whole sale markets. Thatte et al. [2013] is for example dealing with the uncertainties in forecasting the electricity production from a wind farm utilising energy storage, concluding that the combination of wind power and energy storage leads to better utilisation of the uncertain wind resource and increased economic performance through the use of energy arbitrage. Thatte et al. [2013] addresses a more general level, while other studies such as Kanakasabapathy and Swarup [2009] are focusing on the bidding strategy, by developing a tool to optimally determine a short-term self scheduling of a pumped hydro storage in the day ahead market and therefore operating at a more specific level.

One article however deviates from the others, as Hu et al. [2010] compare two different types of standalone batteries with the same optimal operating strategy on the Nordic spot market. The main limitations and assumptions in the article are that all the energy in the batteries is discharged in the same day, allowing for purchase of electricity when the spot price is low and selling when the spot price is high in a perfect market. Using this strategy, the article calculates the revenue of respectively polysulfide bromine battery and vanadium redox battery concluding that the batteries will have a payback time of 18 and 45 years, which can be considered inefficient as their lifespan is equal to 15 years.

In general, the articles about optimal operation and bidding strategies for an electricity storage and HSS are very limited, and the few articles which are available are very complex. It also has to be said that, not many of the operated batteries seems to be profitable, for what reason, batteries do not seem to be the best cost effective alternative. However, Thatte et al. [2013], Kanakasabapathy and Swarup [2009] and Hu et al. [2010] all addresses the operating strategy of an electricity storage, allowing this thesis to seek inspiration and knowledge to develop its own strategies in order to optimise the profit from a HSS solution.

CHAPTER

# 3 Research design & theoretical approach

The research design is a general description of how this thesis tend to answer its research question, and thereby, it provides an overview of how the research is structured. Therefore, an elaboration of the strategy chosen will be described and visualised in this chapter. Whereas the interplay between the text and the figure 3.1 is essential in understanding the full design.

As it has been chosen to address HSS with a socio-economic approach, the underlying framework for the thesis is elaborated in chapter 3.1. Henrik Lund's "Choice Awareness Theory" is the basis for this framework, for what reason this chapter guides the reader through an understanding of the field the thesis is operating in, with the purpose of understanding the different choices made throughout the thesis, as it is exemplified in figure 3.1.

To operate in this field, it is chosen to approach the problem deductively, which means that the thesis has its underlying basis in the general understanding of reality, in this case the general perception, that the formation of HSS can improve the economy. This is investigated throughout specific sub-questions dealing with the operation behind the meter and mitigating imbalances explained in the Research Question 1.3. These aspects will contribute to answer the Research Question, by analysing these with the use of feasibility study.

To perform a feasibility study, the section "Methodology" will clarify and substantiate the use of different modeling tools and the data collected, in order to construct a technical energy model, of which will include operation strategies, inspired by earlier studies, to answer the sub-questions and by that the Research Question. The Technical Energy Model will be constructed in a joint Excel spreadsheet, by using the tools of Visual Basic for Applications (VBA) and energyPRO. The model consists of three alternative scenarios and one reference scenario, for what reason the scenarios clarify the approach of the sub-questions elaborated more detailed in section 4.1.

The general analysis can be considered as divided into three parts: an explanatory analysis, a scenario based analysis of the Technical Energy Model and an assessment of the role for HSS in future renewable energy systems.
The explanatory analysis will have its focus on, how the electricity markets are controlled in practice, of which should be considered simultaneous with the understanding of the Technical Energy Model, as especially the flow of cash in the Technical Energy Model

will be elaborated in the chapter. The other part of the analysis, is a careful investigation of how a HSS operates compared to a standalone wind farm and a standalone battery based on a HSS' ability to operate behind the meter, reduce punishment for imbalances and reduce punishment together with participation on the Regulating Power market.

The four different scenarios are all included and analysed in the Technical Energy Model, where the results are compared and assessed. These results are based on NPV calculations including the operation income, - costs and the investment costs. The results are exposed for changes in different variables in a conducted sensitivity analysis.

The sensitivity analysis will in this case allow for an understanding of how the values of independent variables will impact the use of HSS. Meaning, that the sensitivity analysis will serve as a "What if" analysis representing the variables of battery size, electricity prices, the volatility in prices as well as changed investment costs of the battery.
To complete the analysis, an assessment of the possibilities for integrating HSS in the future renewable energy systems is made. This chapter will account for the results from the Technical Energy Model, and discuss the future in relation to how HSS can be utilising the fluctuating RES on a system level, based on a various of articles dealing with the future for HSS.
At last the thesis will conclude and discuss on the used approach for the thesis as well as the results found in the analysis.

To illustrate the structure of the thesis, this is visualised in figure 3.1, which is followed by the theoretical framework of the thesis.

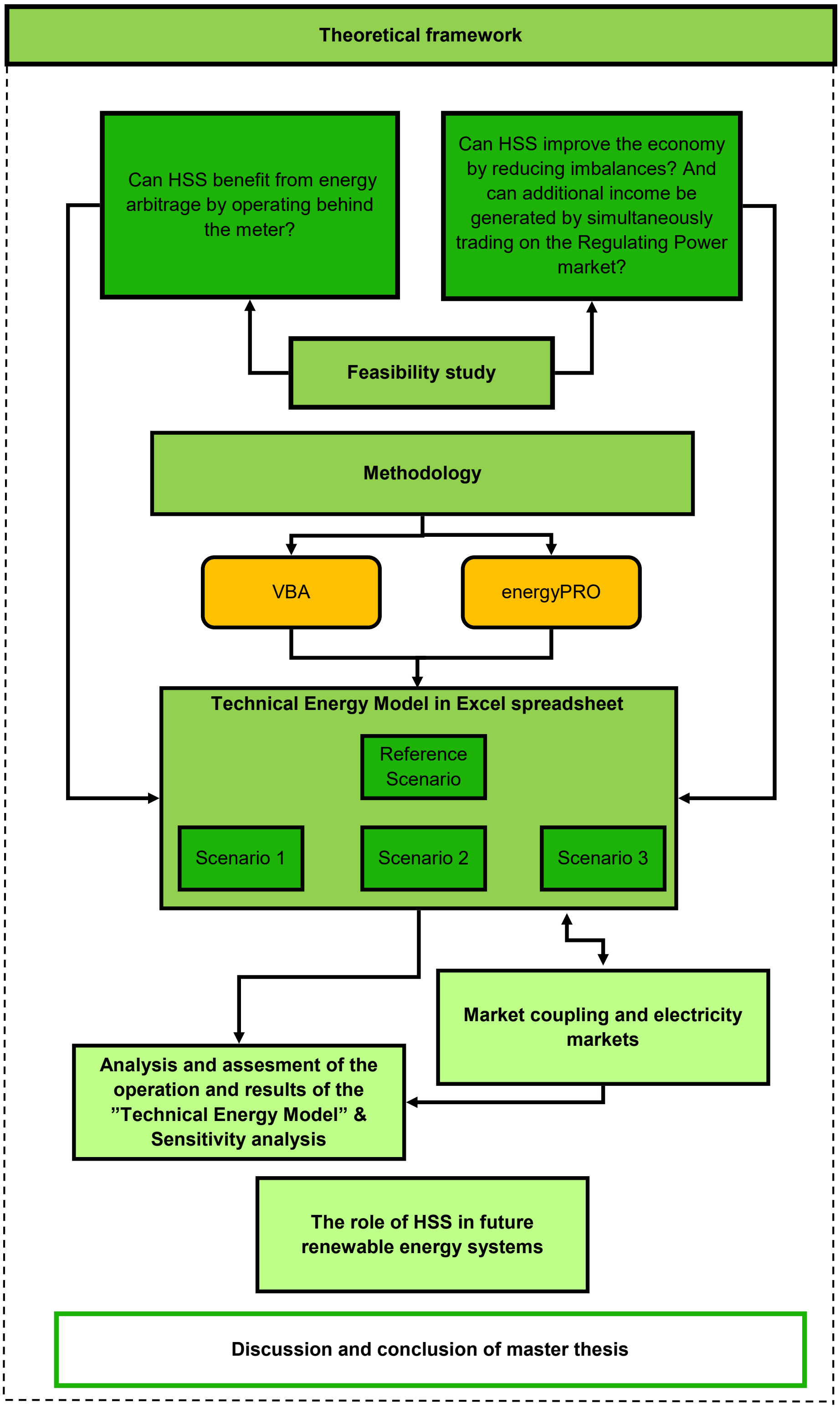


***Figure 3.1.*** Research structure

## 3.1 Awareness of technical alternatives

The Chapter "Awareness of technical alternatives" serves the purpose of determining the theoretical framework of the thesis that is consistent through the thesis. The theoretical framework also reflects the mindset of the thesis as well as the understanding and interpretation. Therefore, this chapter is the underlying understanding of why the thesis has the approach of a socioeconomic analysis, and contributes as a conceptual framework.

This general interpretation is inspired by the theory of Lund [2009] called "The Choice Awareness Theory", which is a theory dealing with the implementation of radical technology changes, such as a transition from a fossil fueled energy system to a renewable energy system, the theory is approached at a societal level. Also, the theory implies that radical changes is affected by its surroundings.[Lund, 2009]

Lund [2009] construct his theory on the basis of the true and false choice concept, however, this is not the exact approach for this study, as the true and false choice is the choice between alternatives or no alternatives. Which is not the case in this topic. Instead this thesis will shed light on different possibilities in developing and expanding the energy system, as well as contributing with knowledge to the field. Such knowledge should contribute to the prevention of the false choice, where no alternatives are investigated, and by that improve the foundation for policies and other public decisions, that has to be made.
This study will address the challenges of public discussions and decision making, in determining the best way to operate a HSS as well as investigating whether the HSS shall be a part of future energy systems, and by that be included as a future alternative. Also, the operation of a HSS will determine, how we as a society, can utilise the use of HSS, in order to optimise the technology and gain profit and social welfare from the technology.

When investigating and assessing this technology and the opportunities related to it, it will lead to an illuminated foundation, where the correct decisions can be made. This will prevent a situation, where a lot of HSS are implemented in different future energy systems, but it turns out to be an incorrect decision, where money could have been spent more efficient on other technologies - or the opposite situation, where HSS turns out to be the best alternative. Such investigation can be done throughout feasibility studies, which is the case for this thesis.
By investigating the feasibility of the HSS technology this will elaborate the possibilities and the general socio-economy for the technology. This will, as described, contribute to decision-making, but also to construct policies that, in form of e.g. subsidies or changed regulations, support the implementation of the technology, if it turns out to be a good alternative to existing storage and power regulating technologies.
This thesis will therefore hopefully be able to contribute with general knowledge to the topic of HSS, which can lead to correct decisions that benefit society.

CHAPTER

# 4 Methodology

The Methodology chapter will serve as the underling understanding of how the thesis tend to structure the analysis. To assess the problem of the thesis, different tools have been chosen, for what reason the chapter will elaborate on why and how these have been chosen and to illustrate how the different methods interact to compose a scenario based assessment of HSS.

## 4.1 Modeling tools and data collection

To evaluate if the use of HSS, consisting of wind turbines and batteries, is a profitable investment and should be considered instead of standalone technologies, it is important to analyse the annual operation and costs of the technologies. This will be done by comparing the value from a standalone battery, in a reference scenario, with the value from a battery included in a HSS, in three alternative scenarios assembled in a Technical Energy Model.
The Technical Energy Model is grounded upon an operating strategy of covering imbalances from a wind farm, and trading on the regulating power market on the one hand, and trading on the Day-ahead market by operating behind the meter on the other hand. For what reason the three alternative scenarios respectively will investigate the profitability for; **Scenario 1:** The use of energy Arbitrage behind the meter; **Scenario 2:** To reduce imbalances generated by the wind farm; **Scenario 3:** To reduce imbalances generated by the wind farm in combination with trading on the Regulating Power market; by comparing them to a reference scenario of which is operated as a standalone battery, with focus on energy arbitrage.

To do so, it has been chosen to use both the energyPRO modelling tool and VBA coding combined via Excel spreadsheet as the fundamental tools in the modelling of the scenarios.
EnergyPRO is a modelling software designed by EMD International to optimise the operation of energy systems in accordance to all preconditions such as weather conditions, tariffs, technical specification etc.[EMD International, 2018] For what reason energyPRO is used for both data collection and scenario establishment, as well as the ability to transfer generated data to Excel spreadsheet is suitable for th combination of the differnt tools used.
EnergyPRO is used in the modeling of the Reference scenario and Scenario 1 as en-

ergyPRO is able to act upon all the time series independent of time, which means that it is able to include future spot prices in its calculation and by that create the optimal scenario not allowing for unpredictability. This is however a part of the spreadsheet and VBA analysis, where e.g. regulating power prices, the need for regulating power and imbalances from the wind farm are kept unpredictable, for what reason Scenario 2 and 3 is modeled in VBA.
VBA coding is a programming language, which can be used to customise Microsoft Office-programs and allows for manually coding of basic commands or functions in a macro, for what reason the macro allows for automatically filling in different functions or commands in an Excel spreadsheet. VBA is therefore used for illustration of cash flows, energy trading, -consumption, -distribution etc. in the modeling of scenarios on an hourly basis.
The Technical Energy Model will therefore be a joint interplay between the VBA, energyPRO and Excel spreadsheet.

Through the operation of the model, it is possible to asses the different scenarios from an economic perspective. A perspective, which has its roots in fundamental investment theory and will have its main focus on calculating the NPV, allowing the thesis to illustrate the feasibility in utilising HSS.

Moreover secondary and primary literature have been used to either gather validated data to establish e.g. the reliable size of a battery or to understand how e.g. electricity markets serve in practice. By analysing both secondary and primary literature, in what is understood as document analysis, it is possible to make decisions on a validated and reliable foundation, as well as document analysis is used to obtain an understanding of the research done in the field of HSS, and thereby assess the role of HSS in future renewable systems.
To understand the modelling and interaction of different methods used in the thesis, an illustration of how the methods are incorporated, is shown i figure 4.1.

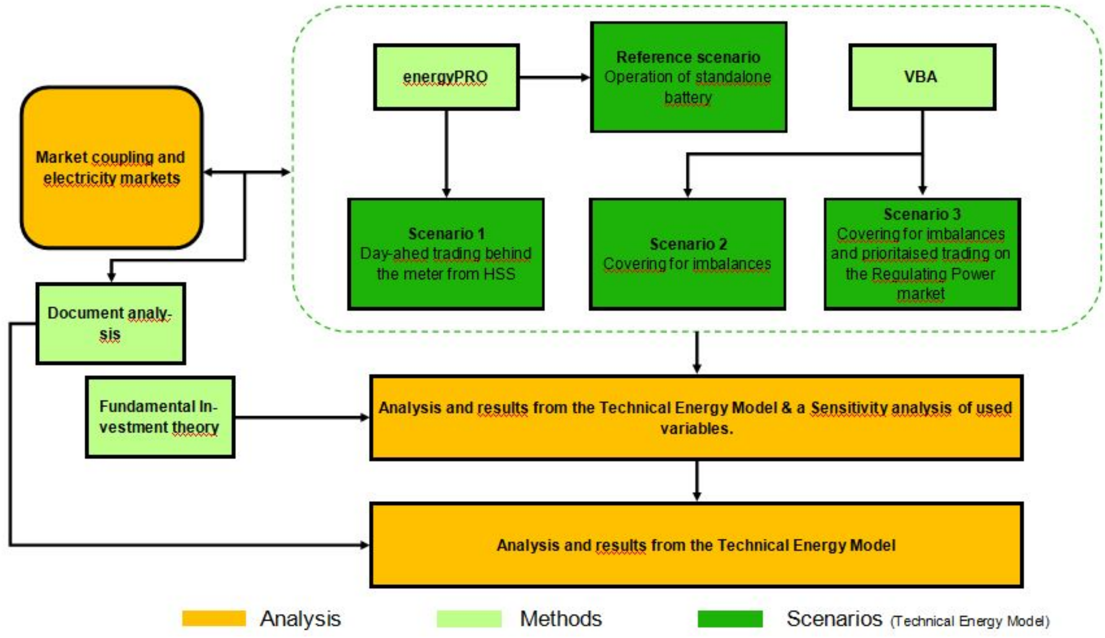


***Figure 4.1.*** An overview of the used methods, and their interaction with the analysis

## 4.2 Technical Energy Model

The Technical Energy Model is as described earlier, a scenario based energy model. The following will specify the structure of the model, divided into general specifications of the wind farm and battery, which is consistent for all scenarios. This is followed by the technical operation and specifications for respectively the Reference Scenario, Scenario 1, Scenario 2 and Scenario 3. The Technical Energy Model is included as an Excel file in the appendix. Whereof the VBA Codes for Scenario 2 and 3 can be found in the appendix C as well as the energyPRO economics for the Reference scenario and Scenario 1 can be found in appendix B.

### Wind farm specifications

All four scenarios in this assessment of standalone battery storage and HSS are based upon electricity production from wind turbines. The wind farm specifications used in this case are based upon the onshore wind farm located in Klim, Denmark. The reason for using an existing wind farm as an example is to get a realistic aspect in the analysis of the HSS. The wind farm consists of 22 wind turbines with a capacity of 3.2 MW each. This makes the aggregated capacity for the wind farm 70.4 MW, which makes it the biggest onshore wind farm in Denmark, when measuring the annual production [Vattenfall, 2016]. To generate the production from the wind turbines the specific power curve for the SWT-3.2-133 wind turbine model was needed [Danish Wind Industry Association, 2014]. This is illustrated in figure 4.2 below, and shows the aggregated production at a given wind speed. The cut-in wind speed is 3 m/s, while the cut-out wind speed is 27 m/s, which causes a shutdown of the turbine due to high wind speeds and risks of

damaging the turbine. The full capacity for the wind turbine is reached at a wind speed of 13 m/s.
The power curve is generated and downloaded from the WindPRO modelling tool, which includes power curves for several types of wind turbines. The power curve is used in energyPRO in combination with the in energyPRO included ETA5 weather data to generate hourly production values for the wind farm during a year. The wind data is based on the year of 2016, therefore the hourly and annual production are consistent through out all scenarios.

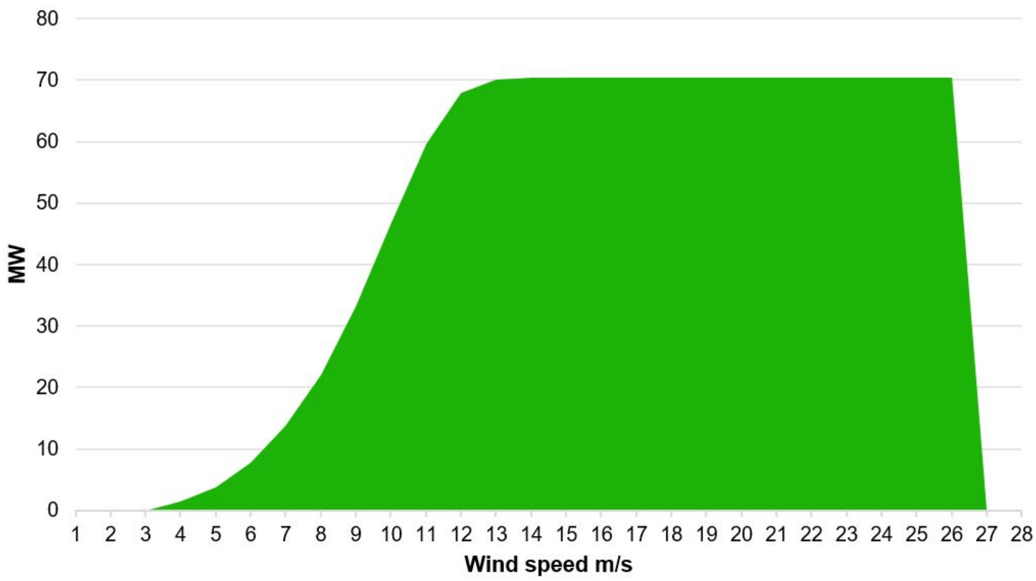


***Figure 4.2.*** The aggregated capacity for the wind farm at a given wind speed

Further, the operation strategy for the wind farm is consistent in all scenarios. It is a simple strategy, that rely on the variable O&M costs for the wind farm, which is set to be 2.5 €/MWh based on the technology catalogue from Danish Energy Agency [2018].
The operation strategy for the wind farm is therefore to offer the production to a price higher than 2.5 €/MWh on the spot market, and by that only produced when the spot price exceeds 2.5 €/MWh. If the spot price is below or equal to 2.5 €/MWh while the wind farm is producing electricity, this would result in a production without any profit, which does not make sense when considering the wind farm as a production unit. The production strategy is illustrated in equation 4.1:

$C_p$ = *Costs of production (O&M)*
$S_h$ = *Hourly spot price*

$$\text{If} \quad C_p < S_h \quad \text{then} \quad \text{Wind farm generates electricity} \tag{4.1}$$

### Generation of imbalances

The hourly production data from the wind turbine are inserted in the Technical Energy Model and multiplied with a randomly generated deviation factor to imitate the uncertainty related to the production prognosis for a wind farm. This deviation factor is set to 12%, which means that the traded production on the spot market can deviate with up to 12% in both negative and positive direction compared to the actual production. An example could be a forecasted production of 50 MWh during an hour, and therefore 50 MWh traded on the spot market. The wind farm will then produce between 44 MWh and 56MWh during the hour due to the 12% deviation factor. This will result in an imbalance between +6 MWh and -6MWh. Because the imbalances and the traded production are based on the actual production, a few exceptions occur. If the actual production data from energyPRO multiplied with deviation factor exceeds the 70.4 MWh, the forecasted and thereby traded production is of course limited to the 70.4 MWh, so it does not surpass the max capacity for the wind farm.
The level of 12% is an assumption supported by Wang et al. [2011], who estimates the performance of regional forecasting to be up to 8-10% of the nominal wind farm power for forecasting 24 hours ahead. Pousinho et al. [2011] who asses several approaches of wind power forecasting has come up with an average value of 5.41% for the Mean Absolute Percentage Error (MAPE) for the suggested forecasting approach in their article, which also applies forecasting for 24 hours. By using a 12% deviation factor, the forecasted production of the wind farm will have a MAPE of around 5.6%, which is close to the approach used in the study of Pousinho et al. [2011], why this deviation factor level is chosen. The MAPE for the forecasted production is calculated as equation 4.2[1].

$A_t$ = *Actual production*
$F_t$ = *Forecasted production*
$n$ = *Number of hours with wind production*

$$\mathrm{MAPE} = \frac{100\%}{n} \sum_{t=1}^{n} \left| \frac{A_t - F_t}{A - t} \right| \tag{4.2}$$

However, it has to be said that there is a big variation in the results and accuracy from the different approaches used in both of the above mentioned articles, why forecasting of wind production is related to a high uncertainty and is very dependent on the input data as well as the time horizon.

[1] Hours with both forecasted full production and actual full production are excluded from the MAPE calculation

### Battery specifications

The battery used in the assessment is consistent and dimensioned the same trough out all scenarios. The battery is based on a real utility scaled lithium-ion battery used in the HSS called *Kennedy Energy Park* located in Australia as mentioned in chapter 1 [Australian Renewable Energy Agency, 2018].
The battery in Kennedy Energy Park has a capacity of 4 MWh and are able to discharge with a capacity of 2 MW, it is assumed to charge with the same capacity in the included scenarios. The battery in Kennedy Energy Park is coupled together with an aggregated capacity of 58.2 MW of PVs and wind power, which is a little less than the capacity of the wind farm used in this assessment.
The efficiency of the included battery is set to 95% for both charging and discharging and is based on Fleer et al. [2016] used for their model based assessment of battery systems. The efficiency level results in the fact, that only 1.9 MW is being filled on the battery when it charges with the full capacity of 2 MW, as well as 2.1 MW leaves the battery at full discharging.
The economy for the battery is also based on Fleer et al. [2016] and takes its basis in the year of 2020. The investment costs related to the battery are 450 €/kWh while the power specific investment costs are 200 €/kW. The O&M costs are set to be a fixed annual value and are equal to 2% of the investment costs. In the Reference scenario and Scenario 1 a variable O&M cost is included to define the bidding strategies, the price level is based on Manuel [2014] and is only 0.3 $/MWh. This is however not included in the financial assessment where the annual fixed O&M costs are used instead. The lifetime of the battery is set to 14 years based on Fleer et al. [2016].

| Technical specifications | |
|---|---|
| Wind farm capacity | 70.4 MW |
| Number of wind turbines | 22 |
| Type of wind turbines | SWT-3.2-133 |
| Battery type | Lithium-ion |
| Battery capacity | 4 MWh |
| Charging capacity | 2 MW |
| Discharging capacity | 2 MW |
| Charging efficiency | 95% |
| Discharging efficiency | 95% |
| Lifetime of battery | 14 years |

***Figure 4.3.*** An overview of the specifications for the wind farm and the battery.

## Reference scenario

The Reference scenario is the underlying understanding of how a standalone battery operates on the electricity markets to generate profit. Therefore, an explanation of the operation in the Reference scenario is dealing with the operation of the battery.

The stand alone battery is designed and modelled exclusively in energyPRO. Here the battery is participating on the Day-ahead market, buying and selling power on an hourly basis.
In general, the operation strategy for a battery is considered different from other strategies for generators, as the batteries can be involved in both buying and selling electricity on different points in time. This allows the storage to keep or buy the electricity in off-peak periods with lower clearing prices and to sell the electricity in on-peak periods with high clearing prices. [Kanakasabapathy and Swarup, 2009]
To do so, the battery is considered to be economical durable when the profit of selling electricity exceeds the costs of storing and retrieving the energy plus the price of energy lost during the process. Therefore, the operation strategy for the battery is closely related to this simple approach. The costs of charging 1 MWh on the battery and the revenues of discharging 1 MWh from the battery are therefore calculated for every hour of the year in energyPRO. This is done as shown in equation 4.3 and 4.4

$C_v$ = *Value of 1 MWh charged electricity*
$D_v$ = *Value of 1 MWh discharged electricity*
$S_h$ = *Hourly Spot Price*
$E$ = *Efficiency*
$O\&M$ = *Variable operation and maintenance cost*
$T$ = *Tariff*

$$C_v = \frac{1}{E} \cdot (S_h + O\&M + T) \tag{4.3}$$

$$D_v = E \cdot (S_h - O\&M) \tag{4.4}$$

The optimal hour of charging the battery during the entire year is then found by energyPRO and is based on the hourly varying spot prices. This is when the spot price, and therefore the value/costs for 1 MWh is at its lowest. This is followed by finding the optimal hour of discharging the battery, when the value of the electricity is at its highest. This procedure goes on until the optimal operation of the battery during the year is achieved. This approach also means that the Reference scenario is considered the optimal way of operating the standalone battery with that spedicific operation strategy.

Based on the understanding of standalone operation of the battery the reference scenario can be visualised as shown in figure 4.4. Noteworthy, is that the meter is separated as the technologies in the Reference scenario is operated as standalone technologies and do not interact with each other. There is therefore no interaction with a potential wind farm and the battery is just practicing energy arbitrage by exploiting the price differences in the market.

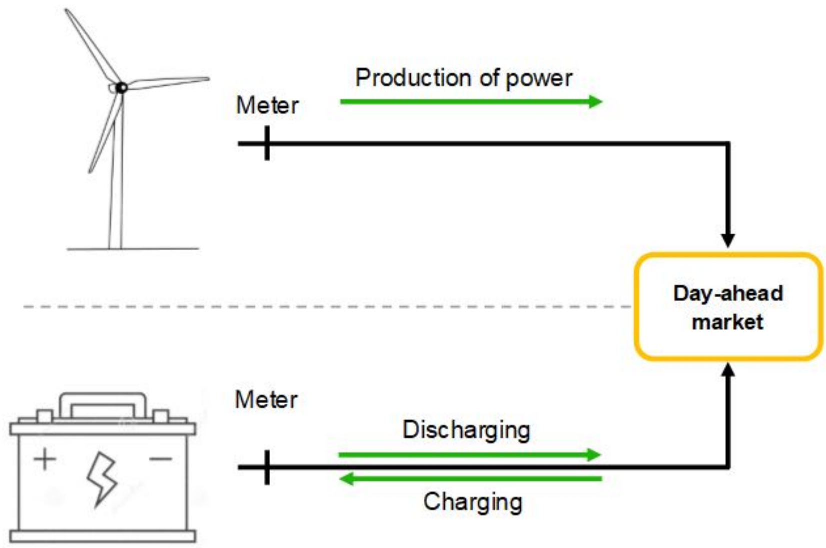


***Figure 4.4.*** Visualised illustration of the Reference scenario, where the battery is operated as a standalone technology and are therefore not interacting with a potential wind farm.

### Scenario 1: Spot sale behind the meter

The first alternative to standalone technologies is the HSS scenario with focus on energy arbitrage, which is very similar to the Reference scenario, that exploits price differences in the markets by buying and selling to different prices. The difference in Scenario 1 is, that the battery is also able to charge directly from the wind farm, which results in exempted grid tariffs and therefore lower prices. Along with the available electricity from the wind farm, the battery is also able to buy electricity from the grid on the Day-ahead market, which is including grid tariffs. All the sold electricity is discharged to the Day-ahead market. The purpose of having this scenario is to see if there are any advantages of being able to operate behind the meter as well as directly on the market. Figure 4.5 illustrates Scenario 1.

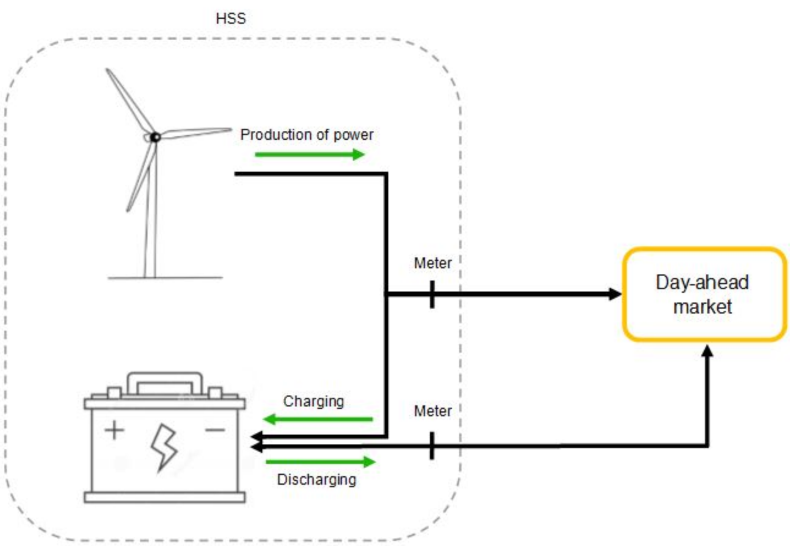


***Figure 4.5.*** A visualised illustration of the operation of the wind farm and battery in Scenario 1, with the focus of energy arbitrage.

In Scenario 1 the imbalances from the wind turbine are excluded and not taken into consideration. The production from the wind turbine is the same as the other scenarios, so when the wind turbines do not produce any electricity, it is not possible for the battery to charge from the wind farm. The alternative is therefore to buy electricity from the grid. The expenditures for the electricity charged from the wind farm is equal to what the wind farm could have sold the electricity to, which means it is the spot price.

To sum up, this scenario therefore consists of a HSS including a wind farm and a battery, that is able charge electricity directly from the grid and from the wind farm. The electricity from the wind farm is exempted for grid tariff. The source of charging is determined by the costs, where the cheapest access to electricity is chosen. Afterwards it sells the electricity to a favourable price, by exploiting the price differences and thereby generate profit.

## Scenario 2: Reducing imbalances

The second hybrid alternative has its focus on reducing the imbalances from the wind production via the extra capacity on the battery. The purpose of doing so, is to reduce the fee that is settled for having imbalances, which is not favorable for the generator of the electricity, as other generators have to get paid for delivering the needed regulating power, that will bring the system in balance.
By reducing the imbalances at the wind farm, especially the negative imbalances where the wind farm has to pay a fee, the costs for fees should be lowered and by that improve the total economy for the HSS.
In this scenario the battery will charge and discharge every time it is able to reduce or

neutralise an imbalance and thereby lower the costs for settlement of imbalances. The settlement of imbalances is further explained in section 5.3.

Some imbalances can however be relatively costly to reduce. This is for example the case when the price for surplus payment is high, while the fee due to low prices are minor. A high payment is then used to over a small fee. This is to some extent solved by not charging the surplus electricity if the spot price exceeds 41.9 €/MWh. It is then considered to be better to get the payment than to reduce the fee.

The determination of 41.9 €/MWh is based on the 0.95-quantile of the spot prices. This means that positive imbalances will not be charged to the battery, when the spot prices is among the highest 5%. The level of 5% is an assumption. This trading is to some extent based on speculations due to the fact, that the settlement of the surplus production can be based on the downward regulation price as well as the spot price, as explained in section 5.3. The downward regulation price can differ from the spot price, but in this case the spot price is used as a general indicator to estimate the electricity price level and therefore hopefully generate extra profit in the best hours of the year. In case of a fully charged or discharged battery, there will be hours where the battery cannot contribute to the reduction of the imbalances.
The scenario does not include grid tariffs at all, because the electricity entering the battery comes from the wind farm and not the grid. Due to the fact that the wind farm only produces when the spot price is above the variable O&M costs there will be no production or imbalances when spot prices are below the level of the O&M costs.

Figure 4.6 illustrates the HSS and the way it is operated, as written above the only electricity that is charged on the battery is the positive imbalances from the wind farm. This means that there is no trading with the battery, it is only used as a buffer for the wind farm.

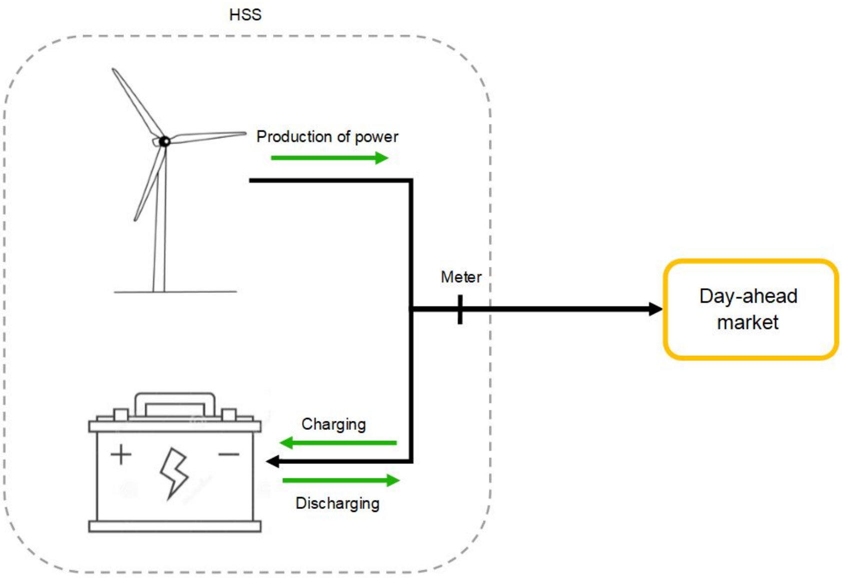


***Figure 4.6.*** Visualised illustration of the operation in Scenario 2, with the focus of reducing imbalances from the wind farm.

To sum up, Scenario 2 is a HSS, where the battery reduces the imbalances from the wind turbines and by that reduces the fees payed to the TSO. This is done in a simple way, where the battery charges when positive imbalances occur and discharges when negative imbalances in the wind production occur. Due to the restricted capacity it cannot necessarily mitigate all imbalances, why there still are fees for negative imbalances and payments for surplus production. The combination with the wind fqrm means that all charging on the battery is exempted for grid tariffs. In cases where the spot price exceeds 41.9 €/MWh it is assessed that it is economical beneficial to sell the surplus production, and therefore not charge the battery.
The imbalances are not known before the operational hour, just as the regulating power prices and the need for regulation are not known before the operational hour is over, which determines the settlement price.

## Scenario 3: Reducing imbalances combined with participation on the Regulating Power market

The third hybrid alternative is very similar to the second alternative mentioned above, by which it takes its foundation on this alternative, why the first priority is to reduce the imbalances.
Due to the fact that several successive hours with a battery that is either fully charged or discharged can result in a nonfunctional battery, when it comes to reducing the imbalances, this scenario includes participation on the regulation market, which is illustrated in figure 4.7.
The battery will therefore buy or sell electricity to the Regulating Power market, when

the battery is nonfunctional in reducing the imbalance. An example of non-functionality can be three successive hours of negative imbalance from the wind farm, and a battery that is empty in the start of the three hours. Without participating on the Regulating Power market, the battery is not capable of reducing the imbalance by discharging and delivering electricity. By participating on the market, it is able to buy electricity in one of the hours, and then be able to reduce the negative imbalance and the resulting fee in the following hour. It is assumed that it is possible to estimate the imbalance in the following hour, by which it is possible for the battery to buy or sell correct amounts of electricity, so the following hourly imbalance can be covered.
The argument for buying electricity to cover an imbalance is, that the downward regulation prices often are low, while an imbalance is settled to higher prices. This of course means, that a certain price difference is needed to generate the profit taking the loss into account.
Just as Scenario 2, the spot price is taken into consideration. If it exceeds 41.9 €/MWh the positive imbalances are not charged to the battery, but instead sold as surplus electricity due to the high price. The high price can also result in a sale of the already charged electricity on the battery, which then can be sold on the Regulating Power market. The opportunity of buying electricity from the Regulating Power market also leads to purchase of electricity, when the spot price is 0 €/MWh or less.

Due to the purchase of electricity on the Regulating Power market, grid tariffs are applied to the electricity bought on the market, while the surplus production from the wind farm that is charged on the battery is exempted from grid tariffs.

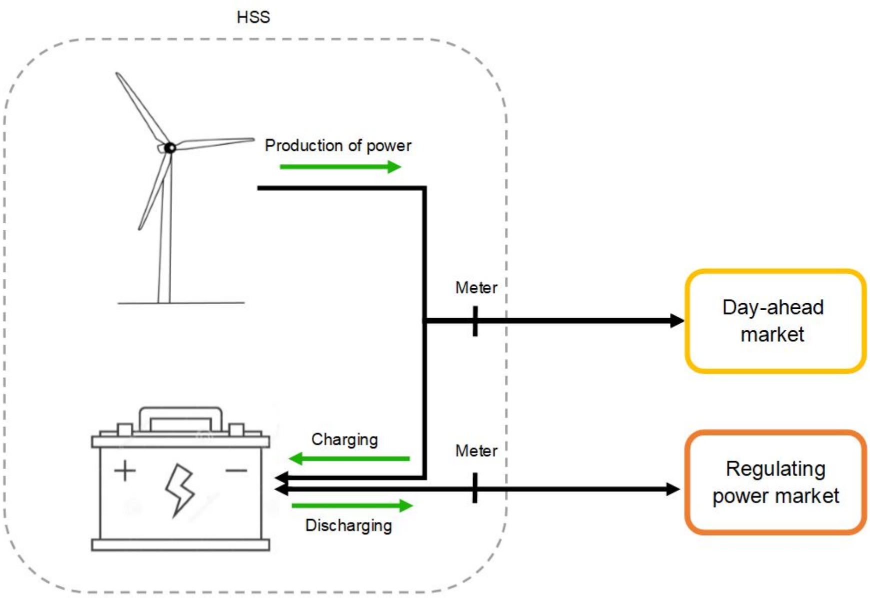


***Figure 4.7.*** Visualised illustration of the operation in Scenario 3, with the focus of both reducing imbalances and participating on the regulating power market if possible.

To sum up, the last scenario is similar to scenario 2, as the priority is to reduce the punishment for imbalances by charging the battery in cases of positive imbalances, while the battery is discharging in cases of negative imbalances. In this scenario the battery has access to the Regulating Power market, where it in hours without imbalances or non-functionality due to being fully charged or discharged can participate.
When the spot price exceeds 41.9 €/MWh it does not charge the battery, but sells the surplus electricity instead. The same applies to prices below 0 €/MWh, where the battery will buy downward regulating power if possible and if there is a need for downward regulation. Grid tariffs are applied to the electricity bought on the Regulating Power market. In this scenario it is assumed that it is possible to estimate the imbalance in the following hour, to be able to buy cheap electricity on the Regulating Power market and cover the imbalance with it.

## 4.3 Economy and prices

The assessment of the different ways of operating a HSS has its focus on the financial aspect. The hourly time series data included in the assessment are based on the year 2016 both when it comes to the spot price and regulating power prices. The prices are based on the price area of DK1 in Denmark. Perfect spot price prognosis for the following operational day are assumed in the assessment, this means that the gate closure for the Day-ahead market is not taken into account. Opposite to this, is the regulating power prices, which are not known before the operational hour ends. This is due to the uncertainty related to the determination of these prices, which are based on the need for regulating power. Therefore the prices are also used to determine when the need for upward- and downward regulation appear. It is assumed that there is a need for downward and upward regulation, when the regulation prices are different from the spot price. The need for upward- and downward regulation is used to calculate the settlement of the imbalances, that occur in the production from the wind farm.

### Fundamental investment theory

To asses the different scenarios, a calculation that determines the NPV is used. The NPV calculation is used to analyse the profitability of the investment, in this case the battery. The value of specific future cash flows are presented in the present value of the currency, which makes the value of the cash streams comparable to the investment costs, which has a present value. When comparing the present value of the future cash flows with the investment costs, it is possible to see whether the investment will be profitable or unprofitable . A positive NPV indicates a profitable investment, while a negative NPV indicates an unprofitable investment, which should not be carried out due to the loss of money. [Investopedia, n.d.] Equation 4.5 on next page shows how the NPV is calculated.

$C_0$ = *Initial investment costs*
$C_t$ = *Net cash inflow during the time period t*
$r$ = *Discount rate*
$t$ = *Number of time periods*

$$\mathrm{NPV} = \sum_{t=1}^{T} \frac{C_t}{(1+r)^t} - C_0 \tag{4.5}$$

The discount rate included in the NPV calculations is set to 4%, which is based on the recommendations from the Danish Ministry of Finance [2013]. They suggest this level of the discount rate for investments with a lifetime shorter than 35 years. The NPV calculations are only made for the battery it self, and not the investment of wind turbines, because the turbines cost the same as ell as producing the same amount of electricity in all the scenarios, which results in the same NPV for the wind farm, why this is excluded. The grid tariffs included in the costs are based on the rates of the Danish TSO Energinet [2018]. The grid tariff is set to 10.74 €/MWh and is added to the electricity bought from the grid. Electricity flowing behind the meter from the wind farm directly to the battery is therefore exempted from grid tariffs in this analysis, as already explained.

## 4.4 Limitations

When focus is on regulating power in this assessment, this refers to the Manual or Tertiary Reserves. The Primary and Secondary Reserves are excluded due to the fact, that Manual Reserves are better suited to use in a HSS, where higher amounts of electricity are produced. Participation on the Primary Reserve and Secondary Reserve markets are probably more well suited for stand alone batteries, because of the smaller amounts of electricity on these markets and the need for quick regulation. This has also already been investigated as research has been made on standalone batteries participating in the FCR market, as written in the literature study in Chapter 2. This assessment excludes the benefits of the compiled costs that are achieved when building a HSS. This is e.g. soft costs as labour and planning as well as hardware e.g. transmission lines, controllers and inverters. As explained in chapter 1 there will be benefits of constructing one combined project instead of to separate projects on several fields. Another limitation in this assessment is the technical aspect of participating in the market, e.g. minimum sale and purchase of electricity or requirements for the capacity on the different power markets.

This methodology makes the foundation for the following analysis, that will asses the four scenarios as well as the operation of these, and compare the economy.

CHAPTER

# 5 Market coupling and electricity markets

When investigating the optimal operation of a HSS it is important to know the conditions and surroundings for such systems. Some of the parameters that have a big influence on the HSS is the general electricity system, the different electricity markets and the opportunities related to these markets.

The European electricity systems consist of two main parts - the physical infrastructure and the electricity markets.
The physical infrastructure consists of the electricity generators, that in today's systems are generators such as coal, gas or nuclear based power plants, hydro power plants or fluctuating RES in form of wind turbines, PV's etc. The electricity is transported via the electricity grid, which can be divided into two parts, the transmission grid and the distribution grid. The transmission grid is used for long distance bulk transport of electricity and is managed by the Transmission System Operator (TSO). The distribution system delivers the electricity to the residential areas, where consumers/prosumers and industries consumes the electricity. The distribution grid transports the electricity at a lower voltage than the transmission system and is managed by the Distribution System Operater (DSO). [European Parliamentary Research Service, 2016]
The infrastructure, and thereby the distribution of the generated electricity is illustrated in figure 5.1.

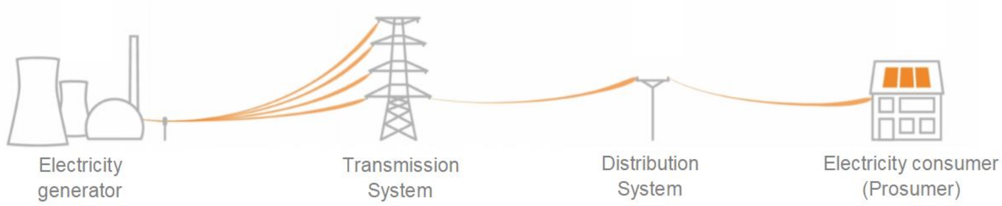


***Figure 5.1.*** A simple illustration of the typical electricity infrastructure. [European Parliamentary Research Service, 2016]

The electricity markets are instead considered as platforms, where the cash flows are organised. These are often taking place at power exchanges, who organises the trading made between the different actors on the market. The two main actors are the generators mentioned above, who produce and sell the electricity at the market and the electricity suppliers, who buy the electricity from the generators and sell it to the consumers. The residential consumers are therefore not participating themselves, but are indirectly represented by the electricity supplier.[European Parliamentary Research Service, 2016] Another example of an actor could be larger industries, that can both act as a producer and a consumer of electricity.

The markets consists of different structures with different time horizons, settlements and ways of trading. Especially the time horizon separates the different markets, where the Regulating Power markets include trading in the operation hour, the Intraday market takes place up to around an hour before the operation hour, the Day-ahead market includes trading the day before, while the Future and Forward markets deals with delivery of electricity weeks and years out in the future. [European Parliamentary Research Service, 2016]

The markets have different functions due to the time horizon. The Regulating Power markets have the function of balancing and stabilizing the grid, the Intraday market is suitable for generators and suppliers to smoothen out the production or consumption and by that reach the already traded amount on the Day-ahead market, which is used for the bulk amounts of electricity. Lastly the Future and Forward markets is suitable for freezing the price in the future, and by that be more sure to know the price. An example could be CHP plants. These plants have a big task in delivering the needed heat, and especially in the winter time where the demand is increasing. By participating on the Forward market, these plants can freeze the price, and sell some of the electricity, which they indirectly are forced to produce, to a fixed amount, that they find acceptable. Using this approach is less risky compared to a total rely on the spot price, which can be much more varying.

The electricity markets in general are therefore very complex and include a lot of different purposes and practices. This thesis however, will only be focusing on the Regulating Power markets, the Intraday market and the Day-ahead market. All of these will be elaborated further in section 5.2.

## 5.1 An interconnected European electricity market

Common for the European electricity markets is, that they during the past two decades have been part of a deregulation of the European electricity system, which has been driven by EU legislation, with the purpose of reducing the governments role.

The deregulation is characterised by replacing inefficient regulation, resulting in a liberalised market structure, with the purpose of securing a reliable delivery of electricity at the lowest cost to consumers.[Makkonen et al., 2012]

This EU legislation is based on the *Target Design Model*, where the main goal is to reach an increased interconnected Europe, whit uniform electricity prices across Europe. [European Parliamentary Research Service, 2016]

Therefore, the European electricity markets have, during the last decade, transformed into more interconnection and market coupling across the border lines in Europe. Back in

October 2014 the European Council recommended the Member States of EU to achieve the interconnection of at least 10% of their installed electricity generation capacity from power plants by 2020. This means the Member States should have completed the establishment of transmission lines being able to transfer the expected capacity in the following few years. [European Commission, 2015]

The reasons for increasing the market coupling across Europe are several. One of them is to increase the security of supply, in case of outages from stable power plants. By expanding the electricity infrastructure it becomes possible to increase the im- and export across the borders. This also supports the integration of RES in the European sector. This can be exemplified in cases where fluctuating RES as PVs or wind turbines produce a lot of electricity and thus lowering the electricity price. By exporting electricity to countries with a high price, this will lead to a lower price for the certain country or price area, as well as the price area, where the fluctuating electricity is being produced, can continue the renewable electricity production without using curtailment or similar methods to stabilise the balance between production and consumption.[European Commission, 2015]
A result of the market coupling is therefore an increased security of supply, lower electricity costs across Europe, less need for stable power plants and better integration of the increasing amounts of fluctuating RES.[European Commission, 2015]

One of the key elements in the Day-ahead Market Coupling process is the Price Coupling of Regions (PCR), which is made on the initiative of seven European power exchanges. The PCR is a common project for different European Power Exchanges to calculate the electricity prices across Europe respecting the capacity of the relevant network elements as interconnectors on day-ahead basis. This leads to a harmonisation of the European electricity markets, but also increased transparency and social welfare. The PCR is used to couple the majority of the European countries, as shown in figure 5.2, and the PCR is open to other power exchanges, that wish to join. The project emphasises the increased interest for cross-border electricity trading across Europe.[EPEXspot, 2016]

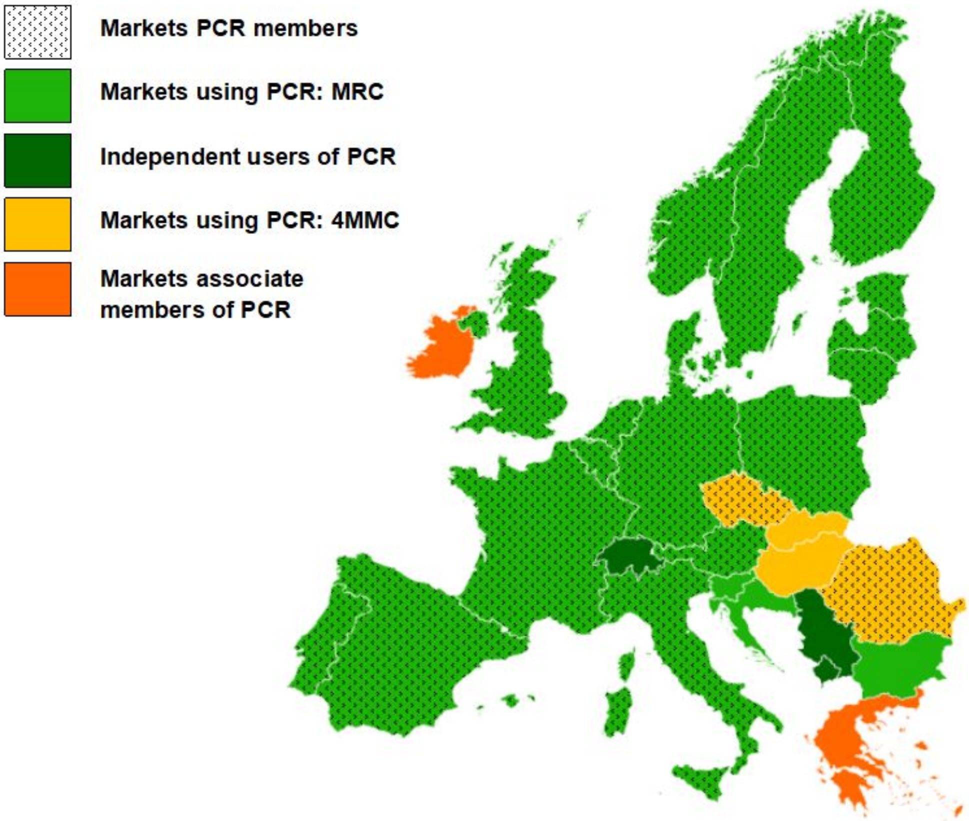


***Figure 5.2.*** PCR users and members across Europe - The MRC is the the pan-European Multi-Regional Coupling project that covers 19 countries in Europe [EPEXspot, n.d.a], while the 4MMC is the markets of the Czech Republic, Slovakia, Hungary and Romania. [EPEXspot, 2016]

The benefits from market coupling are achieved by using the so-called implicit auctions where the prices and capacities are calculated. This means that actors on the market do not actually receive allocations of cross-border capacity themselves. Instead generators, electricity suppliers and consumers bid on their own exchange, which then uses the available cross-border capacities to lower the price differences between different price- and market areas.[EPEXspot, n.d.a]
The market coupling and increased electricity trading across borders result in expansions of the transmission lines between the different European countries, examples shown in figure 5.3 are the NSNLink cable between Norway and Great Britain, the Cobra cable between Denmark and the Netherlands and NordBalt cable between Sweden and Lithuania. Aggregated, these three projects provide an additional capacity of 2.8 GW of possible direct electricity trading between the six countries.[Energinet, 2017b]
The development of an interconnected Europe however also means, that decisions and development in different countries and areas have a much larger impact on neighbouring areas than previous.

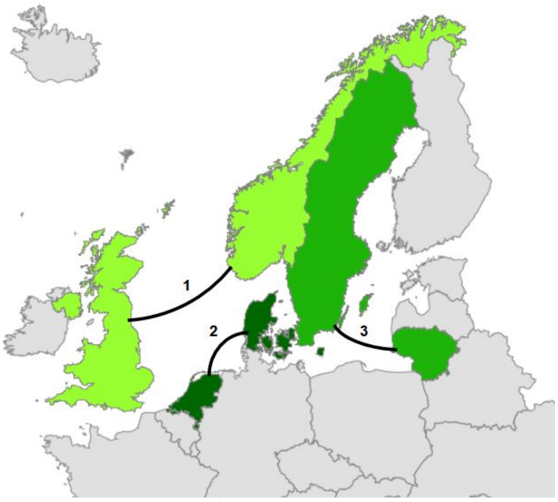


***Figure 5.3.*** Cross border market coupling - **1:** NSN Link - 1400 MW **2:** Cobra Cable - 700 MW **3:** NordBalt - 700 MW [Energinet, 2017b]

Despite this increased market coupling, expansion of transmission lines and a goal of achieving convergent prices across Europe, the goal are still not yet achieved. Examples of this is the different quarterly average wholesale electricity prices across Europe in fourth quarter of 2017. Here, countries like Norway, Denmark and Sweden had the lowest prices of around 30-31 €/MWh, while the Southern European countries like Italy, Portugal and Greece were paying twice the price for their electricity with the highest average price of 61-62 €/MWh. [European Commission, 2018]
The increased ability to trade in the different markets across Europe will therefore hopefully induce a convergent price in the different European countries. An elaboration of the different markets follows below.

## 5.2 Wholesale electricity markets

The majority of electricity which is traded in Europe takes place on the wholesale markets via different power exchanges. An example of a power exchange is Nord Pool, of which the Scandinavian and Baltic countries as well as Finland, Germany and the UK [Nord pool, n.d.a] are affiliated. Another power exchange is the EPEXspot, which includes the main part of the Western European countries like France, Germany, Benelux, the UK as well as Austria and Switzerland [EPEXspot, n.d.b]. As described in the beginning of this chapter, the Day-ahead market, Intraday market and Regulating Power market will be elaborated in this section. This is done with an underlying basis in the Danish electricity system, which due to the market coupling and the increased uniformity is very similar to other European countries, when it comes to practices. There can of course be smaller variations.
The following descriptions of the electricity markets will therefore take its basis in a Danish context.

## Day-ahead market

More than 70% of the electricity sold via Nord pool is done through the Day-ahead market called Elspot. Because of the market coupling in Europe, this market is today a part of an interconnected Northwestern European market, where trading across the main part of Europe takes places.[Energinet, 2016]

The Day-ahead market is based on purchase- and sales bids from generators and buyers of electricity. The actors have to make their bids before 12 a.m. CET, and the bids should include price and amount the actors want to sell or buy. The bids are made on hourly basis throughout the operational day, that goes from midnight to midnight the following day. Another way of bidding is by using block bids, that count at least three consecutive hours. These block bids are only accepted in full, and the reason for giving block bids instead of hourly bids can be because of high start-up costs for e.g. CHP plants, that results in a need for longer periods of production. Block bids are however only accepted if the sales price is lower than the average spot price in the specific period of time, and if the purchase price is higher than the average spot price. [Energinet, 2016]

After the power exchange has received all the bids, a system price is made by matching the purchase and sales bids with the presumption that the electricity can flow freely on the market, without taking into consideration, that bottlenecks at the transmissions lines can occur. This presumption means, that the electricity is expected to flow from low price regions towards regions with higher prices, and by that equalise the differences in price and cause an equal price across Europe.[Energinet, 2016]

In reality that is not the case, because these bottlenecks can result in the fact that electricity cannot flow freely. This is however a problem that the market coupling and expansion of transmission lines are supposed to mitigate or minimise. Because of the bottlenecks, different price areas are created across Europe. The spot prices across these price areas can vary because of the bottlenecks, which results in more expensive units have to be started up, instead of the cheaper alternative in form of import from other price areas. A price limit is however set, which means that as a general rule on Elspot, prices under ÷500 EUR/MWh or higher than 3,000 EUR/MWh is not accepted. These bottlenecks also results in the fact, that bilateral trades between producers and consumers only are made inside a price area, in which there per definition are no bottlenecks and the electricity can flow freely. When spot prices in each single price area are calculated they are released to the actors in each price area, so they know how much they have sold and bought. This is all done before 1 p.m. the day before the operational 24 hours.[Energinet, 2016] The spot price determination is illustrated in figure 5.4

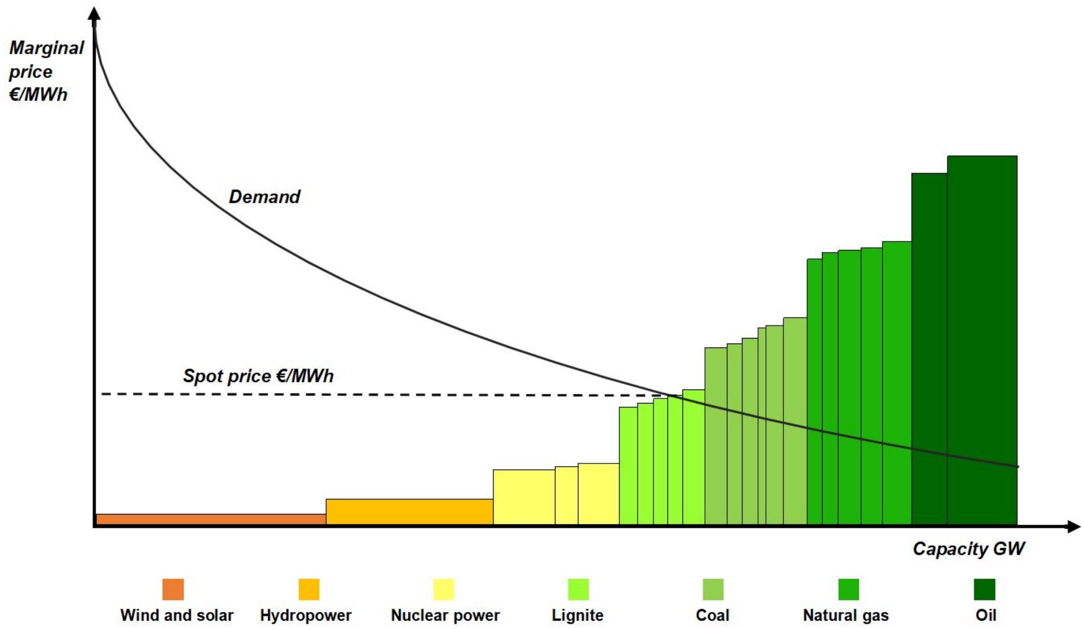


***Figure 5.4.*** Determination of the hourly spot price illustrated trough a merit order curve

The example in figure 5.4 shows, that demand and supply intersect around the lignite units, which means that the specific spot price for this hour is determined by the marginal costs for these units. This means, that the spot price is determined by the last activated sales bid and by that also the most expensive unit being used to produce electricity. All buyers of electricity have to pay that price, as well as all generators are being payed that price, no matter the marginal costs for the specific unit. This also means, that the more cheap RES capacity available results in a lower spot price, because the point of intersection will move to the left towards cheaper units as nuclear, hydropower or wind and solar. The opposite situation will occur in cases with low RES capacity available, by which more expensive units as coal or natural gas units have to be started up.
Another thing that can affect the spot price is of course the demand for electricity. A higher demand will move the intersection point towards more expensive units, and by that cause a higher spot price. The opposite will occur with a low demand for electricity. These tendencies are often expressed by the higher prices during the peaking periods in the morning and evening, while prices during the night time often are lower, because of the lower demand.

Despite the purchase- and sales bids, it is not always possible for an actor to deliver or consume the sold or bought electricity on the Day-ahead market, which can lead to a difference in the expected consumption and production, and by that cause an imbalance of electricity. Thus, there is a need for a market where the actors can trade them self into balance, in order to be able to deliver or consume the traded electricity. This is the Intraday market.

## Intraday Market

The Intraday market supplements the Day-ahead market and helps actors to come closer to a necessary balance between traded amounts and produced or consumed amounts. This signifies, that it is possible for actors to trade themselves into balance, if for example power plants is forced to stop, if wind turbines produces less electricity than expected due to unforeseen weather conditions or for a various of different reasons, the actors plan is not in balance after the gate closure of the Day-ahead market. The trading done on the Intraday market is significant smaller than the trading done on the Day-ahead market. However, the difference is expected to be reduced as fluctuating RES becomes a larger part in the production of power, making the production less reliable, why the need for markets like the Intraday market increases. [Energinet, 2016]

The Nordic Intraday market, which is operated by Nord Pool, is covering the Nordic, Baltic, UK and German markets. At 2 p.m. the day before the operational day Nord Pool announces the available capacities on the transmission lines. After which, transactions are available until the hour before operation.
The Intraday prices are based on a pay-as-bid auction basis for all transactions, unlike the Day-ahead market. This means, that the price for the same product may vary during the trading period, making the principles of the Intraday auction similar to the stock market. Just as on the Day-ahead market, it is possible to place block bids. The block bids can cover 1-32 hours, and is different from an ordinary auction bid as the whole block bid needs to be accepted, whereas an ordinary offer can be partial accepted.[Nord pool, n.d.b]
Further, Intraday markets across Europe is being market coupled as this writing, trying to establish a joint trading platform for the whole of Western Europe. The Intraday market managed by Nordpool covers connections in the Nordic countries together with the interconnections between Sweden-Germany, Norway-The Netherlands and East Denmark-Germany. The capacity, which is not used for the traded electricity on the Day-ahead market or other purposes, are disposable for implicit trading on the Intraday market in the case of Elspot. [Energinet, 2016]
If an actor does not manage to trade into balance within the auctions of the Intraday market, the TSO in the given area will regulate the system in order to have a balanced grid.

## 5.3 Imbalanced electricity system

Imbalance in electricity markets occur when the factual production is not consistent with the expected production. All electricity production can vary, but especially fluctuating sources of electricity, are practically impossible to forecast in comparison to e.g. power plants, although weather forecasting makes the production more reliable. Hence, it is difficult to maintain the balance, for which reason balance operators rarely keep within their plans for an operational hour. Imbalances do not only occur due to production e.g. can consumers affect the balance by using more or less power than predicted.
It is important that the grid is in balance in the instant of operation, as an imbalance between consumption and production can affect the frequency in the system, and in worst cases result in a disconnection of consumers. A system which is not in balance after the transactions on the wholesale markets is managed by the TSO in order to obtain a stable frequency of 50 Hz in the transmission grid. However, the consumption of power is sometimes higher than the power produced, for what reason the frequency will fall below 50 Hz. In this particular case the TSO must make sure, that one or more generators deliver the needed power, which is done by purchasing power from the generators, who are able to deliver. When such need for regulation occurs it is referred to as upward regulation. If the opposite happens, meaning the production of power is higher than the consumption, the frequency will rise above 50 Hz. For what reason the TSO must ensure that generators reduce their production of power or consumers increase the consumption in order to equalise the production and consumption. Such regulation will be refereed to as downward regulation. Upward and downward regulation is part of the system services, which are used in order to balance a system within the hour of operation.

### System services

System services are having the purpose of compensating the imbalances that different actors could not cover on the Wholesale markets or imbalances that occur due to unforeseen events during the operation hour. The system services are managed by the TSO, for what reason reserved capacity will be available in the operation hour, as upward or downward regulation.

An explanation of how system services perform is explained with the focus on the price area of DK1 in Denmark. The system services are delivered by different actors in different areas, and must be available during an operation hour. The services are divided into three function areas; frequency stabilisation, frequency restoration and balance equalisation and are delivered by 3 different types of reserves:

- **Frequency Containment Reserve** (FCR) is called the primary reserve and consists of production and consumption units that automatically reacts on frequency variations in the grid. By using frequency measuring equipment this reserve type

stabilises the frequency, and is able to activate within seconds. The regulating units are fine tuning the frequency and should be able to deliver the needed capacity until the aFRR units can take over the stabilisation of the grid. A requirement is therefore, that the FCR units are able to stay active for at least 15 minutes. The needed ovrall capacity is relative to the electricity production in the transmission area, but the amount for the Danish DK1 has been relatively stable during the last years, and counts a demand of around 20 MW reserved capacity for the purpose. This relatively small amount of MW also indicates, that this is a limited market.
The market works like the Day-ahead market, where the actors once a day can make their bid on both upward- and downward regulation, the gate closure is at 15 p.m. The difference from the Day-ahead market is, that the bids are separated into 6 blocks of 4 consecutive hours and all accepted bids receives a disposable amount equal to the most expensive accepted bid. If the units are activated, these are settled at normal upward- and downward regulating prices. [Energinet, 2017c]

- **Automatic Frequency Restoration Reserve** (aFRR) is called the secondary reserve and has an effect regulation of 15-minutes. This reserve is intended to release the FCR, equalise imbalances which are to small for the manual reserves and to restore the agreed balance in the Danish-German connection. These units are not automatically stabilising the grid, but act upon an automatic generated signal from the TSO sent to the balance responsible party, who distributes the signal to the units participating in the aFRR market. These units are often plants running on partial load or plants that have a very quick start-up. One of the reason for using plants running on partial load is, that a requirement for participating on the secondary reserve market is, that the offered capacity should be symmetrical. This means the plant should be able to deliver equal amounts of both upward- and downward regulation.
  The market is based on the principle of pay-as-bid, why the TSO chooses the cheapest units. If the units are activated, they are compensated the same way, with an amount related to the ruglation. This is for upward regulation the spot price + 100 DKK/MWh and downward regulation is the spot price - 100 DKK/MWh. Thus the prices can not exceed the upward regulating price nor go below the downward regulating price in the Regulating Power market. Today, 100 MW aFRR in West Denmark is reserved via import from Norway, why the TSO will only buy aFRR from generators, when the need for aFRR exceeds the 100 MW. [Energinet, 2017c]

- **Manual Reserves** (mFRR), also known as regulating power or tertiary reserves, cover most of the Danish reserves and is the capacity that after agreement with the TSO, is reserved by the actors to manually balancing of the grid within the operation hour. The needed capacity is determined by the capacity of the biggest unit/transmission line in the price area. The manual reserves must be able to deliver maximum power within 15-minutes. The TSO buys disposable capacity, which is often only positive capacity, which means the ability to deliver upward regulation,

thus they have the ability to buy disposable downward regulation. This purchase of manual regulating power is done via daily auctions. The generators are payed after the same principle as aFRR, where the disposable amount is determined by the most expensive activated bid. The auction for disposable regulating power are taking place in the morning, where the TSO announces the expected needed capacity at 9 a.m. while the result of the auctions are announced on their webpage at 11 a.m.
The actual market for regulating power takes place on the joint Nordic Regulating Power market called "Nordic Operational Information System" (NOIS). Here the generators who won the auctions for disposable capacity are obliged to make their bids for a predefined time period and hand it in to the TSO at 5 p.m. the day before. Meanwhile other actors can voluntarily bid on both upward- and downward regulating power, if they find it attractive. That can be done up to 45 minutes before the operation hour.
During the operation hour, the bids are activated and a regulating power price is calculated based on the same principle as in the Day-ahead market, which is the hourly marginal price. This means that all units are payed the same settlement price. Usually the regulating power price is equal in all the Nordic price areas, thus bottlenecks can lead to different prices in the areas. [Energinet, 2017c]

These voluntarily offers allow different actors to participate on both the Day-ahead market and potentially the Regulating Power Market, which increases the opportunities for generating profit.

A significant amount of the above mentioned system services are however purchased through bilateral agreements between the TSO and different market players. As illustrated in figure 5.5, the price for reserves and regulating power is often higher than both the electricity on the Day-ahead and Intraday markets. This is due to the fact, that the need for regulating power is more critical. A factor that makes the price higher is also the fact, that some generators must reserve capacity to be able to deliver regulating power, without being certain that the demand for regulation will occur.
As described above, the actors are compensated through a disposable payment and a activate payment, which means they get a payment for having reserves disposal and they get an extra payment when these are activated. This can also result in higher prices for regulating power.

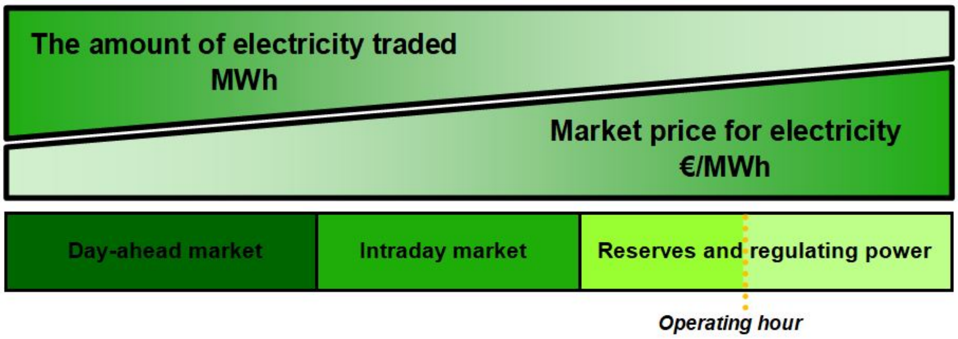


***Figure 5.5.*** Price varieties and electricity amounts related to markets and time periods.

In for example the Danish system, proactive planning is used, for what reason more slow starting units, such as the manual reserves can be used in order to accommodate imbalances. Doing so, is utilising the fact that regulating power is less costly than aFRR. [Energinet, 2017c]

Despite all the different markets and possibilities for trading, actors however, are not always able to trade themselves into balance, which therefore results in imbalances. The amount of electricity delivered or consumed is therefore not consistent with the traded amount. Different settlements determine the fee or extra payment for delivering another amount than planned. These settlements are managed by the TSO at the end of the 24 hour of operation, and will be further elaborated below.

## Settlements of imbalances

On the Regulating Power market, it is the TSO's responsibility to equalise the production and demand, within an operation hour, and it is done through purchase of upward- and downward regulation, as described above.
As this regulating power, the transaction of imbalances is settled after the hour of operation. For what reason, the imbalances between the different actors' operation plan and the consumed or delivered electricity are settled, which is done on an hour by hour difference.
The imbalances is in Denmark calculated from either the "one-price model" or the "two-price model" - separately calculated for "consumption & trading" and "production".[Energinet, 2016]

### One-price model

The one-price model is used when calculating consumption & trading. Imbalance in the consumption & trading is defined by Energinet [2017a] as *"Production plan + registered consumption + plan of transaction[1] "*. If the imbalance is positive, the actual consumption has been less than the planned, causing a need for downward regulation. Thus, a

[1] positive and negative values determine if the plan of transaction is for purchase (positive) or sales (negative)

negative imbalance is equal to a consumption, which is higher than planned, causing a need for upward regulation. In the One-price model, there is one way to calculate the costs of imbalances:

1. All imbalances are calculated with the areas regulating power price

**Two price model**

The two-price model is used when calculating for production. Imbalance in the production is defined by Energinet [2017a] as *"registered production - production plan"*, which signifies that, if the production is positive, the actor of balance causes a need for downward regulating, due to the actual production is higher than the production planned. In the two-price model there are two ways of calculating the cost of imbalances:

1. Imbalances following the systems overall imbalance is calculated with the areas regulating power price
2. imbalances not following the systems overall imbalance is calculated with the area spot price

In order to exemplify the two price model, figure 5.6 illustrates which prices is used in terms of the overall system balance and the balance of the responsible parties.

| | | Imbalance in the overall system | |
|---|---|---|---|
| | | Negative (Upward regulation needed) | Positive (Downward regulation needed) |
| Balance responsible parties imbalance | Negative | *Upward regulating price* | *Spot price* |
| | Positive | *Spot price* | *Downward regulating price* |

***Figure 5.6.*** Illustration of prices in the two price model - actors as electricity suppliers or generators etc. are here illustrated as *balance responsible parties*.

This means, that if a generator has excess production, and the system in general has a need for upward regulation the electricity generator will be payed according to the spot price, because the excess production mitigates the problem. If the system instead was in need of downward regulation, and the generator therefore indirectly reinforced the situation, the generator will only be payed according to the regulating price, which in this case is lower than the spot price.

It is the TSO's responsibility to make the settlement for the actors. It is done separately for production, consumption and transaction, e.g. an actor responsible for both production and consumption will receive two statements every day.[Energinet, 2016]

#### Summation of Market coupling and electricity markets

To get a complete overview of how the electricity markets are functioning, figure 5.7 has been conducted. The figure is an illustration of all the explained markets, and how they interact in a joint European market.

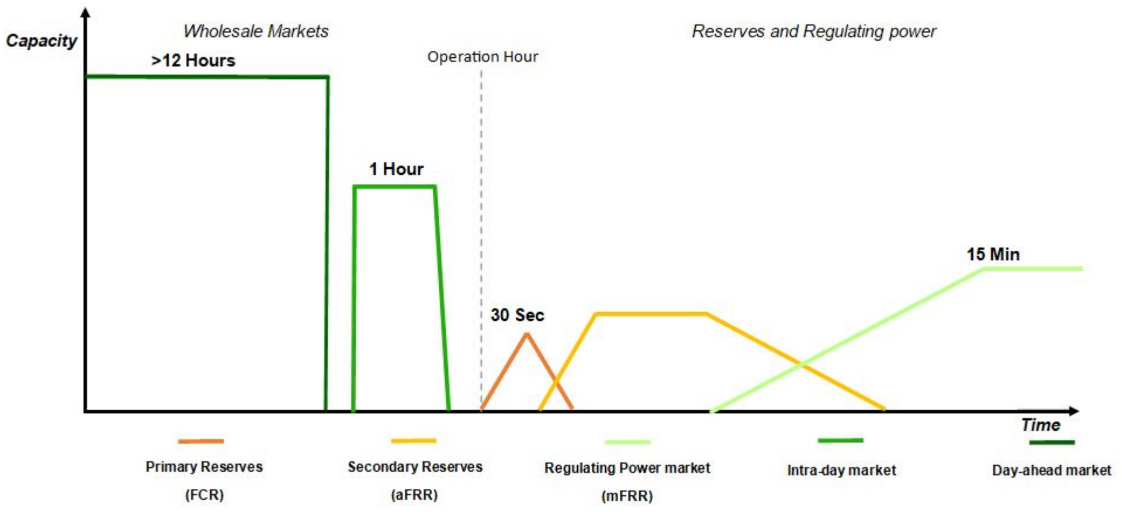


***Figure 5.7.*** Overview and compilation of electricity markets

The figure is divided up between the wholesale markets and the reserve markets. This is done as wholesale markets, includes electricity amounts traded and determined before the hour of operation, while the bids and trades of reserves are activated within the hour of operation. The whole sale markets share the largest amount of traded electricity, while the reserves, primarily the regulating power, is used in order to cover for imbalances in the overall system. Moreover, trading in the Day-ahead market needs to be carried out minimum 12 hours before the operation hour, while the Intraday market is available after the Day-ahead market and up to around 1 hour before the operation. The reserves on the other hand become activated in the operation hour, for what reason the FCR must be able to deliver within 15-30 seconds, whilst the aFRR partly automatically regulates, in order to release an active FCR, letting the slower mFRR maintain the frequency.

By describing and now understanding the electricity markets, this chapter provides a general understanding of how the electricity markets are functioning. It is therefore possible to understand the principles of calculating the flow of electricity and the flow of cash, when trading. Therefore, the whole concept of electricity markets, the opportunities and practices related to these as well as the settlements are vital in order include these in the Technical Energy Model and thereby asses the different scenarios.

CHAPTER

# 6 Results from the Technical Energy Model

The results from the Technical Energy Model is divided into an illustration of the operation during 24 hours, based on the data explained in the methodology, and economic calculations of how the different scenarios perform compared to each other. This is further supplemented with a sensitivity analysis to clarify how changes in different variables affect the different scenarios.

## Operation of energy scenarios

To give an overview of the different scenarios and how they operate, every scenario is illustrated in a visualisation in comparison with the spot price and the imbalances generated from the wind farm as seen in figure 6.1. However, the Reference scenario and Scenario 1 are not affected by the imbalances as these scenarios do not take imbalances into account.

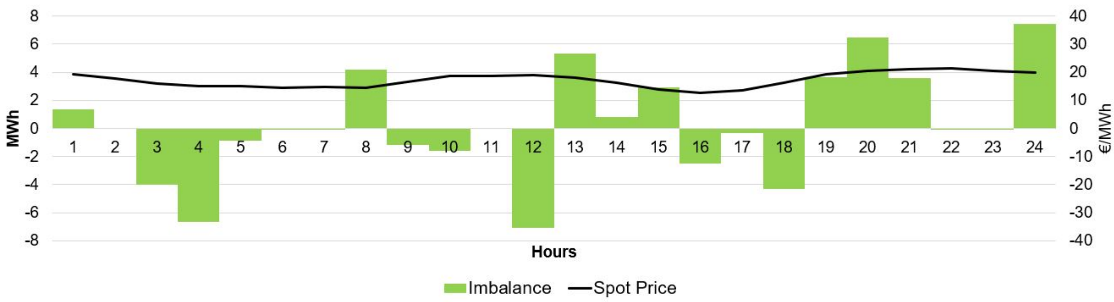


***Figure 6.1.*** Spot price and imbalances for all scenarios on the $17^{th}$ of April 2016 in a 24 hour span.

Figure 6.1 shows the imbalances and the hourly spot prices, which both are parameters that affect the different scenarios. While the spot price is essential to the Reference scenario and Scenario 1, the imbalances are significant for the operation of Scenario 2 and 3. The following will describe the operation of every scenario for 24 hours on Sunday the $17^{th}$ of April 2016 - and all included numbers can be found in Appendix A. Further, figure 6.1 shows, that the imbalances are very varying in both size and direction, as well as the spot price is relatively stable with a small increase around the peaking hours around noon and supper. The reason for the relatively late peak in the morning could be due to the fact that it is a Sunday. All hours contain imbalances except hour 11 and 22,

this is due to the fact, that the forecasted production is equal to the actual production. This only happens in 37 hours in the modelled year, why two hours in one day must be considered as very unusual. Other examples of no imbalances could be caused by low prices or low wind speeds. Hour 2 is characterised by low wind speeds, which results in low production and therefor an almost non-existing imbalance.
When analysing the battery's function in the Reference scenario, figure 6.2 reveals that the standalone battery operates by buying and selling electricity dependent on the spot price as described earlier.

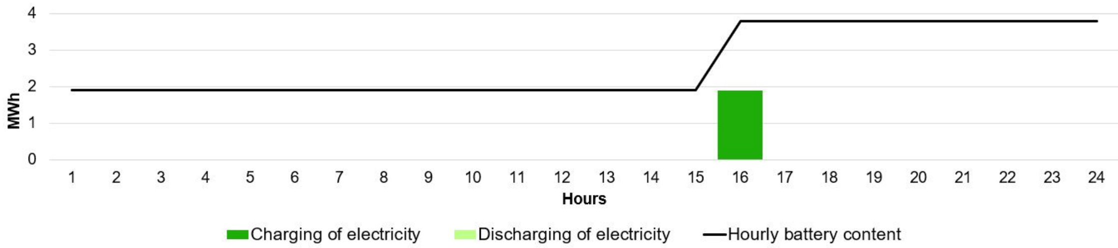


***Figure 6.2.*** Operation of battery in the Reference scenario, on the $17^{th}$ of April 2016 in a 24 hour span.

The battery sells and purchases electricity during the 24 hours, as a result of fluctuating prices. The battery charges when the price is low, illustrated in hour 16 and discharges again when the price is considered high enough to gain profit, this is however not illustrated as the battery do not discharge within the 24 hours, why the price must be too low to gain profit. This is due to the fact that, EnergyPRO calculates the value of 1 MWh charged to the battery and 1 MWh discharged from the battery, and assess these numbers to evaluate and determine in which hours the battery will charge and discharge. In such calculations both grid tariffs, O&M costs and the efficiency of the battery are included. This means, that a certain price difference is needed to generate the expected profit, for what reason the relatively stable prices result in small price differences, and therefore no incentives for discharging during the 24 hours.
The battery in the Reference scenario actually stays fully charged until the $28^{th}$ of April, because of low and stable prices. Such circumstances of course challenge the economy for the battery. This is not the case for the battery in Scenario 1, whose operation is illustrated in figure 6.3.

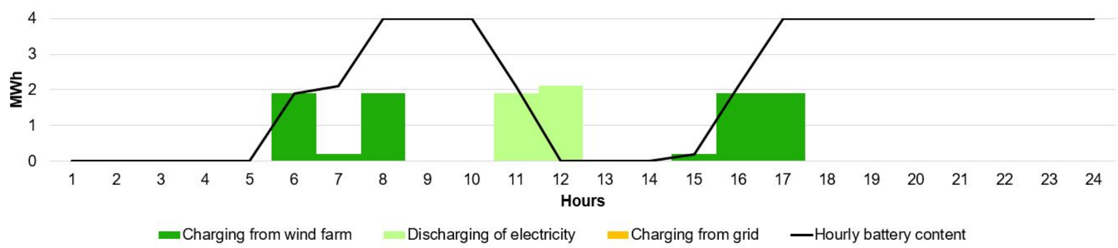


***Figure 6.3.*** Operation of Scenario 1, on the $17^{th}$ of April 2016 in a 24 hour span.

Contrary to the battery in the Reference scenario, the battery in Scenario 1, Scenario

2 and Scenario 3 interacts with the wind farm behind the meter, for what reason, the battery can utilise the excess power from the wind farm, which in figure 6.3 is described as the general charging.
Scenario 1 as explained in the methodology, is having the same setup as the Reference scenario. This allows the battery to charge from the wind farm, not paying the grid tariff, for what reason the battery charges and discharges more often. Opposite to the Reference scenario, the battery in scenario 1 charges in the hours of 6, 7 and 8, and again in hour 15,16 and 17, which causes the battery to discharge in between. In the 24 hour span, the battery does not charge from the grid, as the wind farm produces in all hours. Due to the saved grid tariffs, the price differences during the day has suddenly become favorable, why the battery can generate profit in an increased number of hours compared to the Reference scenario.
In both Scenario 2 and Scenario 3 the operation strategy is to cover the imbalances from the wind farm. How this is done for scenario 2 is shown in figure 6.4.

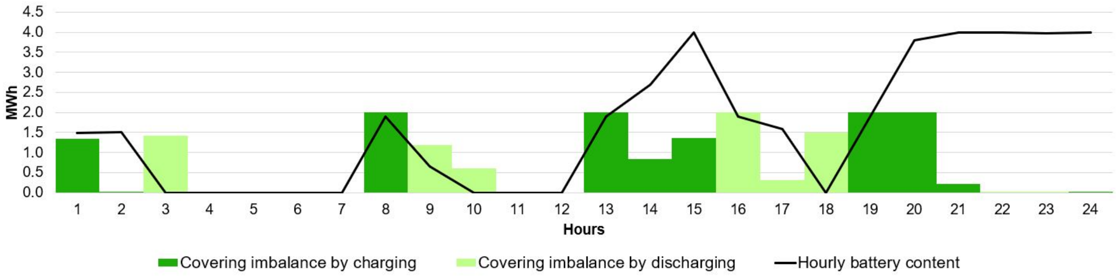


***Figure 6.4.*** Operation of Scenario 2 on the $17^{th}$ of April 2016 in a 24 hour span.

On the basis of the operation strategy, the figure visualises how the battery mitigates imbalances in almost every hour. Thus, it can be seen, that the storage system charges and discharges dependent on the imbalances and not the spot price.
As seen the battery cannot cover the positive imbalance in hour 24 because it is fully charged in hour 23. In this case it is not a bad situation, because the surplus production will result in a payment, and as seen in figure 6.1 the spot price is relatively high, which results in a higher revenue. However, the opposite situation occurs in hour 4,5,6,7 and 12 where the battery cannot reduce negative imbalances due to an empty battery. Thereby the battery cannot mitigate the negative imbalance, and the HSS must pay a fee. This situation illustrates the limitation for the battery, in form of restricted capacity, very well.

Despite the restricted capacity the general utilisation of the battery is much higher in this scenario than in the two former scenarios. The operation strategy is rather simple in scenario 2, as the battery's function is to cover as much of the imbalances as possible, by moving around the production from the wind farm. Because of unknown imbalances before the operational hour, it cannot act upon prices and wait a few hours to cover an imbalance, which will result in a higher fee. With such an approach the battery could have ignored the imbalance in hour 9, and used the electricity to cover the negative imbalance in hour 12, where the price is higher. However, due to the unpredictability for imbalances as well as the Regulating Power prices and demands, this is not possible.

Exactly as Scenario 2, Scenario 3 utilises the electricity from the wind turbine by covering imbalances. In addition, the operation strategy in scenario 3 allows the battery to participate on the Regulating Power market as explained in the methodology in section 4.2. A visualisation of an operation day, is exemplified in figure 6.5.

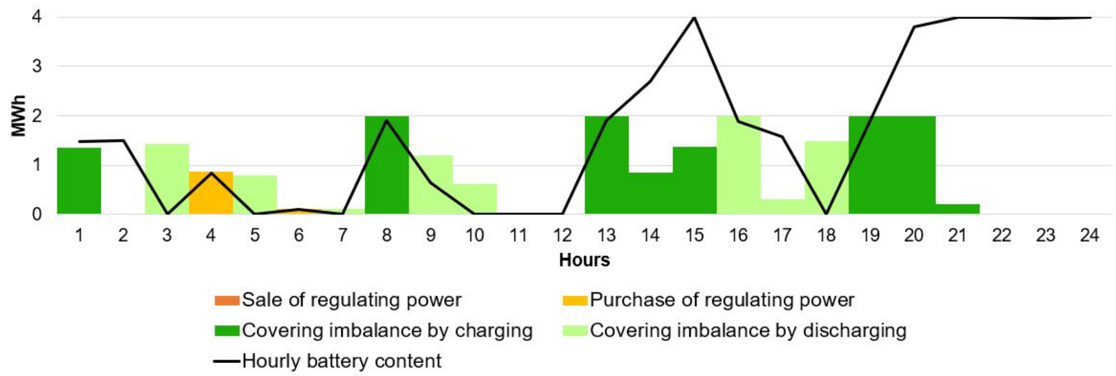


***Figure 6.5.*** Operation of Scenario 3, on the $17^{th}$ of April 2016 in a 24 hour span.

In the figure, it is shown that the operation strategy allows the battery to purchase electricity on the Regulating Power market as illustrated in hour 4 and 6. In these hours the battery is trading, to be able to cover the imbalance in the following hour, which is not possible in Scenario 2, due to a lack of electricity on the battery. Contrary, the battery does not sell electricity within the 24 hours, primarily due to the fact that imbalances are higher prioritised exemplified in hour 23, where a minor imbalance prevents the battery from selling electricity.
Further the battery, could have bought electricity in hour 11, where there is no imbalance, however there is no need for downward regulation in that hour, which means the battery cannot buy the needed electricity.

Although, these visualisations provide an overview of the operation strategies in the different scenarios, it is difficult to see the overall effects from the different strategies. Therefore, the costs and revenues related to the participation on the markets are calculated on an hourly basis in the Technical Energy Model. This, together with the cost of investing in the battery as well as the O&M costs are resulting in an economical analysis of investing in a utility scaled battery, based on the operation strategy and framework for this thesis. The economical analysis and the results are presented below.

## Economical results

It is found in the Technical Energy Model, that all four scenarios result in an operational income, which is negative. This means that the generated profit on the market is less

than the annual O&M costs. This results in an annual expense in the operation of the battery in all four scenarios.
Looking at figure 6.6, the operational income from installing the battery is calculated annually for every scenario. The operational income is calculated by subtracting the operating expenditures from the revenues resulting in an income of respectively -37,000 €, -25,000 €, -40,000 € and -39,000 €.

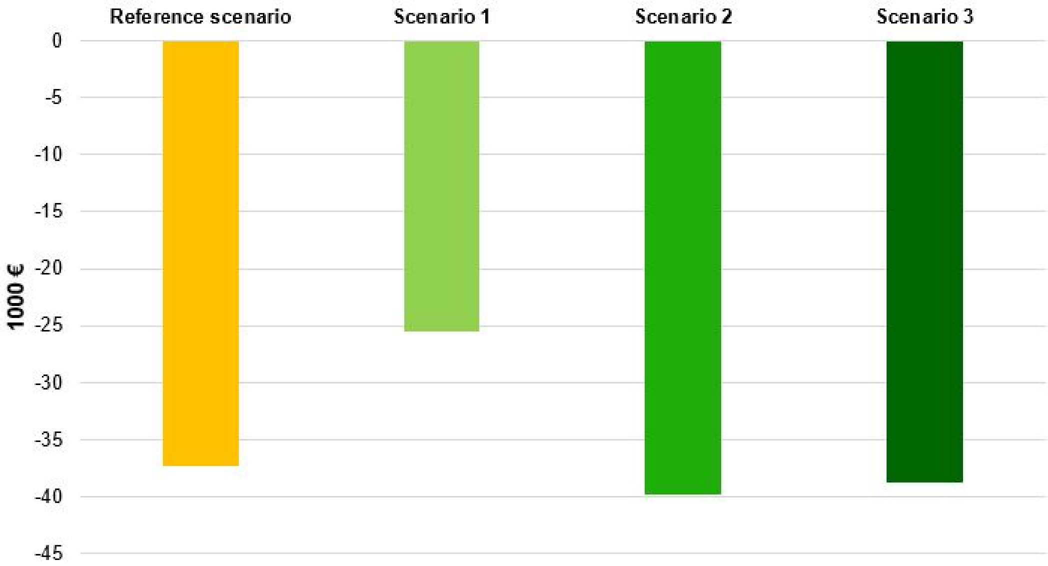


***Figure 6.6.*** Operation income generated from the battery in every scenario.

By analysing these numbers, it is clear that it is not feasible to install a battery regardless the operation and system used in the analysis. However, by installing the battery in a joint HSS, Scenario 1 illustrates, that trading behind the meter allows for an increased income, whereas an operation strategy based on the reduction of imbalances, seems to be ineffective, even with the ability to trade on the Regulating Power market. The low impact from selling and buying regulating power is considered to be the result of imbalances being the 1. priority in scenario 3, for what reason the battery rarely trades on the Regulating Power market.
The annual operation income from the batteries is a reflection of the revenue generated by the battery when the income from the wind farm is subtracted, for what reason the annual operation income is the battery's contribution in the given scenario.
The primary cause to a negative annual operation income, is to be found as the battery in some cases has to pay a tariff for purchasing electricity from the grid, but especially the high fixed O&M costs, for what reason the expenses surpass the revenue of selling electricity. The figure 6.7 illustrates these costs for every scenario, of which, it is shown, that the costs of tariffs is significantly higher for a standalone battery, compared to HSS. The grid tariff in the Reference scenario counts around 5.800 € a year, while the grid tariff covers a minimal amount in scenario 1 and scenario 3. Based on that, one of the main advantages when implementing the HSS seems to be the exemption of tariffs.

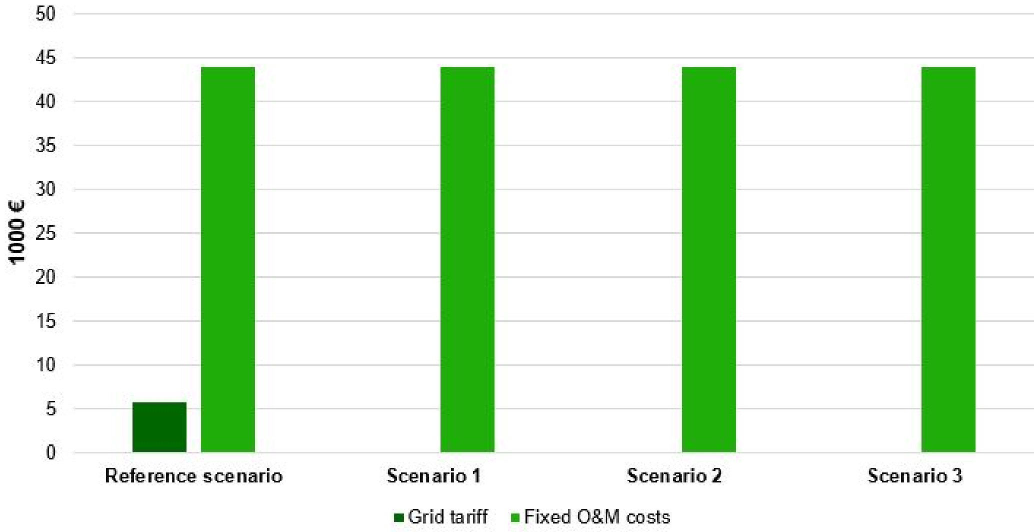


***Figure 6.7.*** Annual operational costs of the batteries.

Thus, the annual costs of installing a battery is surpassing the annual revenue generated, for what reason there is no payback time on the investment. The fact that the operational income from the battery is negative, also results in a negative NPV during a lifetime of the battery, which is illustrated in figure 6.8.

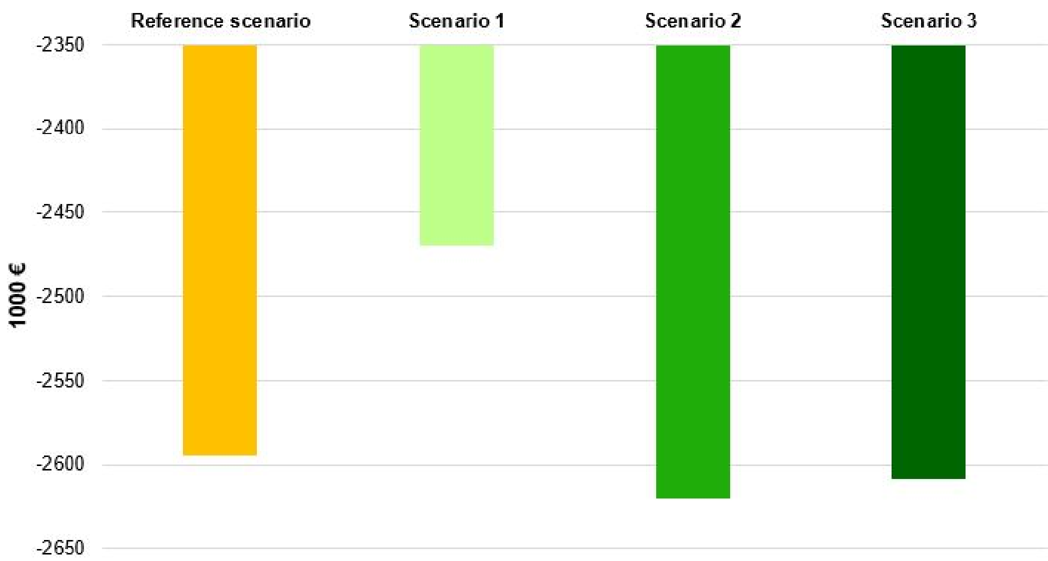


***Figure 6.8.*** NPV during a lifetime for the batteries included in the different scenarios.

Figure 6.8 shows the NPVs for the different scenarios, which are respectively -2,594,000 €, -2,469,000 €, 2,620,000 € and 2,608,000 €. Based on this, it is considered not feasible investing in batteries, within the given framework of this thesis. However, the economical results show, that combining the battery with a wind farm, instead of operating it as a standalone technology, can provide a result, which is improved by 125,000

€/lifetime, at least when it comes to electricity arbitrage.

Based on these results it is possible to investigate, which variables, that can affect the investment and in what magnitude these variables can influence the operation of a HSS, and if changes in these variables potentially can make HSS profitable.

## 6.1 Sensitivity analysis

Despite the fact that investing in a HSS, seems like an unprofitable investment, future development and price changes can potentially change the situation and make the HSS economic sustainable. A sensitivity analysis is therefore conducted to see how such changes affect the HSS. The first parameter which is modified is the volatility in the electricity markets, this counts both the spot price and regulating power prices.
The volatility is increased, while the average electricity price stays the same. This is done as shown in equation 6.1 using the hourly spot price as an example.

$S_h$ = *Hourly spot price*
$\lambda S_h$ = *Average hourly spot price during the year*
$S_r$ = *Sensitivity rate*
$\Delta S_h = (\lambda S_h \times S_r) - \lambda S_h$

$$\textit{New hourly spot price} = \mathrm{S_h} \times \mathrm{S_r} - \Delta \mathrm{S_h} \tag{6.1}$$

Simplified, this is done by multiplying the spot prices with the sensitivity rate and subtracting the difference between the original average spot price and the average spot price after multiplying with the sensitivity rate, the same approach is used for the regulating power prices. This approach causes the volatility in the market to change, but freezes the average spot price in the same level.
The sensitivity rate is in this case 140%, which means an increase of 40%, just as the lower level is a decrease of 40% equal to a sensitivity rate of 60%. This means, that the maximum and minimum spot prices go from a level of around 136.0/-85.5 €/MWh down to 73.4/-21.4 €/MWh, which indicates a big difference. The effects of the increased and decreased volatility can be seen in figure 6.9 below.


***Figure 6.9.*** The NPVs of the four scenarios when price volatility is changed

An interesting effect of the changed volatility is the way it affects the scenarios differently. The Reference scenario and Scenario 1 are affected positively by an increasing volatility, as the NPV becomes less negative. This is presumably due to the operation strategies, which take the price into account and act upon these. The batteries will therefore buy the electricity in low price periods and sell it again in high price periods. In that way, they exploit the price variations which are getting higher along with the price volatility.

Another interesting aspect is the opposite effect in Scenario 2 and Scenario 3. At first sight this can seem a bit strange, but an explanation could be a combination of the operation strategy, and the fact that the generators in the HSS are wind turbines. First of all, the operation strategies do not take the price into account in the same degree as the two energy arbitrage scenarios. This means that there is a limited acting upon the new and more favorable price differences for arbitrage. This in combination with the wind turbines could be the explanation. This is due to the effect of the merit order curve explained in figure 5.4, which shows, that when there is a lot of cheap RES in the system, the overall spot price will often be on a lower level. Low spot prices are therefore often linked to high production from cheap energy sources as wind turbines. So as a generalisation, the higher production from the wind farm, the higher imbalances, but also hours with generally lower spot prices.

All these low spot prices are, due to an increase in volatility, affected negatively in form of a decrease, while the higher prices are affected positively in form of an increase. This means that the payment for the surplus production in scenario 2 and 3 often will be settled to a lower price, just like the settlement for negative imbalances will be settled with lower prices, by which the reduction of imbalances do not have the same negative effect on the economy as when the fees are higher.

This shows, that when the operation strategy considers the price the price and the variations in these, a higher volatility is favorable.

Another parameter is the general price level, where the volatility and thereby the absolute price difference stays the same, but the general value of the electricity is changed. The effects of a price increase of 5 € and 10 € as well as a price decrease of 5 € and 10 € are shown in figure 6.10.

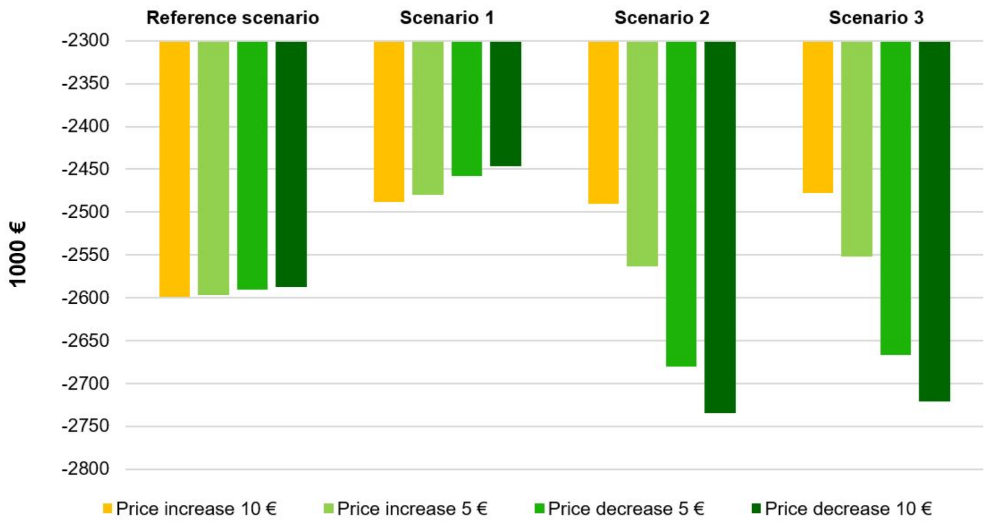


***Figure 6.10.*** The NPVs for the four scenarios when price increases and decreases are applied - both spot price changes and regulating power prices changes are applied.

When applying the price changes to the four scenarios, they are all affected, but in an opposite way than the volatility changes. When looking at the Reference scenario and Scenario 1, these are actually increasing the NPV along with electricity prices are decreased.

A good explanation to this could be the act upon prices and especially better conditions for buying electricity. Exemplified in the 5 € decreasing scenario, all the original spot prices between 0 €/MWh and 5 €/MWh suddenly becomes negative, which results in the fact, that the batteries suddenly are being paid for charging the electricity instead of paying for it. Thus, it is not the price in itself, but a combination of the increased number of negative prices along with the efficiency due to the loss of electricity during charging and discharging, that makes the difference. This loss is taken into consideration when energyPRO calculates the value of 1 MWh electricity on the battery to estimate whether the battery shall charge or discharge. To charge 1 MWh an amount of 1.05 MWh has to be bought, and when discharging 1 MWh from the battery only 0.95 MWh reaches the grid. This, in combination with the negative prices, have a positive effect.
Simplified by an example: When charging in an hour with a spot price of 10 €/MWh this will cost 10.5 € to charge 1MWh to the battery while the revenue for discharging the same amount is 9.5 € which would result in a loss of 1 €. If the price was -10 €/MWh instead, it would be opposite and result in a revenue of 1 €/MWh. This means that hours, that previously was not profitable suddenly becomes profitable, which results in an improved economy for the battery in the Reference scenario and Scenario 1.
The effect of the grid tariff is again easy to see in these two scenarios, when comparing

them. Due to the grid tariff, it is less favourable, because the extra sum added to the price results in less hours with negative prices, and of course in general makes it more unprofitable due to the extra costs.
When looking at Scenario 2 and Scenario 3, it is to some extent the same tendency as the price volatility analysis. When prices are increasing, the payment for surplus production is higher, as well as the fees for negative imbalances, this means the mitigation of these becomes more important for the economy. It of course has to be said, that the value of the electricity from the wind farm charged to the battery also becomes more valuable, but apparently the effect from mitigating higher fees is more important. Another explanation can be the fact, that the income from surplus electricity is higher than the fees for deficit production. The price decrease therefore has a bigger influence on the income.

At the same time, the price decrease also has a higher relative influence on the prices in the three wind HSS scenarios including the wind farm, due to the fact mentioned above, where the correlation between lower prices and wind production is explained. The lower prices also result in less production from the wind farm, because the bid for participating on the spot market is the same, which is equal to the O&M costs for the wind turbine. Therefore, there are less electricity production as well as imbalances and by that less utilisation of the battery, where it can generate value to the HSS. This is also supported by the Reference scenario, which is more stable due to the non existing wind production.

It can be concluded that the increased volatility on the electricity markets has a positive effect on the revenue related to the operation of the batteries, when price difference is included in the operation strategy, as it is in the electricity arbitrage scenarios in the Reference scenario and Scenario 1. While a general price increase is more favorable for the scenarios including wind turbines and especially the scenarios focusing on the reduction of imbalances. Danish Energy [2018b] foresees a lower price increase, but their focus is also on the increased volatility in future prices. If the electricity prices increase along with an increasing volatility with even more negative prices, this could be favorable for operation strategies based on exploiting the price differences in the market. However, it has to be mentioned that the development of electricity prices is very unpredictable and difficult to forecast due to the many parameters that have an influence on the price. These parameters cover political decisions, weather conditions, fuel prices, development of transmission lines, future demand and consumption as well as the development of the supplying sector.

Another parameter that is affecting the NPV for all four scenarios is the investment costs for batteries. Price changes for the investment costs could therefore potentially have a high impact on the feasibility of the scenarios. Due to the fact, that the fixed O&M costs are set to 2% of the investment costs, these are changed along with the investment costs. Figure 6.11 shows how the different NPVs for the scenarios react to changes in the investment costs.

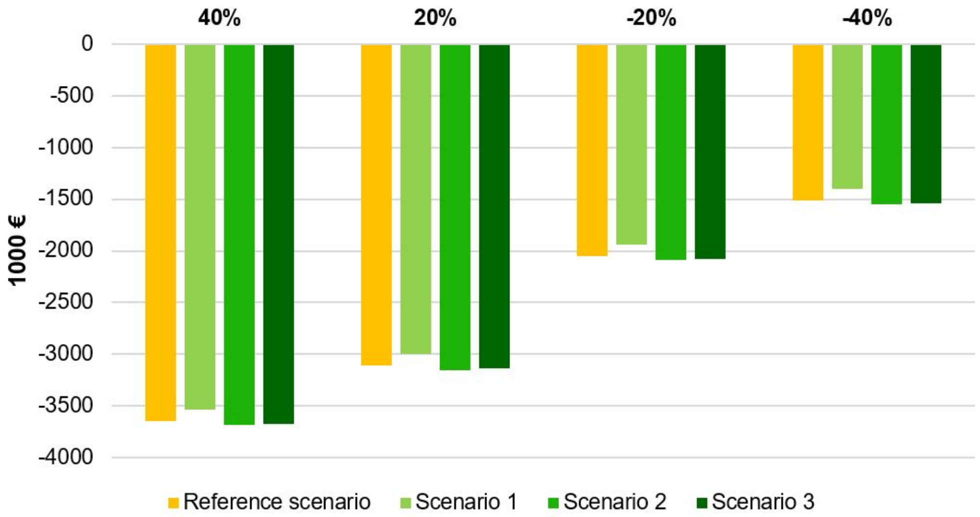


***Figure 6.11.*** The NPV for the four scenarios when investment costs are changed

A reduction in the investment costs of course leads to a better NPV for all of the three scenarios. The sensitivity analysis includes a price increase, but the relevance of this can be discussed due to the fact that all expectations are, that the price for batteries will decrease over the next years, as explained in 1. Despite the expected price reductions, the NPVs are still negative for all scenarios, and a serious price reduction is needed if the NPV should become positive only caused by a potential decrease of investment costs and lower fixed O&M costs. However, this analysis shows, that the lower investment costs will be an important step towards feasible HSS as well as standalone batteries.

The battery included in the energy model used in the analysis is a 2MW/4MWh lithium-ion battery, but the size of batteries can of course vary, as well as different proportions and sizes can be suitable for divergent systems. The model has been simulating a year with different capacities for the battery, to investigate whether this has an influence. The relation between charging capacity and battery capacity has been kept the same, which is 1:2. Figure 6.12 shows the NPV for the scenarios including different sizes of batteries.

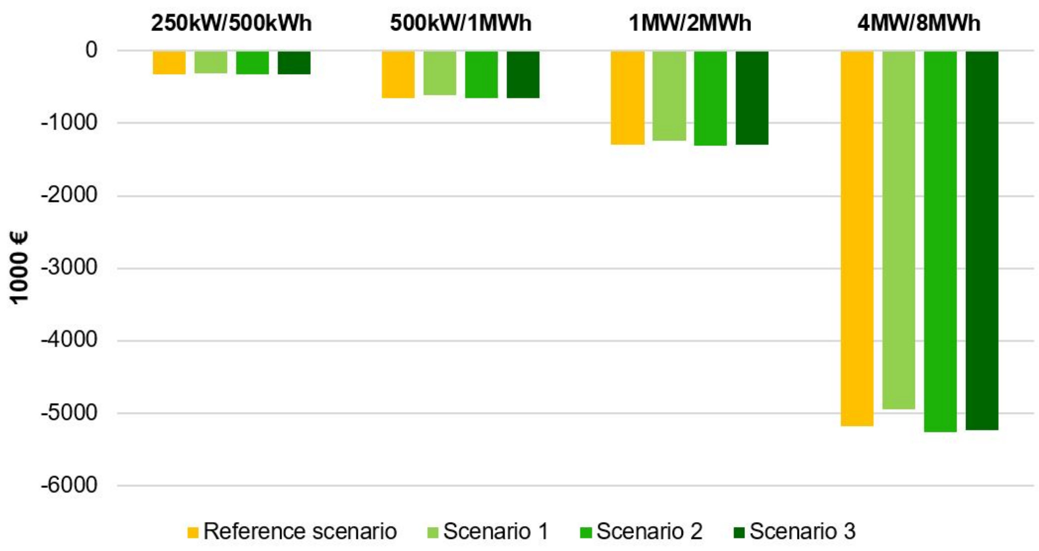


***Figure 6.12.*** The NPV for the four scenarios when capacities for the battery is changed.

The inclusion of the different sized batteries directly changes the NPV, due to the lower investment costs and O&M costs related to the size of the battery. The operation of the HSS and the battery is kept the same, and the annual turnover is almost proportional to the size of the battery. That makes sense when it comes to the Reference scenario and Scenario 1, that trades with electricity. The changed size of the battery does not affect the way it is operated, because this is related to the price and there is no limitation on the access to the amount of electricity in the Reference scenario, why it fills up the battery in the most suitable hours. Therefore, if the battery is doubled in size, it just buys twice as much in this suitable hour. When looking at Scenario 2 and Scenario 3, the size could have an impact due to the fact that some hours contain a limited amount of electricity, due to the imbalances which varies in size. This apparently does not seem to have a greater effect, probably due to the relatively small effect of reducing the imbalances.

The above made analyses show, that reducing costs for the investment and O&M as well as increasing the volatility are suitable for the economy when it comes to energy arbitrage, while the increasing electricity prices especially affects the scenarios with the priority of reducing the imbalances. Such developments of the prices seem to be the tendencies as well as the lifetime of especially lithium-ion batteries are expected to increase with around 100% from 2016-2030 [IRENA, 2017].
However, this analysis indicates a very low feasibility for the HSS and standalone batteries in general. This can be due to limitations for the battery, which is restricted in its operation due to the limited capacity available. This means that in very favorable hours, which can be consecutive, it can only charge and discharge once, compared to generators that can keep delivering the electricity in these favorable hours and by that improve the economy. Despite the relatively unfeasible outlook for HSS, the right tendencies are taking place and opens up for better conditions for implementing electricity storage and HSS in future energy systems.

CHAPTER

# 7 The role of HSS in future renewable energy systems

"The role of HSS in future renewable energy systems" is the last part of the analysis, and will serve as a discussion of how the results from the Technical Energy Model, can influence the future use of HSS. The chapter will discuss the results compared to articles, regarding the use of electricity storage in the future and therefore be the foundation of answering; "to what extent HSS should be a part of a renewable energy systems."

As the world's energy politics strives to a more sustainable approach, significant amounts of fossil energy are and will be replaced with RES now and in the future. Consequently this leads to a shift, for what reason the energy system needs to be reconsidered.
For a long period, the base load of the general European energy systems has been provided by large centralised power plants, from either coal or nuclear power, which are able to regulate their production and by that add flexibility to the system. These are fossil fueled, why the power plants will be phased out or temporary become biomass fired power plants. However it is very challenging to replace all fossil fueled power plants with biomass, as biomass is limited in its production. Therefore, the base load is at present being replaced with more unreliable RES such as wind and solar power. This transition is assessed by the Danish non-commercial lobby organisation called Danish Energy. They conclude that the transition can have consequences for the security of supply, as the ability to always be able to cover the consumption of electricity is declining. [Danish Energy, 2018a]
Among others Germany alone installed 5.3 GW onshore and 1.2 GW offshore wind power in 2017, resulting in the annual production covering 20 % of the yearly electricity consumption. Further, Germany strives to phase out electricity produced by nuclear power plants by 2022. Nuclear alone produces 72 TWh, which is 38 % higher than the net-export for the country, for what reason the export from the country is expected to fade the coming years, and therefore might impact surrounding countries dependent of continual power. [Danish Energy, 2018a]
Nevertheless, the fact that large amounts of reliable power disappear in the future years calls for other alternatives in order to maintain the security of supply. Today, multiple directions towards solutions are considered for example Smart Energy Systems, which is also mentioned in the introduction in chapter 1. The concept of Smart Energy Systems is based on the synergy between sectors and is defined by Lund [2009] *"as an approach in which smart electricity-, thermal- and gas grids are combined and coordinated to*

*identify synergies between them to achieve an optimal solution for each individual sector as well as for the overall energy system"*. Further, the concept of market coupling is gaining ground in Europe, meaning that the produced power in one country can be consumed in another country as explained in section 5, one example is Denmark, who is expanding the capacity to surrounding countries. Denmark currently has several transmission lines, making it possible to trade with different countries, and also has additional three connections on the drawing board. These connections are expected to be finished in 2023 and will give Denmark a total transmission capacity of above 10,000 MW, and compared to the expected peak load of 7,000 MW, it is theoretical possible for Denmark to be totally supplied from other countries. [Danish Energy, 2018a]
Moreover there is the possibility of storing the electricity, which also is what this thesis addresses. The possibility of storing electricity are numerous, and this thesis only investigates a minor part of one of the technologies. However it is clear that batteries are gaining ground on both the international and the European markets, primarily as stabilisation in the electricity grid, with arbitrage trading as an important driver for providing profit from the storage.[Danish Energy, 2018a]
The profit from energy arbitrage is exemplified by a battery established in Australia, which generated a turnover of 1 mio. Australian dollars within two days, due to very high prices. In this specific period, the price was 9.26 €/kWh - This is a very high price for electricity and compared to the Nordic spot market the maximum price is set to around 2.95 €/kWh [Danish Energy, 2018a]. Due to the price limitation such price fluctuations will probably never occur in the European market, which is also prevented by the market coupling, that equalises the prices across Europe.

Despite less favourable terms for batteries in the European markets compared to other markets in the world, HSS still attract significant amounts of attention, which eventually in the future might lead to a favourable development within the sector.
Some of the largest players on the market, are positive when it comes to the development of hybrid systems and according to the article *Why hybrids are key to renewables' future* by Snieckus [2018] *"many in the strategy departments at major developers and OEMs reckon the adaptability and flexibility that hybrid renewables plants have demonstrated — even at the pilot level — points to the potential of the decentralised energy system that will in the next decades take shape around the globe."*

However, this statement does not necessarily include the storage aspect, or the fact, that the energy systems are different from country to country. Nonetheless *Morten Dyrholm, senior vice-president of marketing, communications and public affairs at Vestas, points out "that adding hybrid projects, coupled with the falling price of battery storage, are removing the need for fossil-fuel back-up capacity"*.
This is followed by a statement from Antonio de la Torre chief technology officer at Siemens Gamesa, who points out that *"Whatever it is, we are going to make money from energy differently in the future, and hybridisation is how we are going to address this, to find the best answer."*[Snieckus, 2018]
Despite these positive statements about batteries and HSS this thesis indicates a less

favourable future for HSS than indicated by Dyrholm and de la Torre. This is supported by the research mentioned in the literature study in chapter 2. Here, several scientists have made economic calculations for HSS and standalone batteries, that has turned out to show negative or slightly positive results for the storage systems. These results combined with the results from this assessment and the fact that the European electricity markets are not as suitable for storage systems as other places around the world, indicate an unfavourable future for the HSS in Europe. The socio-economy for the systems are far away from being feasible, and therefore other alternatives as Smart Energy Systems and increased transmission capacity across borders, which can provide positive economic results, will probably be the solution to some of the problems related to fluctuating electricity production.
Future policies, that support HSS and batteries in form of subsidies can of course make them much more beneficial, despite they are still socio-economic unfeasible. Such case would of course change the future perspectives for the implementation of HSS.
This is however not considered in this thesis, and will therefore not be included in the considerations of HSS and their future role in Europe. Regardless the bad future prospects for HSS, it seems like big companies will keep developing the systems and spend a lot of time and money on these. This could result in a less negative future and increased development, that can cause better prospects than assumed in this chapter.

Nevertheless it has to be mentioned that this thesis do not cover the whole aspect of HSS and further approach of methods and decisions made through out the thesis, will be more detailed discussed in the following discussion in chapter 8.

CHAPTER

# 8 Discussion

The results composed in the analysis gives an unambiguous answer to the question of whether the combination of batteries and wind farms provides extra value compared to standalone technologies. The outcome of the result do not seem to suggest an investment in HSS at the moment, as well as a European energy system including a large share of these HSS seem to be far away at the moment. Despite the evident results it is difficult to generalise upon the results included in the analysis. First of all, the batteries used in this analysis is based on the lithium-ion technology, that has its pros and cons. However, a lot of other battery technologies exist and could potentially show other results due to their different specifications, prices and operational advantages. The difference in both operation- and investment costs could therefore potentially vary and lead to changed results and conclusions.

Another parameter that should be discussed, and affects the result is the operation strategy of the battery and HSS. The strategies in this thesis are relatively simple and has turned out to be important for the economy. Therefore, in a future analysis the strategies should be developed and especially take the price differences into consideration to operate the scenarios in a profitable way. It is for sure that these can be optimised, but due to very limited research on this specific topic it has been difficult to build upon existing strategies, and by that improve such one. On the other hand, the Reference scenario and scenario 1 are taking prices into consideration, but are not resulting in positive NPVs.
The operation strategy includes several assumptions, which could be improved by calculations, that support some of these assumptions. Thus, taking the price level into account in the reduction of imbalances could improve the strategy, and based on the results it can be debatable whether the first priority should be to cover imbalances without taking future spot prices into account. At least it could be interesting to see how the HSS deals with an active participation on the regulating power market as the first priority instead.
Opposite, these operation strategies have made the foundation for further development of future and more complex operation strategies. Such could also include a wider range of the capabilities related to the use of batteries, where this research includes energy arbitrage, covering imbalances and relatively limited participation on the regulating power market.

Further research for HSS should also include a participation on the Intraday market, which to some extent has the same function as the battery in the HSS included in Sce-

nario 2 and 3, which is to mitigate imbalances. Participation on the Intraday market would therefore probably change the results. An inclusion of the Intraday market could also affect the results positively, due to new possibilities for the battery. This could lead to a more active participation on the Regulating Power market combined with less covering of imbalances due to participation on the Intraday market, but still with the opportunity to add flexibility to the system.
The approach for the analysis is also based on perfect prognosis for the spot price, which makes it possible to act upon the prices, both in the Reference scenario and Scenario 1 and to some extent in the two alternative scenarios. Not knowing these prices and comply with gate closures will probably change the results, but it will also affect the operation strategy, which could open up for new possibilities if both participating on the Day-ahead market, Intraday market and potentially also the Regulating Power market, which is possible due to the different gate closures.

The inclusion of the Intraday market will have an influence, which is the same for a change in the grid tariffs. This is not included in the sensitivity analysis, but as shown in the results, the grid tariff is one of the most important parameters in the analysis. Working behind the meter seems to have a big influence on the economy, and this can be seen as one of the obvious advantages for having a HSS. Future changes in the grid tariffs can therefore become an important part of whether the HSS will become more economic feasible or less feasible.

Another interesting aspect is to separate the trading wit Regulating Power and the reduction of imbalance to see the actual affect of the trading with regulating power. Right now the opportunities in the market are not fully utilised due to the first priority of reducing imbalances. At the moment insignificant reductions of imbalances makes trading with regulating power impossible. Such a separation would mean a new and more complex bidding strategy on the Power Regulating market to optimise the operation of the battery, when participating in the Regulating Power market.

Such approach will add a lot of details to the Technical Energy Model used in this thesis. The energy model is based on the energyPRO modelling tool and mainly spreadsheets and VBA coding. Especially the VBA coding will suffer from a more detailed model, due to the many parameters and calculations needed in such a model. It can be discussed if a more optimal approach could be to make all the operational and technical modeling in energyPRO for all the scenarios, and include the outcome data from energyPRO into a spreadsheet and calculate the cash flow, NPVs etc. with the help from VBA coding to automate some of the processes.
It has turned out to be very time consuming and complex to model the operation of the HSS in excel with VBA coding, in spite of useful and relevant results.
The VBA coding approach therefore sets a natural limit for the complexity of the operation of the system.

### HSS is more than just wind turbines and a battery

This master thesis is focusing on wind turbines in combination with a lithium-ion battery, but a HSS can consist of several generators and storage solutions, which can be combined in many different ways. An interesting perspective to add on the future perspectives for HSS could be another constellation of the system etc. an inclusion of PVs, which have a different generation profile than wind turbines do and could potentially bring other aspects and opportunities to a HSS.

The many different options with HSS are supported by the increasing research in the field, as well as both pilot projects and utility scaled projects around the world are carried out. This interest and focus in the hybrid systems will certainly improve a lot of the important parameters as price and efficiency, but also the way to use the HSS and the best constellation of such systems.
The competitiveness for HSS does therefore look better in the future than right now, but the question is whether the development will work out to the HSS benefits, and improve the systems enough to be competitive enough to all the other technologies. What should be considered is also, that the competing technologies are developing too, and can strengthen their position.
In chapter 1 both Lund et al. [2016] and Energinet [2018] puts their focus on the Smart Energy System approach with a special focus on the power to heat element. This is due to the low costs of storing the excess electricity in form of heat, which according to this analysis is one of the problems with electricity storage. As mentioned in chapter 7 the future and profitability for HSS can be very much related to where and in a what kind of overall system it is integrated. The standalone battery in Australia indicates that extremely high and volatile prices are very suitable for batteries, but looking into European systems, such extreme cases will not happen in the same way due to the increased market coupling across Europe, that increases the security of supply as well as lowering the general prices.
One thing that could be discussed is the use of Danish data and a conclusion based on batteries in a Danish context. The reason for discussing this is the price difference between the Northern part of Europe and Southern part of Europe, where electricity prices differ quite much, as explained in 5. Countries like Italy and Portugal have a much higher average price, the volatility in these countries can be higher too, due to a less reliable security of supply than e.g. the Danish system provides. Using data from e.g. Italy would therefore potentially affect the analysis and the results, why it to some extent can be a bit difficult to generalise and conclude on the behalf of the entire Europe. On the other hand the entire Europe is moving towards more sustainable electricity systems including an increased amount of fluctuating RES, similar to the current Danish system, which was the main argument for using data from Denmark. Nevertheless using data from other countries will have an impact on the results.

CHAPTER

# 9 Conclusion

The interest and the focus on the implementation of HSS and batteries have been increasing the last years, and plenty of the bigger energy companies are investing money and time on these hybrid solutions. This also means, that these solutions are in a development phase, where companies, researchers and the general industry are improving and developing on the systems, which increases the competitiveness compared to other similar solutions, that are able to use and relocate the excess electricity.
The ability for batteries to both relocate and store as well as stabilise the grid in a combination with generators open up for a lot of different opportunities, where the HSS can contribute and generate value streams. These possibilities are very varying as shown in chapter 1.
Some of these possibilities are related to the interaction platforms in form of the markets. The different markets with their related purposes and practices have shown the variety of opportunities in these. This is exemplified with niche markets in form of the Primary reserves, where the opportunity for participation is relatively limited due to a low demand, and the wholesale markets, where the prices are less attractive, but the need for supply and demand are much higher.

Meanwhile the market coupling and expansion of transmission lines across the country borders open up for participation across border lines on different markets and to some extent expands the opportunities. At the same time, a potential effect of the market coupling could be a less volatile market, because the transmission lines makes it possible to start up the cheapest units across Europe and smoothen out the price differences. Thus it is still expected, that the volatility will increase due to the implementation of RES, which will affect the HSS positively, as shown in the sensitivity analysis.

Despite the more volatile future prices, the Technical Energy Model used in this thesis concludes, that investing in a utility scaled HSS seems unprofitable based on the assumptions and terms included in the model. This conclusion is supported by existing research on especially batteries, focusing on other aspects, that show bad economic results. Thus, it can be concluded that adding a battery to an existing wind farm does not seem to improve the operation and economy for the wind farm. Despite being labeled as a bad investment, the HSS still seems like a better investment than investing in standalone batteries, exemplified by the Reference scenario and Scenario 1 in this analysis. One of the main parameters was the exemption of grid tariffs, which can be achieved by investing in HSS instead of standalone technologies. The analysis also

indicates, that a very important instrument for making the most out of the HSS as well as standalone batteries is the operation strategy for the unit. This has a decisive importance for improving the economy, and can easily be compared to parameters as the increasing volatility on the electricity markets as well as the falling investment costs, which both are important parameters for the economy for HSS.
Such external parameters are important and both the development of the volatility and investment costs seem to favour the HSS in the future, why improvement for HSS and standalone batteries are expected.
Thus it must still be concluded, that the future for HSS seem a bit uncertain and their role in future renewable energy systems do not seem to be essential due to the relatively high prices and therefore the poor competitiveness compared to other technologies. Based on the results of this thesis, the extent of HSS in energy systems in the near future will be limited.
This thesis is however only looking at a small part of the opportunities with HSS and the companies and actors inside the business are still developing the technology, why the HSS may not be considered as a technological combination without future potential.

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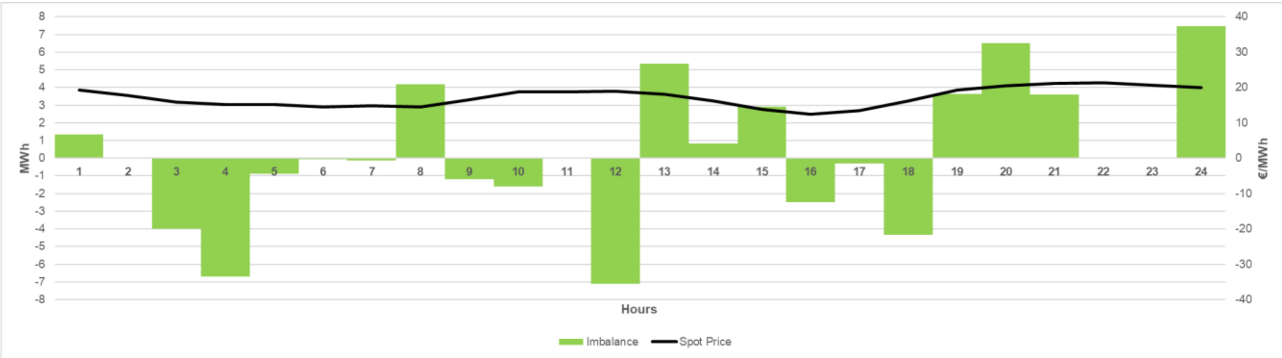
APPENDIX

A

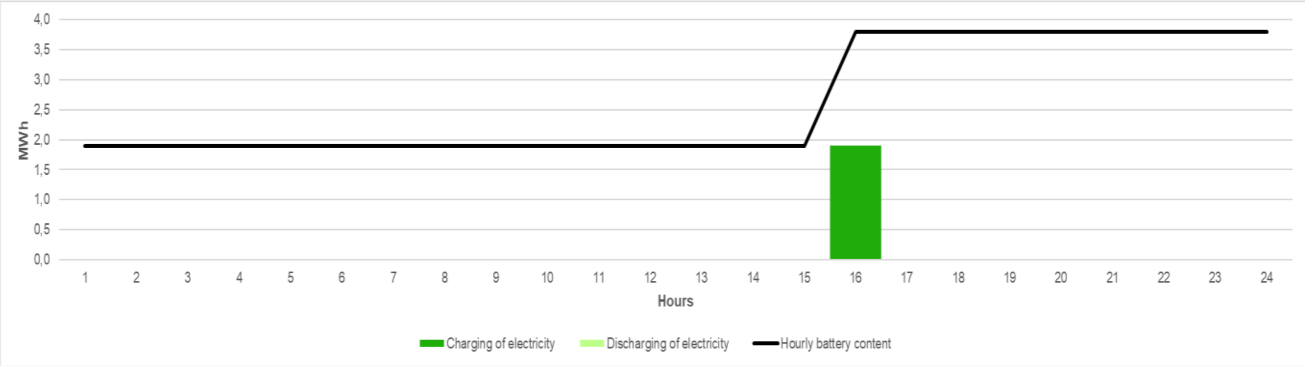
# 24 hour operation - all scenarios

# Spot Price and Imbalances the 17th of April



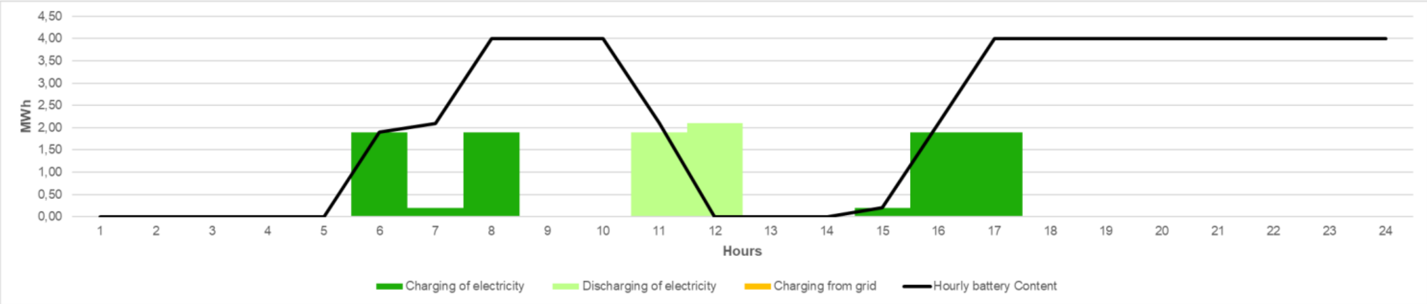

| Hour | Spot Price € | Imbalance MWh |
|---|---|---|
| 1 | 19,33 | 1,35 |
| 2 | 17,74 | 0,01 |
| 3 | 15,85 | -4,00 |
| 4 | 15,13 | -6,68 |
| 5 | 15,15 | -0,88 |
| 6 | 14,57 | -0,06 |
| 7 | 14,82 | -0,12 |
| 8 | 14,57 | 4,16 |
| 9 | 16,48 | -1,19 |
| 10 | 18,69 | -1,60 |
| 11 | 18,69 | 0,00 |
| 12 | 18,94 | -7,11 |
| 13 | 18,16 | 5,36 |
| 14 | 16,16 | 0,84 |
| 15 | 13,82 | 2,90 |
| 16 | 12,52 | -2,50 |
| 17 | 13,52 | -0,30 |
| 18 | 16,16 | -4,33 |
| 19 | 19,35 | 3,64 |
| 20 | 20,51 | 6,51 |
| 21 | 21,2 | 3,61 |
| 22 | 21,29 | 0,00 |
| 23 | 20,64 | -0,02 |
| 24 | 19,93 | 7,47 |

# Operation of Reference scenario the 17th of April.



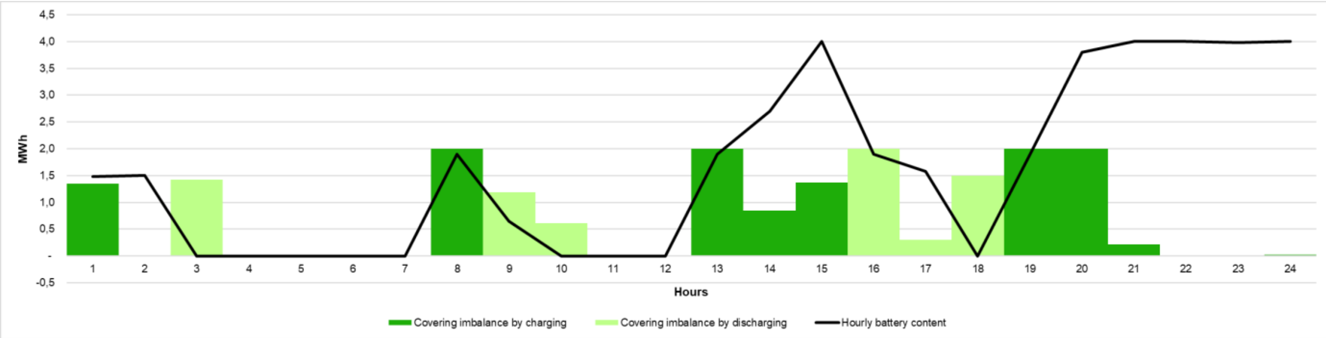

| Hour | Charging of electricity | Discharging of electricity | Hourly battery content |
|---|---|---|---|
| 1 | 0,00 | 0,00 | 1,89 |
| 2 | 0,00 | 0,00 | 1,89 |
| 3 | 0,00 | 0,00 | 1,89 |
| 4 | 0,00 | 0,00 | 1,89 |
| 5 | 0,00 | 0,00 | 1,89 |
| 6 | 0,00 | 0,00 | 1,89 |
| 7 | 0,00 | 0,00 | 1,89 |
| 8 | 0,00 | 0,00 | 1,89 |
| 9 | 0,00 | 0,00 | 1,89 |
| 10 | 0,00 | 0,00 | 1,89 |
| 11 | 0,00 | 0,00 | 1,89 |
| 12 | 0,00 | 0,00 | 1,89 |
| 13 | 0,00 | 0,00 | 1,89 |
| 14 | 0,00 | 0,00 | 1,89 |
| 15 | 0,00 | 0,00 | 1,89 |
| 16 | 1,90 | 0,00 | 3,79 |
| 17 | 0,00 | 0,00 | 3,79 |
| 18 | 0,00 | 0,00 | 3,79 |
| 19 | 0,00 | 0,00 | 3,79 |
| 20 | 0,00 | 0,00 | 3,79 |
| 21 | 0,00 | 0,00 | 3,79 |
| 22 | 0,00 | 0,00 | 3,79 |
| 23 | 0,00 | 0,00 | 3,79 |
| 24 | 0,00 | 0,00 | 3,79 |

# Operation of Scenario 1 the 17th of April



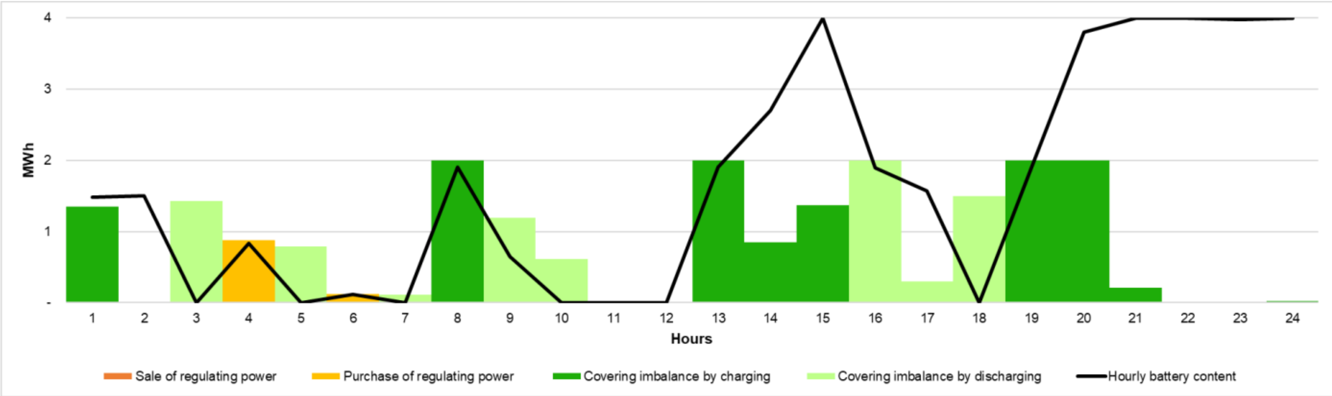

| Hour | Charging of electricity | Discharging of electricity | Charging from grid | Hourly battery Content |
|---|---|---|---|---|
| 1 | 0,00 | 0,00 | 0,00 | 0,00 |
| 2 | 0,00 | 0,00 | 0,00 | 0,00 |
| 3 | 0,00 | 0,00 | 0,00 | 0,00 |
| 4 | 0,00 | 0,00 | 0,00 | 0,00 |
| 5 | 0,00 | 0,00 | 0,00 | 0,00 |
| 6 | 1,90 | 0,00 | 0,00 | 1,90 |
| 7 | 0,20 | 0,00 | 0,00 | 2,10 |
| 8 | 1,90 | 0,00 | 0,00 | 4,00 |
| 9 | 0,00 | 0,00 | 0,00 | 4,00 |
| 10 | 0,00 | 0,00 | 0,00 | 4,00 |
| 11 | 0,00 | 1,89 | 0,00 | 2,11 |
| 12 | 0,00 | 2,11 | 0,00 | 0,00 |
| 13 | 0,00 | 0,00 | 0,00 | 0,00 |
| 14 | 0,00 | 0,00 | 0,00 | 0,00 |
| 15 | 0,20 | 0,00 | 0,00 | 0,20 |
| 16 | 1,90 | 0,00 | 0,00 | 2,10 |
| 17 | 1,90 | 0,00 | 0,00 | 4,00 |
| 18 | 0,00 | 0,00 | 0,00 | 4,00 |
| 19 | 0,00 | 0,00 | 0,00 | 4,00 |
| 20 | 0,00 | 0,00 | 0,00 | 4,00 |
| 21 | 0,00 | 0,00 | 0,00 | 4,00 |
| 22 | 0,00 | 0,00 | 0,00 | 4,00 |
| 23 | 0,00 | 0,00 | 0,00 | 4,00 |
| 24 | 0,00 | 0,00 | 0,00 | 4,00 |

# Operation of Scenario 2 the 17$^{th}$ of April




| Hour | Covering imbalance by charging | Covering imbalance by discharging | Hourly battery content |
|---|---|---|---|
| 1 | 1,35 | 0,00 | 1,49 |
| 2 | 0,01 | 0,00 | 1,50 |
| 3 | 0,00 | 1,42 | 0,00 |
| 4 | 0,00 | 0,00 | 0,00 |
| 5 | 0,00 | 0,00 | 0,00 |
| 6 | 0,00 | 0,00 | 0,00 |
| 7 | 0,00 | 0,00 | 0,00 |
| 8 | 2,00 | 0,00 | 1,90 |
| 9 | 0,00 | 1,19 | 0,65 |
| 10 | 0,00 | 0,61 | 0,00 |
| 11 | 0,00 | 0,00 | 0,00 |
| 12 | 0,00 | 0,00 | 0,00 |
| 13 | 2,00 | 0,00 | 1,90 |
| 14 | 0,84 | 0,00 | 2,70 |
| 15 | 1,37 | 0,00 | 4,00 |
| 16 | 0,00 | 2,00 | 1,89 |
| 17 | 0,00 | 0,30 | 1,58 |
| 18 | 0,00 | 1,50 | 0,00 |
| 19 | 2,00 | 0,00 | 1,90 |
| 20 | 2,00 | 0,00 | 3,80 |
| 21 | 0,21 | 0,00 | 4,00 |
| 22 | 0,00 | 0,00 | 4,00 |
| 23 | 0,00 | 0,02 | 3,98 |
| 24 | 0,02 | 0,00 | 4,00 |

# Operation of Scenario 3 the 17th of April




| Hour | Hourly battery content | Sale of regulating power | Purchase of regulating power | Covering imbalance by charging | Covering imbalance by discharging |
|---|---|---|---|---|---|
| 1 | 1,49 | 0,00 | 0,00 | 1,35 | 0,00 |
| 2 | 1,50 | 0,00 | 0,00 | 0,01 | 0,00 |
| 3 | 0,00 | 0,00 | 0,00 | 0,00 | 1,42 |
| 4 | 0,83 | 0,00 | 0,88 | 0,00 | 0,00 |
| 5 | 0,00 | 0,00 | 0,00 | 0,00 | 0,79 |
| 6 | 0,11 | 0,00 | 0,12 | 0,00 | 0,00 |
| 7 | 0,00 | 0,00 | 0,00 | 0,00 | 0,11 |
| 8 | 1,90 | 0,00 | 0,00 | 2,00 | 0,00 |
| 9 | 0,65 | 0,00 | 0,00 | 0,00 | 1,19 |
| 10 | 0,00 | 0,00 | 0,00 | 0,00 | 0,61 |
| 11 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 12 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 13 | 1,90 | 0,00 | 0,00 | 2,00 | 0,00 |
| 14 | 2,70 | 0,00 | 0,00 | 0,84 | 0,00 |
| 15 | 4,00 | 0,00 | 0,00 | 1,37 | 0,00 |
| 16 | 1,89 | 0,00 | 0,00 | 0,00 | 2,00 |
| 17 | 1,58 | 0,00 | 0,00 | 0,00 | 0,30 |
| 18 | 0,00 | 0,00 | 0,00 | 0,00 | 1,50 |
| 19 | 1,90 | 0,00 | 0,00 | 2,00 | 0,00 |
| 20 | 3,80 | 0,00 | 0,00 | 2,00 | 0,00 |
| 21 | 4,00 | 0,00 | 0,00 | 0,21 | 0,00 |
| 22 | 4,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 23 | 3,98 | 0,00 | 0,00 | 0,00 | 0,02 |
| 24 | 4,00 | 0,00 | 0,00 | 0,02 | 0,00 |

APPENDIX

# B energyPRO data - Reference scenario and Scenario 1

**Reference scenario - battery.epp**





# Operation Income from 01-01-2016 00:00 to 31-12-2016 23:59

**(All amounts in DKK)**

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Revenues** | | | | | | | |
| Sale of electricity | : | 488,1 MWh | at | 321,087* | = | 156.726 | |
| **Total Revenues** | | | | | | | **156.726** |
| **Operating Expenditures** | | | | | | | |
| Purchase of electricity | : | 540,8 MWh | at | 117,071* | = | 63.317 | |
| Operation and maintenance | : | 488,1 MWh | at | 1,88 | = | 918 | |
| Grid tariff | : | 540,8 MWh | at | 80,0 | = | 43.267 | |
| **Total Operating Expenditures** | | | | | | | **107.502** |
| **Operation Income** | | | | | | | **49.224** |

* Average price

**Scenario 1.epp**

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**University License**
January 1, 2018 to September 1, 2018

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# Operation Income from 01-01-2016 00:00 to 31-12-2016 23:59

**(All amounts in DKK)**

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Revenues** | | | | | | | |
| Sale of electricity | : | 1.740,2 MWh | at | 249,949* | = | 434.964 | |
| **Total Revenues** | | | | | | | **434.964** |
| | | | | | | | |
| **Operating Expenditures** | | | | | | | |
| Purchase of electricity | : | 2,8 MWh | at | 172,613* | = | 480 | |
| Operation and maintenance | : | 1.740,2 MWh | at | 1,88 | = | 3.272 | |
| Grid tariff | : | 2,8 MWh | at | 80,0 | = | 222 | |
| Purchase of wind electricity | : | 1.925,4 MWh | at | 153,967* | = | 296.453 | |
| **Total Operating Expenditures** | | | | | | | **300.426** |
| **Operation Income** | | | | | | | **134.537** |

* Average price

APPENDIX

# C VBA Codes

## C.1 Reference wind production

This vba-scenario includes the wind production from the standalone wind farm, which is used to subtract from Scenario 2 and Scenario 3, to see the effect of the battery.

Reference - 1

```
Option Explicit

Const MaxHoursInYear = 8784

 ' Define the variables, used in more subroutines
 Dim Hour As Integer
 Dim SpotPrice(1 To MaxHoursInYear) As Double
 Dim SpotPrice1(1 To MaxHoursInYear) As Double
 Dim SpotSale(1 To MaxHoursInYear) As Double
 Dim UpwardPrice(1 To MaxHoursInYear) As Double
 Dim DownwardPrice(1 To MaxHoursInYear) As Double
  Dim UpwardPrice1(1 To MaxHoursInYear) As Double
 Dim DownwardPrice1(1 To MaxHoursInYear) As Double
 Dim DownwardRegulation(1 To MaxHoursInYear) As Boolean
 Dim UpwardRegulation(1 To MaxHoursInYear) As Boolean
 Dim Imbalance(1 To MaxHoursInYear) As Double
 Dim DeviationFactor(1 To MaxHoursInYear) As Double
 Dim TradedProduction(1 To MaxHoursInYear) As Double
 Dim ActualProduction(1 To MaxHoursInYear) As Double
 Dim PaymentSpotPrice(1 To MaxHoursInYear) As Double
 Dim PaymentDownwardPrice(1 To MaxHoursInYear) As Double
 Dim FeeSpotPrice(1 To MaxHoursInYear) As Double
 Dim FeeUpwardPrice(1 To MaxHoursInYear) As Double
 Dim BalancedPayment(1 To MaxHoursInYear) As Double
 Dim BalancedFee(1 To MaxHoursInYear) As Double



Sub Reference()
'In this reference scenario, the forcasted amount of electricity is traded on the spotmarket, allowing for a settlement of imbalances,
'which is done using the two price model.
'The power is automatically generated, and has a deviation factor of +/- 12 %, not allowing to trade more than 70,4 MWh,
'as this is the capacity of the wind farm - this sub does not include the battery but only the wind production and settlement

   Worksheets("Reference Wind").Range("I5:O8788").ClearContents
   SpotMarketBidding
   FillHourVariables

 For Hour = 1 To [HoursInYear]

 'sale at spot market based on forecastet and traded production
   SpotSale(Hour) = SpotPrice(Hour) * TradedProduction(Hour)

 'Settlement of imbalances based on the two price model

 'Payment because of positive imbalance - settlement with Spot price
   If UpwardRegulation(Hour) And Imbalance(Hour) > 0 Then
      PaymentSpotPrice(Hour) = Imbalance(Hour) * SpotPrice(Hour)
   Else: PaymentSpotPrice(Hour) = 0
 End If

  'Fee because of negative imbalance - settlement with upward price
   If UpwardRegulation(Hour) And Imbalance(Hour) < 0 Then
      FeeUpwardPrice(Hour) = -Imbalance(Hour) * UpwardPrice(Hour)
   Else: FeeUpwardPrice(Hour) = 0
 End If

 'Payment because of positive imbalance - settlement with downward price
   If DownwardRegulation(Hour) And Imbalance(Hour) > 0 Then
      PaymentDownwardPrice(Hour) = Imbalance(Hour) * DownwardPrice(Hour)
   Else: PaymentDownwardPrice(Hour) = 0
 End If

 'Fee because of negative imbalance - settlement with spot price
   If DownwardRegulation(Hour) And Imbalance(Hour) < 0 Then
      FeeSpotPrice(Hour) = -Imbalance(Hour) * SpotPrice(Hour)
   Else: FeeSpotPrice(Hour) = 0
 End If


  'When balance in the system occurs, the settlement will be based on the spotprice
```

```
    If Not UpwardRegulation(Hour) And Not DownwardRegulation(Hour) And Imbalance(Hour) > 0 Then
        BalancedPayment(Hour) = SpotPrice(Hour) * Imbalance(Hour)

    ElseIf Not UpwardRegulation(Hour) And Not DownwardRegulation(Hour) And Imbalance(Hour) < 0 Then
        BalancedFee(Hour) = SpotPrice(Hour) * -Imbalance(Hour)

    Else: BalancedPayment(Hour) = 0 And BalancedFee(Hour) = 0
 End If

 FillInResults

 Next Hour

 End Sub

Sub FillInResults()


'Fill in results in reference scenario

 Worksheets("Reference Wind").Cells(Hour + 4, 9) = SpotSale(Hour)
 Worksheets("Reference Wind").Cells(Hour + 4, 10) = PaymentSpotPrice(Hour)
 Worksheets("Reference Wind").Cells(Hour + 4, 11) = PaymentDownwardPrice(Hour)
 Worksheets("Reference Wind").Cells(Hour + 4, 12) = FeeUpwardPrice(Hour)
 Worksheets("Reference Wind").Cells(Hour + 4, 13) = FeeSpotPrice(Hour)
 Worksheets("Reference Wind").Cells(Hour + 4, 14) = BalancedPayment(Hour)
 Worksheets("Reference Wind").Cells(Hour + 4, 15) = BalancedFee(Hour)


End Sub


Sub FillHourVariables()

  For Hour = 1 To [HoursInYear]


     SpotPrice(Hour) = Worksheets("Market data").Cells(Hour + 4, 3) + [fast]
     DownwardPrice(Hour) = Worksheets("Market data").Cells(Hour + 4, 5) + [fast]
     UpwardPrice(Hour) = Worksheets("Market data").Cells(Hour + 4, 6) + [fast]
     TradedProduction(Hour) = Worksheets("Reference Wind").Cells(Hour + 4, 3)
     ActualProduction(Hour) = Worksheets("Reference Wind").Cells(Hour + 4, 5)
     DeviationFactor(Hour) = Worksheets("Reference Wind").Cells(Hour + 4, 4)
     Imbalance(Hour) = Worksheets("Reference Wind").Cells(Hour + 4, 6)
' Determination of up- and down regulation
      SpotPrice1(Hour) = Worksheets("Market data").Cells(Hour + 4, 3)
     DownwardPrice1(Hour) = Worksheets("Market data").Cells(Hour + 4, 5)
     UpwardPrice1(Hour) = Worksheets("Market data").Cells(Hour + 4, 6)
      UpwardRegulation(Hour) = SpotPrice1(Hour) + 1 < UpwardPrice1(Hour)
     DownwardRegulation(Hour) = SpotPrice1(Hour) - 1 > DownwardPrice1(Hour)

  Next Hour
End Sub

Sub SpotMarketBidding()



FillHourVariables

'Bids on the spotmarket based on forecastet production using the deviation factor
For Hour = 1 To [HoursInYear]

    If SpotPrice(Hour) <= [VariableCostsWind] Then
        TradedProduction(Hour) = 0
    ElseIf ActualProduction(Hour) / DeviationFactor(Hour) > [MaxWindCapacity] Then
        TradedProduction(Hour) = [MaxWindCapacity]
    Else: TradedProduction(Hour) = ActualProduction(Hour) / DeviationFactor(Hour)
    End If

'When there is no trading - the imbalance will always be set to 0
```

Reference - 3

```
    If TradedProduction(Hour) = 0 Then
    Imbalance(Hour) = 0
    Else: Imbalance(Hour) = ActualProduction(Hour) - TradedProduction(Hour)
    End If


'Fill in the bidding result and imbalances
Worksheets("Reference Wind").Cells(Hour + 4, 3) = TradedProduction(Hour)
Worksheets("Reference Wind").Cells(Hour + 4, 6) = Imbalance(Hour)

Next Hour


End Sub
```

## C.2 Scenario 2

This scenario reduces the imbalances created in the wind production.

Scenario2 - 1

```
Option Explicit

Const MaxHoursInYear = 8784

 ' Define the global variables, used in more subroutines
 Dim Hour As Integer
 Dim SpotPrice(1 To MaxHoursInYear) As Double
 Dim SpotSale(1 To MaxHoursInYear) As Double
 Dim UpwardPrice(1 To MaxHoursInYear) As Double
 Dim DownwardPrice(1 To MaxHoursInYear) As Double
 Dim DownwardRegulation(1 To MaxHoursInYear) As Boolean
 Dim UpwardRegulation(1 To MaxHoursInYear) As Boolean
 Dim Imbalance(1 To MaxHoursInYear) As Double
 Dim TradedProduction(1 To MaxHoursInYear) As Double
 Dim ActualProduction(1 To MaxHoursInYear) As Double
 Dim PaymentSpotPrice(1 To MaxHoursInYear) As Double
 Dim PaymentDownwardPrice(1 To MaxHoursInYear) As Double
 Dim FeeSpotPrice(1 To MaxHoursInYear) As Double
 Dim FeeUpwardPrice(1 To MaxHoursInYear) As Double
 Dim BalancedPayment(1 To MaxHoursInYear) As Double
 Dim BalancedFee(1 To MaxHoursInYear) As Double
 Dim Charging(1 To MaxHoursInYear) As Double
 Dim Discharging(MaxHoursInYear) As Double
 Dim BatteryContent(0 To MaxHoursInYear) As Double
 Dim BatteryUtilization(1 To MaxHoursInYear) As Double
 Dim ReducedImbalance(1 To MaxHoursInYear) As Double
 Dim BalancedPrice(1 To MaxHoursInYear) As Double
 Dim PowerToWindImbalance(1 To MaxHoursInYear) As Double
 Dim PowerFromWindImbalance(1 To MaxHoursInYear) As Double

Sub Scenario2()
'Scenario 1 includes a battery of 4 MWh, where imbalances from the wind farm are covered. The battery will therefore be used to mini
mize punishment
'when having an imbalance, no matter if the imbalance are positive or negative.

Worksheets("Scenario2").Range("E5:H8788").ClearContents
Worksheets("Scenario2").Range("K5:Q8788").ClearContents
Reference.SpotMarketBidding
FillHourVariables

    For Hour = 1 To [HoursInYear]

'Charging the battery

    If Imbalance(Hour) = 0 Then
       PowerToWindImbalance(Hour) = 0 And PowerFromWindImbalance(Hour) = 0


    ElseIf Imbalance(Hour) > 0 And SpotPrice(Hour) > [MaxSpotPrice] And Hour < 8784 Then
        PowerFromWindImbalance(Hour) = 0

    ElseIf Imbalance(Hour) > 0 And BatteryContent(Hour - 1) = [BatteryCapacity] Then
        PowerFromWindImbalance(Hour) = 0

    ElseIf Imbalance(Hour) > 0 And Imbalance(Hour) >= [ChargingCapacity] And BatteryContent(Hour - 1) <= [ChargingCapacity] * [Cha
rgingefficiency] Then
        PowerFromWindImbalance(Hour) = [ChargingCapacity]

    ElseIf Imbalance(Hour) > 0 And Imbalance(Hour) <= [ChargingCapacity] And [BatteryCapacity] - Charging(Hour) >= BatteryContent(
Hour - 1) Then
        PowerFromWindImbalance(Hour) = Imbalance(Hour)

    ElseIf Imbalance(Hour) > 0 And Imbalance(Hour) <= [ChargingCapacity] And (Charging(Hour) + BatteryContent(Hour - 1)) >= [Batter
yCapacity] Then
        PowerFromWindImbalance(Hour) = ([BatteryCapacity] - BatteryContent(Hour - 1)) / [Chargingefficiency]

    ElseIf Imbalance(Hour) > 0 And Imbalance(Hour) >= [ChargingCapacity] And BatteryContent(Hour - 1) >= [ChargingCapacity] / [Char
gingefficiency] And (Charging(Hour) + BatteryContent(Hour - 1)) >= [BatteryCapacity] Then
        PowerFromWindImbalance(Hour) = ([BatteryCapacity] - BatteryContent(Hour - 1)) / [Chargingefficiency]
```

```
    ElseIf Imbalance(Hour) > 0 And Imbalance(Hour) >= [ChargingCapacity] And BatteryContent(Hour - 1) <= [ChargingCapacity] / [Char
gingefficiency] And (Charging(Hour) + BatteryContent(Hour - 1)) <= [BatteryCapacity] Then
        PowerFromWindImbalance(Hour) = [ChargingCapacity]


'Discharging the battery

    ElseIf Imbalance(Hour) < 0 And BatteryContent(Hour - 1) = 0 Then
    PowerToWindImbalance(Hour) = 0

    ElseIf Imbalance(Hour) < 0 And -Imbalance(Hour) >= [DischargingCapacity] And BatteryContent(Hour - 1) >= [DischargingCapacity] /
 [Dischargingefficiency] Then
    PowerToWindImbalance(Hour) = [DischargingCapacity]

    ElseIf Imbalance(Hour) < 0 And -Imbalance(Hour) <= [DischargingCapacity] And BatteryContent(Hour - 1) >= -Imbalance(Hour) / [Di
schargingefficiency] Then
    PowerToWindImbalance(Hour) = -Imbalance(Hour)


    ElseIf Imbalance(Hour) < 0 And -Imbalance(Hour) >= [DischargingCapacity] And BatteryContent(Hour - 1) <= [DischargingCapacity] /
 [Dischargingefficiency] Then
    PowerToWindImbalance(Hour) = BatteryContent(Hour - 1) * [Dischargingefficiency]

    ElseIf Imbalance(Hour) < 0 And -Imbalance(Hour) > BatteryContent(Hour - 1) And BatteryContent(Hour - 1) <= [DischargingCapacity
] / [Dischargingefficiency] Then
    PowerToWindImbalance(Hour) = BatteryContent(Hour - 1) * [Dischargingefficiency]

    ElseIf Imbalance(Hour) < 0 And -Imbalance(Hour) > BatteryContent(Hour - 1) And BatteryContent(Hour - 1) >= [DischargingCapacity
] / [Dischargingefficiency] Then
    PowerToWindImbalance(Hour) = [DischargingCapacity]

    ElseIf Imbalance(Hour) = 0 Then
       PowerToWindImbalance(Hour) = 0 And PowerFromWindImbalance(Hour) = 0

    Else: PowerToWindImbalance(Hour) = 0 And PowerFromWindImbalance(Hour) = 0
End If

 BatteryContent(Hour) = BatteryContent(Hour - 1) + PowerFromWindImbalance(Hour) * [Chargingefficiency] - PowerToWindImbalance
(Hour) / [Dischargingefficiency]

'The utilization of the battery
    BatteryUtilization(Hour) = BatteryContent(Hour) - BatteryContent(Hour - 1)

'The new and reduced imbalance caused by the battery
    ReducedImbalance(Hour) = Imbalance(Hour) - PowerFromWindImbalance(Hour) + PowerToWindImbalance(Hour)

'sale at spot market based on forecastet and traded production
    SpotSale(Hour) = SpotPrice(Hour) * TradedProduction(Hour)

 'Settlement of imbalances based on the two price model and the new and reduced imbalance

 'Payment because of positive imbalance - settlement with Spot price
    If UpwardRegulation(Hour) And ReducedImbalance(Hour) > 0 Then
        PaymentSpotPrice(Hour) = ReducedImbalance(Hour) * SpotPrice(Hour)
    Else: PaymentSpotPrice(Hour) = 0
 End If

  'Fee because of negative imbalance - settlement with upward price
    If UpwardRegulation(Hour) And ReducedImbalance(Hour) < 0 Then
        FeeUpwardPrice(Hour) = -ReducedImbalance(Hour) * UpwardPrice(Hour)
    Else: FeeUpwardPrice(Hour) = 0
 End If

 'Payment because of positive imbalance - settlement with downward price
    If DownwardRegulation(Hour) And ReducedImbalance(Hour) > 0 Then
        PaymentDownwardPrice(Hour) = ReducedImbalance(Hour) * DownwardPrice(Hour)
    Else: PaymentDownwardPrice(Hour) = 0
 End If

 'Fee because of negative imbalance - settlement with spot price
    If DownwardRegulation(Hour) And ReducedImbalance(Hour) < 0 Then
```

```
       FeeSpotPrice(Hour) = -ReducedImbalance(Hour) * SpotPrice(Hour)
    Else: FeeSpotPrice(Hour) = 0
 End If


  'When balance in the system occurs, the settlement will be based on the spotprice
    If Not UpwardRegulation(Hour) And Not DownwardRegulation(Hour) And Imbalance(Hour) > 0 Then
       BalancedPayment(Hour) = SpotPrice(Hour) * ReducedImbalance(Hour)

    ElseIf Not UpwardRegulation(Hour) And Not DownwardRegulation(Hour) And Imbalance(Hour) < 0 Then
       BalancedFee(Hour) = SpotPrice(Hour) * -ReducedImbalance(Hour)
  Else: BalancedPayment(Hour) = 0 And BalancedFee(Hour) = 0
 End If

FillInResults

Next Hour

End Sub

Sub FillInResults()

'Fill in results in scenario 2

 Worksheets("Scenario2").Cells(Hour + 4, 5) = BatteryContent(Hour)
 Worksheets("Scenario2").Cells(Hour + 4, 6) = PowerFromWindImbalance(Hour)
 Worksheets("Scenario2").Cells(Hour + 4, 7) = PowerToWindImbalance(Hour)
 Worksheets("Scenario2").Cells(Hour + 4, 8) = ReducedImbalance(Hour)
 Worksheets("Scenario2").Cells(Hour + 4, 11) = SpotSale(Hour)
 Worksheets("Scenario2").Cells(Hour + 4, 12) = PaymentSpotPrice(Hour)
 Worksheets("Scenario2").Cells(Hour + 4, 13) = PaymentDownwardPrice(Hour)
 Worksheets("Scenario2").Cells(Hour + 4, 14) = FeeUpwardPrice(Hour)
 Worksheets("Scenario2").Cells(Hour + 4, 15) = FeeSpotPrice(Hour)
 Worksheets("Scenario2").Cells(Hour + 4, 16) = BalancedPayment(Hour)
 Worksheets("Scenario2").Cells(Hour + 4, 17) = BalancedFee(Hour)


End Sub
Sub FillHourVariables()

'Hourly data are filled into the hour variables
    For Hour = 1 To [HoursInYear]

     SpotPrice(Hour) = Worksheets("Market data").Cells(Hour + 4, 3)
     DownwardPrice(Hour) = Worksheets("Market data").Cells(Hour + 4, 5)
     UpwardPrice(Hour) = Worksheets("Market data").Cells(Hour + 4, 6)
     TradedProduction(Hour) = Worksheets("Reference Wind").Cells(Hour + 4, 3)
     ActualProduction(Hour) = Worksheets("Reference Wind").Cells(Hour + 4, 5)
     Imbalance(Hour) = Worksheets("Reference Wind").Cells(Hour + 4, 6)
     Charging(Hour) = Imbalance(Hour) * [Chargingefficiency]
     Discharging(Hour) = Imbalance(Hour) * [Dischargingefficiency]
     UpwardRegulation(Hour) = SpotPrice(Hour) + 1 < UpwardPrice(Hour)
     DownwardRegulation(Hour) = SpotPrice(Hour) - 1 > DownwardPrice(Hour)


  Next Hour
End Sub
```

## C.3 Scenario 3

This scenario reduces the imbalances created in the wind production, and when possible the battery also participates on the Regulating Power market.

Scenario3 - 1

```
Option Explicit

Const MaxHoursInYear = 8784

 ' Define the global variables, used in more subroutines
 Dim Hour As Integer
 Dim SpotPrice(1 To MaxHoursInYear) As Double
 Dim SpotSale(1 To MaxHoursInYear) As Double
 Dim UpwardPrice(1 To MaxHoursInYear) As Double
 Dim DownwardPrice(1 To MaxHoursInYear) As Double
 Dim DownwardRegulation(1 To MaxHoursInYear) As Boolean
 Dim UpwardRegulation(1 To MaxHoursInYear) As Boolean
 Dim Imbalance(1 To MaxHoursInYear) As Double
 Dim TradedProduction(1 To MaxHoursInYear) As Double
 Dim ActualProduction(1 To MaxHoursInYear) As Double
 Dim PaymentSpotPrice(1 To MaxHoursInYear) As Double
 Dim PaymentDownwardPrice(1 To MaxHoursInYear) As Double
 Dim FeeSpotPrice(1 To MaxHoursInYear) As Double
 Dim FeeUpwardPrice(1 To MaxHoursInYear) As Double
 Dim BalancedPrice(1 To MaxHoursInYear) As Double
 Dim Charging(1 To MaxHoursInYear) As Double
 Dim Discharging(MaxHoursInYear) As Double
 Dim BatteryContent(0 To MaxHoursInYear) As Double
 Dim ReducedImbalance(1 To MaxHoursInYear) As Double
 Dim BalancedPayment(1 To MaxHoursInYear) As Double
 Dim BalancedFee(1 To MaxHoursInYear) As Double
 Dim SaleRegulatingPower(1 To MaxHoursInYear) As Double
 Dim PurchaseRegulatingPower(1 To MaxHoursInYear) As Double
 Dim RegPower(1 To MaxHoursInYear) As Double
 Dim PowerToWindImbalance(1 To MaxHoursInYear) As Double
 Dim PowerFromWindImbalance(1 To MaxHoursInYear) As Double
 Dim ImbalancePower(1 To MaxHoursInYear) As Double



Sub Scenario3()
'Sub Scenario 3 includes a battery of 4 MWh, where imbalances from the wind park are covered. The battery will therefore be used to minimize punishment
'when having an imbalance, whatever the imbalance is positive or negative.

Worksheets("Scenario3").Range("E5:J8788").ClearContents
Worksheets("Scenario3").Range("M5:U8788").ClearContents
Reference.SpotMarketBidding
FillHourVariables

    For Hour = 1 To [HoursInYear]



'Covering an imbalance by charging the battery

    If Imbalance(Hour) = 0 Then
      PowerToWindImbalance(Hour) = 0 And PowerFromWindImbalance(Hour) = 0

    ElseIf Imbalance(Hour) > 0 And BatteryContent(Hour - 1) = [BatteryCapacity] Then
        PowerFromWindImbalance(Hour) = 0

    ElseIf Imbalance(Hour) > 0 And SpotPrice(Hour) > [MaxSpotPrice] Then
        PowerFromWindImbalance(Hour) = 0


    ElseIf Imbalance(Hour) > 0 And Imbalance(Hour) >= [ChargingCapacity] And BatteryContent(Hour - 1) <= [ChargingCapacity] * [Chargingefficiency] Then
        PowerFromWindImbalance(Hour) = [ChargingCapacity]

    ElseIf Imbalance(Hour) > 0 And Imbalance(Hour) <= [ChargingCapacity] And [BatteryCapacity] - Charging(Hour) >= BatteryContent(Hour - 1) Then
        PowerFromWindImbalance(Hour) = Imbalance(Hour)

    ElseIf Imbalance(Hour) > 0 And Imbalance(Hour) <= [ChargingCapacity] And (Charging(Hour) + BatteryContent(Hour - 1)) >= [BatteryCapacity] Then
```

```
        PowerFromWindImbalance(Hour) = ([BatteryCapacity] - BatteryContent(Hour - 1)) / [Chargingefficiency]

    ElseIf Imbalance(Hour) > 0 And Imbalance(Hour) >= [ChargingCapacity] And BatteryContent(Hour - 1) >= [ChargingCapacity] / [Char
gingefficiency] And (Charging(Hour) + BatteryContent(Hour - 1)) >= [BatteryCapacity] Then
        PowerFromWindImbalance(Hour) = ([BatteryCapacity] - BatteryContent(Hour - 1)) / [Chargingefficiency]


    ElseIf Imbalance(Hour) > 0 And Imbalance(Hour) >= [ChargingCapacity] And BatteryContent(Hour - 1) <= [ChargingCapacity] / [Char
gingefficiency] And (Charging(Hour) + BatteryContent(Hour - 1)) <= [BatteryCapacity] Then
        PowerFromWindImbalance(Hour) = [ChargingCapacity]



'Covering an imbalance by discharging the battery

    ElseIf Imbalance(Hour) < 0 And BatteryContent(Hour - 1) = 0 Then
        PowerToWindImbalance(Hour) = 0

    ElseIf Imbalance(Hour) < 0 And -Imbalance(Hour) >= [DischargingCapacity] And BatteryContent(Hour - 1) >= [DischargingCapacity] /
 [Dischargingefficiency] Then
        PowerToWindImbalance(Hour) = [DischargingCapacity]

    ElseIf Imbalance(Hour) < 0 And -Imbalance(Hour) <= [DischargingCapacity] And BatteryContent(Hour - 1) >= -Imbalance(Hour) / [Di
schargingefficiency] Then
        PowerToWindImbalance(Hour) = -Imbalance(Hour)


    ElseIf Imbalance(Hour) < 0 And -Imbalance(Hour) >= [DischargingCapacity] And BatteryContent(Hour - 1) <= [DischargingCapacity] /
 [Dischargingefficiency] Then
        PowerToWindImbalance(Hour) = BatteryContent(Hour - 1) * [Dischargingefficiency]

    ElseIf Imbalance(Hour) < 0 And -Imbalance(Hour) > BatteryContent(Hour - 1) And BatteryContent(Hour - 1) <= [DischargingCapacity
] / [Dischargingefficiency] Then
        PowerToWindImbalance(Hour) = BatteryContent(Hour - 1) * [Dischargingefficiency]

    ElseIf Imbalance(Hour) < 0 And -Imbalance(Hour) > BatteryContent(Hour - 1) And BatteryContent(Hour - 1) >= [DischargingCapacity
] / [Dischargingefficiency] Then
        PowerToWindImbalance(Hour) = [DischargingCapacity]

    ElseIf Imbalance(Hour) = 0 Then
        PowerToWindImbalance(Hour) = 0 And PowerFromWindImbalance(Hour) = 0

    Else: PowerToWindImbalance(Hour) = 0 And PowerFromWindImbalance(Hour) = 0
    End If

 'Sub calculation of battery content before participation on regulation market

BatteryContent(Hour) = BatteryContent(Hour - 1) + PowerFromWindImbalance(Hour) * [Chargingefficiency] - PowerToWindImbalance(
Hour) / [Dischargingefficiency]


'Participation on regulating power market

If PowerToWindImbalance(Hour) > 0 Or PowerFromWindImbalance(Hour) > 0 Then
    PurchaseRegulatingPower(Hour) = 0 And SaleRegulatingPower(Hour) = 0

ElseIf Hour = 8784 Then
    PurchaseRegulatingPower(Hour) = 0 And SaleRegulatingPower(Hour) = 0

'Purchase of downward regulating power

ElseIf BatteryContent(Hour) = [BatteryCapacity] And DownwardRegulation(Hour) Then
    PurchaseRegulatingPower(Hour) = 0

ElseIf Imbalance(Hour + 1) > 0 And SpotPrice(Hour + 1) > [MaxSpotPrice] And DownwardRegulation(Hour) Then
    PurchaseRegulatingPower(Hour) = 0

ElseIf Imbalance(Hour + 1) < -[ChargingCapacity] And BatteryContent(Hour) = 0 And DownwardRegulation(Hour) Then
    PurchaseRegulatingPower(Hour) = [ChargingCapacity]

ElseIf Imbalance(Hour + 1) < 0 And BatteryContent(Hour) = 0 And DownwardRegulation(Hour) Then
```

```
    PurchaseRegulatingPower(Hour) = -Charging(Hour + 1) / [Chargingefficiency]

ElseIf Imbalance(Hour) = 0 And SpotPrice(Hour) <= 0 And BatteryContent(Hour) <= [BatteryCapacity] - ([ChargingCapacity] * [Charging
efficiency]) And DownwardRegulation(Hour) Then
    PurchaseRegulatingPower(Hour) = [ChargingCapacity]

ElseIf Imbalance(Hour) = 0 And SpotPrice(Hour) <= 0 And BatteryContent(Hour) > [BatteryCapacity] - ([ChargingCapacity] * [Charginge
fficiency]) And DownwardRegulation(Hour) Then
    PurchaseRegulatingPower(Hour) = ([BatteryCapacity] - BatteryContent(Hour)) / [Chargingefficiency]

' Sale of upward regulating power

ElseIf BatteryContent(Hour) = 0 Then
    SaleRegulatingPower(Hour) = 0

ElseIf Imbalance(Hour) = 0 And Imbalance(Hour + 1) = 0 And SpotPrice(Hour) > 0 And SpotPrice(Hour + 1) < 0 And UpwardRegulation
(Hour) Then
    SaleRegulatingPower(Hour) = [DischargingCapacity]

ElseIf Imbalance(Hour + 1) > [ChargingCapacity] And BatteryContent(Hour) = [BatteryCapacity] And UpwardRegulation(Hour) Then
    SaleRegulatingPower(Hour) = [DischargingCapacity]

ElseIf Imbalance(Hour + 1) > 0 And BatteryContent(Hour) = [BatteryCapacity] And UpwardRegulation(Hour) Then
    SaleRegulatingPower(Hour) = Discharging(Hour + 1) * [Dischargingefficiency]


ElseIf Imbalance(Hour) = 0 And SpotPrice(Hour) > [MaxSpotPrice] And BatteryContent(Hour) > [DischargingCapacity] And UpwardReg
ulation(Hour) Then
   SaleRegulatingPower(Hour) = [DischargingCapacity]

ElseIf Imbalance(Hour) = 0 And SpotPrice(Hour) > [MaxSpotPrice] And BatteryContent(Hour) < [DischargingCapacity] And UpwardReg
ulation(Hour) Then
   SaleRegulatingPower(Hour) = BatteryContent(Hour) * [Dischargingefficiency]


Else: PurchaseRegulatingPower(Hour) = 0 And SaleRegulatingPower(Hour) = 0
End If

BatteryContent(Hour) = BatteryContent(Hour) + PurchaseRegulatingPower(Hour) * [Chargingefficiency] - SaleRegulatingPower(Hour) /
[Dischargingefficiency]



'The new and reduced imbalance caused by the battery
    ReducedImbalance(Hour) = Imbalance(Hour) - PowerFromWindImbalance(Hour) + PowerToWindImbalance(Hour)

'sale at spot market based on forecastet and traded production
    SpotSale(Hour) = SpotPrice(Hour) * TradedProduction(Hour)

 'Settlement of imbalances based on the two price model and the new and reduced imbalance

 'Payment because of positive imbalance - settlement with Spot price
    If UpwardRegulation(Hour) And ReducedImbalance(Hour) > 0 Then
        PaymentSpotPrice(Hour) = ReducedImbalance(Hour) * SpotPrice(Hour)
    Else: PaymentSpotPrice(Hour) = 0
 End If

  'Fee because of negative imbalance - settlement with upward price
    If UpwardRegulation(Hour) And ReducedImbalance(Hour) < 0 Then
        FeeUpwardPrice(Hour) = -ReducedImbalance(Hour) * UpwardPrice(Hour)
    Else: FeeUpwardPrice(Hour) = 0
 End If

 'Payment because of positive imbalance - settlement with downward price
    If DownwardRegulation(Hour) And ReducedImbalance(Hour) > 0 Then
        PaymentDownwardPrice(Hour) = ReducedImbalance(Hour) * DownwardPrice(Hour)
    Else: PaymentDownwardPrice(Hour) = 0
 End If

 'Fee because of negative imbalance - settlement with spot price
    If DownwardRegulation(Hour) And ReducedImbalance(Hour) < 0 Then
```

```
       FeeSpotPrice(Hour) = -ReducedImbalance(Hour) * SpotPrice(Hour)
    Else: FeeSpotPrice(Hour) = 0
 End If


  'When balance in the system occurs, the settlement will be based on the spotprice
    If Not UpwardRegulation(Hour) And Not DownwardRegulation(Hour) And Imbalance(Hour) > 0 Then
       BalancedPayment(Hour) = SpotPrice(Hour) * ReducedImbalance(Hour)

    ElseIf Not UpwardRegulation(Hour) And Not DownwardRegulation(Hour) And Imbalance(Hour) < 0 Then
       BalancedFee(Hour) = SpotPrice(Hour) * -ReducedImbalance(Hour)


  Else: BalancedPayment(Hour) = 0 And BalancedFee(Hour) = 0
 End If


FillInResults


Next Hour

End Sub

Sub FillInResults()

'Fill in results in scenario3

 Worksheets("Scenario3").Cells(Hour + 4, 5) = BatteryContent(Hour)
 Worksheets("Scenario3").Cells(Hour + 4, 6) = SaleRegulatingPower(Hour)
 Worksheets("Scenario3").Cells(Hour + 4, 7) = PurchaseRegulatingPower(Hour)
 Worksheets("Scenario3").Cells(Hour + 4, 8) = PowerFromWindImbalance(Hour)
 Worksheets("Scenario3").Cells(Hour + 4, 9) = PowerToWindImbalance(Hour)
 Worksheets("Scenario3").Cells(Hour + 4, 10) = ReducedImbalance(Hour)
 Worksheets("Scenario3").Cells(Hour + 4, 13) = SpotSale(Hour)
 Worksheets("Scenario3").Cells(Hour + 4, 14) = SaleRegulatingPower(Hour) * UpwardPrice(Hour)
 Worksheets("Scenario3").Cells(Hour + 4, 15) = PurchaseRegulatingPower(Hour) * DownwardPrice(Hour)
 Worksheets("Scenario3").Cells(Hour + 4, 16) = PaymentSpotPrice(Hour)
 Worksheets("Scenario3").Cells(Hour + 4, 17) = PaymentDownwardPrice(Hour)
 Worksheets("Scenario3").Cells(Hour + 4, 18) = FeeUpwardPrice(Hour)
 Worksheets("Scenario3").Cells(Hour + 4, 19) = FeeSpotPrice(Hour)
 Worksheets("Scenario3").Cells(Hour + 4, 20) = BalancedPayment(Hour)
 Worksheets("Scenario3").Cells(Hour + 4, 21) = BalancedFee(Hour)




End Sub
Sub FillHourVariables()

'Hourly data are filled into the hour variables
    For Hour = 1 To [HoursInYear]

     SpotPrice(Hour) = Worksheets("Market data").Cells(Hour + 4, 3) + [fast]
     DownwardPrice(Hour) = Worksheets("Market data").Cells(Hour + 4, 5) + [fast]
     UpwardPrice(Hour) = Worksheets("Market data").Cells(Hour + 4, 6) + [fast]
     TradedProduction(Hour) = Worksheets("Reference Wind").Cells(Hour + 4, 3)
     ActualProduction(Hour) = Worksheets("Reference Wind").Cells(Hour + 4, 5)
     Imbalance(Hour) = Worksheets("Reference Wind").Cells(Hour + 4, 6)
     Charging(Hour) = Imbalance(Hour) * [Chargingefficiency]
     Discharging(Hour) = Imbalance(Hour) / [Dischargingefficiency]
     PowerToWindImbalance(Hour) = Worksheets("Scenario3").Cells(Hour + 4, 9)
     PowerFromWindImbalance(Hour) = Worksheets("Scenario3").Cells(Hour + 4, 8)
     ImbalancePower(Hour) = PowerFromWindImbalance(Hour)
     UpwardRegulation(Hour) = SpotPrice(Hour) + 1 < UpwardPrice(Hour)
     DownwardRegulation(Hour) = SpotPrice(Hour) - 1 > DownwardPrice(Hour)


  Next Hour
End Sub
```