ME55035 ME-EPT Thesis

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Energy storage for decentralized renewable energy generation

to mitigate connection scarcity on the MV-grid

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Challenge the future

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Energy storage for decentralized renewable energy generation to mitigate connection scarcity on the MV-grid

by

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This thesis is in cooperation with the TU Delft and Qirion B.V., a subsidiary of Alliander N.V.
Picture is of a solarfarm in Delftzijl [1]

Acknowledgements

Before I invite you to read my graduation thesis, I would like to acknowledge some people who helped me a lot during my graduation process.

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I have spent a long time on this thesis. It was not always easy, especially during the corona lockdown, motivation was sometimes hard to find, but I am really proud of my work and learned a lot along the way. I hope you will enjoy reading it.

Dick Hofman

Den Hoorn, Friday 12th June, 2020

Executive Summary

The goal of this research is to be used as a framework for adding energy storage to aid in the connection of decentralized renewable energy generation in areas with limited connection availability to the electricity grid.
The dependence on fossil fuels is reduced with the aim to reduce greenhouse gas emissions. In the Netherlands this means that natural gas is slowly faded out of our society. One consequence of this is the electrification of some functionalities that natural gas had, like heating houses and cooking. Additionally, more and more people are choosing to drive electric vehicles. On the supply side more and more renewable energy sources are being installed to increase the renewable energy mix in our electricity market. Because the supply and demand of electricity increases faster than new cables can be installed, the electricity grid is put under strain. The electricity grid was designed, decades ago, to only transport electricity from central, large energy generation plants to the consumer. However, nowadays there are also developers that are building 'decentralized' PV parks and wind farms. These decentralized generation systems are unable to be connected to the MV-grid.
Energy storage has been identified to be a valuable asset to help with the penetration of renewable energy. Energy storage can help to match the supply and demand, improve the power quality, improve the variability of the power supply and smooth out the peaks of over-generation most associated with the congestion on the MV-grid. It is also possible to (temporally) replace the necessary grid reinforcement. However, energy storage is still very expensive. So it needs to be examined how energy storage can be interesting for this problem. A knowledge gap exist on energy storage for decentralized renewable energy generation for the Dutch medium-voltage grid. Additionally, no method was available to simulate such an problem. So this was researched in this study. The study has included a suitable financial model, various energy storage systems and operating strategies. Additionally, the interest of the developer of the DG plant and the DSO were included. For the developer the study has investigated the profitability of the system. The DSO is interested in minimizing the cost and resources of the connection of the hybrid DG system. From this the following research questions are formulated:
Under what conditions can energy storage for decentralized renewable energy generation be economically feasible to mitigate connection scarcity on the medium-voltage grid?

This was answered in three steps. Firstly, a model was built to accurately simulate energy storage in a hybrid DG system. This model must satisfy all technical requirements and be applicable to the Dutch electricity markets.
Secondly, the simulation model was used to examine the hybrid system design to optimally profit from the storage system. From this it was concluded that a small energy storage system adds relatively more value in energy output and earnings than a large storage system. Additionally, it identified the pumped heat electrical storage system as the most profitable system for decentralized generation and the best performing technology is the LFP Li-ion battery. Also, storage is more beneficial for PV solar energy than for wind energy. In this section it was also found that in alleviating connection scarcity, grid reinforcement is more profitable than energy storage.
And thirdly, different operating strategies for the hybrid system were investigated to optimally use the energy storage system. For a hybrid system with cable capacity limitations, peak shaving of over-generated

energy is the most profitable operating strategy.

This research has shown that energy storage can improve the energy output and revenue of a decentralized system with connection capacity limitations. Nevertheless, not adding energy storage is more profitable. A small energy storage system with a PV solar park can become economically feasible and more interesting than grid reinforcement. For this, energy storage technologies need to improve, especially the capital cost need to reduce, with more than half of the current cost. Additionally, this hybrid system needs to be located where grid reinforcement is costly or not possible.

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Nomenclature

Abbreviations

AC	Alternating current
AFC	Alkaline Fuel Cell
aFRR	automatic Frequency Restoration Reserve
BESS	Battery Energy Storage System
CAES	Compressed Air energy storage
CAPEX	Capital Expenditure
CRF	Capital Recovery Factor
DAM	Day Ahead Market
DC	Direct current
DG	Decentralized Generation
DSO	Distribution Systems Operator
ESS	Energy Storage System
EV	Electric Vehicle
FBESS	Flow Battery Energy Storage System
FCR	Frequency Containment Reserve
FES	Flywheel Energy Storage
GPLK	Gepantserde Papier-Lood Kabel
HFCS	Hydrogen Fuel Cell System
HV grid	High-voltage grid
IRL	Industry Readiness Level
LA	Lead-acid battery
LAES	Liquid Air Energy Storage
LCOE	Levelized Cost of Energy
LFP	Lithium Iron Phosphate
Li-ion	Lithium-ion battery
LV grid	Low-voltage grid
MDOD	Maximum Depth of Discharge
mFRR	manual Frequency Restoration Reserve
MV grid	Medium-voltage grid
NaNiCl	Sodium Nickel Chloride battery
NaS	Sodium Sulfer battery
NMC	Nickel Manganese Cobalt
NPV	Net Present Value
OPEX	Operational Expenditure
PEMFC	Proton Exchange Membrane Fuel Cell
PHES	Pumped Heat Electrical Storage
PHS	Pumped Hydro storage
PRP	Program Responsible Party
PV	Photo-voltaic
SCESS	Supercapacitor Energy Storage System
SMES	Superconducting Magnetic Energy Storage
SOC	State of Charge
TES	Thermal Energy Storage
TSO	Transmission Systems Operator
VRB	Vanadium Redux flow Battery
XLPE	Cross-linked Poly-Ethyleen
ZnBr	Zinc Bromide flow battery

Symbols

η	efficiency
$^{\circ}$C	Celsius
A	Ampere
Al	Aluminium
Cu	Copper
GWh	gigawatt hour
Hz	Hertz
kV	kilovolt
kVA	kilovolt-ampere
kW	kilowatt
kWh	kilowatt hour
M€	Million euros
MW	megawatt
MWh	megawatt hour
MWp	megawatt peak
PTU	Program Time Unit
V	volt
yr	year

1 Introduction

The Dutch climate agreement of 2019 aims to reduce the national greenhouse gas emissions with 49% by 2030 compared to the 1990 level [13]. One big measure in this reduction, is to scale down the amount of natural gas used in households and industry. The ministry of economic affairs and climate has very recently announced that from 2022 the natural gas fields in the north of the Netherlands will be closed [14]. A part of the functions of this Dutch natural gas will be picked up by natural gas from abroad and from the North Sea. However, because of the goal to reduce greenhouse gas emissions, a part of the functionalities of natural gas needs to be replaced by (green) electricity. This electrification will cause strain on the electricity transportation network [8]. Old electricity cables are not designed to handle the load required for houses switching from gas- to electric cooking and the charging of electric cars which are increasingly more common. Furthermore, more energy is being generated by renewable energy sources like wind and solar. This is not only done in big wind farms and solar panel farms, but also 'decentralized', by small developers. Wind turbines and photo-voltaic (PV) solar panels require a lot of space to optimally profit from the wind and the sun. This promotes less densely populated areas over high densely populated areas. This is also favorable since the land is cheaper. However, these areas have smaller electricity cables which are not able to handle the power capacity of the new energy source. This is especially a problem at peak generation and peak demand. Furthermore, the erratic and unpredictable power generated by these decentralized renewable energy sources exacerbate the congestion.

By adding energy storage system (ESS) to the energy generation system, peaks can be 'shaved' and the electricity could be transported when the electricity cable is not at maximum capacity. Thus a smaller cable could be used. If a smaller cable does not need to be replaced or if a new cable is able to stay small, it would, of course, save money and resources.

Qirion is a subsidiary of Alliander, one of the largest Dutch energy network companies that provides the distribution of electricity to consumers and businesses [15]. Qirion is interested to investigate the strategies to optimize the connection of decentralized renewable energy generation (DG) to their electricity distribution grid. In collaboration with Qirion I have researched the use of energy storage systems on decentralized energy generation for their electricity distribution grid.

1.1 Problem statement

In fig. 1 a simple depiction of the electricity grid is shown. First the electricity is generated in a power station, then that power is transported and eventually distributed to the users. The electricity transportation network consists of four levels based on their voltage rating [16]:

- High voltage net - 110 kV to 380 kV
- Medium voltage net (used for transport) - 10 kV to 50 kV
- Medium voltage net (used for distribution) - 400 V to 10 kV
- Low voltage net - 230 V to 400 V

Congestion due to renewable energy generation is an issue on all levels, as all levels need to be in balance on its own and with each other. A distribution systems operator (DSO), like Alliander [15], is only responsible for the medium and low voltage electricity distribution, so the high voltage grid, which is maintained by the transmission systems operator (TSO) [17], will be left outside the scoop of my research.

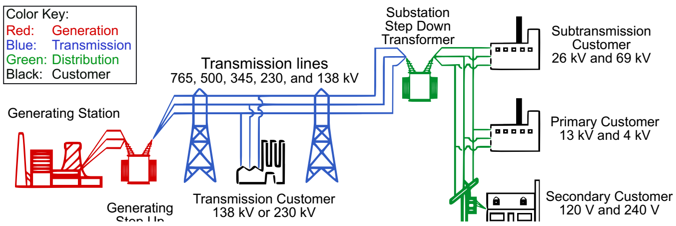


Figure 1: Simplified electricity grid with centralized generation and distribution [2]

Figure 2 shows a better depiction of the current electricity grid. In this picture several examples of decentralized generation are depicted. A solar park, marked as 'Zon', and a farm with a personal wind turbine are directly connected to the medium voltage distribution network. These are examples of places where congestion and imbalance on the medium voltage distribution network grid occur. The low voltage grid can also become congested, but congestion on the medium voltage grid is at the moment more pressing. There are a lot of developers willing to invest in decentralized renewable energy, however the DSO is unable to connect all the solar and wind farms due to capacity limitations of the distribution net [1, 18, 19]. Alliander reports to have various areas in the Netherlands where the availability on the distribution net is limited, these are shown in fig. 3. On the right map it is especially clear that congestion on the distribution net due to a surplus of renewable energy generation is a big issue.

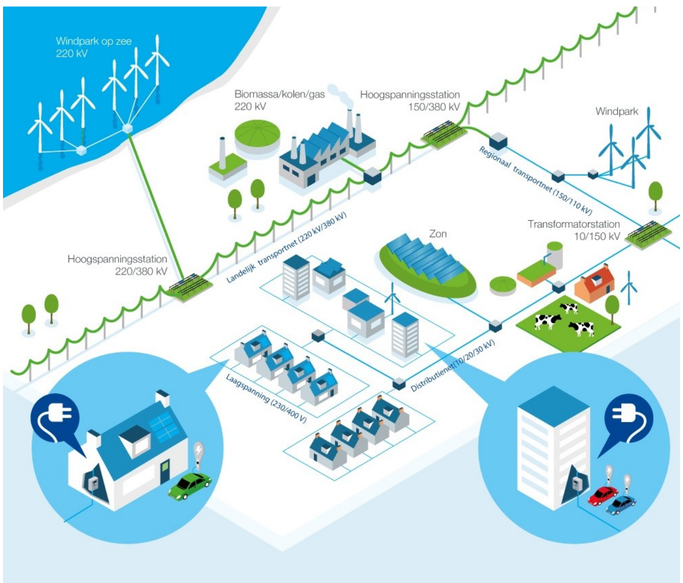
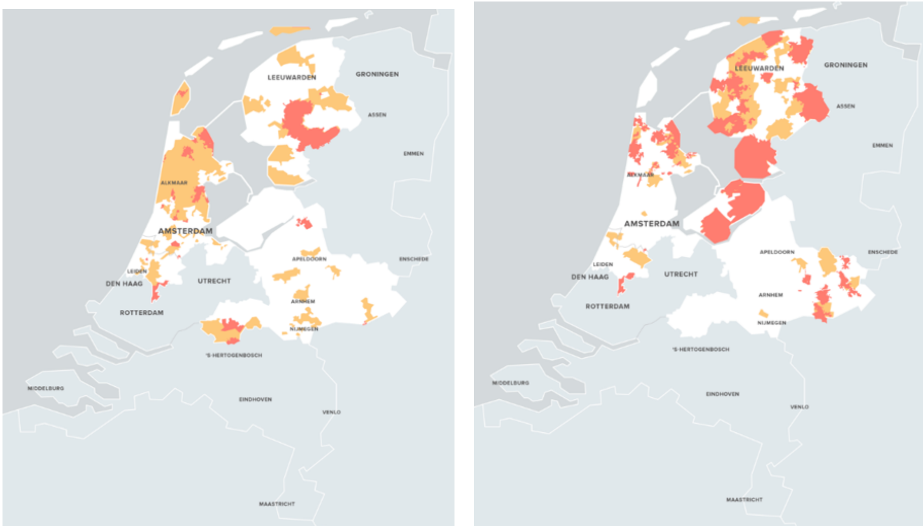


Figure 2: Depiction of an electricity grid in the energy transition with centralized and decentralized energy generation [3]

If the renewable energy could be generated with absolute control the congestion issue would be a lot less significant. However, renewable energy is very unpredictable and irregular and it often does not match with demand. This is additionally aggravated by the simultaneity of the renewable energy. For example, if it is



(a) Demand **(b)** Supply

Figure 3: Electric transport capacity availability on the distribution network of Liander for installation of extra capacity. For both more demand and more supply. Orange is limited availability, red is no availability. [20]

sunny, it is sunny in the whole region.

Energy storage has nowadays become a valuable asset for renewable energy sources. Due to the erratic behavior of the weather, the power supplied by these renewable energy sources does not always match the demand. Energy storage systems have been shown to add value to renewable energy, by improving the power quality, by bridging the generated power to moments with higher demands and by providing better energy management. It therefore helps renewable energy to penetrate the energy market [7, 21, 22]. This also applies for decentralized renewable energy generation. An additional advantage of DG utilizing ESS is better compatibility with the grid. Peaks that can occur during generation can be smoothed out over time. An electricity cable does not have to be installed to facilitate peak power, but an smaller cable could be used to connect the DG to the grid. Energy storage could thus be used as an alternative to grid reinforcement [23]. However, when it is expected that more capacity is required in the future, grid reinforcement is inevitable. But grid reinforcement can take many years to realize as it is a labor intensive process. Energy storage can be, for these occasions, a temporary solution. This way a DG system can already be utilized before the grid is reinforced. Furthermore, Alliander has identified energy storage as one of the first preventive measures to combat grid congestion [20].

1.2 Literature review

There is an abundance of scientific research done into the role of energy storage for renewable energy generation.

There are very useful review papers about the different energy storage systems and their applications [7, 9]. In [7] all the different energy storage systems are described and subsequently classified based on their power rating and energy capacity. This can be matched to various storage applications based on the required response time and discharge duration. For example, a supercapacitor is rated at 1 kilowatt (kW) to 500 kW and at 0.1 kilowatt hour (kWh) to 1 kWh. This makes the supercapacitor suitable for applications with high response time and low discharge duration, e.g. power quality applications. In section 2.4 these papers and the different energy storage systems are discussed further.

In addition, a lot has been done on the optimal sizing and placement of energy storage systems in distributed networks [21, 22, 24, 25, 26].
In [26] battery storage sizing indicators and techniques are reviewed for different applications. In the papers that are reviewed, a differentiation between two sizing criteria is made: economic and technical indicators. Hybrid indicators are also possible where the battery size is optimized for an economic indicator and technical indicators are used as constraints. Probabilistic, analytical and direct search-based methods are described as battery energy storage sizing techniques.
In [22] the energy storage system size is calculated based on the difference in supply and load. Firstly, the daily load of a residential house is determined. Secondly, the amount of PV and/or Wind that is required is calculated for the load. Afterwards, the energy output for the PV panels or wind turbines is determined. This output is compared with the daily load. Finally, the mismatch of the load and supply is calculated to determine the energy storage size. A distinction is made between the minimum and maximum required storage. The minimum required storage signifies the amount of storage to support the daily load. The maximum indicates the required capacity to manage the total generated energy. This study also identifies several economic and social constraints: Net present value (NPV), Levelized Cost of Energy (LCOE), Cost of Emissions and Renewable Fraction.
[25] calculates the optimal size of a battery energy storage system using a heuristic method for the purpose of peak load shaving and load curve smoothing in a transmission and distribution grid. This method is also applied to a real case in Hawaii. A ratio of 1.32 was calculated for the optimal battery energy storage system (BESS) capacity in the transmission grid in reference to the distribution grid.
In [24] a probabilistic method is applied to find the optimal ESS size under uncertain demand and generation, again neglecting economic constraints. Subsequent work would focus on a more general setting as in this paper the worst-case scenario was discussed. In the latest two papers, only technical constraints are considered.
[21] considers both economic and technical aspects to find the optimal size and placement of an ESS. In this paper, multiple storage systems are distributed over several locations in a transmission network. A three stage method is proposed to first determine the location of the storage systems, to find the optimal energy and power ratings and subsequently find the overall performance of the final system. However, it is not clearly stated in the paper where some of the used values are attained and used (e.g. the energy price).
Most of these studies focus predominately on the mathematics of the problem and except for [21] only technical constraints are considered in these studies. In additional papers found in [26], that include economic indicators, often only the investment cost of the power system is studied. This is important information for the investor of the generation and storage system, but the consequences on the connection to the grid and the subsequent congestion are neglected. Thus the interests of the DSO should also be included to consider the interest of both the stakeholders. More on energy storage system optimization criteria and techniques can be found in section 2.6.

There are master theses, previously done, that do provide a more inclusive research into energy storage

sizing in the Dutch electricity grid and market, but these have focused on large scale energy generation [5] and low voltage grid demand [27].
[5] researched how battery energy storage can be optimally designed and operated for onshore wind farms in the Netherlands. The wind farm considered in this study is about 60 megawatt (MW) and will be connected to the high voltage grid. The optimal battery for this wind farm would be a Li-ion battery with a capacity of 60 megawatt hour (MWh) - 80 MWh, depending on market price variation. However, energy storage was still deemed as expensive. Furthermore, it is recommended to improve the financial model to apply the NPV or LCOE and to include interest rates.
In [27] the NPV is used to calculate the added value of a low voltage electrical energy storage system for a DSO. This study focused mostly on the deferral of grid reinforcements by adding storage. However, it was concluded that energy storage was not economically efficient for a low voltage electricity grid due to the high cost of battery storage. Furthermore, the effect of future advancements in the costs of energy storage systems are not discussed.
So energy storage is still very expensive. However, the benefits are not only economic and there are still areas worth exploring to see when it does get economically feasible and under what conditions.

What is missing in the literature, is an inclusive study on decentralized renewable energy generation with energy storage for the Dutch medium voltage grid. This should include a suitable financial model, various energy storage systems, management strategies and the direct stakeholders, which are the developer and the DSO.

1.3 Research questions

Research Question

- Under what conditions can energy storage for decentralized renewable energy generation be economically feasible to mitigate connection scarcity on the medium-voltage grid?

This main research question will be answered by means of three sub questions. The first problem is that there is no available method to simulate an energy storage system that is utilized for a decentralized renewable energy generation system. The goal of this model is to find the optimal size of an energy storage system based on the different boundary conditions. So the first question is how to build such a simulation model that satisfies all the technical requirements of energy storage and decentralized energy generation and that is applicable to the Dutch medium voltage grid and electricity markets.
The model is first applied on the hybrid generation and storage system. The size and type of all the subsystems need to be determined. This consists of finding which energy storage system technology is best suited for decentralized energy generation on the MV grid scale. Also what type of decentralized energy generation system best benefits from energy storage. Additionally, the size of the grid connection is an important factor in the effectiveness of energy storage and the profitability.
Subsequently, there are different energy management strategies for the hybrid system. How to operate the energy storage system to optimally use it in the hybrid system? Throughout the interests of the developer and the DSO are not to be neglected. Eventually this is all combined to answer the main research question.

Sub Questions

∗ How to build a simulation model to optimize the use of energy storage in a decentralized renewable energy generation system?

∗ What are characteristics of a hybrid generation and storage system to optimally profit from the storage system?

∗ What are beneficial operating strategies to optimally use the energy storage system in the hybrid system?

The goal of this research is not only to answer these questions but also to be used as a framework for new energy storage projects to aid in the connection of decentralized renewable energy generation in areas with limited connection availability to the electricity grid. So this report could be used in the selection of an energy storage system and operating strategy for the hybrid DG system and the proposed simulation model could be used to calculate the optimum size of the ESS and the profitability of the project.

1.4 Approach

The approach for this thesis is as follows. First a literature study was conducted to define the research questions and to set the boundaries of the research. Also, in the literature study all the background information, variables, assumptions and constraints needed to perform the rest of the research, was gathered. This meant that first a description of the Dutch electricity system, grid and markets was required [16, 17, 28]. Subsequently, energy storage systems and their applications were evaluated [7, 9, 10]. Furthermore, the

possible energy generation and storage configurations were researched. Finally the requirements for an energy storage system size optimization problem were gathered and optimization techniques were reviewed [5, 26, 21].
To build the model to simulate the ESS behavior in a hybrid system a simple system model needed to be chosen which incorporated the three subsystems: the generation system, the energy storage system and the connection system to the grid. The technical requirements of these systems had to be satisfied. The results were judged based on the interests of the stakeholders: the developer and the DSO. The developer is mostly interested in the return on the investment and how it can maximize the profit on the DG and ESS system. The DSO is responsible for connecting the DG to the distribution network. The DSO wants to reduce the connections costs as much as possible. This means that it is in the DSO's best interest to use existing electric infrastructure if that is possible. So if it can use the ESS to minimize the cable capacity requirements, grid reinforcement can be postponed or even be avoided.
Firstly, the model was applied to determine suitable energy storage systems based on the improvement in performance and profitability of the system. Secondly the different DG systems were compared to see if energy storage better benefited a PV solar park, a wind farm or a generation park with a combination of the two. Thirdly influence of varying the size of the connection system from the DG/ESS system to the external grid on the performance and profitability was examined.
When a hybrid system was chosen that performs best from the addition of storage, several energy management strategies could be compared so that the energy storage system was optimally used, for both the developer and the DSO.

2 System description and analysis

In this section the context for this thesis is provided. A clear description of the relevant systems are described to provide the relevant background information. And these systems are analyzed to find the variables, assumptions and constrains that are used in this thesis.
Firstly, a description of the Dutch electricity system and in particular the Dutch medium voltage distribution grid is given. Secondly, the Dutch electricity markets are reviewed. Thirdly, the energy storage technologies applicable for decentralized renewable generations are examined. Subsequently, more information about the decentralized generation systems is given. Afterwards optimization indicators and techniques are reviewed for the sizing of the ESS's. Finally, alternative solutions to energy storage and grid reinforcement, that can prevent grid congestion, are concisely discussed.

2.1 Dutch electricity system

In fig. 4 a simple depiction of the electricity grid is shown. First the electricity is generated in a power station, then that power is transported over high voltage transmission lines, typically between 110 kV to 380 kV, to a substation which lowers the voltage to 10 kV to 50 kV. This power is subsequently distributed to the industry and to consumers. For the consumers and for some businesses the voltage is additionally stepped down to 230 V to 400 V. The whole Dutch electricity net is AC, which stands for alternating current. AC alternates its current at a specific frequency. The frequency of the Dutch AC electricity net is 50 Hz [16]. The counterpart to AC is DC, direct current, which does not alternate the direction of current.

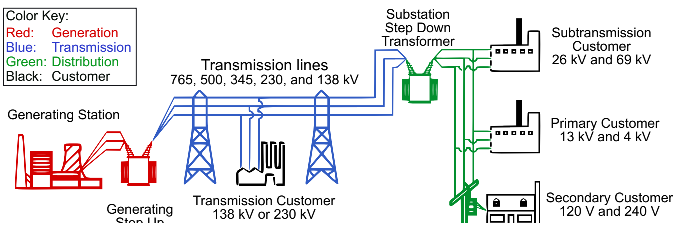


Figure 4: Simple electricity grid [2]

However, fig. 4 only depicts the physical layer of the electricity system. In fig. 5 a schematic of the full Dutch electricity system is shown. A distinction between a physical and an institutional layer is made. The physical layer consists of generation (power plants), the transmission and distribution networks and the load, by which businesses and households are meant. The institutional layer consist of the electricity producers, the TSO, the DSO, the consumers and the various electricity markets. Different actors in the institutional layer have control over different parts in the physical layer. This is indicated with the double pointed arrows. The single pointed arrows are indicate the direction of electricity trades.

The TSO, TenneT in the Netherlands, is responsible for three tasks. Firstly, they have to manage the high voltage electricity grid. Secondly, they manage the import and export of electricity across borders, to other so called control areas. Thirdly, they are responsible to match the demand and supply by managing the injection and withdrawal of electricity in the grid. This includes maintaining the 50 Hz grid frequency [17].

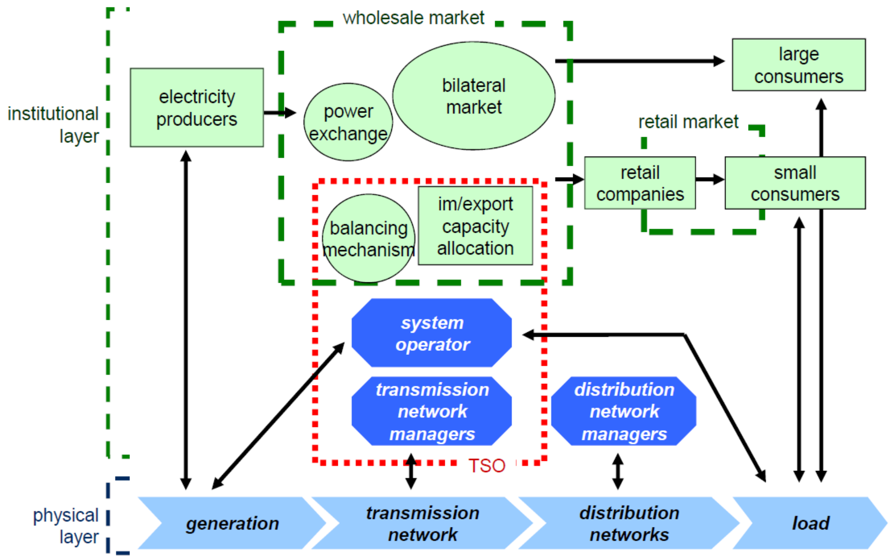


Figure 5: Schematic of the Dutch electricity system. Arrows with only one arrow head indicate the electricity trade direction. Double pointed arrows illustrate which institutional actor controls which part the physical layer. [17]

In the Netherlands there are eight DSO's. The biggest three are Liander, Enexis en Stedin. Liander is, like Qirion, a subsidiary of Alliander. Liander is the DSO in four provinces in the Netherlands: Noord-Holland, Flevoland, Friesland en Gelderland [29]. The DSO is responsible for the MV and LV electricity grid. (In the Netherlands the DSO's are also responsible for the natural gas network). The lower voltage electricity grids includes the electricity cables and substations/transformers. Moreover these components is explained in the next section.
It is important to note that if a party requests a connection to the (HV/MV/LV) grid, the TSO/DSO is obligated to install that connection by law. This applies to generation and consumption. The system operator is always responsible for at least a part of the connection costs. However it is not always clear how much this is, but it is sought to be taken into account in this thesis. For the other part of the connection costs for the developer there are fixed tariffs based on the size and type of connection. This is discussed further in the next section.

2.2 Distribution grid

The distribution network is now not as straightforward as seen in fig. 4. Figure 6 shows a better depiction of the current electricity grid. Energy is nowadays also generated by small developers and by consumers with small wind- and solar farms and with personal PV solar panels. This is a change from centralized electricity generation and distribution to a decentralized electricity generation model. There are several advantages to decentralized generation (DG): there is less transport needed from generation to consumer, so there are less energy losses, a reduction of voltage fluctuations, better reliability and power quality [23]. However, as mentioned the current cables that have often been in use for several decades, were not designed to handle to transport the new requested power.

In this subsection more information is given about the components that make up the distribution grid: the

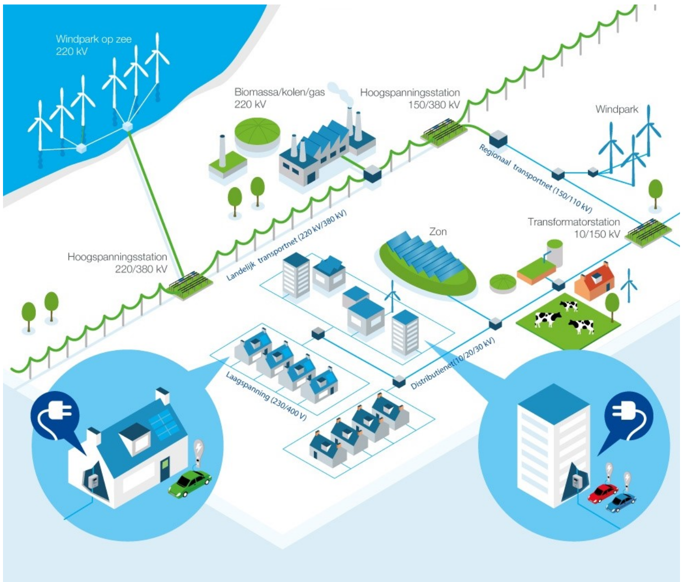


Figure 6: Depiction of the current electricity grid [3]

MV-cables and the transformers. The configuration of the entire decentralized energy generation system is expanded upon in section 2.5.

2.2.1 Medium-Voltage Cables

All electricity cables are comprised of 1, 3 or 4 conductive cores, insulation and a protective jacket, fig. 7. Most MV-cables comprise of 3 conductors. These are either made of copper or aluminium. Until 2005 GPLK cables (Gepantserde Papier-Lood Kabel) were installed. These have a mass-impregnated paper insulation. Nowadays cables with a plastic insulation are used, XLPE (Cross-Linked Poly-Ethylene) cables. MV-cables range from 16 to 800 mm^2. Usually MV-distribution-cables have a conductor profile from 16 to 240 mm^2. MV-transportation-cables generally range from 240 up to 630 mm^2. Conductors up to 300 mm^2 usually comprise of 3 coaxials. For larger cables, generally three single coaxial cables are used. These are for example used for the connection of large DG's .
There are five different potential levels for MV-cables: 6/10 kV, 8.7/15 kV, 12/20 kV, 18/30 kV, 36/50 kV. Hereby the first number indicates the phase voltage and the second number the coupled voltage.
The denotation of a cable is as followed. The first part indicates the insulation and the jacket. Then the potential level of the cable is given. The last part indicates the amount of cores, the core diameter and the core composition (Cu/Al). An example of a cable type is: YMeKrvaslqwd 6/10kV 3x240 Alrm as70. This is a 6/10 kV XPLE cable with 3 coaxial aluminium cable cores of 240 mm^2 [16, 30].

Cables are rated at their power capacity, expressed in kVA, and their current capacity, expressed in A. The rated power capacity is higher than the real power (kW). This is due to skin effect, where only an outer edge of an AC cable is utilized during electricity transport. The power lost due to this effect is called the blind power [31]. In table 1 the rated power and current capacity are shown, as is the real power capacity.
The maximum cable load is restricted by the maximum temperature allowed by the insulation of the cable and by the dehydration of the soil surrounding the electricity cable. The maximum insulation temperature

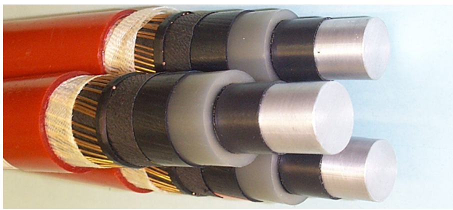


Figure 7: Medium voltage cable [4]

for GPLK cables is 50 °C. XLPE cables have a maximum temperature of 90 °C. However, this does make dehydration of the soil a bigger issue for XLPE cables than for GPLK cables. An optimal current load is given to ensure long cable lifetime. This is 70% or the rated current for a GPLK cable and for a XLPE cable 90% of the rated current.

Table 1: Rated power-, real power - and rated current capacities of MV cables. * measured at LV side of a MV-LV transformer [Qirion]

Rated power capacity	**Real power capacity**	**Cable connection type [A]**
100 kVA	85 kW	3 x 160 A
160 kVA	136 kW	3 x 250 A
250 kVA	212 kW	3 x 400 A*
400 kVA	335 kW	3 x 600 A*
630 kVA	535 kW	3 x 900 A*
1000 kVA	850 kW	3 x 1400 A*
1600 kVA	1260 kW	circa 2300 A*
2000 kVA	1750 kW	circa 2800 A*

2.2.2 Transformers

A transformer is the equipment that is used to transfer electricity from one electrical circuit to one or more other circuits. Usually these circuits are at different voltage levels, but sometimes a transformer is used between equal potential level grids as a booster to compensate for potential losses. The main components of a transformer are the cores and the windings, at least two, but often three windings [32].

There are several types of transformers [16]:

- HV/MV transformers, with and without current compensation
- MV-booster transformers
- MV/LV transformers with compensation

The transport transformers between the HV and MV grids and the distribution transformers between the MV and LV grids are the most decisive transformers.
Several important characteristics of transformers are:

- Rated potential: all the individual winding has a rated potential, in [V].
- Rated power: this is the total power capacity of the transformer, in [VA].

- Relative short-circuit voltage: the voltage of the primary winding in case the secondary winding has short-circuited, in percentile [%] of the rated potential.
- Connection: the phase windings can be connected in several configurations, most common are the triangle-connection and the star-connection.

In this study the rated power is the most important feature and for simplification the other characteristics will be neglected.

2.2.3 Connection costs

The cost of a MV-cable generally depends on the type of cable, the length and the amount of redundancy. Other costs like archaeological diggings will not be taken into account. The cost is mostly determined by the amount of copper or aluminium used, this scales with the volume, diameter times length, of the cable. The capacity of the cable depends on the diameter of the cable. The length of the cable depends on the distance from the DG to the substation of the DSO. However, a DG cannot be connected to every substation. A large DG that requires a 5 MW cable can only be connected to substation that can handle 5 MW, but these are less common than substations with lower capacities. Thus the required cable capacity also influences the length of the cable, so generally a cable with a higher power capacity is also a longer cable. Consumers and suppliers are divided into small and large. This division is set at a connection of 3x80 A. When consumers, large and small, are connected to the grid, a redundant cable is installed to ensure electricity in case of a connection malfunction. However, in general, DSO's are promoting less grid redundancy where possible to facilitate the energy transition. This is not functional for the essential needs, like lighting houses, but it is already applied to decentralized renewable generation. The length price (€/m) is about 1.5x higher if a redundant cable is installed [8, 33].
In table 2 an indication of a MV-cable costs is shown. There is a distinction made between the fixed connection cost [€] and the length price [€/m]. Below 2 MVA redundancy is always included in the price. This is noticeable in the length price.

Table 2: Indication of the cost of a aluminium MV-cable for large connections (> 3x80 A) [33]. Length price is without redundancy, but includes digging and paving of the public road. The connection cost include the 'knip', connection and safety measures. The costs of the transformer and measuring services are not included.

Cable connection	**Connection cost** [€]	**Length price** [€/m]
3x80 A - 100 kVA	4,310.00	45.00
100 - 160 kVA	4,832.00	53.80
160 - 630 kVA	18,340.00	111.90
630 kVA - 1 MVA	25,246.00	111.90
1 - 2 MVA	36,442.00	111.90
2 - 5 MVA 1x240 mm^2	146,058.00	74.36
5 - 10 MVA 2x240 mm^2	245,547.00	111.90
5 - 10 MVA 1x630 mm^2	151,304.00	123.12

However, these costs only represent the cable connection costs that the costumer has to pay. There are more associated costs that the DSO will have to finance. For example, the expansion of the substation and

subsequent grid reinforcement as a result of the added capacity. The interests of the DSO is to keep the connections as affordable as possible. Thus it is important that these costs should also be included in the connection cost calculations.
Grid reinforcements on the MV grid will subsequently necessitate reinforcement higher up in the grid [8]. This is of course only required if there are also congestion issues present or foreseen in the HV grid, but it is more likely that when the MV grid density is low, the HV-grid density is low as well. Thus HV grid congestion could quickly become an issue following MV grid reinforcement. Although the cost of HV grid reinforcement will not fall onto the DG developer or the DSO, it is important to keep these in mind when evaluating the connection costs. For instance, the extension of a transformer can encompass not only the construction of a new transformer connection, but this might also involve the purchase of new land to expand the transformer. Again it will depend on the situation how high these costs are and who will be responsible for them, but it is important to keep these possible subsequent costs in mind.
In a German study on grid-reinforcement of the distribution grid, an average price for the systems operator for all grid expansion is estimated to be between 310 €/kW and 331 €/kW [34]. This study examines the expansion of the entire grid, from LV to HV, thus the connection cost should include subsequent grid-reinforcement and substation expansion.

One note of importance, the sizes and the costs of the DG and its transformer will not be taken into account in this study, but rather seen as a given, section 2.5. The cost of the energy storage system is detailed in section 2.4 and the ESS's transformer will be discussed in section 2.5.

2.3 Electricity markets

In this subsection a description of the Dutch electricity market is provided. Furthermore, the accessible markets for the DG system are identified and methods to deal with imperfect forecasting of renewable energy are described.

The whole electricity market is designed in a way that there is always a supply of electricity to consumers and that this electricity is provided at an fair price, by promoting competition and innovation. Finally, it is designed to ensure social and environmental acceptability. So that there is access to electricity for people with a low income and so that the electricity industry has a low environmental impact [17].
As mentioned before, it is critical that demand and supply match as much as possible. Matching the demand and supply is the responsibility of the TSO, this is TenneT in the Netherlands. There are multiple markets for electricity trading. These markets are designed by TenneT in a way that ensures a perfect balance in demand and supply at all times. The markets can be split into three categories based on the time period, from long term electricity trading to very short trading: forward market, spot market and balancing markets.

Forward market
In the forward market large volumes of energy are traded. About 85% of the energy traded in the Netherlands is traded in the forward market. This market, also known as the bilateral market, is confidential, so there is not much data about the energy prices and duration of the contract, but most contracts are not settled more than a year in advance, although more than a couple of days in advance of the delivery [17].

Spot market

The second market, the spot market, comprises of the day ahead and the intraday market. In the day ahead market (DAM), energy is traded on an hourly basis for the next day. Inaccuracies in the DAM bids, due to production forecast errors, are traded in the intraday market for the same day. Trades may occur from an hour to 5 minutes in advance. The spot market is an international market, which encompasses Austria, the Baltics, Belgium, France, Germany, Great Britain, Italy, Luxembourg, the Netherlands, the Scandinavian countries, Portugal, Spain and Slovenia [28].

Balancing markets

The balancing markets are three different markets: the Frequency Containment Reserve, (FCR), the automatic Frequency Restoration Reserve, the automatic (aFRR) and the manual Frequency Restoration Reserve (mFRR). These are also known as the primary, secondary and tertiary control reserves. These are designed to maintain the 50 Hz frequency on the grid.

In fig. 8 a schematic of the frequency balancing mechanism is shown. The FCR is the first to (automatically) react in case of imbalances, within 30 seconds. The FCR is to limit the deviation from the set frequency. After which the aFRR automatically takes over to ensure operational capability. The aFRR has to react within 5 minutes and needs to be accessible for a longer time period than the FCR. If an even longer discharge time is necessary, the TSO manually activates the mFRR within 15 minutes. As these reserves require different response times, the technical requirements differ per reserve, e.g. the FCR requires a very fast response time and the mFRR requires a high energy capacity. The balancing markets are deployed as positive, more generation, and as well as negative reserves, more consumption [6]. An example of a positive balancing technique is ramping up a pumped hydro plant on stand by. An example of a negative balancing technique is by asking a large greenhouse to temporally use more energy than usual.

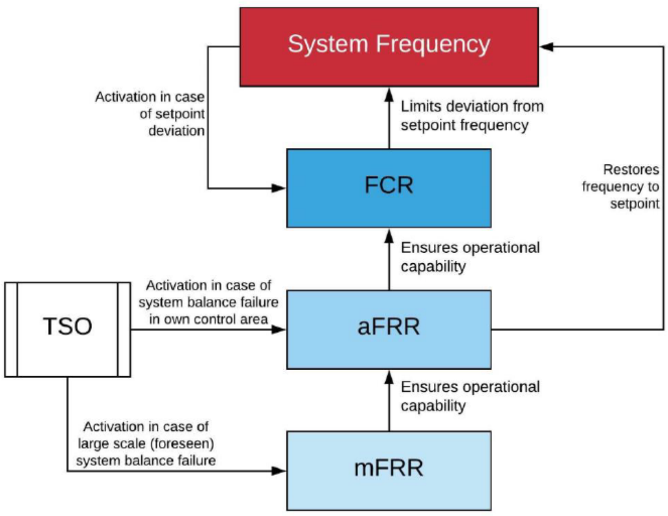


Figure 8: Frequency balancing mechanism schematic [5], based on [6]

Not everyone is however able to trade freely in the electricity markets. Only Program responsible parties (PRP) are able to do so. PRP's are held responsible for certain energy programs. There are a few dozen PRP's in the Netherlands. Most consumers fall under the responsibility of a large supply companies like

Vattenfall or Eneco. There are also PRP's that represent small electricity suppliers. These PRP's submit on behalf of their users an energy program to the TSO. Bids can be submitted to any market, the bilateral market, spot market or the balancing markets. The TSO matches the energy programs for generation and consumption on all markets [17].
An overview of the bidding and delivery of the different markets is depicted in fig. 9.

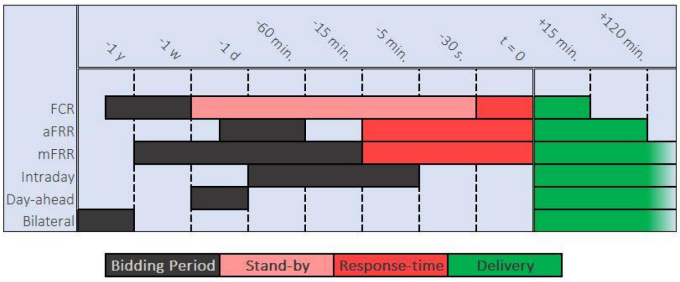


Figure 9: Electricity bidding and delivery depicted for different markets [5]

2.3.1 Accessible markets

The interesting markets for energy storage systems for DG's are identified in a previous thesis [5]. These are the day ahead market and the first two balancing markets:

- Day ahead market (DAM)
- Frequency Containment Reserve (FCR) (primary control)
- Frequency Restoration Reserve (aFRR) (secondary control)

There are several criteria a markets needs to meet to become accessible for an ESS assisted DG. First of all the market needs to transparent for the PRP responsible for the DG. Secondly, the DG and ESS have to match the power requirements of the market. It has to deliver at least what is required in the market. Thirdly, the time scheme of the DG has to match that of market. For the balancing markets the response time of the ESS has to be adequate. And for all markets the delivery has to match, fig. 9. Finally, it has to be economically interesting to bid on the market. It is necessary has to be able to make a profit with trading on the market [5].

The bilateral and intraday markets do not satisfy the first criterion. The trading on both of these markets takes place behind closed doors [27]. This makes these markets inaccessible for the DG operator. Furthermore, the mFRR is inaccessible. Although the bids are disclosed, this is only after delivery. This would make it possible to trade on if a bidding plan is constructed based on historic data. This will however be left outside the scope of this thesis. The DAM, the FCR and the aFRR do satisfy all criteria.

Day ahead market
Trading on day ahead market is the easiest to implement. The prices for the DAM are made public a day ahead. PRP's can submit their bids in a blind auction until 12 o'clock that day of the pricing. Bids have to be submitted in multiples of 100 kWh and there are limits on the bids, -500 €/MWh and 3000 €/MWh. For 2016 the average price of the DAM was 37 €/MWh. There are some costs involved trading on the Spot

market. There is an entrance fee of €25.000 and a membership fee of €10.000 per year. Additionally there is a technical fee of €8000 and a trading fee of €0.07 per MWh for the day ahead market [35].

automatic Frequency Restoration Reserve

Trading on the aFRR market can be modelled as a supplement on the DAM, as done in Sijtsma, 2019 [5]. The imbalance between the forecasted energy and the energy that was actually produced the next day results in either a bonus or a penalty, depending on the imbalance being positive or negative imbalance, respectively.

In fig. 10 an example of a wind farm trading on the DAM and aFRR can be seen. Going over the top row; a DAM bid of 5,5 MWh at a price 43 €/MWh, resulting in a settlement of €236,50. However, only 4,041 MWh is produced by the wind farm. This deficit needs to be balanced by purchasing 1,459 MWh of the grid (Feed out). This 'penalty' would cost, $1,459\ MWh \cdot 46,26$ €$/MWh =$ €$67,52$. In case of over generation, like in row 5, the extra 0,77 MWh can be sold to the grid at a Feed In price of 43,19 €/MWh, for a bonus of €33,26. Selling electricity on high Feed In prices can be seen as trading on the aFRR market.

Wind farm data [MWh]			Market data [EUR/MWh]			Settlement		
Forecast	Production	Imbalance	DAM	Feed Out	Feed In	DAM	Purchase	Sell
5.5	4.041	-1.459	43.00	46.28	30.28	€236.50	-€67.52	€0.00
5.25	3.408	-1.842	43.00	48.28	48.28	€225.75	-€88.93	€0.00
5	4.426	-0.574	43.00	31.28	31.28	€215.00	-€17.95	€0.00
5	5.009	0.009	43.00	29.55	29.55	€215.00	€0.00	€0.27
5	5.77	0.77	39.28	43.19	43.19	€196.40	€0.00	€33.26
5.25	5.63	0.38	39.28	43.28	33.00	€206.22	€0.00	€12.54
5.25	8.371	3.121	39.28	29.28	29.28	€206.22	€0.00	€91.38
5.5	6.895	1.395	39.28	29.28	29.28	€216.04	€0.00	€40.85
5.5	6.24	0.74	35.75	39.19	39.19	€196.63	€0.00	€29.00
5.75	6.354	0.604	35.75	42.28	42.28	€205.56	€0.00	€25.54
6	4.645	-1.355	35.75	41.78	41.78	€214.50	-€56.61	€0.00
6	5.019	-0.981	35.75	41.28	41.28	€214.50	-€40.50	€0.00
6.25	3.696	-2.554	33.72	41.78	41.78	€210.75	-€106.71	€0.00
6.25	5.054	-1.196	33.72	41.67	41.67	€210.75	-€49.84	€0.00
6.25	5.033	-1.217	33.72	41.28	41.28	€210.75	-€50.24	€0.00
6.25	4.661	-1.589	33.72	38.00	38.00	€210.75	-€60.38	€0.00
						Total: € 3,085.47		

Figure 10: DAM and aFRR trading example for a wind farm [5]

Frequency Containment Reserve

The FCR market is an international market with a capacity of 3000 MW in the positive direction and 3000 MW in the negative direction. The total FCR volume is distributed the individual TSO's in the European market. Each is responsible for a percentage or 'frequency bias' of the total volume, based on the size of its control area. For the Netherlands in 2019 this was 3.7%. This means Tennet had to have 111 MW of FCR capacity in upward and downward direction at hand at all times [36].

If an ESS is available for the FCR market. It can be used by the TSO to unload- to or draw energy from the storage system when needed. If an ESS has, for example, a state of charge of 50% and it will have 50% of its capacity available for the TSO in upward and downward direction. For the (possible) use of the ESS, the PRP is compensated.

PRP's can bid in an open auction for the FCR market the next day, however, until July 2019 the FCR market was a weekly market. The minimum bid 1 MW and are accepted as multiples of 1 MW. The maximum bid volume is 25 MW. Bids always have to be provided in both directions, up and down [37]. The average capacity price of accepted FCR bids in 2013 was 18 €/MW/h [6]. For the period from 07-2019 until 12-2019 the average capacity price was 346.41 €/MW/day or 14.43 €/MW/h [38].

2.3.2 Forecasting

In reality a perfect forecast does not exist. Bids that are submitted are rarely reached perfectly, as it is very hard to perfectly predict the weather and thus the output of a renewable generation system. Scientific research has two methods to deal with forecasts when investigating topics involving renewable energy generation. The simplest method is to assume a perfect forecast. The alternative is to deal with the imperfect predictability of renewable energy.

When investigating trading with a perfect forecast of the supply, demand and electricity market it is possible to find the potential of your system for various energy management strategies. If the output of your system is known, as is the course of the electricity market, it is possible to trade electricity when it is most favorable. Additionally in reality to trade electricity a bid has to be submitted to the TSO responsible for these transactions. It is not guaranteed that all submitted bids will be approved. Often this is not taken into account in these kind of studies as this creates unnecessary complications for the study. The results in such studies are less accurate with imperfect forecasting and are often more positive.

Studies that do include the imperfect forecasting often focus on reducing forecasting errors. By for example researching reducing penalties that are a result of not meeting their bid. The objective being to minimizing forecast error or maximizing revenue despite of forecast errors [26].

In one previous thesis, [27], that focused on the potential benefits of energy storage in the LV-grid, perfect forecasting was assumed. In another thesis, [5], the goal was to find the optimal design for an onshore wind park with restrictions of imperfect real world constraints. Thus it was necessary to include imperfect forecasting.

2.4 Energy storage systems and applications

Different energy storage systems and applications are reviewed in this subsection. Storage systems that match the requirements of decentralized generation need to be defined. Furthermore, storage parameters that will be useful for the optimization are also identified.

Weather has always been hard to predict and is ever changing. The wind is a good example of erratic weather changes. It has instantaneous, diurnal and seasonal wind velocity variations. There is a lot of energy in the wind, which can be extracted for sustainable power production. However, because the unpredictable behavior of the wind, it can be hard to consistently supply power to the grid. Furthermore, the diurnal and seasonal variations can cause a mismatch with the demand [39, 40]. Likewise, the sun is not always able to supply PV-solar panels with power due to clouds and of course the day and night cycle.

For better compatibility with the grid and demand, renewable energy can be stored. There are several technologies that can be used for renewable energy storage [9, 41]:

- Pumped Hydro storage (PHS)
- Compressed Air energy storage (CAES)

- Battery energy storage systems (BESS)
- Flow Battery energy storage systems (FBESS)
- Hydrogen Fuel Cell system (HFCS)
- Flywheel energy storage (FES)
- Superconducting Magnetic energy storage (SMES)
- Supercapacitor energy storage system (SCESS)
- Thermal energy storage (TES)

Also, there are various applications for which energy storage could be utilized. Not every technology could be utilized for every applications; there are both short and long term energy storage applications. An application which requires a discharge duration shorter than 1 minute is considered a short term application, longer than 1 minute is a long term application. The applications are listed below:

- Short term applications
  - Fluctuation suppression
  - Low voltage ride through
  - Voltage control support
  - Oscillation damping
- Long term applications
  - Spinning reserve
  - Load following
  - Peak shaving
  - Transmission curtailment
  - Time shifting
  - Unit commitment
  - Seasonal storage

ESS used for maintaining power quality will need to have a very fast response time, $\sim$ milliseconds. Bridging power applications, like enabling to switch between power generation sources, require ESS's to a have moderate power rating (100 kW - 10 MW) and a response time up to a second. Energy management applications like time shifting and peak shaving require ESS's to have larger capacities (from 1 MW up to and even above 100 MW), however, these large systems do not have fast enough response times. In fig. 11 the energy storage systems are compared at their rated energy capacity versus their power rating. With dotted lines the discharge time of a given ESS is illustrated.
As can be seen, FES, SMES, SCESS are better suited for short term applications, like fluctuation suppression, low voltage ride through, voltage control and oscillation damping. These applications are to stabilize

the load provided to the grid. Improving the power quality requires full power storage up until 1 minute. PHS, HFCS, CAES are more suited for long term applications that require storage from 1 hour up until 12 hours or even months. These include load following, peak shaving, transmission curtailment, time shifting, unit commitment and seasonal storage.
Both battery storage systems, BESS and FBESS, are applicable for most energy storage uses, from 1 minute storage until 10 hours [7, 9].

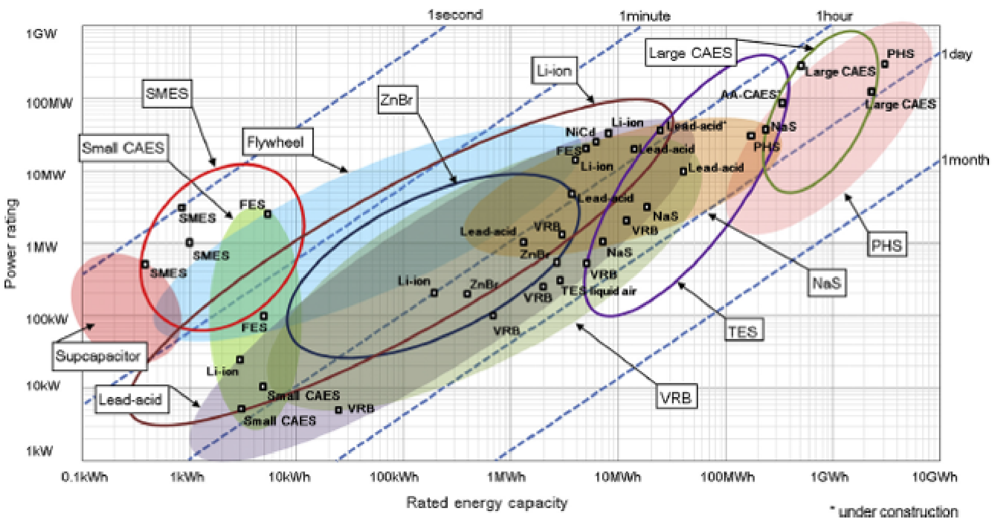


Figure 11: Energy storage systems compared at rated energy capacity vs power rating [7].

The decentralized renewable energy sources that are connected to the medium voltage distribution grid usually generate between the 0.3 MW and 10 MW [16]. This means that these boundaries also apply for the energy storage system. As stated in section 2.3, to trade on the spot markets, bids of at least an hour need to be satisfied. The frequency markets require even lower discharge times, 15 min, but an hour is good lower limit. Additionally, it may be desired to store an entire days of energy production for more favorable days. It is even possible to store several days' worth of energy to overcome bad weather conditions. This results in an upper storage boundary of 720 MWh. This is, however, an unreasonable high estimate as it is very unlikely that production is at a maximum for three days straight. Additionally, it is never required (or even possible) to discharge a full load 720 MWh in one hour. Therefor an upper boundary of 15 MWh is a better assessment. This would fulfill a full days' worth of production with a capacity factor of 20%. More on the capacity factor in section 2.5. A required range of 300 kWh - 15 MWh is validated in fig. 12. The rated capacity for storage applications in the distribution network is also stated to be between 300 kWh and 15 MWh.
An energy storage system with 0.3 MW - 10 MW and 0.3 MWh - 15 MWh can be either used for bridging power or for smaller energy management applications. Thus, based on power and energy ratings, the promising energy storage systems for decentralized generation are: BESS, FBESS, HFCS, FES and TES.

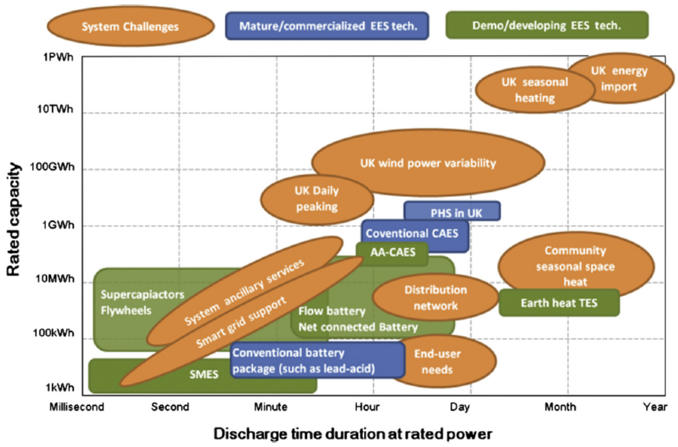


Figure 12: Electrical energy storage systems and system challenges, Discharge time vs rated capacity [7].

2.4.1 Energy storage technologies

In this section the previous identified energy storage technologies are further reviewed. When selecting an energy storage system some storage characteristics are important to understand. The energy capacity of a storage system is the amount of energy that can be stored in the ESS, often in kWh. The power capacity, in kW, is the rate at which a storage system can be charged or discharged. The state of charge (SOC) is the amount of available energy in the ESS. This is expressed in the ratio between the available energy and maximum capacity of the ESS as a number between 0 and 1. However some storage systems cannot be completely empty due to the material properties. The maximum depth of discharge (MDOD) is the maximum amount of energy that can be extracted from the battery without damaging the electrodes. If the MDOD is equal to 0.8, the lower limit SOC is 0.1 and the upper limit 0.9. The C-rate is the ratio between the energy capacity and power capacity. A battery with a C-rate of 1 has a power capacity equal to the energy capacity of the battery, which means it can be fully charged or discharged in one hour. Another important battery characteristic is the lifetime, expressed both in years as in number of full charge and discharge cycles. Finally self-discharge, which is defined as the amount of energy lost when the system is not in operation, is an important characteristic [7, 5].

BESS

Battery energy storage systems are in terms of installed capacity the most common form of energy storage, after pumped hydro storage. The first batteries that resemble current batteries date back to the 18th century [42]. In batteries electric energy is stored in electrochemical cells. Each cell consist of a positive and negative electrode. In an electrochemical reaction chemical energy is converted to electrical energy. The potential difference between the electrodes dictates the amount of energy that can be stored and converted per cell. This depends on the size and the electrode material. There are two types of batteries, primary and secondary batteries. Only secondary batteries are rechargeable. During the charge cycle, the positive electrode is called the anode and the negative electrode the cathode. During the discharge cycle is reversed. There are several interesting secondary battery technologies: Lead-acid batteries, Lithium-ion (Li-ion) batteries and high temperature batteries. Two Li-ion batteries are considered: Lithium nickel manganese

cobalt (NMC) and Lithium iron phosphate (LFP). Two high temperature batteries are considered: Sodium-sulfer (NaS) batteries and Sodium-nickel-chloride (NaNiCl) batteries.
All of these technologies are versatile and generally have a low self-discharge. Lead-acid batteries are the most mature battery technology and therefor have a low capital cost. Additionally, Lead-acid batteries are reliable and have a high cycle efficiency. In a circular economy it is important to note that lead-acid batteries are recyclable. However the main disadvantages of lead-acid batteries are their low cycle lifetime and low depth of discharge. Li-ion batteries are more favorable in that regard, however, they are more expensive. They also contain lithium, which is a unsustainable material. The high energy density and high cycle efficiency are the main advantages of Li-ion batteries. NaS and NaNiCl batteries require a high operating temperature, 250 - 350 °C. This also results in a higher operating costs. They also have a low self-discharge and high cycle life. NaS batteries are recyclable and require low maintenance. NaNiCl batteries are, however, considered more stable than NaS batteries [7, 10].

FBESS

Flow batteries have, similar to 'normal' batteries, electrochemical cells where energy is stored in chemical components. In two tanks, the anolyte and the catholyte tank, two liquid electrolytes are stored. The liquid is pumped from the tanks to the cell where the liquids flow past each other separated by a membrane. At this intersection a electrochemical reaction is facilitated to produce a electric current [43].
There are two types of flow battery that are commonly considered for energy storage: Vanadium Redux flow battery (VRB) and Zinc Bromine flow battery (ZnBr).
There are a lot of similarities with the normal batteries. But one key advantage of the flow batteries is that power is independent of the capacity. The power is determined by the size and number of the cells and the capacity is determined by the concentration of the electrolyte and the size of the storage tanks. The separation of storage tank and electrochemical cell also results in a low self-discharge [7]. Additionally flow batteries are durable and have high cycle efficiency, but they do require an auxiliary maintenance and pump system. VRB batteries have a quicker response time than ZnBr batteries, but the vanadium present in the VRB battery is expensive and ZnBr have a higher energy density. ZnBr batteries also have deep discharge capabilities, but the energy- and power capacities are not fully independent. They also contain corrosive materials and require a temperature control system. Flow batteries are a young technology and a lot of research is done to reduce the high capital cost [9, 10].

FES

In a flywheel energy storage systems a generator/motor converts electrical energy to kinetic energy by spinning a flywheel. To ensure low drag losses, the flywheel is placed in a vacuum chamber. High end bearings or in some cases magnetic bearings should reduce friction. The storage capacity depends on the rotational speed and the inertia of the flywheel [44]. Flywheels have a very high cycle efficiency and fast response time, however, they have high capital costs and although a lot is done to prevent frictional losses, flywheels often suffer from a high self-discharge [45].

TES

Thermal energy storage is possible in a range of technologies, but they all work on the same principle of an absorbent mass capable of storing heat, or the lack of heat in some cases. The heat can, for example, be stored in insulated water tanks or in porous concrete where air is used to 'charge' and 'discharge' the

concrete. As long as the tank is kept stable and insulated a low self-discharge is feasible. A disadvantage of most thermal energy storage technologies is a low cycle efficiency. This is also because most technologies are only just emerging, i.e. have a low industry readiness level (IRL) [7, 46].
Two examples of thermal energy storage are Pumped Heat Electrical Storage (PHES) and Liquid Air Energy Storage (LAES). In a PHES system heat is stored by using a heat pump to pump a working gas, like argon, from a 'cold' tank to a 'hot' tank, both filled with gravel, to store heat. This process can be reversed, the heat pump then acts as a heat engine to produce mechanical work to drive a generator. This system is very low cost as it does not require expensive materials.
In a LAES system air is cooled until it liquefies. The liquefied air is stored in a tank. When the air is able to come from the liquid state to the gaseous state it expands, this expansion turns a generator to produce electricity again. This principle is comparable to Compressed Air Energy Storage (CAES), but has a higher power density, which could make it interesting for DG energy storage.

HFCS

Hydrogen fuel cell systems used for energy storage need to consist of two systems, the electrolyser that splits water into hydrogen and oxygen using electricity and the fuel cell that combines hydrogen en oxygen to water to produce electricity. In the electrolyser at the anode electrode, oxygen is produced and on the cathode side, hydrogen. In eq. (1) the half reactions that occur in an alkaline electrolyser are shown. In the fuel cell this reaction is reversed [47]. The number of cells and the size of the storage tank determine the power and energy capacity respectively.

$$Anode\ half\ reaction: 4OH^-_{(aq)} \rightleftharpoons O_{2(g)} + 2H_2O_{(l)} + 4e^- \tag{1a}$$

$$Cathode\ half\ reaction: 4H_2O_{(l)} + 4e^- \rightleftharpoons 4OH^-_{(aq)} + 2H_{2(g)} \tag{1b}$$

$$Full\ reaction: 2H_2O \rightleftharpoons 2H_2 + O2 \tag{1c}$$

The low density of hydrogen requires that hydrogen is stored at a very high pressure (350/700 bar) or in a liquefied state. This does require additional energy. Additionally, the cycle efficiency of the entire system is not very high. This is between 20% and 68%, compared to 90% for some battery technologies. Furthermore, systems cost are relatively high. However, HFCS's have a low self-discharge and are very scale-able. This can make them attractable for long term energy storage. Hydrogen can also be used directly for heating applications, as a fuel for hydrogen fuel cell cars or as stock for some chemical products, like methanol [7].
The two most mature fuel cell technologies are the Proton Exchange Membrane Fuel Cell (PEMFC) and Alkaline Fuel Cell (AFC). The pro's and con's of both technologies are represented in table 3. From the two, PEMFC is better suited to follow a dynamic renewable energy source [11, 12]. However, the papers referenced in tables 4 and 5 do not differentiate between HFCS technologies. So for consistency with the other storage technologies and for simplification only a general HFCS system is considered.

2.4.2 ESS technology comparison

In the following tables, tables 3 to 5, the previous mentioned energy storage systems are compared, based on their (dis)advantages (table 3) and technical specifications (tables 4 and 5) that where described in the previous section.
When selecting an energy storage technology it important to know the requirements of the system. Depending on the application, different technologies can be better suited, but all could be implemented for decentralized renewable energy generation.

Multiple times the high operational costs of the high temperature batteries were mentioned, but the operational costs of these systems and the other ESS technologies are not given. Because in this study the operational and maintenance costs, also known as OPEX, will be neglected. The reasoning is that firstly the values for the operational costs in the sources were very inconsistent or not even mentioned. In [10] for instance only the operational costs of the NaS were mentioned, 80 $/kW/yr. For the other systems there was no value stated. The range of costs differed strongly per article, 3 to 9 €/kW/yr according to one source [48] and 20 till 80 $/kW/yr in [7]. However, this paper also values one system at 0.0153 €/kW/yr. The value highly depends on what is included in the operations and maintenance of the system. This is difficult because storage systems are often a part of a larger generation system which already needs servicing. The location is also very decisive in the OPEX. One paper has estimated that the OPEX is between 11% and 33% of the investment costs [49], depending on the location alone. Locations can unfortunately not be taken into account in this study. Because of these reasons and because some sources state that the costs are relatively low compared to the other values, the operational costs will be neglected in this study.

Table 3: ESS technologies advantages and disadvantages [7, 9, 10, 11, 12].

Technology	**Advantage**	**Disadvantage**
	Batteries	
General	Versatile, Low self-discharge, Capital cost are expected to drop over 50 % by 2030	
Lead-acid	Low cost compared to other BESS, High reliability, High cycle efficiency	Low cycling times, Low energy density, Low depth of discharge
	Mature technology, Recyclable	Poor performance at low and high ambient temperature
Li-ion	High energy density, High cycle efficiency	High capital cost, Requires lithium
NaS	Recyclable, High cycle life, Low maintenance necessary	High temperature, High operation costs
NaNiCl	Safer than NaS, High cycle life	High temperature, High operation costs
	Flow batteries	
General	Power and Energy capacity are independent, Low self-discharge, High cycle efficiency	Requires a maintenance system
	High cycle life and durable, Capital cost are expected to drop over 50 % by 2030	High capital cost, but expected to reduce dramatically
VRB	Quick response time	High cost of vanadium, Low energy density
ZnBr	Deep discharge capabilities, High relative energy density	Capacities not fully independent, Corrosive materials used
		High self-discharge, Needs temperature control
	Flywheel Energy Storage	
FES	Fast response time, No aging/High cycle lifetime	High self-discharge, Low energy density
	Low maintenance, Mature	Sensitive to external shocks
	Thermal Energy Storage	
General		Low IRL as ESS, Low cycle efficiency
PHES	Low cost	
LAES	Power density is 4 - 6 times than CAES	
	Hydrogen Fuel cell system	
General	Suitable for long term storage, H2 can be used as feed stock for industry or fuel	Low cycle efficiency, Requires purified feed water
	Low self-discharge, High Depth of discharge	Many safety measures required
AFC	Most mature technology	Slow response time
PEMFC	Dynamic	Requires unsustainable materials

Table 4: ESS technologies technical specifications, based on the most recent number of cited in IRENA 2018 and Luo et al. 2015 [10, 7].

Technology	**Self-discharge** [% per day]	**Lifetime** [years]	**Cycle times** [cycles]	**Response time**	**Depth of discharge** [%]
Batteries					
Lead-acid	0.1 - 0.3	3 - 15	250 - 2500	milliseconds	50 - 60, 80 [22]
Li-ion (NMC)	0.1 - 0.3	5 - 20	1000 - 5000	milliseconds	83 - 100
Li-ion (LFP)	0.1 - 0.3	5 - 20	1000 - 10,000	milliseconds	83 - 100
NaS	0.05 - 1	10 - 25	1000 - 10,000		100
NaNiCl	< 5	7 - 22	1000 - 7500		100
Flow batteries					
VRB	Small	5 - 20	10,000+	Fast	100
ZnBr	Small	5 - 20	10,000+	Fast	100
Flywheel energy storage					
FES	20 %/hour	15 - 25	20,000+	seconds	100
Thermal energy storage					
PHES	0.05 - 1	5 - 20	10,000	Not fast	100
LAES	Small	25+	10,000	minutes	100
Hydrogen fuel cell system					
HFCS	Small	5 - 20	1000 - 20,000	seconds	100

Table 5: Table 4 continued. ESS technologies technical specifications, based on the most recent number of cited in IRENA 2018 and Luo et al. 2015 [10, 7].

Technology	**Cycle efficiency** [%]		**Energy density** [Wh/L]		**Capital cost** [$/kWh]	
	2016	2030	2016	2030	2016	2030
Batteries						
Lead-acid	80 - 82	84 - 86	50 - 100	50 - 100	147 - 263	50 - 240
Li-ion (NMC)	95, 92 - 96	97	200 - 735	200 - 735	200 - 700	77 - 340
Li-ion (LFP)	92, 92 - 96	94	200 - 650	200 - 650	200 - 700	77 - 340
NaS	80	85	140 - 300	140 - 300	263 - 735	120 -330
NaNiCl	84	87	150 - 280	150 - 280	315 - 490	130 -200
Flow batteries						
VRB	70, 85	78	15 - 70	15 - 70	315 - 1100	108 - 360
ZnBr	70	78	20 - 70	15 - 70	500 - 1680	150 - 576
Flywheel energy storage						
FES	83, 90 - 95	89	20 - 200, 20 - 80	20 - 200	1500 - 6000	1000 - 3900
Thermal energy storage						
PHES	30 - 60		80 - 500		20 - 60, 100	
LAES	55 - 80		8 - 36		260 - 530	
Hydrogen fuel cell system						
HFCS	20 - 66		500 - 3000		500, 1500 - 3000	

2.5 Decentralized generation system and system configuration

In this subsection more information about decentralized renewable energy generation systems is provided. In this thesis the focus is on PV solar panels and wind turbines. The possible system configurations of the hybrid ESS and DG system are also illustrated. This will include the electricity cables and transformers.

2.5.1 Generation system

PV solar panels

In the Netherlands solar capacity has grown in 2018 with 1500 MW on top of what was installed by the end of 2017. This is an increase of 71 % with companies, largely due to the construction of solar farms, and 37 % with households [50].

PV solar panels are often connected to the LV network. Larger PV-systems and PV-systems that are cumulatively connected to the grid, are connected to the medium-voltage grid. It is good to note that the simultaneity of PV-systems is high. Especially on clear days all PV-systems can produce at maximum power, which can cause congestion on the grid.

One solar PV panel produces between the 40 and 50 V of direct current. Before the panels can be connected to the grid, a transformer needs to convert the electricity to alternating current. Often the maximum allowable current of the transformer limits the short-circuit capacity [16].

The capacity factor is the ratio of the actual energy production of the PV solar system and the total potential energy production of the system [51]. In the Netherlands the PV solar capacity factor is low due to a low insolation. Often a capacity factor of 10% is used, however, an average of 8.6% was calculated using latest data in [52].
So the results obtained from this study are location bound, because the generation data that is used is specific for the Netherlands. The results from this study will not be applicable in other countries with more or less insolation. This also applies for the wind energy as other locations have different weather patterns so will obtain different results.

Wind turbines
In the Netherlands the potential of wind turbines and especially off-shore wind turbines is large compared to other forms of energy generation. It is estimated that off-shore wind has the potential to produce twice the amount of the total current Dutch demand for electricity. This has not stayed unnoticed by the government and industry, causing a large increase of wind energy.
Wind turbines produce AC current and are mostly connected to the medium-voltage grid. The power capacity of a single wind turbine is often too large for the low voltage grid. A capacity of 1 MW leads to a current of 1.4 kA on the LV grid [16]. In the Netherlands a capacity factor of 24% was achieved in 2017 for onshore wind production [52].

2.5.2 Hybrid system configurations

In this section possible decentralized generation and energy storage system configurations in the hybrid system are discussed. Figure 13 shows a schematic of the different DG and ESS technologies in one electricity system. As shown a wind turbine is connected to an AC bus, as is a flywheel energy storage system. PV, battery, flow battery and hydrogen fuel cell systems are connected on the DC bus [45].
Figures 14 and 15 show two simplifications of the first schematic. Each individual system has their own transformer. This is essential as if, for example, the ESS and PV panels are both connected to the same converter, it is not possible to direct the electricity to charge or discharge the ESS. When the ESS is empty it automatically gets charged when the PV panels produce electricity. This is not always desired. The generation systems have a one directional transformer and the ESS a bidirectional transformer as it has to charge and discharge. Between the AC and DC bus there is an additional AC/DC bidirectional converter. The difference between figs. 14 and 15 is how the ESS is connected to the grid. Both of these configurations are possible, but fig. 14 is more common as the PV transformer is not also bidirectional, thus cheaper.
The efficiency of a transformer is typically very high, between the 95% and 99% [53, 54]. The cost for the power transformer of an ESS is found to be between 302 €/kW and 490 €/kW. This cost depends on the type of conversion and storage system. However, these do include other technology specific auxiliary components, such as pumps for a flow battery [45, 22].

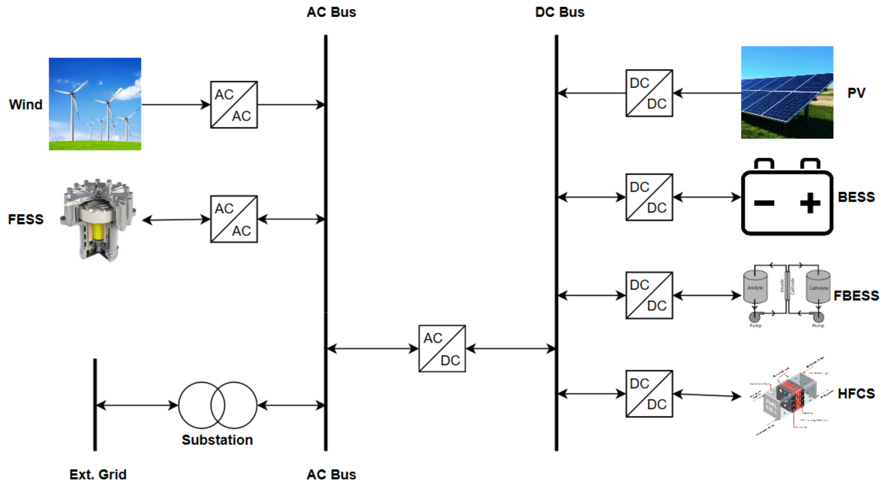


Figure 13: Electric circuit of a hybrid system with a PV solar- and wind park and different storage technologies [45].

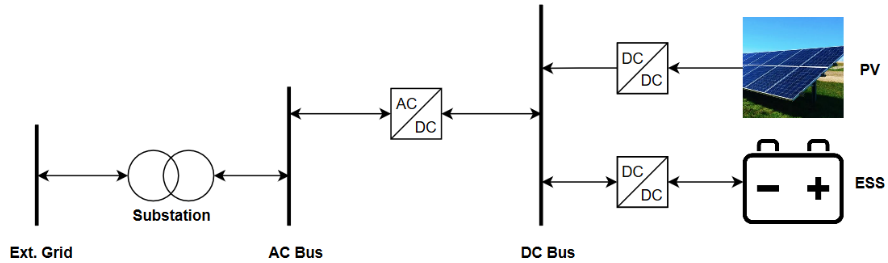


Figure 14: Simplified electricity circuit: option 1

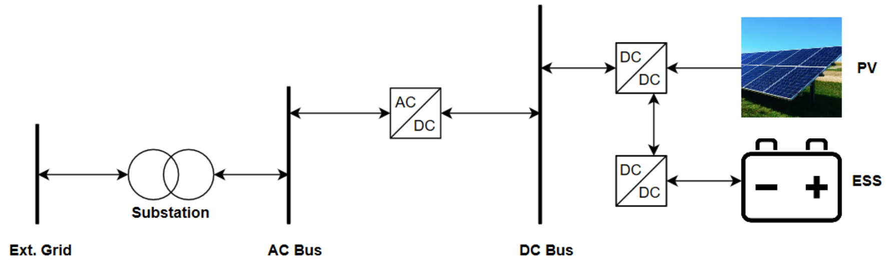


Figure 15: Simplified electricity circuit: option 2

2.6 Optimization techniques

To find the optimum size of an energy storage system for decentralized generation, an optimization program was written in Python [55]. Such an optimization program requires an objective and constraints. The objective can be to either maximize or minimize a particular indicator. These indicator could also be used as constraint. Various economic and technical indicators are reviewed in this section. Subsequently several optimization techniques are discussed.

In literature it is found that the best optimization methodology will mostly dependent on the type of storage and generation application [26].

2.6.1 Economic indicators

Economic indicator can be used to determine the economical viability of a system. The following frequently used indicators are discussed:

- Total/Annualized costs
- Profit
- Payback time
- Levelised costs of energy (LCOE)

The most simple economic indicator is the total cost of the energy storage system, which is the sum of the capital cost of the storage unit and the transformer, eq. (2). However, often the cost of the system is expressed as the annualized cost. The annualized cost is defined as the sum of the yearly operational costs and the total cost times the capital recovery factor (CRF) eq. (3) [56, 57]. In [45, 58] the annualized cost of the system is extended to include the benefits of the system, the revenue earned by trading with the external grid. So the profitability of a system defined as the revenue of the energy sold over a year minus the annualized cost of the system eq. (4b). The objective of such a optimization would be to maximize the profit of the system.

$$Cost_{total}\ [€] = c_e \cdot Energy_{capacity} + c_p \cdot Power_{capacity} \tag{2a}$$

$$(c_e = capital\ cost\ coefficient, energy\ capacity\ [€/kWh]) \tag{2b}$$

$$(c_p = capital\ cost\ coefficient, power\ capacity\ [€/kW]) \tag{2c}$$

$$CRF = \frac{r(1+r)^L}{(1+r)^L - 1} \tag{3a}$$

$$(r = interest\ rate\ [-]) \tag{3b}$$

$$(L = lifetime\ [years]) \tag{3c}$$

$$Cost_{annual}\ [€/year] = Cost_{total} \cdot CRF + Cost_{operational}\ [€/year] \tag{3d}$$

$$Revenue\ [€/year] = \sum_{day}^{year} Energy\ [kWh/day] \cdot Energy_{price}\ [€/kWh] \tag{4a}$$

$$Profit\ [€/year] = Revenue - Cost_{annual} \tag{4b}$$

In [56] to better match the demand on a Crete, a Greek island, an NaS battery was added to a 170 MW wind turbine park. The objective was to minimize the annualized cost of the system while reducing wind curtailment. This is mostly achieved by charging at night when there is less demand and the energy price

is low. A 288 MWh/40 MW NaS system appeared to be the optimal size while reducing wind curtailment with 13%.
[57, 45, 58] are similar studies about grid-connected microgrids which focus on reducing the annualized cost and subsequently maximizing the profit. All these studies conclude that energy storage is still very expensive, but it is notable that these studies all take place in isolated grids, mostly on islands. In these locations grid reinforcement is often very expensive, this is why energy storage is considered. This will also be investigated later in my thesis.

In [22] the energy storage system size is calculated based on the difference in supply and load, as discussed in section 1.2. This is assessed for several case studies. An off-grid- and a grid-connected configuration, with a PV solar array, wind turbine and both, are compared with and without storage. The goal in this study was to calculate benefits of storage. These benefits are measured in several, different economic and social, indicators: Payback time, Levelized Cost of Energy (LCOE), Cost of Emissions and Renewable Fraction. As the Cost of Emissions and Renewable Fraction are not economic indicators, they will be discussed in section 2.6.3
The payback time can be calculated by the total cost of the system divided by the revenue minus the yearly operational costs eq. (5). For the case study mentioned, the payback time for a PV array and storage system the payback time would be just over 4 years. For wind and storage and both with storage it would be just over 2 years, with the PV, wind and storage system having a payback time of 2.05 years.

$$Payback\ time\ [year] = \frac{Cost_{total}}{Revenue - Cost_{operational}} \tag{5}$$

The LCOE is the average cost of energy that is produced by the system. It calculated with the annualized cost divided by the cumulative electricity exported to the grid, eq. (6). For the LCOE it is the objective to minimize the annualized investment and operational costs while maximizing the amount of energy to sell [59]. In the case study in [22] the biggest decrease in LCOE was for the off-grid systems when aided by a storage unit. This was for the PV array even four times less. For the grid-connected wind and hybrid configurations the LCOE was 0.316 \$/kWh and 0.302 \$/kWh respectively.
In a different study, [60], the LCOE of a storage aided generation system on a tropical island near Singapore is minimized using a particle swarm algorithm (moreover in section 2.6.4). The LCOE improved with increasing renewable energy penetration.

$$LCOE[€/kWh] = \frac{annualized\ Costs\ [€/year]}{Energy_{exported}\ [kWh/year]} \tag{6}$$

2.6.2 Technical indicators

There are also technical indicators which can be optimized. A simple sizing methodology is to size an ESS to bridge the supply and demand curve [22]. However it is possible that that is not the optimum size for an ESS for a particular DG system. Technical indicators can be split into two operational categories, dynamic characteristics and steady state operations [26].
Dynamic characteristics have a time horizon smaller than 1 minute. To improve the dynamic characteristics of a system there are two main technical indicator, the voltage stability and the frequency regulation. Both

are to regulate the power quality of the system within the allowable limits[61].
However my research will focus more on steady state operation with a time horizon greater than 1 minute. Some relevant indicators are discussed for these operations:

- Reliability
- Renewable energy curtailment
- Constant power output

The reliability of the generated renewable energy is utilized as technical indicator in [57]. Also in [25] the optimal size of a battery energy storage system is calculated to increase the reliability. Using an heuristic method it was possible to shave the peak load and smooth the load curve in a distribution- and transmission grid.
Renewable energy curtailment is to purposefully cut off of the energy supply to avoid over-generation, as performed in [56]. Minimizing this is of social importance, but it can also be economically beneficial.
It is also possible to size an ESS for a constant power output, to avoid frequency balancing up stream [26, 62]. In [62] a battery system was investigated to be used as a power buffer for a wind turbine. A wind turbine with a capacity of almost 2 MW warranted a BESS of 1.33 MW/0.68 MWh to smooth the power output within acceptable limits.
The previous indicators are operational indicators, but there are also technical system parameters that could be used as indicators for optimization. These are for example: Cable capacity, Cycle efficiency, Cycle life time, Depth of discharge and (dis)charge rates. However these system parameters are often used as optimization constraints rather than objectives. In that way these parameters were used in previous mentioned literature.

2.6.3 Additional indicators

As mentioned section 1.2 the paper [22] describes two optimization indicator next to Payback time and LCOE: the Cost of Emissions and Renewable Fraction. These are not technical or economic, but rather are environmental or social optimization indicators.
The cost of emissions can be defined in two different ways. First, it can be defined by comparing the amount greenhouse gasses produced while operating the system with and without storage, in kg/year. When operating the system with storage module, more green energy that can be used instead of grey energy, which results in a reduction of emissions. Secondly this reduction can also be expressed in literal cost of emission if an penalty for green house gasses is implemented. The Renewable Fraction is defined as the ratio of the annual renewable power production and the total energy production, $RF = E_{pv}/E_{tot}$. In the case described in the paper, a maximum reduction of 13000 kg/yr was obtained with for a 12 kW PV + 100 kWh storage system replacing a 12 kW PV system with a 10 kW diesel generator. Additionally the RF increased with almost 60% for this case.

2.6.4 Optimization techniques

There are several methodologies to optimize the sizing of an ESS. There are probabilistic methods, analytical methods, direct search-based methods [26] and machine learning.
Analytical methods are the most widely used optimization technique. This is because it is straight forward to use. In this technique outcomes of an optimization problem are analysed against a performance criteria.

The results are generated by varying a particular (set of) decision variable(s) for different configurations. However, it does require a lot of computational resources. Analytical algorithms are used in [22, 58, 62].
Probabilistic techniques generally generate a wide range of solutions, the optimum solution can subsequently be deduced. This method is very useful when limited data is available, but it is limited in number of optimizable indicators that can be used. A well-known probabilistic optimization technique is the Monte Carlo approach. A probabilistic framework is utilized in [24].
Direct search-based methods can be split up into mathematical optimization techniques and heuristic optimization techniques. Direct search-based methods are an improvement on analytical methods as they do not require as much computational simulations. Mathematical techniques especially improve the computational efficiency, but it has an issue of robustness. For mathematical based methods an objective function is defined and iteratively solved to find the optimum solution. The number of computational simulations can be reduced by using numerical methods like Newton's method [63]. However, as the formulation of the objective function gets more complicated, robustness issues can arise. This is especially an issue for non-linear optimization problems. Because of this heuristic methods have become more popular. These techniques are not proven mathematically, but use nature inspired algorithms such as Particle Swarm Optimization, as used in [60]. Heuristic methods do, however, not always find an optimal solution, but for practical optimization problems it often adequate.
A combination of these optimization techniques is also feasible. These methods should ensure robustness and that the global optimum will be reached at a fairly computational efficient manner.

In Python there are multiple packages available that offer optimization methods to tackle optimization problems. One commonly used is the scipy.optimize.minimize function [64]. For this function an objective function needs to be formulated and a decision variable needs to be defined. Optional is to add boundaries for the variable and optimization constraints. Various direct search-based mathematical optimization techniques can be chosen as optimization solver, including: Newton-Conjugate Gradient method (Newton-CG), Broyden–Fletcher–Goldfarb–Shanno algorithm (BFGS) and Sequential Least SQuares Programming (SLSQP). Depending on the constraints and boundaries either, BFGS, L-BFGS-B (Limited-memory BFGS) or SLSQP is used on default (no bounds and constraints, bounds but no constraints, bounds and constraints available, respectively).

2.7 Alternatives to energy storage and grid reinforcement

About a hundred years ago the electricity network was designed to transport electricity from large power plants, such as coal- and gas fired power stations, to the consumers. Nowadays those consumers and other entrepreneurs are able to generate their own electricity and even export back to the grid. The electricity grid was not designed to handle the extra decentralized generated energy. This can cause local grid congestion due to over-generation. This is more likely in areas that are less densely populated. Low land prices make these areas more attractive for sun- and wind park developers. Additionally these areas commonly have lower electrical network capacities. This would be easily solved by reinforcing the grid to cope with the additional capacity requirement. However, this often takes a lot of time to realize. Also, grid reinforcement is a very expansive and labor intensive job. So alternatives are necessary to facilitate this energy transition. Energy storage is a great solution as it can match the energy supply in time with the energy demand.

Energy storage at the generation source can also prevent higher capacity requirements higher up in the electricity grid as the power output of the DG can be modulated. However, next to energy storage and grid reinforcement there are several other mitigations for grid congestion. In this section some of these alternatives will be discussed in short. Following is a list of the relevant alternatives [8]:

1. Grid switching
2. Less redundancy
3. Heat networks
4. Cable pooling
5. Dynamic pricing
6. Smart charging
7. Energy curtailment

A hierarchy for these solutions is arranged by Liander, from congestion prevention to reaction measures. As seen in fig. 16, the solutions at the bottom of the pyramid, first, and the solutions at the top, last. First are preventive technical solutions, such as energy storage, but also autonomous control over decentralized generation systems. Second are incentive measures to change supply and demand behavior, for example making agreements to charge electric vehicles at night or price agreements for energy generation outside peak supply. Third are market solutions such as flex prices and fixed electricity transport limits. Last there are direct interventions.

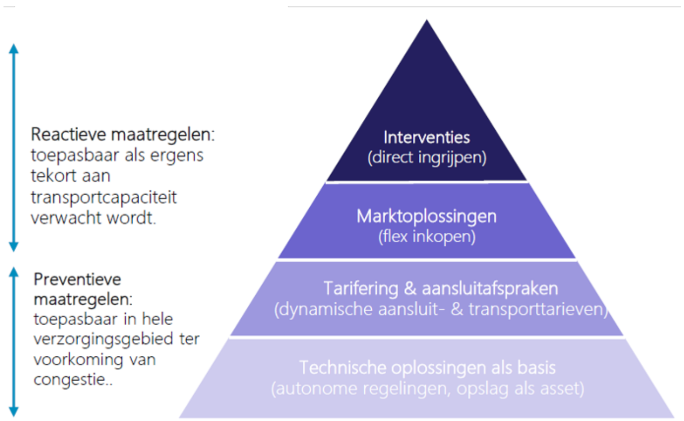


Figure 16: Liander net congestion solution hierarchy [8]

The first four solutions, Grid switching, Less redundancy, Cable pooling and Heat networks, are technical preventive measures. Solutions 5 and 6, Dynamic pricing and Smart charging, are incentive measures and the last one, energy curtailment, is a reactive solution.

Grid switching

Grid switching is a method to use the electricity grid more efficiently. Grid switching allows congested sections of a grid to be alleviated by other grid sections. If there are multiple sections that connect two substations the electricity travels through the shortest section. However, if there is a (possible) congestion grid switching allows other sections to take over, alleviating the problem.

Less redundancy

Now, by rule, it is necessary to install a redundant cable for each new connection to grid. This means that for a connection with a capacity requirement of 5 MW, 10 MW is installed. This is to ensure electricity for all users, even when maintenance for one cable is required. However, due to the energy transition, more is demanded from the electricity grid and DSO's are not able to facilitate the new demands fast enough. By decreasing the required amount of redundancy, DSO's will be able to install new DG's with no redundancy and save on connection costs and times.

Cable pooling

Cable pooling is the act of connecting a wind park and a solar park to the grid with one connection. When the sun shines it is often not very windy and vice versa. This way the cable can be optimally utilized. A DG is always connected at full capacity. If a neighboring solar and wind park, both with a power capacity of 5 MW, are installed, they should be connected with one 10 MW cable or two 5 MW cables. By connecting them with one connection of 5 MW the cable is utilized more efficiently. The hybrid energy park would rarely produce more than their single maximum capacity, of 5 MW, such that only 3% or 4% of the produced energy, needs to be curtailed. This deficit is more than compensated by amount saved in connection costs. For example, in a the Dutch city of Nijmegen half a million euros where saved by cable pooling a PV solar and wind farm. The resources that are saved can now be utilized for other pressing DG connections or grid reinforcements [65, 66].

Heat networks

Heat networks, or district heating, can alleviate the electricity grid as more homes use heat pumps for heating (This was not mentioned in [8]). In heat networks a heated liquid, often oil or water, carries heat from heat sources, which can be a steel factory or a refinery, to consumers or sometimes to another heat demanding industry such as green houses. This makes heat networks not only an alternative to gas, but as more homes switch to heat pumps, which require a lot of electricity, it can also be used to relieve the electricity grid for the demand for heat [67].

Dynamic pricing

Dynamic pricing should incentives industry and consumers to up- and downscale activities based more on availability of supply, as electricity prices would decrease with the increase of supply and vice versa. As a result more pricing agreements will be made between distinct necessary capacity and controllable capacity.

Smart charging

As more and more electric vehicles (EV) are being bought, more strain is placed on the distribution grid. EV's are often charged when people come home from work and plugged in. This creates a new peak load that the electricity grid was not designed for. Smart charging should become the new norm, where the DSO and consumer should be able to both benefit from. EV's should thus be charged when supply is high, demand relatively low and subsequently the dynamic electricity price low.

Energy curtailment

Energy curtailment is, as mentioned in section 2.6, to purposefully cut off of the energy supply to avoid over-generation. Wind turbines can do this by either pitching there turbine blades to cut through the wind less efficiently, thus producing less energy or the wind turbine transformer can cut-off the energy supply by dissipating some electricity as heat. PV solar array only use the latter. Curtailment can be voluntary and involuntary. Voluntary is when for instance a wind park and coal plant operator chooses to shut down the wind park instead of the coal plant as it is cheaper and easier to restart. Involuntary is when the operator has no choice but to shut down a wind park to prevent over-generation [68]. This defined, voluntary curtailment can be seen as a preventive measure and involuntary curtailment as a reactive measure.

3 Simulation model

The goal of this study is to investigate the role of energy storage for decentralized renewable energy storage for mitigating limited cable capacity in the MV-grid. This is done using a simulation model where the behavior of an ESS can be simulated for different hybrid generation systems and different operating strategies. This model is also able to find the optimum storage size based on the objective of the optimization. In section 2.6 several financial and technical indicators were mentioned to be used as optimization objectives. Three financial objectives were identified: maximizing Profit, minimizing Payback time and minimizing LCOE. For this thesis, the focus will be placed on the profitability of the system.

In this section, the model that will be used to simulate the ESS behavior and eventually size of the ESS, is discussed. The model will be discussed in reference to fig. 17. This is a flowchart depicting the analytical simulation model that will be implemented in Python. The model is initiated with an initial estimate of the ESS size, the model parameters and the power supply- and financial data. Subsequently, the behavior of the storage system and the interaction with the external grid are calculated for each time step from the beginning until the end of the time period. By the end of the year the required ESS capacities and revenues are calculated as are the cost of the system. Finally, the objective can be calculated and optimized by iterating the starting ESS size.

This power supply as the output of the generation system, is illustrated in section 3.1. Subsequently the financial markets and data are explained. Afterwards the hybrid system model is discussed. These two sections describe the constraints and parameters that are needed for the ESS simulation. All these parts will be combined in section 3.4. The storage operation strategies of charging and discharging, will be discussed and the energy flow in the system can be calculated based on the technical constraints. Following this are the methods to determine the ESS capacities and the energy output. Finally the calculations for the costs, revenue and profit are given.

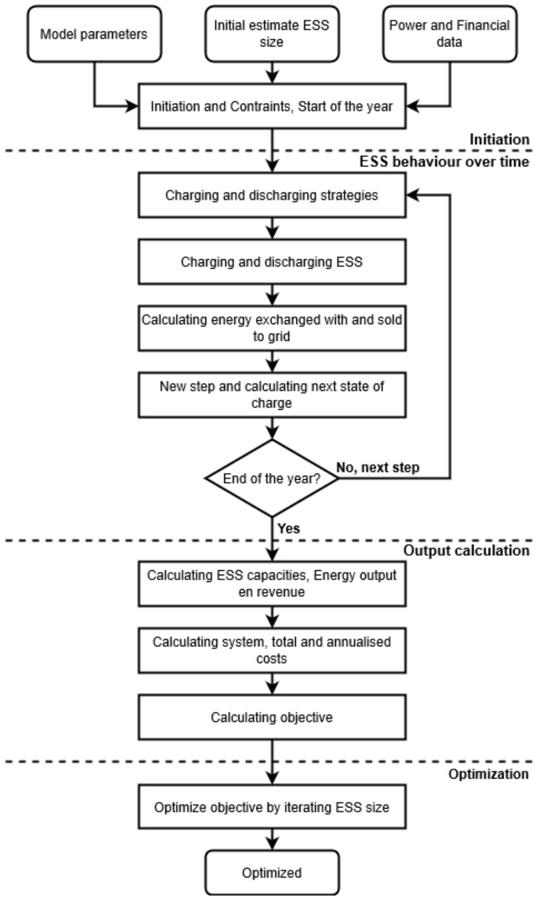


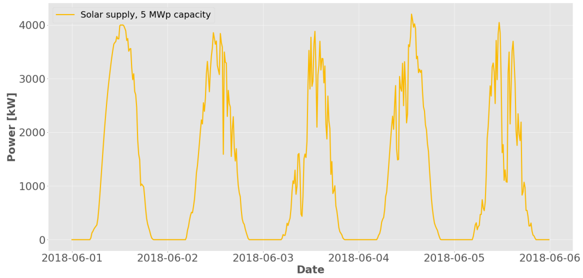
Figure 17: Analytical flowchart of the simulation model, simplified

3.1 Supply data

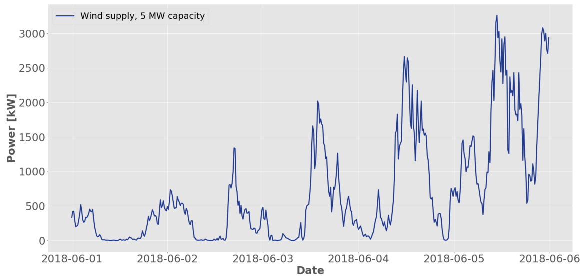
Renewable energy generation systems have variable power output dependent on the weather conditions. The output is also dependent on the type of PV panel/wind turbine, size, solar angle/turbine height, the location of the generation system, etc. Because of all these variables it was decided to take the power output curve of a DG as a given and only make it dependent on the size of the DG. There are two power output curves normalized on the capacity of the generation system, one for PV solar energy and one for wind energy. The power supply curves of the DG systems are from the year 2018 in the Netherlands and are provided by Qirion.

The power supplied by the DG system is shown in fig. 18. This is for five days in the summer, but it is provided for the entire year. These figures illustrate the power supply for an installed capacity of 5 megawatt peak (MWp) PV solar-, 5 MW wind energy and 5 MW combined respectively. The provided data has an Program Time Unit (PTU) of 15 min.

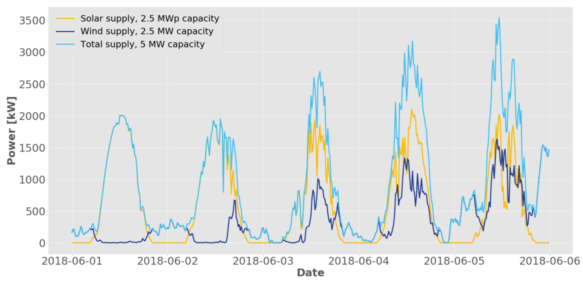
The maximum power supplied by the 5 MWp PV solar generation system over the entire year is 4655 kW and in that time it produces 5.3 GWh of electrical energy. For a 5 MW wind generation system this is 5000 kW and 12 GWh. The capacity factors are 12.2%, 27.4% respectively and 19.8% when they are combined in a solar/wind hybrid system. That system produces maximum 4685 kW and 8,7 GWh over the entire year.



(a) Installed capacity: 5 MWp PV solar.



(b) Installed capacity: 5 MW Wind.



(c) Installed capacity: 2.5 MWp PV solar and 2.5 MW wind.

Figure 18: Power supply with different installed capacities for five days in the summer.

The capacity factors of the solar and the wind energy data is higher than the average, which are 10% and 24%. An additional noticeable difference between the wind and solar energy curves, is that solar energy has a more consistent diurnal cycle than wind. Wind energy does have day and night effects, but there are longer periods of high and low winds that exceed the day and night cycle.
For simplification of the ESS sizing, it was chosen to only include the power supply of the DG and not the demand of the consumers.

This power supply data set is used for all simulation models except if stated otherwise.

3.2 Financial data

As discussed in section 2.3 there are three accessible markets for ESS aided DG's: the Day ahead market (DAM), Frequency Containment Reserve (FCR) and the automatic Frequency Restoration Reserve (aFRR). The data of these markets that will be used in the simulation models are shown in this section.
For the trading on these electricity markets a perfect forecast is assumed. This is not realistic, however this significantly simplifies the energy management strategy algorithm. Additionally for our purpose it is sufficient, maybe even preferred. The goal is to investigate the potential of electricity trading with the ESS, DG hybrid system. In this case the best case scenario of the trading strategies will be found, which will give a good indication of the potential. Additionally, for the same reasons, the costs that are involved with trading on the various electricity markets are not included. Thus a program responsibility party (PRP) would take care of these costs, but the hybrid system is operate as a separate program.
It is important to note for trading strategies that electricity supplied by the its own generation system is considered free as the costs of the generation system are not included in this study. Additionally the supply data from the previous section and financial data presented in this section are not directly linked. So the one is not influenced by changes in the other in the simulation model.

Day ahead market

The day ahead market has an hourly price in [€/kWh]. The PTU of the algorithms is 15 minutes, thus the price for four PTU's is equal. The spot market prices used are from the year 2018, as is the supply data. The data is taken from ENTSO-E [69]. The average DAM price is 0.0525 €/kWh with a maximum of 0.175 €/kWh and a minimum of 0.0006 €/kWh. In fig. 19 an example for five days of day ahead market prices are shown.
Perfect forecast for the DAM implies that the submitted bid is always approved and reached, thus the bid is equal to the energy that is exported to the grid. This avoids over- and under generation fines. Additionally the Spot market trading costs, discussed in section 2.3, will be not included.

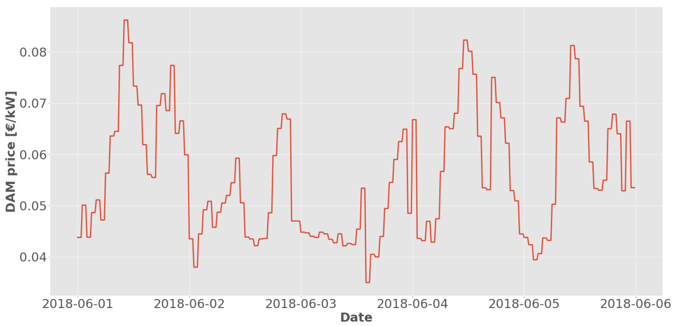


Figure 19: Day ahead market price. Five days in the summer.

Frequency Containment Reserve

The data used for the FCR market are taken from the general website of the German TSO's [70]. As the FCR market is restructured in July of 2019. Only data from July 2019 until December 2019 is used in the simulation algorithm. In that period the maximum FCR price is 998 €/MW, minimum is 150 €/MW. The

mean FCR price is 347 €/MW. There is only one FCR price for the whole day and bids must be placed in increments of 1 MW. If a bid is approved that amount of capacity needs to be reserved the whole day for use by the TSO. One bid of 1 MW is for 1 MW positive and negative, thus for such a bid 2 MW of capacity needs to be reserved. FCR is the primary control reserve and will be used as first resort to combat frequency imbalances in the grid. A storage unit is only required to supply the demanded power capacity for 15 minutes, as mentioned in section 2.3, after which the aFRR mechanism would take over. So the amount of energy capacity ([kWh]) required, is a quarter of the amount of requested power capacity ([kW]). The Dutch FCR market has a total reserved capacity of 111 MW.
A perfect forecast is assumed, so the FCR prices and ESS availability are known by forehand. Furthermore, all submitted bids to the FCR markets are approved and reached.
An example of five days of the course of FCR prices is shown in fig. 20.

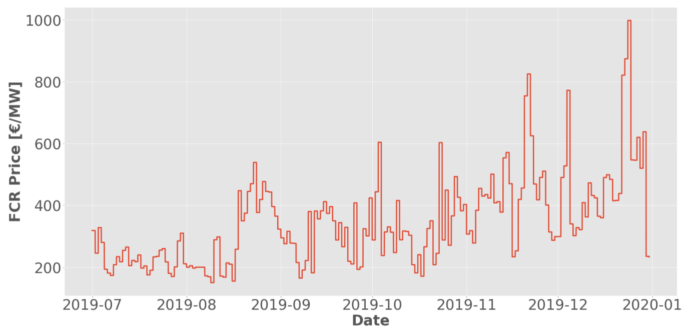


Figure 20: FCR market price, fixed per day. From July 2019 until December 2019.

automatic Frequency Restoration Reserve

The data used for the aFRR market are from the year 2018 and are taken from TenneT [71]. In fig. 21 the supply and demand in the Dutch grid are shown, in yellow and blue respectively. In green the difference between the curves is visualized. This is the imbalance in the grid. If it positive there is too much supply available and if it is negative there is more demand than supply. This imbalance in energy also represents a frequency imbalance. Just as the example described in section 2.3, fig. 10, the Feed in and -out prices can represent the aFRR market prices. If the imbalance is positive, too much supply available, an ESS can aid the grid by buying energy from the grid and storing it until the imbalance becomes negative. With perfect forecast it is possible to buy and sell electricity at favorable moments and generate revenue. An example of five days of Feed-in and -out prices are shown fig. 22.
The maximum Feed-in price is 0.50 €/kWh, the minimum is -0.419 €/kWh and the mean is 0.0495 €/kWh. For the Feed-out price is this 0.515 €/kWh, -0.419 €/kWh and 0.0524 €/kWh, respectively. The maximum positive imbalance on the Dutch grid is 230,784 kWh/PTU, negatively this is -355,233 kWh/PTU.

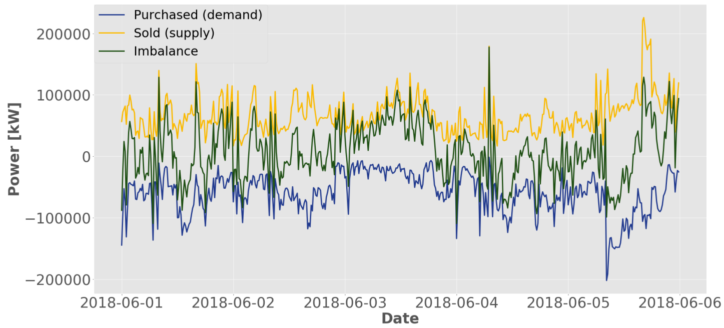


Figure 21: Imbalance on the electricity grid. Five days in the summer. Yellow is supply, blue is demand and red the imbalance: difference between supply and demand.

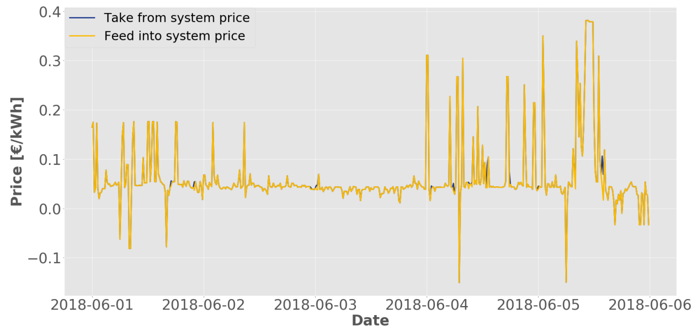


Figure 22: Feed into system price, yellow, and feed out of system price, blue. Five days in the summer.

3.3 Hybrid system model

In this section the technical components of the simulation models are discussed. The electrical configuration of the generation and storage hybrid system, as discussed in section 2.5, is illustrated. Subsequently, the technical constraints of the system are a discussed.

In table 6 all the variables that are used in the equations are labelled.

3.3.1 Energy storage systems

Following is a list of energy storage systems that are considered in the simulation models:

- Ideal energy storage system (Ideal)
- Battery systems (BESS)
  - Lead-acid (LA)
  - Li-ion NMC
  - Li-ion LFP

Table 6: Table of variables, their signs and units

Variable	Sign	Unit
Energy storage specifications		
Cycle efficiency	η_{cycle}	-
Charge efficiency	η_{charge}	-
Discharge efficiency	$\eta_{discharge}$	-
Transformer efficiency	$\eta_{transformer}$	-
Self-discharge per PTU	SD	PTU^{-1}
Maximum depth of discharge	MDOD	-
Lifetime	Life	years
Cycle lifetime	CLife	cycles
Capital cost ESS	$CAPEX_{ESS}$	€/kWh
Capital cost transformer	$CAPEX_{trans}$	€/kW
Capital cost Cable	$CAPEX_{cable}$	€/kW
Energy density	ρ_{energy}	kWh/L
C-rate ratio	Crate	-
Simulation algorithm		
ESS size	ESS	kWh
Energy capacity	E_{cap}	kWh
Power capacity	P_{cap}	kW
Cable capacity	CC	kW
State of charge	SOC	kWh
State of charge upper limit	SOC_{UL}	kWh
State of charge lower limit	SOC_{LL}	kWh
Energy supply	E_{sup}	kWh/PTU
Power supply	P_{sup}	kW
Maximum C-rate	$C_{rate,\ max}$	kWh/PTU
Energy charging the ESS	ESS_{in}	kWh/PTU
Energy discharged from ESS	ESS_{out}	kWh/PTU
Energy exported to grid	E_{grid}	kWh/PTU
Day ahead market price	DAM_{price}	€/kWh
Interest rate	r	-
Energy sold	$Sold$	€
Program time unit	PTU	0.25 h
Moment in time	i	-
Last moment in time	N	-

- Sodium-Sulfur (NaS)
- Sodium-Nickel-Chlorine (NaNiCl)

- Flow batteries (FBESS)
  - VRB
  - ZnBr
- Flywheel (FES)
- Thermal energy storage (TES)
  - PHES
  - LAES
- Hydrogen fuel cell system (HFCS)

All except for the ideal energy storage system are extensively discussed in section 2.4. This ESS is added to the simulation to investigate how an ideal energy storage system would behave and compare to the other technologies. The ideal energy storage system would have a life time as long as the electricity cables, 40 years. No self-discharge and no maximum depth of discharge. It would be 100% efficient and very cheap, estimated at 50 $/kWh or 45 €/kWh. The storage characteristics of all the ESS technologies are shown in tables 7 and 8. For all the real world technologies the chosen characteristics are an average of the values found in tables 4 and 5 and converted to the units used in the simulation algorithms.

As discussed in section 2.4 a boundary is set for the size of the energy storage systems. The boundaries are set between 300 kWh and 15,000 kWh and 300 kW and 10,000 kW. This ensures great compatibility with decentralized generation system that are connected to the MV-grid, also 300 kW to 10,000 kW.

Table 7: ESS characteristics used in the simulation models.

Technology	**Type**	**Life** [year]	**C_Life** [cycles]	**SD** [PTU^{-1}]	**MDOD** [-]
Ideal	Ideal	40.0	20000	0.0	1.0
Lead-acid	BESS	9.0	1375	2.083e-05	0.633
Li-ion NMC	BESS	12.5	3000	2.083e-05	0.915
Li-ion LFP	BESS	12.5	5500	2.083e-05	0.915
NaS	BESS	17.5	5500	5.469e-05	1.0
NaNiCl	BESS	14.5	4250	0.00026	1.0
VRB	FBESS	12.5	10000	0.0	1.0
ZnBr	FBESS	12.5	10000	0.0	1.0
FES	FES	20.0	20000	0.050	1.0
PHES	TES	12.5	10000	5.469e-05	1.0
LAES	TES	25.0	10000	0.0	1.0
HFCS	HFCS	12.5	10500	0.0	1.0

Table 8: ESS characteristics used in the simulation models, continued

Technology	η_{cycle} [-]	η_{charge} [-]	$\eta_{discharge}$ [-]	**Capex** [€/kWh]	$\eta_{cycle,2030}$ [-]	**Capex$_{2030}$** [€/kWh]
Ideal	1.0	1.0	1.0	45.0	1.0	45.0
Lead-acid	0.81	0.9	0.9	184	0.85	131
Li-ion NMC	0.943	0.971	0.971	405	0.97	188
Li-ion LFP	0.943	0.971	0.971	405	0.94	188
NaS	0.8	0.894	0.894	449	0.85	203
NaNiCl	0.84	0.917	0.917	362	0.87	149
VRB	0.775	0.880	0.880	592	0.78	211
ZnBr	0.7	0.837	0.837	981	0.78	327
FES	0.893	0.945	0.945	3375	0.89	2205
PHES	0.45	0.671	0.671	54.0		
LAES	0.675	0.822	0.822	356		
HFCS	0.43	0.656	0.656	1500		

3.3.2 System configuration

The electrical circuit used for the simulation is shown in fig. 23 or simplified in fig. 24 when only PV solar generation is used. In these models no transformer- and ESS efficiencies and other ESS characteristics were utilized.

In fig. 24 the boundaries of the individual systems in the hybrid system are illustrated. In the red dotted rectangle is the DG system. As stated in section 3.1 only the size of the DG system will be taken into account in the algorithms. This also excludes the DG's transformer. Thus the power supply profiles section 3.1 are the resulting output of the DG system and transformer. In green the connection system, which consists of the AC/DC transformer and the connection cable to the external grid. These are characterized by one value, the cable capacity in kilowatt. In blue the ESS system is depicted. This consists of the DC/DC transformer and the storage unit. The storage unit will be characterized by the energy capacity in kilowatt hour and power capacity in kilowatt. The DC/DC transformer by its power capacity. This value will be equal to the required power capacity of the storage unit. Both the AC/DC and DC/DC transformer will have an efficiency of 97%.

The transformer cost of the ESS system is fixed at 421 €/kW (sections 2.2 and 2.5). This is chosen to be equal for all storage technologies. Because the difference in cost for the power capacity of the different technologies, which is already relatively small, is as a consequence of technology specific auxiliary components. This difference is also included in the capital costs of the energy storage systems. For the simplification of the simulation model a fixed power capital cost coefficient of 421 €/kW, will therefor be used.

3.3.3 Technical constraints

In this section the technical constraints for the simulation model will be discussed. (Flow) Batteries, flywheels, hydrogen fuel cells and thermal energy storage systems all have physical constraints that dictate

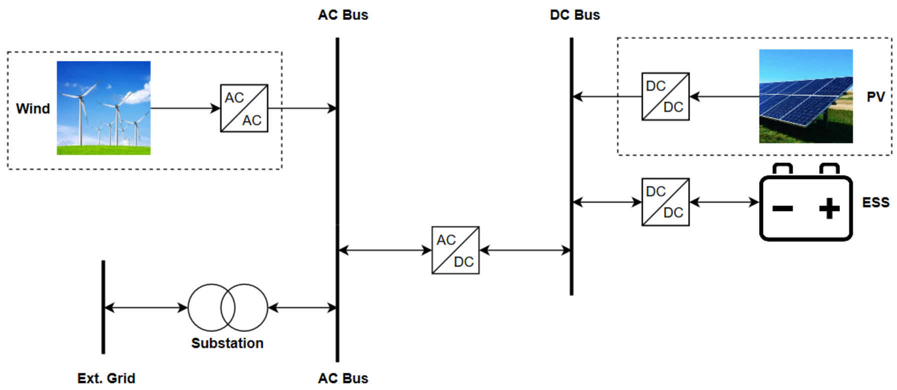


Figure 23: Electricity system schematic with wind and solar energy generation

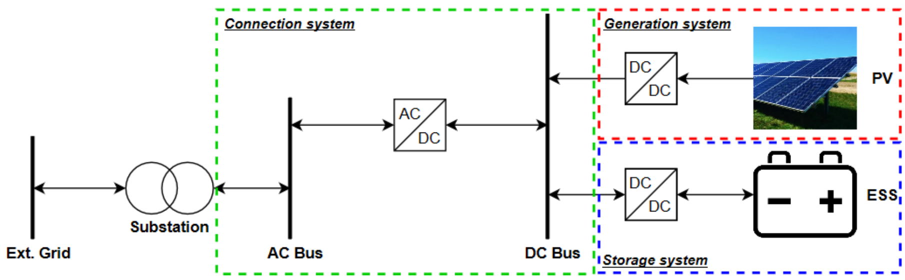


Figure 24: Electricity system schematic with system boundaries. Red generation system, blue ESS system and green connection system.

their behavior. For instance all have a specific cycle efficiency. When a lead-acid battery is charged and discharged only about 80% of the energy that was put into the systems, is retrieved. In section 2.4 there are three other energy storage system specific constraints mentioned, C-rate, depth of discharge and self-discharge. Next to these the laws of physics teach us that energy cannot be created nor destroyed. So conservation of energy is also very important [5]. The following constraints will dictate the behavior of the hybrid system:

1. Conservation of Energy, system
2. Conservation of Energy, storage
3. Maximum depth of discharge
4. C-rate
5. Cable capacity
6. Self-discharge
7. One-way transport

First, the conservation of energy of the systems states that the amount of energy that is exported to the grid is equal to the amount that is generated by the system and the amount (dis)charged to the storage unit, eq. (7). The conservation of energy of the storage system states that the stage of charge for the next point in time, (i+1), is equal to the current state of charge, (i), plus the amount charged or minus the amount discharged to or from the ESS eq. (8a). Herein the charge and discharge efficiencies are assumed to be equal for simplification: the square root of the cycle efficiency, eqs. (8b) and (8c). This is not always the case as it may differ per ESS technology depending the specific design chooses, but this is outside the scoop of this study.

Constraint 1, Conservation of energy, system:

$$E_{grid}(i)\ [kWh/PTU] = E_{sup}(i)\ [kWh/PTU] + ESS_{out}(i)\ [kWh/PTU] - ESS_{in}(i)\ [kWh/PTU] \tag{7}$$

Constraint 2, Conservation of energy, storage:

$$SOC(i+1)\ [kWh] = SOC(i) + ESS_{in}(i)\cdot(\eta_{charge}\cdot\eta_{transformer}) - ESS_{out}(i)/(\eta_{discharge}\cdot\eta_{transformer}) \tag{8a}$$

$$\eta_{charge} = \sqrt{\eta_{cycle}} \tag{8b}$$

$$\eta_{discharge} = \sqrt{\eta_{cycle}} \tag{8c}$$

The third constraint is the depth of discharge. Some energy storage technologies, like a lead-acid battery, degrade faster when fully charged or discharged. For a ESS with a MDOD of 0.8 the lower SOC limit is 10% of the energy capacity of the ESS and the upper limit 90%, eqs. (9a) and (9b). The state of charge of the ESS must stay between these bounds, eq. (9c).

Constraint 3, MDOD:

$$SOC_{LL}\ [kWh] = \frac{1-MDOD}{2} * ESS\ size \tag{9a}$$

$$SOC_{UL}\ [kWh] = (1-\frac{1-MDOD}{2}) * ESS\ size \tag{9b}$$

$$SOC_{LL} \leq SOC \leq SOC_{UL} \tag{9c}$$

The fourth constraint is the C-rate of the battery. It is assumed that the maximum power capacity of the battery and transformer are equal to the energy capacity of the battery, in other words, the C-rate is equal to 1. The charge and discharge rate of the battery may not exceed the C-rate of the battery eq. (10).

Constraint 4, C-rate:

$$C_{rate,\ max}\ [kWh/PTU] = ESSsize\cdot Crate \tag{10a}$$

$$ESS_{in}(i)\ [kWh/PTU] \leq C_{rate,\ max} \tag{10b}$$

$$ESS_{out}(i)\ [kWh/PTU] \leq C_{rate,\ max} \tag{10c}$$

The amount of energy exported to the grid is limited by the power capacity of connection cable. eq. (11) defines that the energy exported to the grid cannot exceed cable capacity in terms of energy capacity per PTU, [kWh/PTU].

Constraint 5, Cable capacity:

$$E_{grid}(i)\ [kWh/PTU] \leq CC\cdot PTU \tag{11}$$

The last constraint defines the self-discharge of the energy storage system. The self-discharge is expressed in the state of charge lost per PTU, eq. (12).

Constraint 6, Self-discharge:

$$SOC(i)\ [kWh] = SOC(i) - SOC(i) \cdot SD \tag{12}$$

An additional constraint on the system is that cables are only to transport electricity in one direction. This means that the battery is unable to charge and discharge at the same time. This also applies to grid exchange. It is only possible to either sell to or buy from the grid, but not at the same time.

Constraint 7, One-way transport:

$$If\ ESS_{in} \neq 0,\ ESS_{out} = 0 \tag{13}$$

$$If\ ESS_{out} \neq 0,\ ESS_{in} = 0 \tag{14}$$

3.4 Simulation model

Now the power supply data (section 3.1), the financial data (section 3.2), the model parameters and the constraints (section 3.3) are all defined, the flowchart depicted at the start of this chapter, in fig. 17, can be expanded to fig. 25. At the end the optimization of the decision variable is explained in short.
The first step in the model is to initiate all the data and defining the constraints as expressed in section 3.3.3. After the initiation the behavior of the storage system and the energy output in the model can be calculated. This is done in a couple steps:
First a charging and a discharging strategy needs to be chosen. Based on the strategy, the state of charge, supply and financial data the ESS is then either charged or discharged. Charging the battery can either be directly from the supply or from the grid. When the ESS is charged the ESS is unable to discharge.
After the amount of energy exchanged with the storage system is calculated, the amount that is exchanged with the grid is calculated. Knowing the electricity price for that time, also the cost or revenue are also calculated.
The next action is to calculate the state of charge of the ESS for the next time step. These steps are repeated from the start of the available data until the end.
At the end it is known how much energy is exported to the grid, how much energy is supplied by the generation system and the revenue made over that time period. Furthermore, the behavior of the energy storage system over time is computed. The necessary power capacity of the storage system and transformer can be determined. The number of charge and discharge cycles used in the ESS can additionally be counted.
From these outputs the system costs can be calculated. With the revenue and the annualized system costs the yearly profit can be determined.
In this simulation model the ESS size, in kWh, is the decision variable. The ESS size can be varied from 0 kWh to 15,000 kWh, the boundaries defined in section 2.4, to find the maximum profit. With a larger storage system the total costs increase, but the possible revenue can also increase as more energy can be stored for more favorable times.
With this model it is possible to alter the starting parameters, supply and financial data and choose different charging and discharging strategies to use of the ESS in the system, resulting in different model outputs.

There are several charging and discharging strategies considered. These are formulated as realistic strategies in situations with cable capacity limitations and the capability to trade on the electricity markets. For instance, when considering a fixed electricity price, it is not beneficial to buy electricity from the grid to sell again at a later point in time, especially considering charge and discharge losses. But when the electricity price is variable over time, this is a possibility. The six charge and six discharge strategies considered, are listed below. There are more strategies imaginable, but with six charge and discharge strategies there are already enough charge- and discharge strategy combinations possible. These combinations are reviewed in section 6.

Charge strategies:

1. No charging
2. Charge from supply when limited by cable capacity
3. Charge from supply when electricity price is not favorable
4. Charge from grid when electricity price is favorable and there is no supply
5. Charge from grid when there is no supply
6. Charge from supply until ESS is full

Discharge strategies:

1. No discharging
2. Discharge when cable capacity allows
3. Discharge when electricity price is favorable
4. Discharge when electricity price is favorable and there is no supply
5. Discharge when there is no supply
6. Discharge when ESS is (partly) full

Charging strategy 2 is the direct implementation of constraint 5, eq. (11). So if the power supply is larger than the capacity of the connection cable, the energy will be stored in the ESS, if not already full. Otherwise the supply is curtailed at the cable capacity. In this model, this strategy is always utilized. This strategy never contradicts other strategies which buy energy from the grid, because of constraint 7, one-way transport. Additionally, the electricity provided by the generation system is considered free, as stated in section 3.2. This energy is therefore given precedence to the energy bought from the grid. Determining when the electricity price is favorable for strategies 3 and 4 depends on the financial data used and can also be different per season. Selecting a good sell and buy price point is important the maximize the revenue, however, it is not the goal of this thesis to determine the optimum price points. Furthermore, a dynamic buy/sell price point is also to complex for this thesis. Good, fixed price points will be estimated for these strategies to still get a good insight of the possibilities of electricity trading with an ESS aided DG system. Only one strategy or combination of strategies is chosen per computation. So this does not change per iteration step. Before the charging of the ESS, for each step in the program, until $i \leq N$, the charge condition is checked.

First a charging strategy is chosen and when the charge conditions are met for one step (for one i), the ESS is charged. The constraints depend on the strategy chosen. This differs for when the battery is charged from the power supply or when it charged with energy bought from the grid. When charging from supply the amount charged is dictated by the supply at that time, the cable capacity (constraint 5, eq. (11)), the state of charge before charging (constraint 3, eq. (9c)), the C-rate of the ESS system (constraint 4, eq. (10) and the efficiencies of the ESS system and transformer. The amount that is still being exported is defined as the new energy supply which is either the old supply minus the amount charged or the maximum capacity that is possible to be exported to grid. This is calculated using eq. (15), where the minimum value of the first three x equations is used for the $\mathrm{ESS_{in}}$ and the minimum value the last two x equations are used for the redefined $\mathrm{E_{sup}}$.

$$ESS_{in}(i) = min(x) \tag{15a}$$
$$x = E_{sup}(i) - \frac{CC \cdot PTU}{\eta_{transformer}} \tag{15b}$$
$$x = \frac{(SOC_{UL} - SOC(i))}{\eta_{charge} \cdot \eta_{transformer}} \tag{15c}$$
$$x = C_{rate,\ max} \tag{15d}$$
$$E_{sup,new}(i) = min(x) \tag{15e}$$
$$x = E_{sup}(i) - ESS_{in}(i) \tag{15f}$$
$$x = CC \cdot PTU / \eta_{transformer} \tag{15g}$$

When the storage system is being charged with energy from the grid, the charging amount is determined using eq. (16). Here the 'supply' to the system, from the grid, is first determined and subsequently the amount of energy charged to the system. When energy is bought from the grid it is marked as negative. As previously the cable capacity, MDOD and C-rate constraints and cycle and transformer losses dictate the amount eventually being charged to the storage system.

$$E_{sup}(i) = -1 \cdot max(x) \tag{16a}$$
$$x = \frac{CC \cdot PTU}{\eta_{transformer}} \tag{16b}$$
$$x = \frac{(SOC_{UL} - SOC(i))}{\eta_{charge} \cdot \eta_{transformer}} \tag{16c}$$
$$x = C_{rate,\ max} \tag{16d}$$
$$E_{in}(i) = -1 \cdot E_{sup} \cdot \eta_{transformer} \tag{16e}$$

There is only one discharging method, regardless of the discharge strategy, since the discharged energy is always sold to the grid. So only the discharge conditions differ when a other discharge strategy is chosen. The amount discharged is also governed by the same constraints and efficiency losses as for the charging methods, eq. (17).

$$ESS_{out}(i) = min(x) \tag{17a}$$

$$x = (CC \cdot PTU/\eta_{transformer} - E_{sup}(i)) \tag{17b}$$

$$x = (SOC(i) - SOC_{LL}) \cdot (\eta_{discharge} \cdot \eta_{transformer}) \tag{17c}$$

$$x = C_{rate,\ max} \tag{17d}$$

When the (new) supply and the amount of energy discharged from the system are known the amount exported to the grid are calculated, using the first constraint, the conservation of energy of the system, eq. (18). Subsequently the income for that period in time can be calculate to multiply the exported amount of energy with the momentary electricity price, eq. (19).

$$E_{grid}(i) = (E_{sup}(i) + ESS_{out}(i)) \cdot \eta_{transformer} \tag{18}$$

$$Sold(i) = E_{grid}(i) \cdot E_{price}(i) \tag{19}$$

This is followed by the computation of the state of charge for the next step, according to constraint 2, conservation of energy of the storage system eq. (20). As the supply is already redefined in the charging function, when necessary, the $\mathrm{ESS_{in}}$ is not included in this calculation. Finally the self-discharge is considered in the computations as defined in constraint 6, eq. (12).

$$SOC(i+1) = SOC(i) + ESS_{in}(i) \cdot (\eta_{charge} \cdot \eta_{transformer}) - ESS_{out}(i)/(\eta_{discharge} \cdot \eta_{transformer}) \tag{20}$$

Following this, the end of the time period is checked. If the time period has ended, it is possible to determine the total amount exported and supplied, as the total revenue for that time period.
Normally the initial state of charge of the ESS is $\mathrm{SOC_{LL}}$. However, if the at the end of the time period the ESS is not empty but full, $SOC(i = N) = SOC_{UL}$, the sequence is run again with the initial state of charge also full. This seems the fairest method as all calculations start and end with the same state of charge. It is also possible to discharge the entire state of charge left in the ESS at the end of the time period. These two methods do not vary much. The only time this occurs in the result is in section 5.2. The difference between these two methods is €300, which is insignificant in context of the entire yearly revenue.

The amount of total charge and discharge cycles and the maximum used power capacity can also be equated at the end of the time period. One cycle is counted by looking at the amount charged or discharged for one time step in relation to the ESS size, depending on whether the storage unit is charged or discharged. Since one full cycle is a full charge and discharge, the one time step cycle is divided by 2, eq. (21). The power capacity of the system is defined as the maximum used (dis)charge capacity. For this the maximum value assumed by either the $\mathrm{ESS_{in}}$ or $\mathrm{ESS_{out}}$ over the time period is used as the necessary power capacity of the storage and transformer system, eq. (22).

$$Cycle(i) = 0.5\frac{abs(ESS_{in \cup out}(i))}{ESS} \tag{21a}$$

$$Cycles = \sum_{i=0}^{N} Cycle(i) \tag{21b}$$

$$P_{cap}\ [kW] = Max_{i=0}^{N}(abs(ESS_{in \cup out}(i))/PTU) \tag{22}$$

The system costs and profit are subsequently computed. The equations stated below are already referenced in section 2.6, but some are slightly altered. First the total cost of the system needs to be calculated using eq. (23). In this equation the storage size [kWh] times the energy capital cost coefficient [€/kWh] is added to the power capacity of the storage unit [kW] times the power capital cost coefficient [€/kW]. The energy capital cost coefficient per technology is given in table 8. The power capital cost coefficient is given in section 3.3.2. The annualized cost is calculated using eq. (25). The capital recovery factor (CRF), as a function of the interest rate and the lifetime of the storage unit, is used to annualize the total cost, eq. (24). The revenue is the amount of energy sold times the momentary electricity price. This is calculated for every PTU and these are summed for the entire yearly revenue, eq. (27). The difference between the revenue and the annualized cost is the yearly profit, eq. (28).

Two assumptions are made for these calculations. As stated in section 2.4 the operational costs are neglected in the calculations for the annualized costs. And the interest rate for most calculations is set at 6% as done in [22]. For an investor in a competitive environment an interest rate of 10% to 15% can be considered, however, for a DSO an interest rate between 5% and 10% is more suitable [27]. It is noted that Alliander is able to loan at rates even lower than 5%. In 2019 a weighted average cost of capital of 3.5% was calculated [72]. The effect of the interest rate on the cost is discussed in section 4.3.

$$Cost_{total}\ [€] = CAPEX_{ESS} \cdot ESS + CAPEX_{trans} \cdot P_{cap} \tag{23}$$

$$CRF = \frac{r(1+r)^L}{(1+r)^L - 1} \tag{24}$$

$$Cost_{annual} = Cost_{total} \cdot CRF \tag{25}$$

$$Energy_{output} = \sum_{i=0}^{N} E_{grid}(i) \tag{26}$$

$$Revenue = \sum_{i=0}^{N} Sold(i) \tag{27}$$

$$Profit = Revenue - Cost_{annual} \tag{28}$$

When the cost of the connection is also included, which is important in the minimization of the distribution grid requirements, the cost of the cable is added to the total cost of the storage unit. The capital cost coefficient of the cable found in section 2.2, averaged at 320.5 €/kW. Total cable cost are the required cable capacity times the cable cost coefficient. To annualize the cable cost the CRF of the cable is used where the N is the life time of the cable, 40 years.

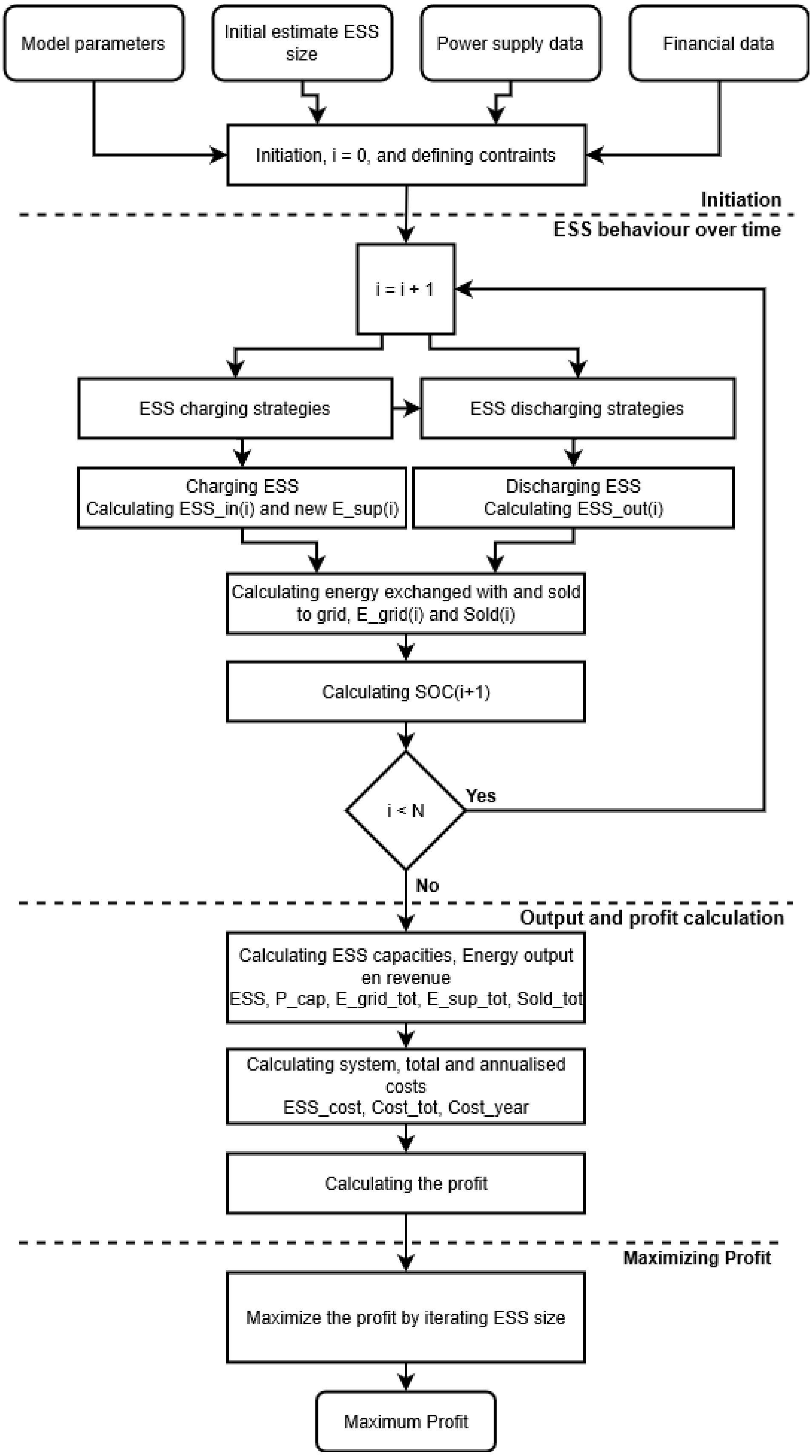


Figure 25: Analytical flowchart of the simulation model

3.4.1 Optimization model

The model described in this chapter is mostly used to simulate the behavior of the ESS and calculate, among other things, revenue, costs and profit of the system. The maximum profit and subsequent optimum storage size can be determined with two methods. The simplest method is by calculating the profit for every energy storage size, from 0 MWh to 15 MWh, and determining the optimum from all these values. This method, called exhaustive search, is most commonly used for the sizing of the storage unit in this thesis. It is not the fastest method, but it is often fast and easy enough to evaluate the results.
The other method is with an optimization technique discussed in section 2.6.4. This method is also implemented in the Python model, however, the focus of this thesis was mostly on the simulation of the ESS. In the model an existing direct search-based mathematical optimization technique is implemented, the scipy.optimize.minimize function. The objective function is to maximize the profit, eq. (29) (or minimize the negative profit), where the revenue and the cost are both a function of the energy storage size. This optimization is a bounded constrained minimization with the boundary $0\ MWh < ESS < 15\ MWh$ and the constrains as mentioned in section 3.3.3. The default solver for this minimization is the L-BGGS-B algorithm.

$$minimize(Cost_{annual}(ESS) - \sum_{i=0}^{N}[E_{grid}(ESS,i) \cdot E_{price}(i)]) \tag{29}$$

Summary

In this chapter the simulation model to simulate the ESS in a hybrid DG system, was described. The hybrid system consists of three subsystems: The generation system, the connection system and the energy storage system. They consists of the following characteristics:

- Generation system:
  - PV solar park or a wind farm
  - Boundaries: 0.3 MW - 10 MW
- Connection system:
  - Boundaries: 0.3 MW - 10 MW
- Energy storage system system:
  - BESS, FBESS, FES, TES and HFCS
  - Boundaries: 0 MWh - 15 MWh and 0 MW - 10 MW

The inputs for the model are power supply, financial data, a decision variable and model parameters. The outputs are the ESS size, the energy output, revenue, system costs and the objective of the model is to maximize profit of the system. The profit is defined as the difference between the yearly revenue and the annualized cost.
The simulation model needs abide by seven technical constraints:

1. Conservation of Energy, system

2. Conservation of Energy, storage
3. Maximum depth of discharge
4. C-rate
5. Cable capacity
6. Self-discharge
7. One-way transport

There are six charge and discharge strategies that can applied in the model, table 9. These dictate how the ESS operates.

Table 9: Charging- and discharging strategies

#	**Charging strategy**	#	**Discharging strategy**
1	No charging	1	No discharging
2	From supply, limiting cable capacity	2	Cable capacity not limiting
3	Supply, Price is not favorable	3	Price is favorable
4	Grid, Price is favorable & no supply	4	Price is favorable & no supply
5	Grid, When no supply	5	When no supply
6	Supply, Until ESS is full	6	When (partly) full

The following model parameters are included in the simulation model:

Energy storage parameters:
- Cycle efficiency
- Transformer efficiency
- Self-discharge
- Maximum depth of discharge
- Lifetime
- Cycle lifetime
- Capital cost ESS
- Capital cost transformer
- C-rate ratio

System parameters:
- ESS size
- Time period
- Power supply
- Cable capacity
- Electricity price
- Interest rate
- Charging strategy
- Discharging strategy

4 Model verification and validation

In this section the simulation model described in the previous chapter, will be verified and validated based on several cases. The goal is to determine capabilities and limitations and to assure the correctness of the simulation model. In other words, that the constraints are met, the behavior of the ESS is not unpredictable and the results are logical. This is to legitimize the conclusions drawn from the results of the model.

4.1 Base Case: No Storage

The first case that will be investigated is to set the baseline of system capabilities. In this case a PV solar power park of 5 MWp is installed in location with limited grid capabilities. There is only an 1 MW cable that connects the generation system to the external grid.

As more renewable energy is needed to combat climate change and most renewable energy projects are realized in low densely populated areas with limited grid capabilities, such cases are more likely to be occurring nowadays. Furthermore, this case is a great base case to look at the potential of energy storage and/or the influence of grid reinforcement. But in the base case no energy storage will be added.

The model will calculate the total profit over the entire year. The used supply data is the power output of a 5 MW peak PV park for 2018, as can be seen in section 3.1. For simplicity a fixed electricity price is chosen, the average day ahead market price, 0.0525 €/kWh. Furthermore, as this is the base case there are no systems costs. The 5 MWp PV park and 1 MW connection are seen as a given.

The power output of the system is depicted in fig. 26. This is for five days in the June. As can be seen most of the power supplied by the generation system is curtailed to fit the cable capacity. The results for the entire year can be seen in table 10. Less than 52% of the total produced energy is eventually exported to the grid. The income from this is 145,000 €.

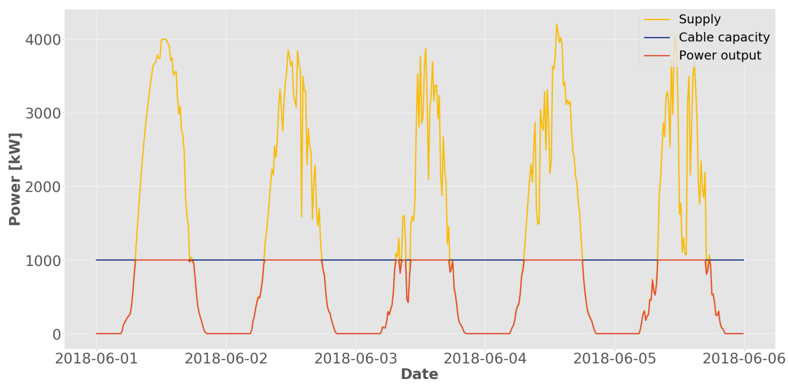


Figure 26: Base case power output. Supply of the PV park, in yellow, Cable capacity, in blue and the Power output to the grid in kW, in red.

4.2 Case 1: Standard storage case

In this case the base case is expanded on by the addition of an energy storage system. The supply, cable capacity and financial model stays the same, but an Ideal ESS is added so less energy needs to be curtailed. The ESS size will range from 0 to 15,000 kWh. The second charge and discharge strategy are chosen for

Table 10: Base case results: 5 MWp PV, 1 MW cable, no storage, fixed electricity price

Result	Unit	Value
Energy supplied	GWh	5.35
Energy exported	GWh	2.76
Total costs	€	0
Revenue	€/year	145,000
Profit	€/year	145,000

Table 11: Case 1 model parameters, *decision variable

Parameter	Unit	Value
Energy storage parameters		
Cycle efficiency	-	1
Charge efficiency	-	1
Discharge efficiency	-	1
Transformer efficiency	-	0.97
Self-discharge	PTU^{-1}	0
Maximum depth of discharge	-	1
Lifetime	years	40
Cycle lifetime	cycles	20,000
Capital cost ESS	€/kWh	45
Capital cost transformer	€/kW	421
C-rate ratio	-	1
System parameters		
ESS size*	kWh	0 - 15,000
Time period	-	01/01/18 - 31/12/18
Power supply	kWp	5000
Cable capacity	kW	1000
Fixed electricity price	€/kWh	0.0525
Interest rate	-	0.06
Charging strategy	Charge from supply when limited by cable capacity	
Discharging strategy	Discharge when cable capacity allows	

this case. So when the power supply exceeds the cable capacity the ESS is charged until full and when the cable capacity is sufficient again, the ESS will discharge. For the model parameters, the Ideal ESS has no cycle losses, but the transformer connected does have a efficiency of 97%. Furthermore, the interest rate is set at 6%. The PV solar park and connection to the grid are again not included in the cost calculations. A summary of the model parameters is given in table 11.

First the flow of energy in the system is analyzed. In fig. 27 the power output of the system of Case 1 is shown. This is for comparison the same five days in June as in the base case. So the power supply, yellow,

and cable capacity, blue, are the same, but the power output, in red, is clearly larger. In fig. 28 the amount of energy stored in the Ideal ESS is shown over the same time period. It is not representative of the overall year as at the start of the five days, the storage unit is empty, which might not be the case if the days before this period were particularly sunny. However, it gives a good indication of the behavior of the ESS over time. For these figures the largest ESS size was considered, 15 MWh.
The results of the whole year for all the ESS sizes, from 0 - 15 MWh, are shown in table 12.

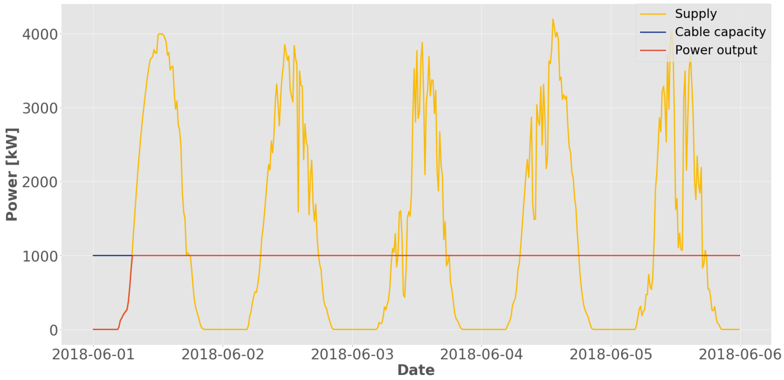


Figure 27: Case 1 power output. Supply of the PV park, in yellow, Cable capacity, in blue and the Power output to the grid, in red, in kW over time, five days in June.

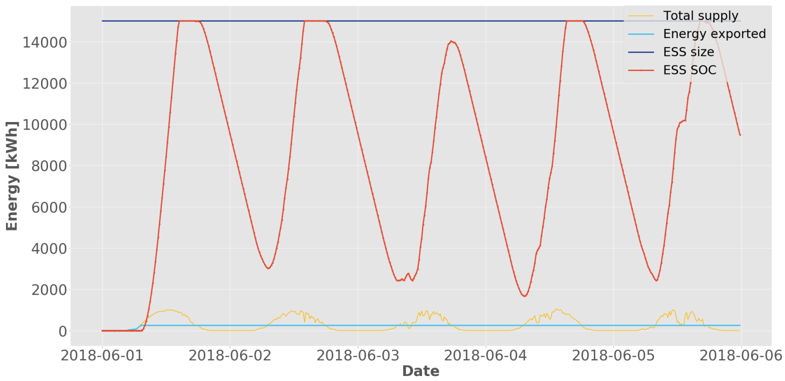


Figure 28: Case 1. Showing the electricity supply, yellow, and output, light blue, and ESS size (15 MWh), dark blue, and state of charge, red, in kWh over time, five days in June.

In fig. 29 the power capacity, top graph, and the number cycles, bottom graph, are shown. The power capacity rises quickly to stop at a maximum of 3624 kW. In the first, linear, part the power capacity is limited by the C-rate of the ESS. So with a C-rate ratio of 1, the maximum C-rate is 1000 kW for a 1000 kWh ESS. However, when the storage system becomes larger than 3000 kWh the supply limits the initial growth. This is because the 5 MWp PV solar park has a maximum power output of 4655 kW, so with a cable capacity of 1000 kW a maximum of 3655 kW is needed to be stored at once. The maximum power capacity was most likely reached while charging as the discharge rate is limited by the cable capacity. So the maximum theoretical value of 3655 kW was probably not reached as at the moment of that maximum value, the ESS was already partly full.
In the bottom graph, the amount of full charge and discharge cycles were counted over the entire time

Table 12: Case 1 results: 5 MWp PV, 1 MW cable, Ideal ESS, fixed electricity price

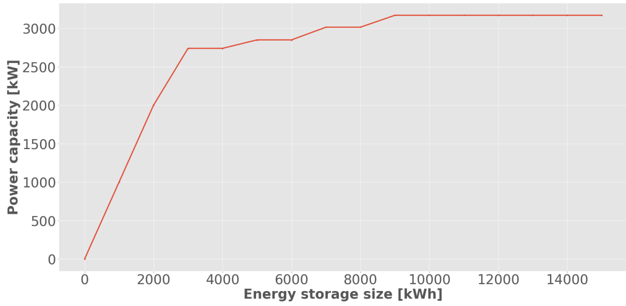
ESS size	**MWh**	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Power capacity	MW	0	1	2	3	3.47	3.47	3.47	3.62
Cycles	-	0	312	280	262	249	238	228	218
Exported	GWh	2.76	3.05	3.29	3.50	3.70	3.88	4.05	4.20
Total cost	M€	0	0.47	0.93	1.40	1.64	1.69	1.73	1.84
Revenue	10^3 €/year	145	160	173	184	194	204	213	220
Profit	10^3 €/year	145	129	111	91	85	92	97	98
ESS **size**	**MWh**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
Power capacity	MW	3.62	3.62	3.62	3.62	3.62	3.62	3.62	3.62
Cycles	-	209	201	192	184	176	167	158	150
Exported	GWh	4.33	4.46	4.57	4.66	4.74	4.80	4.84	4.87
Total cost	M€	1.89	1.93	1.98	2.02	2.07	2.11	2.16	2.20
Revenue	10^3 €/year	228	234	240	245	249	252	254	256
Profit	10^3 €/year	102	106	109	111	111	112	111	110

period. The blue line represents the maximum amount of cycles allowed in a year. The theoretical lifetime of the Ideal ESS is 40 years and the theoretical cycle lifetime is 20,000. If 20,000 cycles are reached within 40 years the storage system needs to be replaced sooner than 40 years. To reach the lifetime of 40 years, a yearly maximum of 20,000/40 = 500 cycles are allowed. This is the yearly cycle lifetime. In this case that limit is not exceeded. As the ESS size is smaller at first the cycles are relatively larger, but slowly drop, from 209 cycles at 1 MWh to 150 cycles at 15 MWh.

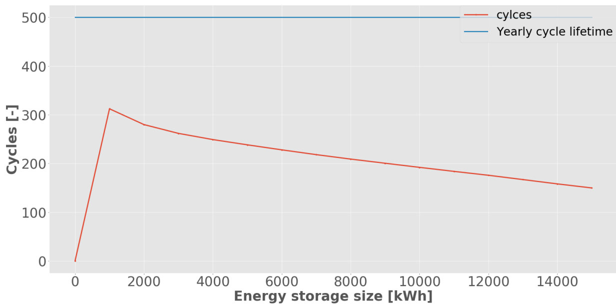
There is 2.11 GWh more energy exported with a 15 MWh ESS than without storage. This is an increase of 77%. With storage 91% of the total supplied energy has been able to be exported. This can be seen in fig. 30a, where the amount of energy in comparison with the total supply is plotted. This amount increases faster in the first part than near the end. So a small ESS instead of no ESS has more effect than a large ESS compared to a small ESS. In the first 3 MWh of the graph the increase is 13% and in the last 3 MWh, from 12 MWh until 15 MWh, this is only 3%.
This is similar for the revenue generated by the system in the time period, as seen in fig. 30b.

The total costs of the system as a function of the ESS size can be seen in fig. 31. The total system cost comprise in this case of the storage and the power system costs. The storage cost is a function of the energy capacity of the ESS. This is a linear function, so the increase is also gradual. The power system cost is a function of the power capacity of the transformer and in extent the ESS. The power capacity increase is however not linear, as visible in fig. 29. Although power capacity is considerably smaller than the energy capacity for the 15 MWh ESS, the power cost make up the majority of the total system cost. This is due to the low energy capacity capital coefficient of the Ideal ESS, which is only 45 €/kWh compared to the 421 €/kW of the power capacity capital coefficient. This value is equal for all storage technologies. The maximum total system cost is 2.2 M€.

The profit is calculated by the difference in the annualized costs and the yearly revenue of the system. The



(a) Power capacity, as a function of the ESS size.

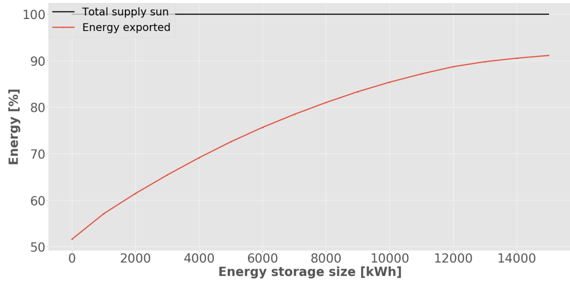


(b) Number of cycles as a function of the ESS size.
The red line represents the total amount of cycles that occurred and the blue line the maximum amount of full cycles allowed in a year.

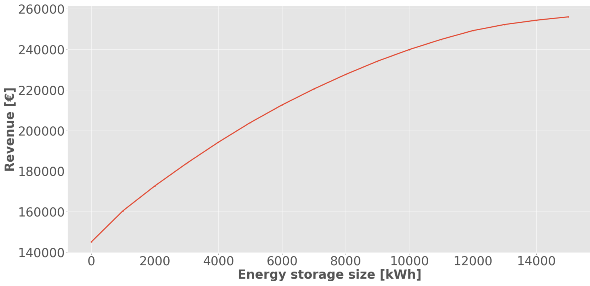
Figure 29: Case 1. Power capacity and number of cycles as a function of the ESS size.

profit of the hybrid system with an ESS from 0 MWh to 15 MWh is illustrated in fig. 32. The simulation model calculated that the system without storage has the maximum profit, as the costs are zero without storage. With the addition of storage this drops quickly until the costs stagnates. This ends with a local minimum at 4 MWh. The profit increases again when more revenue has been generated with the increase of ESS size. At 12 MWh a local maximum is reached. At this point the revenue increase stagnates and the costs increase becomes more influential again. In this case the hybrid system is always profitable with an Ideal ESS up to 15 MWh.

So in this standard storage case the energy storage system did add value to the hybrid system with energy transportation limitations, by increasing the energy output and the revenue. However, the maximum profitable system is one without storage. This was expected as it is often concluded in the reviewed literature that energy storage is still not profitable. In the following chapters the profitability of various hybrid system designs will be discussed and in particular when a system does become profitable.



(a) Total energy supplied and exported, as a function of the ESS size.



(b) Revenue, as a function of the ESS size.

Figure 30: Case 1. Energy output and revenue as a function of the ESS size.

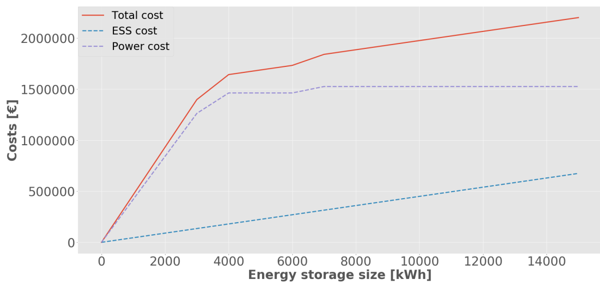


Figure 31: Case 1. Total system costs with power system and storage system costs, as a function of the ESS size.

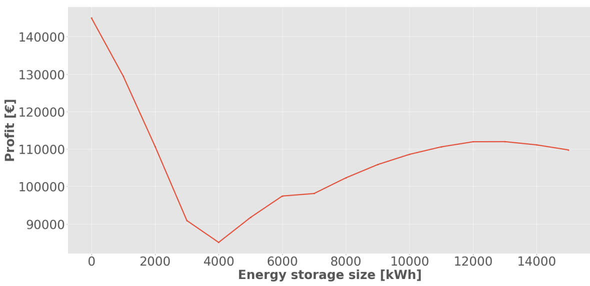


Figure 32: Case 1. Profit, as a function of the ESS size.

4.3 Model validation and sensitivity analysis

In this section all the relevant parameters will be analyzed to check their effect on the model. The results of which will be discussed in the following chapters, as not all parameters have direct implementation. For the first case an Ideal energy storage system was used. The ideal storage system does not have any losses, however, this is not realistic of course. So the effects of efficiency losses, maximum depth of discharge and self-discharge on the ESS behavior and its output are examined. Furthermore, a 5 MWh PV solar park was used. The effects on the system are discussed for when this is substituted with for instance a wind farm. The final subsystem is also discussed, the connection cable to the grid. Subsequently the scalability of this model is tested. It is expected that the results are scalable from the base cases, 5 MWp PV and 1 MW cable, to a system with 50 MWp PV and 10 MW cable. For these analyzes a fixed electricity price was used to exam the results of one year production, but in reality this price fluctuates. It is important to find the impact of a dynamic price. Subsequently the interest rate is an important parameter. If a project is commercial the interest rate will be higher than when a DSO is responsible, as a Dutch DSO is able to loan at more much lower rates. Finally some charging strategies are checked to see if the simulation model is also able to trade. This is tested with different buy/sell price points.
An overview of the values of the parameters used for the validation- and sensitivity analysis of the model is given in table 13.

Table 13: Overview of the values of the parameters for the model validation and sensitivity analysis.

Section	Parameter	Unit	Values
ESS behavior	Cycle efficiency	-	0.5, 1
ESS behavior	Self-discharge	PTU^{-1}	0.5, 1
ESS behavior	Maximum depth of discharge	-	0.5, 1
Supply	PV solar park size	MWp	0.3, 5, 10
Supply	Wind farm size	MW	5
Cable capacity	Cable capacity	MW	1, 2, 5
Scalability	PV solar park size & Cable capacity	MWp & MW	5 & 1, 50 & 10
Electricity price	Fixed electricity price	€/kWh	0.0006, 0.0525, 0.175
Electricity price	Dynamic electricity price	€/kWh	range: 0.0006 - 0.175
Interest rate	Interest rate	%	5, 6, 10, 15
Charging and discharging strategies	Charging strategy	-	2, 3, 4
Charging and discharging strategies	Discharging strategy	-	2, 3, 4
Buy/sell price	Buy price	€/kWh	0.045, 0.05
Buy/sell price	Sell price	€/kWh	0.06, 0.065

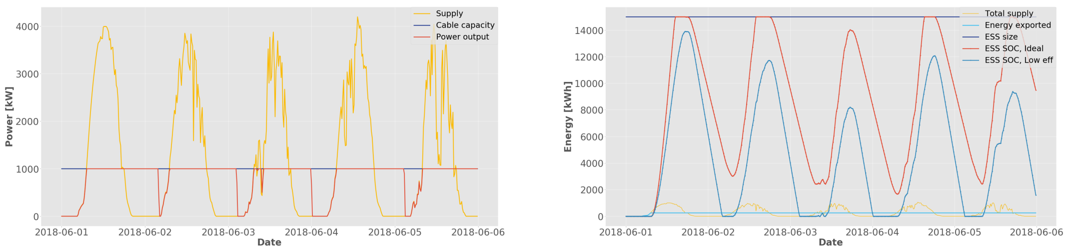
4.3.1 ESS behavior

This section is to get a better understanding of the ESS behavior as a result of ESS characteristics, more specifically the cycle efficiency, maximum depth of discharge and self-discharge. Only the power output and state of charge are analyzed as a more extensive comparison between ESS technologies is made in section 5.1.

Cycle efficiency

The effect of efficiency losses is illustrated with the an Ideal ESS, but with a low cycle efficiency of 50%. The ESS does not have a self-discharge and no maximum depth of discharge, so only the effect of the cycle efficiency is illustrated in fig. 33. Compared with the Ideal ESS it can be seen that in fig. 33a not as much energy is exported to the grid. This is due to the cycle losses, where only about 71% of the charged energy is actually charged to the ESS. And then only 71% of the energy discharged, is actually discharged. In fig. 33b this is clearly visible as the ESS is not able to get completely charged.

A lower cycle efficiency has a negative on the power output of the entire hybrid system and the maximum state of charge of the storage system. This is expected, so the model simulates this correct.



(a) Power output over time. Supply of the PV park, in yellow, Cable capacity, in blue and the Power output to the grid, in red, in kW.

(b) State of charge over time. Showing the electricity supply, yellow, and output, light blue, and ESS size (15 MWh), dark blue, all in kWh. State of charge of the ideal system in red and of the SOC of the ESS with low cycle efficiency in light blue.

Figure 33: Power output and ESS behavior for a 15 MWh ESS, five days in June. Influence of low cycle efficiency.

Maximum depth of discharge

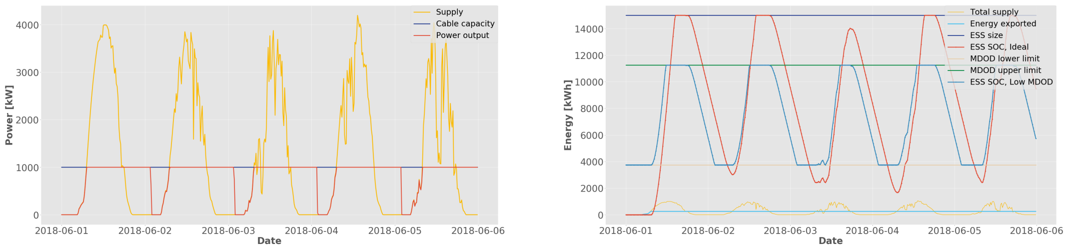
For the effect of the maximum depth of discharge five days of summer are simulated for a system with an Ideal ESS, but with MDOD of 0.5. So it is not able to use 50% of its total size. In fig. 34b the upper and lower SOC limits are highlighted.

A lower MDOD has a negative on the power output of the entire hybrid system and the maximum state of charge of the storage system. This is expected, so the model simulates this correctly.

Self-discharge

The ESS has a high self-discharge. It loses 50% of the total charge per day. The power output and ESS behavior are shown in fig. 35.

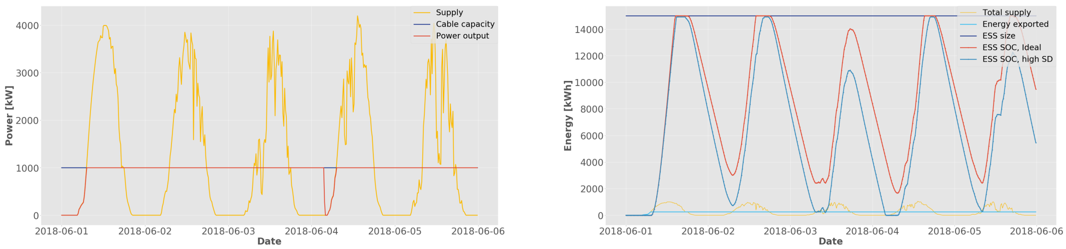
A higher self-discharge has a negative on the power output of the entire hybrid system and the maximum state of charge of the storage system. This is expected, so the model simulates this correctly.



(a) Power output over time. Supply of the PV park, in yellow, Cable capacity, in blue and the Power output to the grid, in red, in kW.

(b) State of charge over time. Showing the electricity supply, yellow, and output, light blue, and ESS size (15 MWh), dark blue, all in kWh. State of charge of the ideal system in red and the SOC of the ESS with low MDOD in light blue. Also the upper and lower SOC limits are plotted

Figure 34: Power output and ESS behavior for a 15 MWh ESS, five days in June.
Influence of low maximum depth of discharge.



(a) Power output over time. Supply of the PV park, in yellow, Cable capacity, in blue and the Power output to the grid, in red, in kW.

(b) State of charge over time. Showing the electricity supply, yellow, and output, light blue, and ESS size (15 MWh), dark blue, all in kWh. State of charge of the ideal system in red and the SOC of the ESS with high self-discharge in light blue.

Figure 35: Power output and ESS behavior for a 15 MWh ESS, five days in June.
Influence of low self-discharge

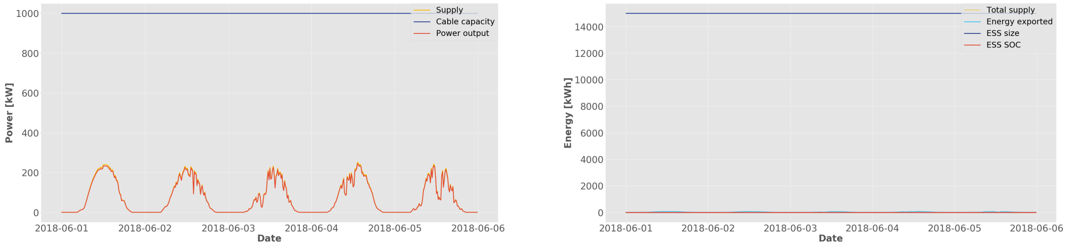
4.3.2 Supply

The influence of supply data should also be significant. So for this part of the sensitivity analysis the PV solar park capacity will be varied between 300 kWp and 10 MWp. Furthermore, decentralized renewable energy generation can also be wind energy, so the effect on the simulation model of a wind farm instead of a PV solar park is also examined. A more extensive investigation of the influence of the type and size of the generation system will be executed in section 5.2, so this only contains the effect on the energy output and ESS behavior for five days in the summer. The other model parameters are the same as in Case 1.

300 kWp and 10 MWp PV solar park

When the PV park is smaller than 1 MWp the ESS should be charging as the cable will be able to handle the power output of the PV park. For the 10 MWp PV park, with a maximum power output of 8400 kW, the ESS is not able to store everything produced over the 1 MW in a day. The outputs for a 300 kW PV solar park as illustrated in fig. 36 and the outputs of the 10 MW PV park in fig. 37. The 5 MWp PV solar park of the standard storage case had an more moderate output figs. 27 and 28.

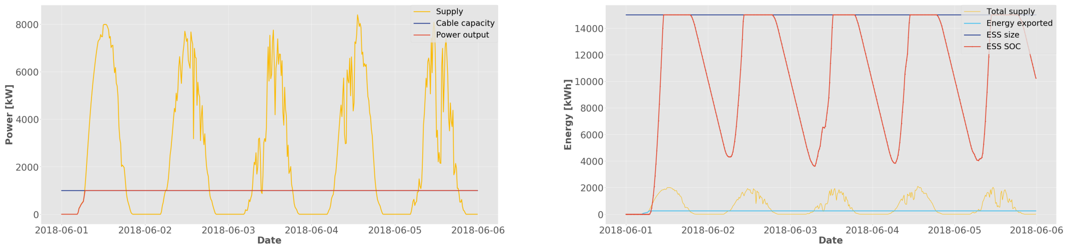
A smaller power supply has a negative on the power output of the entire hybrid system and the maximum state of charge of the storage system. A larger power supply has a positive on the power output of the system and the maximum state of charge is reached more often. This is expected, so the model simulates this correctly.



(a) Power output over time. Supply of the PV park, in yellow, Cable capacity, in blue and the Power output to the grid, in red, in kW.

(b) State of charge over time. Showing the electricity supply, yellow, and output, light blue, ESS size (15 MWh), dark blue, and State of charge in red, all in kWh.

Figure 36: Power output and ESS behavior for a 15 MWh ESS, five days in June.
Small PV solar energy generation park, 300 kWp.



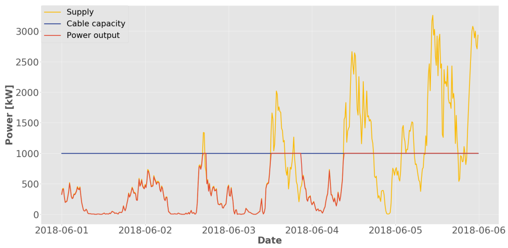
(a) Power output over time. Supply of the PV park, in yellow, Cable capacity, in blue and the Power output to the grid, in red, in kW.

(b) State of charge over time. Showing the electricity supply, yellow, and output, light blue, ESS size (15 MWh), dark blue, and State of charge in red, all in kWh.

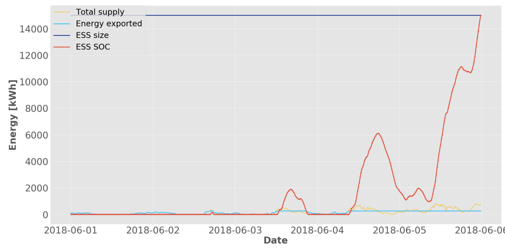
Figure 37: Power output and ESS behavior for a 15 MWh ESS, five days in June.
Large PV solar energy generation park, 10 MWp.

5 MW Wind farm

The wind farm profile looks very different from the solar energy park profile as shown in section 3.1. Wind energy does have a diurnal cycle, but this is a lot less consistent than with solar energy where of course no energy is produced at night. However, the computations should differ. The results, shown in fig. 38, are as anticipated, storing energy when the power output of the wind farm exceeds the cable capacity. So the model simulates this correctly.



(a) Power output over time. Supply of the PV park, in yellow, Cable capacity, in blue and the Power output to the grid, in red, in kW.



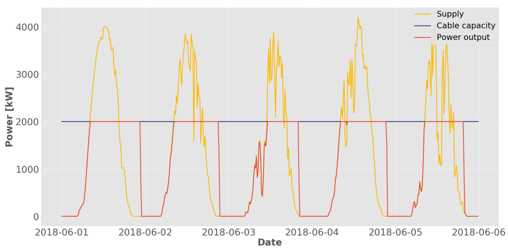
(b) State of charge over time. Showing the electricity supply, yellow, and output, light blue, ESS size (15 MWh), dark blue, and State of charge in red, all in kWh.

Figure 38: Power output and ESS behavior for a 15 MWh ESS, five days in June.
5 MW wind energy park.

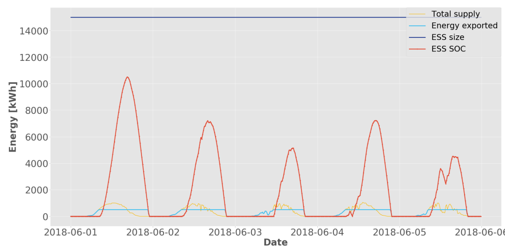
4.3.3 Cable capacity

The cable capacity is an important parameter in this model. It dictates how much energy at once can be exported to the grid. For this part the will be two systems compared to the standard storage case (5MWp PV & 1 MW cable):
- 5 MWp PV park with a 2 MW connection cable.
- 5 MWp PV park with a 5 MW cable.

It is expected that the system with the 2 MW connection cable is less dependent on the energy storage system and the 5 MW cable system not at all, as all the energy can be exported without supply curtailment. The outputs for both the 2 MW CC, shown in figs. 39 and 40, are calculated for the same five days in June. In comparison with figs. 27 and 28 the base load of the system with a cable capacity of 2 MW is a lot higher resulting in a SOC much lower, fig. 39. In the system with a cable capacity of 5 MW all the energy is exported without the help of the storage system, so the SOC stays zero.



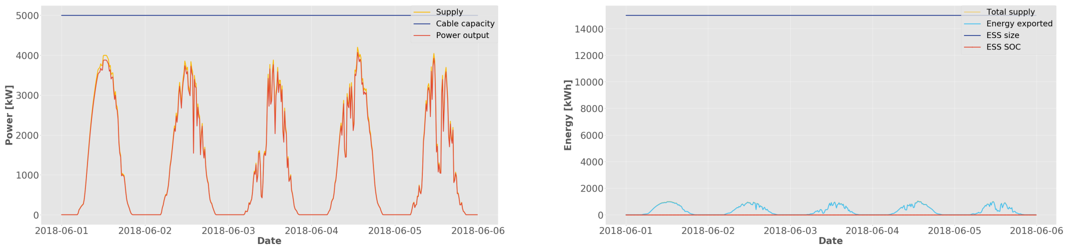
(a) Power output over time. Supply of the PV park, in yellow, Cable capacity, in blue and the Power output to the grid, in red, in kW.



(b) State of charge over time. Showing the electricity supply, yellow, and output, light blue, ESS size (15 MWh), dark blue, and State of charge in red, all in kWh.

Figure 39: Power output and ESS behavior for a 15 MWh ESS, five days in June.
2 MW connection cable instead of 1 MW cable

A higher cable capacity also results in less ESS cycles, because less stress is put on the storage system. The maximum number of cycles in the standard storage case, fig. 29, was reached with 1 MWh ESS, 312 cycles. With a 2 MW cable capacity this is reduced to 285 cycles. For the 15 MWh Ideal ESS this reduction is even more significant, 150 cycles for the standard Case 1 and 65 cycles for the system with the 2 MW



(a) Power output over time. Supply of the PV park, in yellow, Cable capacity, in blue and the Power output to the grid, in red, in kW.

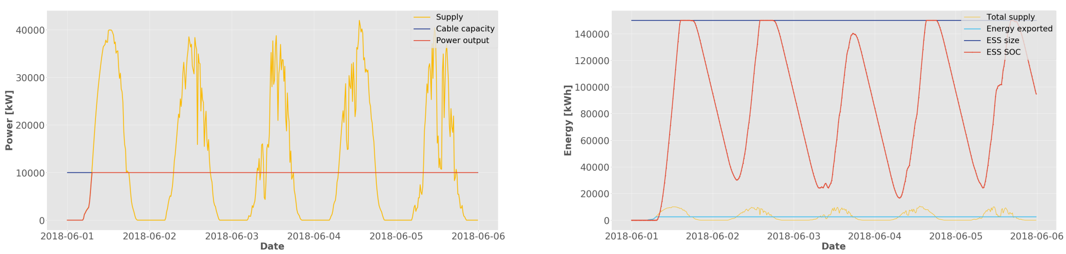
(b) State of charge over time. Showing the electricity supply, yellow, and output, light blue, ESS size (15 MWh), dark blue, and State of charge in red, all in kWh.

Figure 40: Power output and ESS behavior for a 15 MWh ESS, five days in June.
5 MW connection cable instead of 1 MW cable

connection cable.
A higher cable capacity results in a higher power output of the hybrid system and a lower maximum state of charge of the storage system. This is expected, so the model simulates this correctly.

4.3.4 Scalability

To investigate the scalability of the model a simple comparison is done between the results of Case 1 and the same case but with a hybrid system ten times larger. This system with a PV park of 50 MWp and a cable capacity of 10 MW is evaluated with a ESS system from 0 to 150 MWh. The outputs are shown in figs. 41a and 41b. The power output and state of charge for five days in summer are really similar to the Case 1. The exported amount of energy and the generated revenue also scale with a factor of ten. The proportional revenue gain is also equal to 77%. So now it is known that the model is scalable, the model can be applicable to other situations for which the same boundary conditions apply. In other words, the results of a 5 MWp hybrid PV solar system with a 1 MW connection are scalable to a 10 MWp PV park with a 2 MW connection.



(a) Power output over time. Supply of the PV park, in yellow, Cable capacity, in blue and the Power output to the grid, in red, in kW.

(b) State of charge over time. Showing the electricity supply, yellow, and output, light blue, and ESS size (150 MWh), dark blue, and state of charge, red, in kWh.

Figure 41: Power output and ESS behavior for an Ideal ESS, five days in June.
Scalability analysis. 50 MWp PV solar park, 10 MW cable capacity, 150 MWh ESS

4.3.5 Electricity price

In Case 1 the electricity price was set at the mean 2018 day ahead market price, however, the mean DAM price might differ from year to year. The influence of the electricity price is thus interesting to investigate. The potential of the electricity price will be tested for three different fixed DAM prices and the dynamic DAM price. All the other parameters will equal to Case 1. Electricity prices:
- The mean DAM price = 0.0525 €/kWh
- The minimum DAM price = 0.0006 €/kWh
- The maximum DAM price = 0.175 €/kWh
- Dynamic DAM price.

The results are depicted in fig. 42. The maximum DAM price is 3.3 times higher than the mean DAM price, so it is expected that the revenue is also 3.3 times higher. This is the case. This also so for the minimum DAM price, which is about 1% of the mean price. The relative revenue gain from the addition of the ESS is, also as expected, proportional when the minimum- or maximum DAM price is used, 77% from 0 MWh to 15 MWh. It is important to know that when the power output and electricity price are known a good estimate of the revenue can be made. Also when different electricity tariffs apply, like with households or subsidised projects.
The dynamic/realistic DAM price has different results from the fixed mean DAM price. The fixed price gives a fairly accurate prediction as it maximally differs about 5% from the dynamic DAM price, revenue. From this point on the dynamic DAM price, as discussed in section 3.4, will be used in the computations.
A higher electricity price has a positive effect on the revenue of the energy output of the hybrid system. Also, the resultant revenue of a fixed electricity price is scalable to the resultant revenue of an other fixed prices, but a dynamic electricity price gives different results. This is expected, so the model simulates this correctly.

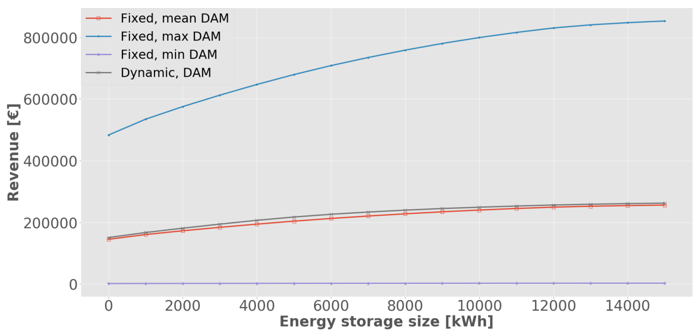


Figure 42: Revenue, as a function of the ESS size. The top line is the revenue with a fixed electricity price, maximum DAM price. Bottom line fixed minimum DAM price. The middle two the fixed mean DAM price and a dynamic DAM price.

4.3.6 Interest rate

The interest rate has a great effect on the annualized cost. Who owns the ESS is therefor very important. An commercial developer has to calculate a higher interest rate than a DSO. As the moment it is not possible

for a DSO to store energy, it can only distribute energy. But in the future this might change, so this becomes interesting. The annualized cost calculated with different interest rates, **5%, 6%, 10% and 15%**, is shown in fig. 43. The 15 MWh ESS system with a interest rate of 6% is 14% more expensive than with an rate of 5%. With an interest rate of 10% and 15% the system is 75% and 250% more expensive respectively.
A higher interest rate results in a higher annualized cost. This is expected, so the model simulates this correctly.

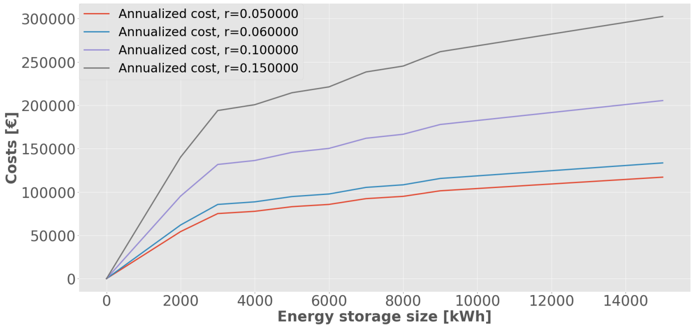


Figure 43: Annualized cost as a function of the ESS size. With different interest rates, 5%, 6%, 10% and 15%.

4.3.7 Charging and discharging strategies

In this part the effects of the different charging strategies will be discussed. As not all charging and discharging strategy combinations can be shown, only some will be highlighted to see how they affect the ESS behavior. No conclusions will be drawn as this will be done in the following chapters.
The model parameters described in Case 1 will be utilized again apart from the charge and discharge strategies of course. Additionally for trading a dynamic electricity price is needed, so the dynamic DAM price is used. Two different operation strategies are compared:
1^{st} strategy:

- Charge ESS with energy from supply when electricity price is not favorable
- Discharge ESS when price is favorable

2^{nd} strategy:

- Charge ESS with energy from the grid when price is favorable & there is no supply
- Discharge ESS when price is favorable & there is no supply

The 1^{st} operating strategy corresponds with charging strategy 3 and discharging strategy 3 from table 9. The 2^{nd} strategy corresponds with charging strategy 4 and discharging strategy 4.
For both it is necessary to define sell and buy price points to define when the electricity price is considered (un)favorable. These will be highlighted more in the next section, but for now they are arbitrarily chosen at $Price_{buy}$ = 0.05 €/kWh and $Price_{sell}$ = 0.06 €/kWh. In fig. 44 the variable DAM price over a time period of five days is depicted.
Note, as discussed in section 3.4, the storage system is also charged when the power supply exceeds the cable capacity.

1^{st} strategy

The two extra horizontal lines represent the buy and sell price points. In fig. 45a the power output of the system is shown. The first part of the first power supply peak is charged directly to the ESS, as also visible in fig. 45b. This is because the electricity price is not favorable. The power output is maximum at 1 MW at two moments: when the PV park is still producing energy, but the ESS is already fully charged (discharge strategy 2) and when the ESS is able to discharge when the electricity price is favorable (discharge strategy 3). The three figures, fig. 45 are situated underneath each other so the time periods coincide and influence on each other can be observed more clearly.

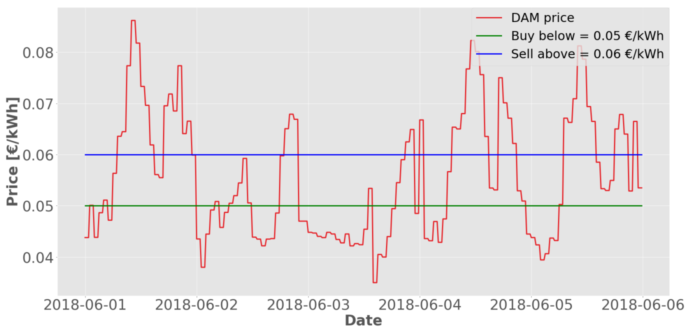
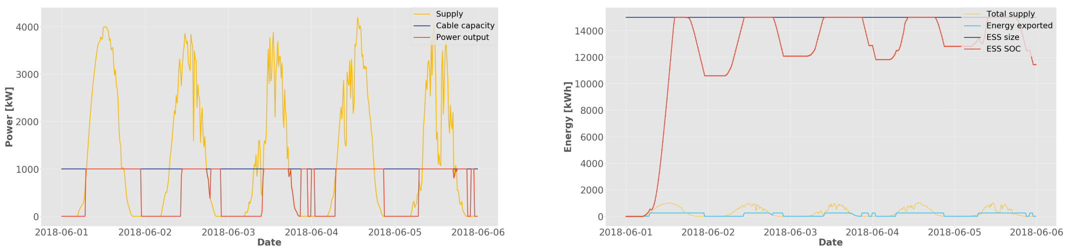


Figure 44: Day ahead market price over time, with buy/sell price points plotted.
Price_{buy} = 0.05 €/kWh in green and Price_{sell} = 0.06 €/kWh in blue.



(a) Power output over time. Supply of the PV park, in yellow, Cable capacity, in blue and the Power output to the grid, in red, in kW.

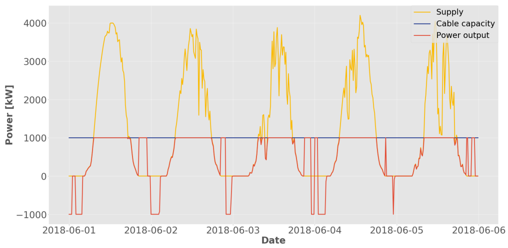
(b) State of charge over time. Showing the electricity supply, yellow, and output, light blue, and ESS size (15 MWh), dark blue, and state of charge, red, in kWh.

Figure 45: Power output and ESS behavior for a 15 MWh Ideal ESS, five days in June.
1^{st} strategy: Charge ESS with energy from supply when electricity price is not favorable. Discharge ESS when price is favorable.

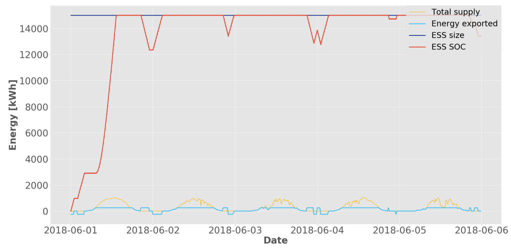
2^{nd} strategy

The results are placed underneath each other, fig. 46. At the start of the time period the electricity price is low, so some electricity is purchased from the grid and stored in the ESS. With daylight the power output is limited at the cable capacity, not all energy produced by the PV park is stored in the ESS as it was already partly filled at the start. Some electricity is exported after sunset when the electricity price is favorable, and so on.

Comparison



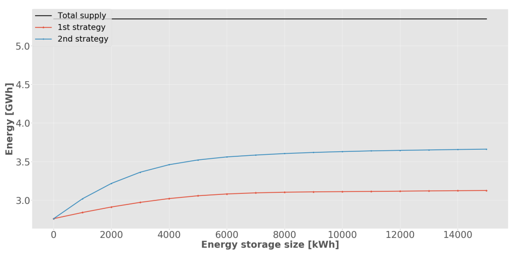
(a) Power output over time. Supply of the PV park, in yellow, Cable capacity, in blue, and the Power output to the grid, in red, in kW. Positive for export and negative for import.



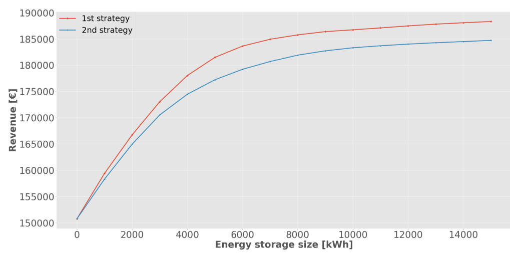
(b) State of charge over time. Showing the electricity supply, yellow, and output, light blue, and ESS size (15 MWh), dark blue, and state of charge, red, in kWh.

Figure 46: Power output and ESS behavior for a 15 MWh Ideal ESS, five days in June.
2nd strategy: Charge ESS with energy from the grid when price is favorable & there is no supply. Discharge ESS when price is favorable & there is no supply

Comparing figs. 45b and 46b it is noticeable that the ESS is less utilized with the 2nd strategy as there are not as many moments when the ESS is able to discharge as there are with the 1st strategy. So the storage system stays full more often. Still more energy is exported with the 2nd strategy over the time period. This is illustrated in fig. 47a. The total energy output as a function of the ESS are plotted for both operating strategies. The 2nd strategy exports more energy over a year's time than the 1st strategy. However, more revenue is generated when the 1st strategy is implemented, fig. 47b. The system is able to export more energy as it also imports energy, although it does have to pay for the imported energy, so less revenue is cumulated. It is interesting that it is possible to generate more revenue with less energy depending on the trading strategy. More storage operating strategies are examined in section 6.
The ESS charges and discharges when expected, for both operating strategies. This results in different total energy outputs and revenues. This is expected, so the model simulates this correctly.



(a) Energy output of a year as a function of the ESS size. 1st strategy in red and 2nd strategy in blue.

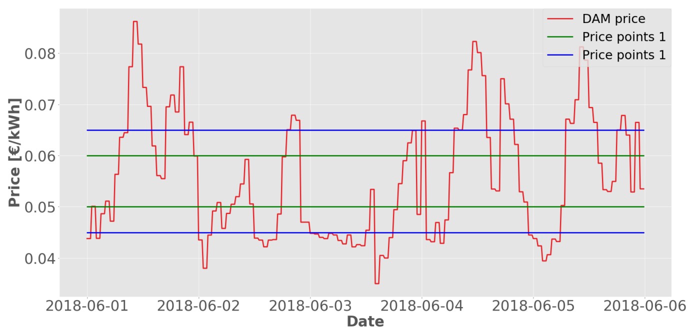


(b) Revenue of a year as a function of the ESS size. 1st in red and 2nd in blue.

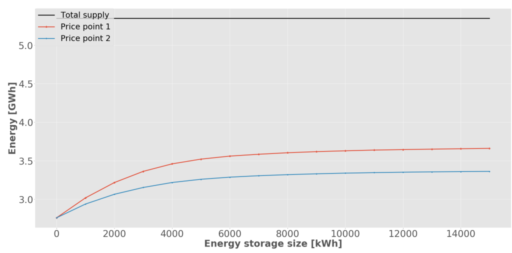
Figure 47: Energy output and revenue comparison between two operating strategies.
1st strategy: Charge ESS with energy from supply when electricity price is not favorable. Discharge ESS when price is favorable.
2nd strategy: Charge ESS with energy from the grid when price is favorable & there is no supply. Discharge ESS when price is favorable & there is no supply

4.3.8 Buy/sell price

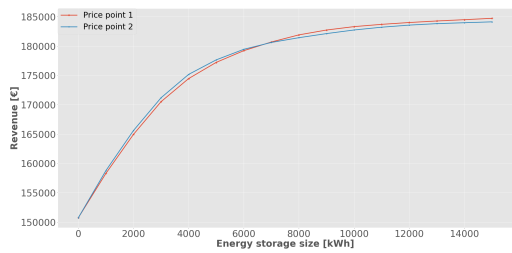
The selection of a good sell and buy price point is important for the maximization of the revenue, although, as stated in section 3.4, it is not the goal of this thesis to determine the optimum price points. Good, fixed price points will be estimated for these strategies to still get a good insight of the possibilities of electricity trading with an ESS aided DG system. A dynamic buy/sell price point will be outside the scope of this study. In this analysis part the influence of the buy/sell price point on the results are discussed. The 2nd operating strategy from the previous sensitivity analysis section, Charging and discharging strategies, is implemented. Two buy/sell price points are compared:
Price points 1: Price_{buy} = 0.05 €/kWh, Price_{sell} = 0.06 €/kWh.
Price points 2: Price_{buy} = 0.045 €/kWh, Price_{sell} = 0.065 €/kWh.
In fig. 48a the price points are shown over the DAM price for five days in June. Price points 1 are colored green and Price points 2 blue.
The energy outputs of the computations with the two price points are depicted in fig. 48b. When price points 1 are implemented more energy is exported. This is because the buy and sell range are larger than for price points 2. However, the revenues are comparable because 1 cent more profit is attained per kWh with price points 2.
A lower buy price point results in more energy being bought from the grid. A higher sell point does not ensure a higher revenue.



(a) Day ahead market price in red, five days in June.
Price points 1 in green and Price points 2 in blue. The Bottom two horizontal lines represents the buy price points and top two horizontal lines the sell price points.



(b) Energy output of a year as a function of the ESS size.
Price points 1 in red and Price points 2 in blue.



(c) Revenue of a year as a function of the ESS size.
Price points 1 in red and Price points 2 in blue.

Figure 48: Energy output and revenue comparison between two buy/sell price points. Price points 1: Price_{buy} = 0.05 €/kWh, Price_{sell} = 0.06 €/kWh. Points 2: Price_{buy} = 0.045 €/kWh, Price_{sell} = 0.065 €/kWh.

Summary

In the literature it was found that energy storage can add value to a generation system. In this chapter this was also concluded for a hybrid system with cable capacity limitations. The system had a higher energy output and revenue with the addition of a storage system. The most profitable system was, however, one without storage, because cost of the storage system was higher than the extra revenue that was generated.

The model described in section 3.4 is also verified in this section and there are fortunately no abnormalities found in the outcomes of the system. Additionally it is now known what effects the different parameters had on the systems' behavior and output:

- Lower cycle efficiency: lower power output and less amount of energy stored.
- Lower MDOD: lower power output and less amount of energy stored.
- Higher self-discharge: lower power output and less amount of energy stored.
- Smaller power supply: lower power output and less amount of energy stored.
- Larger power supply: higher power output and more amount of energy stored.
- Larger connection capacity: higher power output and less amount of energy stored.
- Different scale, but same supply and cable proportion: similar results.
- Higher electricity price: higher revenue
- Fixed electricity prices were scalable, dynamic electricity price showed different results
- Higher interest rate: higher annualized cost
- The charging and discharging strategies work as designed
- Lower buy price point: more energy being bought from the grid.
- Higher sell price point: did not yield a higher revenue

So with full confidence this model can be used to find the optimum ESS size for different storage applications for various decentralized renewable energy generation systems.

5 Hybrid system results and analysis

In this section the hybrid system consisting of the generation and storage system will be examined. In the previous section the model was validated and the sensitivity of some model parameters was analyzed. It was clear that the type and size of the generation system, the ESS system and the cable capacity greatly influence the ESS behavior and power output. So in this section first the different ESS technologies will be compared and secondly the influence of the generation system on the profitability of the total system will be investigated and thirdly the connection to the external grid will be discussed.

5.1 Energy storage technologies

In this section the different energy storage technologies will be compared for a single case, to see which systems is the most profitable. All the storage technologies that are included in this model are listed below:

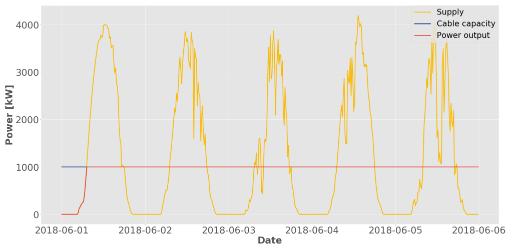
- Ideal energy storage system (Ideal)
- Battery systems (BESS)
  - Lead-acid (LA)
  - Li-ion NMC
  - Li-ion LFP
  - Sodium-Sulfur (NaS)
  - Sodium-Nickel-Chlorine (NaNiCl)
- Flow batteries (FBESS)
  - VRB
  - ZnBr
- Flywheel (FES)
- Thermal energy storage (TES)
  - PHES
  - LAES
- Hydrogen fuel cell system (HFCS)

The ESS characteristics have a large influence on the results of the computations, as discussed in section 4.3. Until now only the Ideal energy storage system, which does not have any efficiency losses, a maximum depth of discharge or self-discharge, is examined in the storage cases. However, in reality storage technologies do have these losses. Additionally, the Ideal ESS has a very long lifetime and cycle lifetime. These are also unrealistic. So it is essential to see how these real storage technologies compare to the Ideal ESS and each other. The model parameters are listed in table 14.

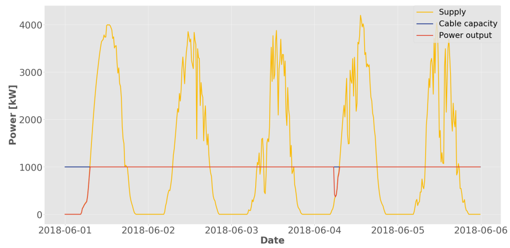
Table 14: Model parameters ESS technology comparison, *decision variable

Parameter	Unit	Value
ESS size*	MWh	0 - 15
PV solar capacity	MWp	5
Cable capacity	MW	1
Dynamic DAM price	€/kWh	-
Transformer efficiency	-	0.97
Interest rate	-	0.06
Charging strategy	Charge from supply when limited by cable capacity	
Discharging strategy	Discharge when cable capacity allows	

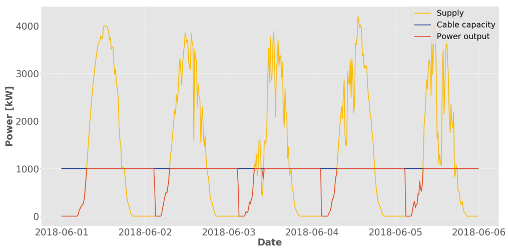
First of all, the power output and ESS behavior for a 15 MWh ESS for five days in June will be evaluated. In fig. 49 the power output of the hybrid system with an Ideal ESS, a LFP Li-ion battery, Lead-acid battery and a Flywheel ESS are illustrated, as an example for all technologies. Thus fig. 50 illustrates the state of charge of the Ideal ESS, a LFP Li-ion battery, Lead-acid battery and a Flywheel ESS corresponding with the images in fig. 49. The figures representing the battery systems also plot the maximum depth of discharge limits.



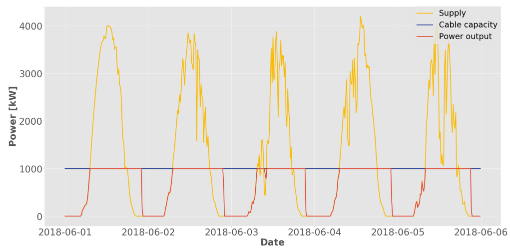
(a) Ideal ESS. Power output over time. Supply of the PV park, in yellow, Cable capacity, in blue and the Power output to the grid, in red, in kW.



(b) LFP Li-ion BESS. Power output over time. Supply of the PV park, in yellow, Cable capacity, in blue and the Power output to the grid, in red, in kW.



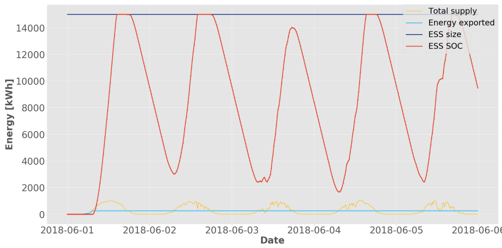
(c) Lead-acid BESS. Power output over time. Supply of the PV park, in yellow, Cable capacity, in blue and the Power output to the grid, in red, in kW.



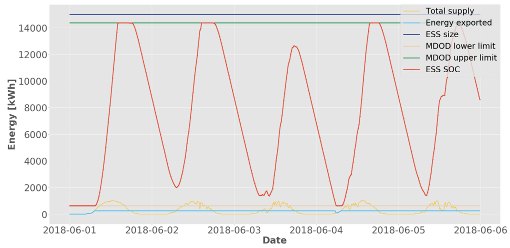
(d) Flywheel ESS. Power output over time. Supply of the PV park, in yellow, Cable capacity, in blue and the Power output to the grid, in red, in kW.

Figure 49: Power output for a 15 MWh ESS, five days in June.
Comparison between an Ideal ESS, LFP Li-ion BESS, Lead-acid BESS and Flywheel ESS.

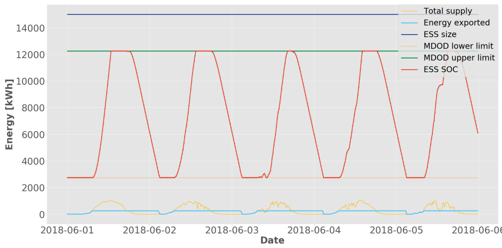
Secondly, the energy output and revenue results of the computations are shown. In fig. 51 all the storage technologies are compared with their energy output, as a function of the ESS size, resulting from simula-



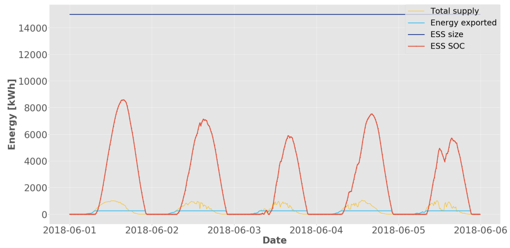
(a) Ideal ESS.
State of charge over time. Showing the electricity supply, yellow, and output, light blue, ESS size (15 MWh), dark blue, and State of charge in red, all in kWh.



(b) LFP Li-ion BESS.
State of charge over time. Showing the electricity supply, yellow, and output, light blue, ESS size (15 MWh), dark blue, and State of charge in red, all in kWh. Also the upper and lower SOC limits are plotted.



(c) Lead-acid BESS.
State of charge over time. Showing the electricity supply, yellow, and output, light blue, ESS size (15 MWh), dark blue, and State of charge in red, all in kWh. Also the upper and lower SOC limits are plotted.



(d) Flywheel ESS.
State of charge over time. Showing the electricity supply, yellow, and output, light blue, ESS size (15 MWh), dark blue, and State of charge in red, all in kWh.

Figure 50: ESS behavior for a 15 MWh ESS, five days in June.
Comparison between an Ideal ESS, LFP Li-ion BESS, Lead-acid BESS and Flywheel ESS.

tions of a whole year. The revenue curve follows the same trend.
The ideal system has the best performance. The second best are both Li-ion batteries. The FES system is by far the worst system. The lead-acid has a noticeably different curve. Because it has a low depth of discharge it has a relatively slow start. However, it has a good cycle efficiency, which compensates for the bad performance of the low MDOD when the ESS size increases. The energy output gain and revenue gain of the different storage technologies are also shown in table 15. Sometimes the energy output gain is higher than the revenue gain and vice versa. This has likely the same reason as that the revenue gain is not equal to the energy output gain in general, as first seen in section 4.3. With a fixed electricity price these gains are equal, but due to the variation in price the revenue gain turns out lower than the energy output gain. This can also go the other way, where the revenue gain is larger.

All technologies become less profitable with the increase of the ESS size. It can thus be concluded the system costs grow faster than the revenue is increased. All except the Ideal ESS eventually become unprofitable. The flywheel-, hydrogen- and both flow battery systems are especially unprofitable due to their high CAPEX and in the case of the FES and HFCS, bad performance.
In fig. 52 the yearly profit of all technologies, except the four mentioned before, are shown. The PHES is the least unprofitable real storage technology. This is the case despite that it is one of the most poorly performing technologies with an revenue increase of only 39%. It was already concluded in section 4, but

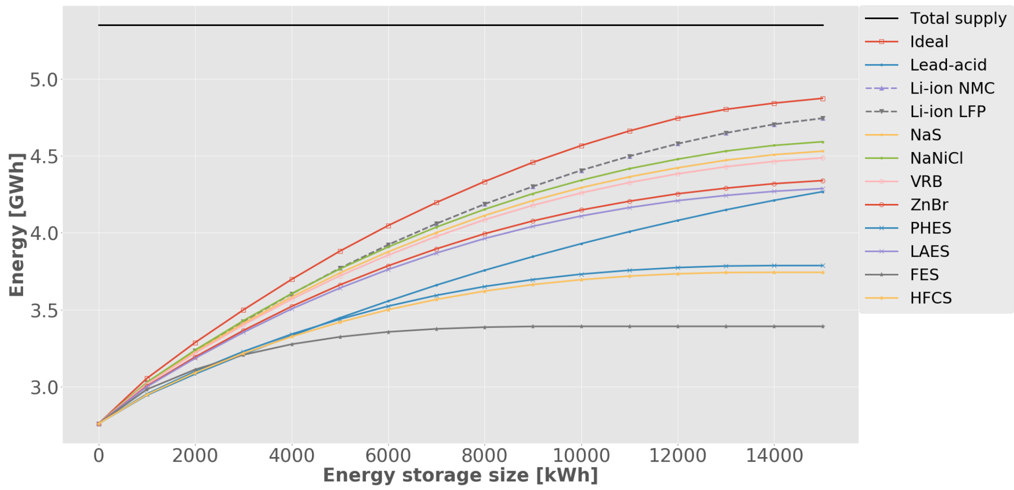


Figure 51: Energy output as a function of the ESS size. A comparison of all technologies.
Ideal ESS in red with square markers. Lead-acid in blue with dot markers. Both Li-ion batteries with the dotted lines and triangle markers, similar results. High temperature batteries, NaS and NaNiCl, in yellow and orange with dot markers. Flow batteries with circle markers. Thermal energy storage systems with x markers. Flywheel and HFCS with star markers.

Table 15: ESS technologies compared based on relative energy output gain and revenue gain, from 0 MWh ESS to 15 MWh ESS

Technology	**Energy output gain** [%]	**Revenue gain** [%]
Ideal	77	74
Lead-acid	55	56
Li-ion NMC	72	70
Li-ion LFP	72	70
NaS	64	63
NaNiCl	66	65
VRB	63	62
ZnBr	57	57
FES	23	25
PHES	37	39
LAES	55	55
HFCS	36	37

again it is clear that the capital cost of the ESS is a big factor in the profitability of the system. The LAES is second least unprofitable system. This is partly because it has a very long lifetime, far longer than any other real storage system. So the annualized costs of the LAES are one of the lowest of all the technologies. A detailed table with the energy output, revenue, costs and profit of all storage technologies at 15 MWh can be seen in table 16.

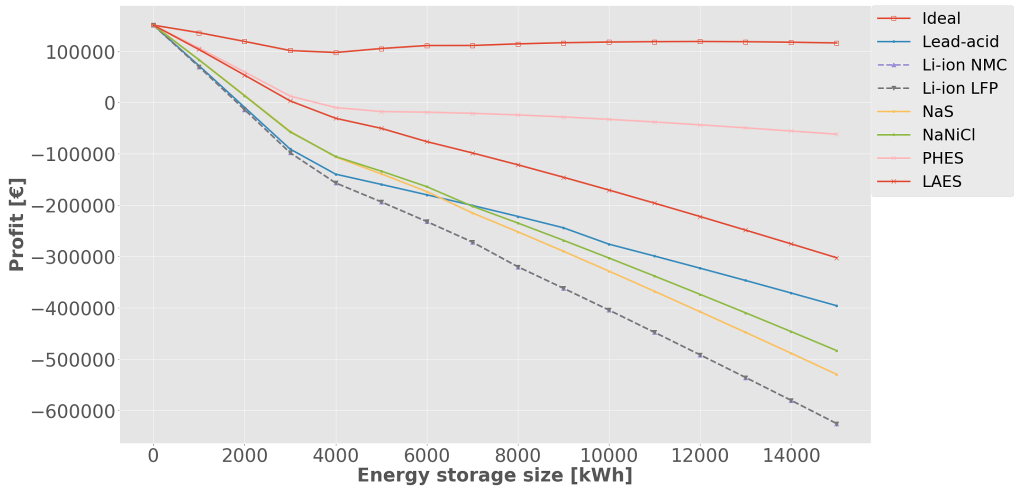


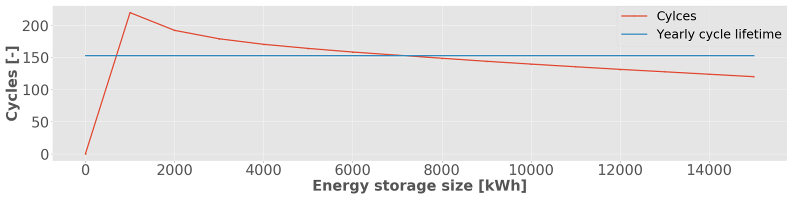
Figure 52: Profit as a function of the ESS size. A comparison of all technologies, except for VRB, ZnBr, FES and HFCS.
Ideal ESS in red with square markers. Lead-acid in blue with star markers. Both Li-ion batteries with the dotted lines and triangle markers, similar results. High temperature batteries, NaS and NaNiCl, in yellow and orange with dot markers. Thermal energy storage systems with x markers.

Table 16: ESS technologies compared based on energy output, revenue gain, annualized costs and profit at a size of 15 MWh

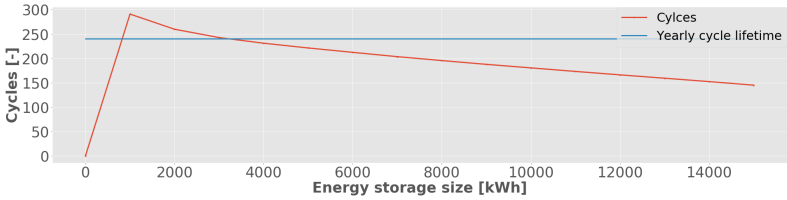
Technology	Energy output [GWh]	Revenue 10^3 [€]	Annualized costs 10^3 [€]	Profit 10^3 [€]
Ideal	4.87	262	146	116
Lead-acid	4.27	235	631	-396
Li-ion NMC	4.74	256	882	-626
Li-ion LFP	4.74	256	882	-626
NaS	4.53	246	775	-530
NaNiCl	4.59	249	732	-483
VRB	4.47	244	1,206	-963
ZnBr	4.34	236	1,884	-1,647
FES	3.39	188	4,547	-4,359
PHES	3.79	209	270	-62
LAES	4.29	234	536	-303
HFCS	3.74	207	2,787	-2,580

Based on this some ESS technologies will be discussed more thoroughly. The Ideal ESS is good to keep in reference as a benchmark. The three least unprofitable systems, the PHES and LAES thermal energy storage systems and the Lead-acid battery. The Li-ion batteries had the best performance of all the ESS technologies.
So these ESS technologies are considered the best storage systems for aiding decentralized generation systems. However, some more consideration is needed. For instance, the cycle lifetime of the Lead-acid

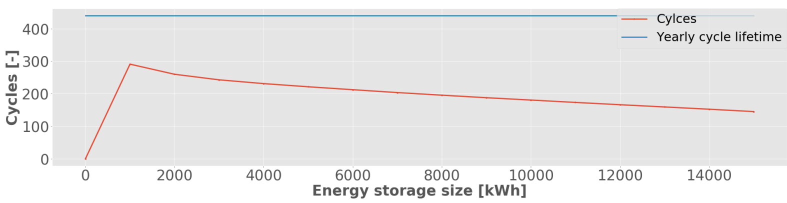
battery is remarkably low. When examined as done in section 4.2, the cycle lifetime is not sufficient for smaller ESS sizes. Illustrated in fig. 53a. The yearly cycle lifetime of the Lead-acid battery is the total lifetime divided by its lifetime in years, about 153 cycles. However, at 1 to 7 MWh this amount is exceeded. So its lifetime would become shorter than the expected 9 years. Subsequently, there are several small differences between the NMC and LFP Li-ion batteries, one of which is the cycle lifetime. The cycle lifetime of the LFP battery is almost twice as much as the cycle lifetime of the NMC battery. Thus the yearly maximum allowable cycles for the LFP and NMC are 440 and 240 respectively. The number of cycles occurring in operation of a year is plotted in fig. 53b for the NMC and fig. 53c for the LFP battery. Until 3 MWh the yearly cycle lifetime is exceeded in the NMC battery. Of the three battery systems discussed, the LFP Li-ion battery system will still be in consideration for DG systems applications.
These cycle results only hold for a 5 MWp PV & 1 MW cable system, however, with a larger cable capacity the ESS will be, as explored in section 4.3, less utilized. This might make a Lead-acid- or NMC BESS available again.



(a) Lead-acid battery, number of cycles and yearly cycle lifetime as a function of the ESS size.



(b) NMC Li-ion battery, number of cycles and yearly cycle lifetime as a function of the ESS size.



(c) LFP Li-ion battery, number of cycles and yearly cycle lifetime as a function of the ESS size.

Figure 53: Number of cycles and yearly cycle lifetime for three different BESS's.
The red line represents the total amount of cycles that occurred and the blue line the maximum amount of full cycles allowed in a year.

The two thermal energy storage systems have a drawback as well. They have a slow response time. This can make them ill-suited for some application that require systems to quickly ramping up and down, such as peak shaving, where it has to follow the supply within seconds. Still, for applications with response

times in the minutes like for instance trading on the DAM market where the market price is fixed for an hour, TES systems should still be considered.
So for the subsequent of the research the Ideal ESS and LFP Li-ion battery will be considered.

5.1.1 Economic feasibility of energy storage

There is still a lot of research done in the field of energy storage to improve the performance and reduce the costs. The cycle efficiency and capital costs two characteristics of the technologies that are predicted to improve considerately by 2030, as illustrated in section 2.4. This applies mostly to the battery and flow battery technologies, although the flywheel will improve in costs as well. Values for other storage technologies were unfortunately not found.
As discussed previously, the two most promising technologies are the LFP Li-ion BESS and PHES TES. Although both are only profitable for small sizes. So it was investigated how to improve the storage system to make the system profitable up to a ESS size of 15 MWh, based on improvements of CAPEX's and cycle efficiency.

Table 17: Economic feasibility of LFP Li-ion BESS and PHES TES at a size of 15 MWh.
Improvements in Cycle efficiency, $CAPEX_{ESS}$ and $CAPEX_{transformer}$ to the ESS profitable at 15 MWh.
The improved value in bold.

Technology	**Cycle efficiency** [-]	**$CAPEX_{ESS}$** [€/kWh]	**$CAPEX_{transformer}$** [€/kWh]
Current values			
Li-ion LFP	0.94	405	421
PHES	0.45	54	421
Predicted 2030 values			
Li-ion LFP	0.97	188	-
$CAPEX_{ESS}$ improvement until profitable at 15 MWh			
Li-ion LFP	0.94	**45.4**	421
PHES	0.45	**18**	421
Cycle efficiency improvement until profitable at 13 MWh*			
PHES	**1**	54	421
$CAPEX_{ESS}$ and $CAPEX_{transformer}$ improvement until profitable at 15 MWh			
Li-ion LFP	0.94	**205**	**271**
PHES	0.45	54	**273**

The results are shown in table 17. The Li-ion battery already has the highest energy output, so the most pressing characteristic is improving is the capital cost. The system can become profitable at 15 MWh, this does take, however, a lot more than the cost reduction predicted by 2030.
There is no 2030 prediction for the PHES thermal energy storage system. The capital cost of the PHES storage system is already relatively low, so the most important improvement for this system is the cycle efficiency, now only 45%. But without efficiency losses, and original costs, the system is still not profitable at 15 MWh. Only just at 13 MWh.

One important factor in the costs are the power systems costs. This was already discussed in section 4.2, where it also dictated the overall costs for an Ideal ESS. It can be seen that this too affects the profitability of the system. For the PHES system only reducing this cost is sufficient. For a hybrid system with a Li-ion LFP battery, only reducing the transformer cost would not sufficient. To be profitable at 15 MWh the energy capacity capital costs should reduce with 200 €/kWh and the power capacity capital cost with 150 €/kW.

Energy storage is still very expensive for decentralized renewable energy generation on a MV-scale. The performance and capital costs will improve by 2030, unfortunately the reduction in costs would not be sufficient for a large Li-ion battery to become profitable. Additionally improving only the cycle efficiency of a cheap storage system, like the PHES, would also not be sufficient for a large system. The transformer necessary for operating a storage system also needs to become cheaper to make an energy storage system more economically interesting.

5.2 Generation system

The generation system is very critical in the selection of the storage system. In section 4.3 the fact that the size and type of the generation system have an effect on the behavior of the ESS and the power output is clear. In this section the generation type, wind and solar energy, will be investigated on the energy output, the revenue and the profitability of a ESS system. Two notable differences between wind and solar energy are the capacity factor and the consistency of the diurnal cycle. In the Netherlands wind energy has a higher capacity factor than solar energy. Solar energy has a more consistent diurnal cycle than wind.
Four generation configurations will be compared, all with a total capacity of 5 MW, table 18. Next to solely PV sun and solely wind it is also interesting to see the influence of a generation system comprising 50%/50% of PV solar and wind. Additionally at Alliander often a 5:1 split is used for a generation mix, due to the difference in capacity factor. Model parameters are listed in table 19.

Table 18: The four generation system configurations, of all 5 MW total, compared in this section.

Type	**PV solar capacity [MW]**	**Wind capacity [MW]**	**Capacity factor [%]**	**Diurnal cycle Consistency**
Only PV sun	5	0	12.2	High
Only wind	0	5	27.4	Low
50/50	2.5	2.5	19.8	Low
5:1	4.17	0.83	14.7	High

The results are shown in fig. 54 and table 20 (the revenue curve is similar to the energy output curve). The relative energy output- and revenue gain for the 5 MWp PV park is notably larger than for the other DGs. It can be stated that energy storage is better applicable for PV solar DG's than for wind energy DG's. In section 4.3. Due to the higher capacity factor of the base result, so without storage, is higher for the wind DG than for the solar DG. However, the 50/50 system, with a lower capacity factor, has a better performance than the solely wind DG. This is so because of the complimentary nature of a sun and wind, as mentioned before (section 2.7). When it is sunny, it is often not very windy and vice versa. The energy

Table 19: Model parameters generation system comparison, *decision variable

Parameter	Unit	Value
ESS size*	MWh	0 - 15
PV solar capacity	MWp	5
Cable capacity	MW	1
Dynamic DAM price	€/kWh	-
Transformer efficiency	-	0.97
Interest rate	-	0.06
Charging strategy	Charge from supply when limited by cable capacity	
Discharging strategy	Discharge when cable capacity allows	

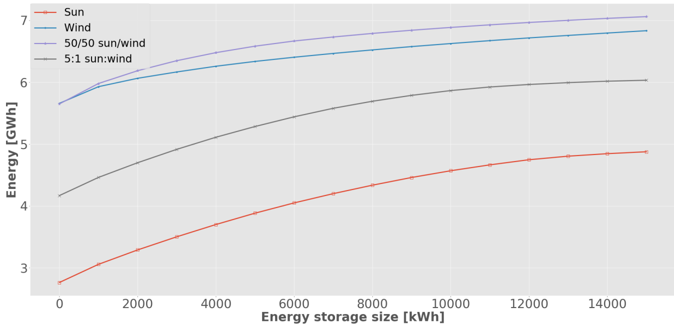
output- and revenue gain are both higher for this system than the 5 MW wind system. The profit loss is also less for this system. This is because the ESS greatly improves the PV park's diurnal power output, where the wind farm is affected less.

So for the following sections the generation system will be solely PV solar energy, as the effect of storage is the most positive.

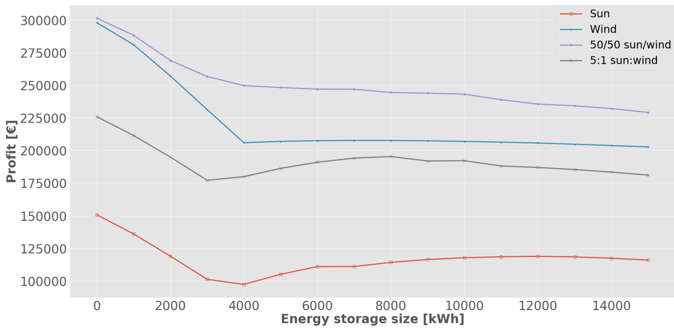
This conclusion is drawn with confidence as the difference between the PV and wind DG's is clear, but it is worth exploring with more supply data from different years so the reasoning behind it can be narrowed down. As for now it can be a function of the capacity factor or the regularity of the diurnal cycle which is more prominent in solar energy.

Table 20: 5 MW DG systems compared based on energy output, revenue gain and profit at a size of 15 MWh

DG system	Energy output			Revenue			Profit		
	[GWh]		[%]	10^3 [€]		[%]	10^3 [€]		[%]
result	0 MWh	15 MWh	gain	0 MWh	15 MWh	gain	0 MWh	15 MWh	loss
Sun	2.76	4.87	77	151	262	74	151	116	23
Wind	5.66	6.83	21	298	359	20	298	203	32
50/50	5.65	7.06	25	301	375	24	301	230	24
5:1	4.17	6.03	45	226	324	43	226	181	20



(a) Total energy supplied and exported, as a function of the ESS size. A comparison of generation systems.
x-axis: ESS size [kWh] 0 - 15,000. y-axis: Energy [GWh] 3 - 7.



(b) Profit, as a function of the ESS size. A comparison of generation systems.
x-axis: ESS size [kWh] 0 - 15,000. y-axis: Profit [€] 1e5 - 3e5.

Figure 54: Energy output, revenue and profit as a function of the ESS size. A comparison of generation systems. Results of the 5 MWp PV solar park in red with square markers. Results of the 5 MW wind farm with dot markers. Results of the 50/50 system, 2.5 MWp PV park and 2.5 MW wind farm, with the star markers. Results of the 5:1 system, 4.17 MWp PV park and 0.83 MW wind farm, with the x markers.

5.3 Connection system

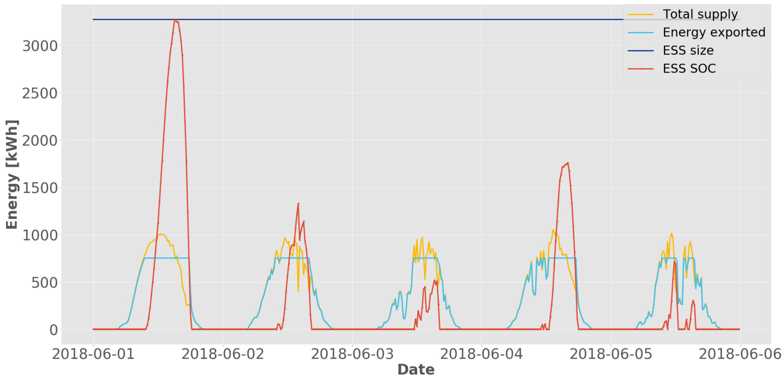
The entire hybrid system consists of three subsystems, the generation system, the storage system and the connection system. The effect on the ESS size and profitability of the first two subsystems are discussed in the previous sections. In section 4.3 the effect on the power output of increasing the cable capacity is already illustrated. In this section the cable capacity will be used to determine the appropriate size of the storage system. In the method discussed in this section, the cable capacity will be the decision variable instead of the ESS size. Furthermore, the cost of the connection system will also be included in this section, which has been neglected until now. Also for the first time the optimum will be indicated in the results because of the inclusion of the cable capacity cost the maximum profit is not always easily visible in the figures.
The model parameters are listed in table 21. So the decision variable is now the cable capacity. Where the model outputs were first the energy output, required power capacity and number of cycles, now the model output are the ESS size [kWh], the energy output and the required power capacity.

Table 21: Model parameters connection system comparison, *decision variable

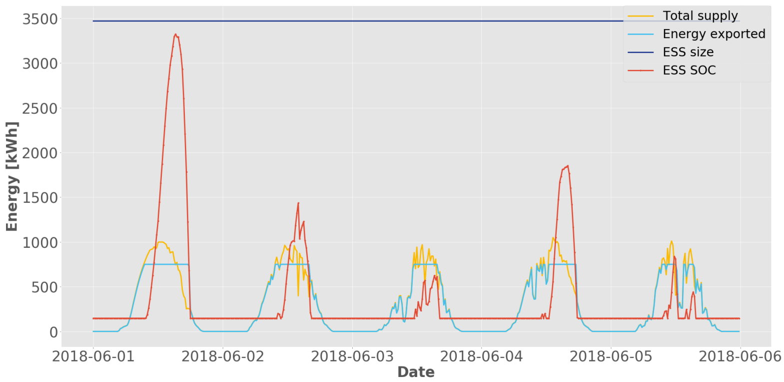
Parameter	Unit	Value
Cable capacity*	MWh	0 - 5
PV solar capacity	MWp	5
Dynamic DAM price	€/kWh	-
Cable lifetime	years	40
Cable cost coefficient	€/kW	320.5
Transformer efficiency	-	0.97
Interest rate	-	0.06
Charging strategy	Charge from supply when limited by cable capacity	
Discharging strategy	Discharge when cable capacity allows	

The determination of the ESS size is different than usual. So when the power output of the DG exceeds the cable capacity the ESS is charged. The maximum state of charge that is reached over the time period is the eventual ESS size. Two examples with a cable capacity of 3 MW are shown in fig. 55. In fig. 55a the state of charge for five days in June are shown. On the first day the SOC reaches 3.27 MWh. This is not surpassed in the following days, so this will be the size of the energy storage system for a 3 MW cable. In fig. 55b the same is calculated, but now for a LFP lithium-ion battery. Due to a lower cycle efficiency the maximum SOC is expected to be smaller than the Ideal ESS, which is true, 3.18 MWh. However, it has a MDOD lower than 1, so the plot needs to be shifted. The SOC_{UL} becomes around 3.3 MWh and the eventual ESS size is 3.47 MWh.

This example was, however, for the familiar five days in June. The results for both storage technologies for the entire year are presented below. In fig. 56a the ESS size in kWh as a function of the cable capacity is shown. The optimum ESS size is also depicted, this is set out in the paragraph discussing the profit. The size curve is exponential, meaning with the increase of the cable capacity from 1 MW to 1.5 MW the ESS size decrease is much more significant than the ESS size decrease for a 4 MW to a 4.5 MW cable capacity increase. The power capacity curve is not smooth as the ESS size curve, but has two lumps. The lumps are hard to explain. At these cable capacity and ESS size a low point in the supply, discharge rate and maximum cable capacity coincide, this made it possible for the ESS to discharge a larger amount of energy than expected (with other cable capacities). These lumps will most likely smooth out if the calculated with several supply curves from different years. In the Ideal ESS revenue curve a similar bump occurs as a large amount of discharge coincides with a low DAM electricity price. This anomaly does not occur with a fixed electricity price. So as in section 5.2 more supply and financial data from different years is recommended for further studies.
The energy output- and revenue curves follow the same trend as previous energy output and revenue results. However, they start much higher as in this section the ESS are sized to export as much as energy possible to the grid. With a 1 MW cable capacity and 73.5 MWh Ideal ESS the energy output is 94% of the total energy supply. At 5 MW cable (and 0 MWh) this is 97%. This is the effect of the transformer. The LFP energy output starts at 92% and also ends at 97%. The revenue curves are similar (with the exception of the small anomaly discussed earlier).



(a) Ideal ESS.
State of charge over time. Showing the electricity supply, yellow, and output, light blue, ESS size (15 MWh), dark blue, and State of charge of the ideal system in red, all in kWh
x-axis: Date 2018-06-01 - 2018-06-06. y-axis: Energy [kWh] 0 - 3000.

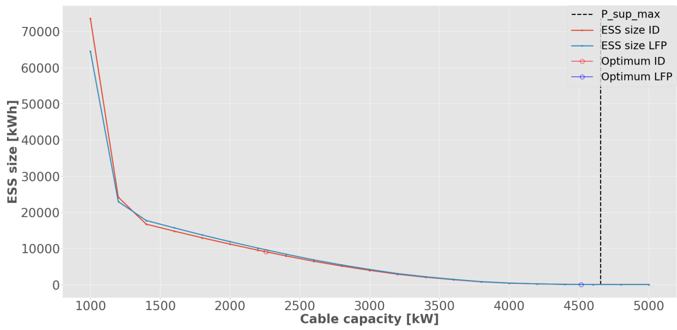


(b) LFP Li-ion BESS.
State of charge over time. Showing the electricity supply, yellow, and output, light blue, ESS size (15 MWh), dark blue, and State of charge of the ideal system in red, all in kWh. Also the upper and lower SOC limits are plotted.
x-axis: Date 2018-06-01 - 2018-06-06. y-axis: Energy [kWh] 0 - 3500.

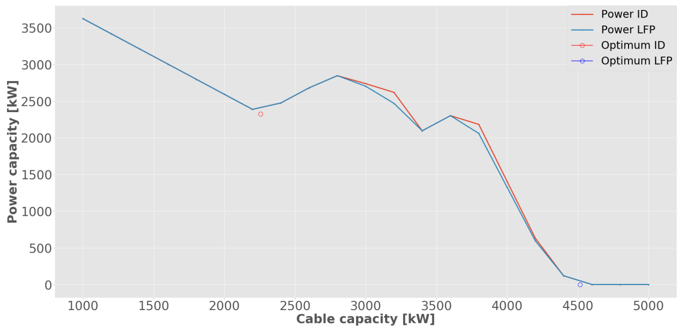
Figure 55: ESS behavior with a 3 MW cable capacity, five days in June.
Top graph with an Ideal ESS, bottom with a LFP Li-ion BESS.

In fig. 57 the total costs of the hybrid system with the Ideal ESS and the LFP BESS are depicted. The calculated optimum is marked with the circle. The lumps in the power capacity have a great effect on the costs of the Ideal system. The LFP is less effected as the energy capacity costs are relatively higher than the power system cost. But the total costs of the LFP are much larger. Notably, the optima due to the maximum profit is located at the (locally) lowest costs for both systems. This indicates that the costs are the driving factor of the profitability of the system in this simulation.

Figure 58 illustrates the profit of the Ideal ESS and a LFP BESS as a function of the cable capacity. The maximum profit, optima, are indicated for both systems as well. Due to the power system cost for the Ideal system a local optimum occurred, however, the overall optimum more resembles the LFP's maximum profit. The maximum profit is expressed as optimum ESS size, revenue and costs, as indicated in the figures shown earlier, are summarized in table 22.



(a) Storage size [kWh] as a function of the cable capacity.
A comparison between a system with an Ideal ESS and a LFP BESS.
x-axis: cable capacity [kW] 1000 - 5000. y-axis: ESS size [kWh] 0 - 70,000.

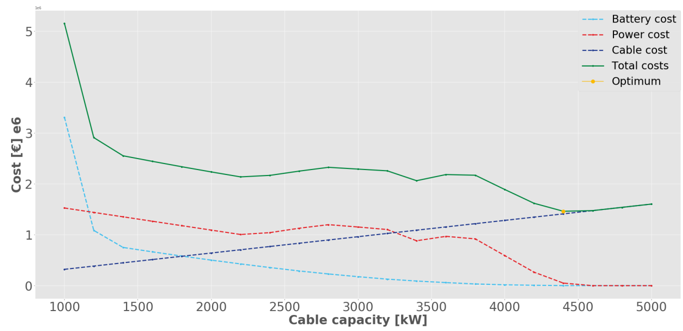


(b) ESS power capacity [kW] as a function of the cable capacity.
A comparison between a system with an Ideal ESS and a LFP BESS.
x-axis: cable capacity [kW] 1000 - 5000. y-axis: Power capacity [kW] 0 - 3500.

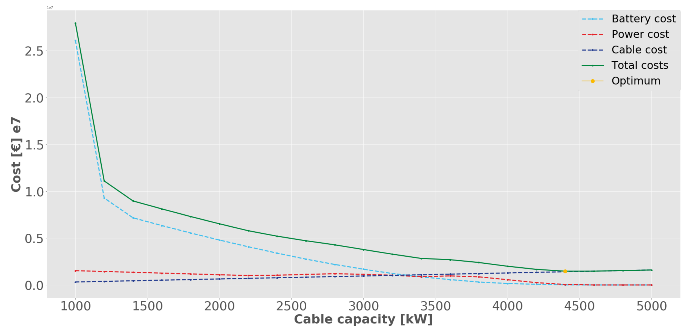
Figure 56: Storage size [kWh] and ESS power capacity [kW] as a function of the cable capacity. A comparison between a system with an Ideal ESS and a LFP BESS.
Ideal ESS in red, LFP BESS in blue. The calculated optima, also in red and blue respectively, are marked with the circles.

Table 22: Optimum ESS size for optimum profit with cable capacity as decision variable. For the Ideal system there is a local optimum which is marked in fig. 56, but there is also an overall optimum.

Optimum	**Cable capacity** [MW]	**ESS size** [MWh]	**Power capacity** [MW]	**Energy output** [GWh]
Ideal local optimum	2.26	9.01	2.33	5.15
Ideal overall optimum	4.52	0	0	5.19
LFP overall optimum	4.52	0	0	5.19
Optimum	**Revenue** 10^3 [€]	**Annualized costs** 10^3 [€]	**Profit** [10^3 €]	
Ideal local optimum	281	140	141	
Ideal overall optimum	273	96	176	
LFP overall optimum	283	96	187	



(a) Ideal ESS. System costs as a function of the cable capacity.
x-axis: cable capacity [kW] 1000 - 5000. y-axis: Cost [€] 0 - 5e6.



(b) LFP Li-ion BESS. System costs as a function of the cable capacity.
x-axis: cable capacity [kW] 1000 - 5000. y-axis: Cost [€] 0 - 2.5e7.

Figure 57: System costs as a function of the cable capacity. A comparison between a system with an Ideal ESS and a LFP BESS.
Total costs is the solid line, the light blue dashed line is the ESS cost, the red dashed line the power systems cost and the dark blue dashed line the cable cost. The calculated optimum is marked with the circle.

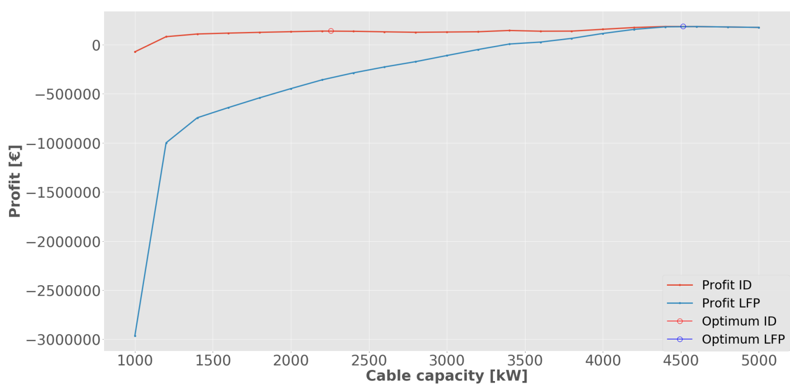


Figure 58: Profit as a function of the cable capacity. A comparison between a system with an Ideal ESS and a LFP BESS.
Ideal ESS in red and LFP in blue. The maximum profit, optima, are indicated with the circles in similar color codes.

5.3.1 Grid reinforcement or energy storage to combat cable capacity limitations

In this thesis a fixed price for the connection system is used, 320.5 €/kW. This is independent of the distance from generation system to the closest MV-substation, type of cable, type of ground and location in the Netherlands. In other words the price per power capacity is not always fixed, but can vary. With the current price grid reinforcement is always more profitable than installing energy storage to combat cable capacity limitations. However, there are situations imaginable where the cable capacity price is so expensive that energy storage is economically more interesting than grid reinforcement. For instance, constructing a cable through the Wadden Sea is a lot more expensive than it is in a rural part of the Netherlands. There are also locations where grid reinforcement is not even possible.
The value for the cable cost for when storage becomes more profitable than grid reinforcement is of course different for each storage technology. For a hybrid system with an Ideal ESS, grid reinforcement is more profitable up to cable cost of 640 €/kW. Above this value energy storage becomes more profitable than grid reinforcement. With a LFP Li-ion battery system this value is a lot higher, 1290 €/kW. There are some margins of error here, because in the calculations cable capacity increments of 1 MW were used.

5.4 Maximum useful ESS size

In section 5.1 in fig. 51 a point occurs for the FES system where the energy size is increased, but no more energy is exported. This figure is re-illustrated in fig. 59. It shows the amount of energy exported by 2 hybrid systems, both with a 5 MWp PV solar DG and 1 MW connection system. One with an Ideal ESS system and one with a FES ESS system. The point where no more energy is exported occurs at about 9000 kWh. This point marks the maximum useful flywheel energy storage system size for a hybrid system with a 5 MWp PV generation system and a 1 MW connection. For the Ideal ESS this point is not reached, so the maximum useful ESS size for this hybrid system is larger than 15 MWh. In this section the maximum useful ESS size is investigated for an Ideal system for different PV solar energy generation system sizes and cable capacities. The equation of the maximum ESS size is an addition to the simulation model, so an instruction of the maximum useful ESS size calculation is also provided.

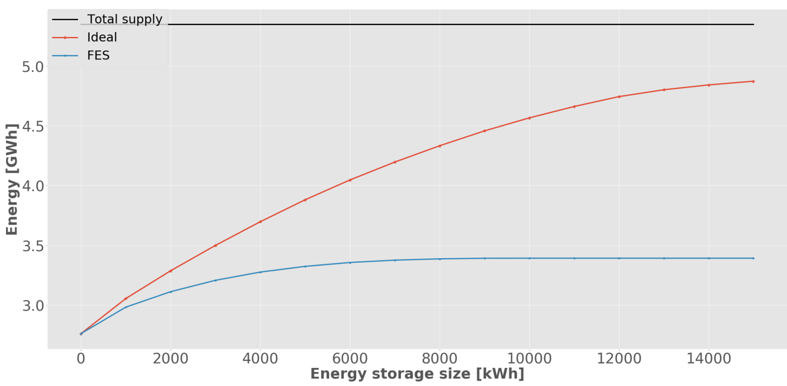


Figure 59: Total energy supplied and exported, as a function of the ESS size.
Results of the 5 MWp PV solar park and a cable capacity of 1 MW. One with an Ideal ESS, marked with stars, and the other with a FES system, marked with dots.

Table 23: Model parameters maximum useful ESS size, *decision variable

Parameter	**Unit**	**Value**
ESS size*	MWh	0 - 30
PV solar capacity	MWp	1, 2, 5, 10
Cable capacity	MW	0.5 - 10, increments of 0.5 MW
Transformer efficiency	-	0.97
Interest rate	-	0.06
Charging strategy	Charge from supply when limited by cable capacity	
Discharging strategy	Discharge when cable capacity allows	

The maximum useful ESS size for a system with a particular DG and connection size, is defined as the point where no more energy will be exported although the ESS size is increased. The maximum useful ESS size is equated by looking at the gradient of the exported energy. Where the gradient is zero, the maximum useful ESS size (MUES) is reached. The gradient is approximated between increments of 100 kWh, eq. (30).

$$MUES = ESS\ in: \tag{30}$$

$$\nabla E_{grid}(ESS) \approx \frac{E_{grid}(ESS + 100\ kWh) - E_{grid}(ESS)}{100\ kWh} = 0 \tag{31}$$

The maximum useful ESS size can be reached for three reasons. The first reason is that the cable capacity is larger than the generation size. So all the energy can be transported without the use of storage. The maximum useful ESS size for such a system is 0.
The second reason is that at a particular ESS size all the generated energy over a time period can already be exported. So the ESS size could be increased, but there is no more storage capacity needed to store the over-generated amount of energy.
The third reason is that the cable capacity limits the amount of energy that can be exported, so the ESS size can still increase and store more energy, but it cannot be exported any more.
Note that it is only calculated using the default charging and discharging strategies. For trading purposes it might be useful to over-dimensioning the ESS.

In this section the maximum useful ESS size is calculated for four PV solar DG capacities with each twenty different the cable capacities. The Ideal energy storage system will be used, as this will function as an absolute top limit for the ESS size as less efficient systems would be smaller than that. The ESS size will again be used as the decision variable with a boundary of 30 MWh. This maximum on the maximum useful ESS size is set because systems requiring storage larger than 30 MWh will not be interesting for our purposes. This will become evident later. A financial model is not included as this is purely a technical analysis. All the model parameters are summarized in table 23.

In fig. 60 the results are shown. Except for this section, the maximum boundary of the storage size in this thesis was set at 15 MWh, as discussed in section 2.4. Although it is technically useful to increase the

storage size to increase the amount of energy exported to the grid, it is not always smart to size the ESS to this maximum useful size. For example, in a 5 MWp PV and 1 MW cable hybrid system an storage size increase from 15 MWh to 30 MWh results in only 3% more energy exported, compared to 77% in the first 15 MWh.
The first reason, the cable capacity is larger than the generation size, for a maximum ESS size can be seen whenever the maximum ESS size becomes 0. The second reason, at a particular ESS size all the generated energy over a time period can already be exported, is the reason for the other maximum ESS sizes. The third reason, the cable capacity limits the amount of energy that can be exported, is unfortunately not visible in fig. 60.

When sizing an energy storage system for a particular decentralized generation system, the values in fig. 60 can be used as boundaries.

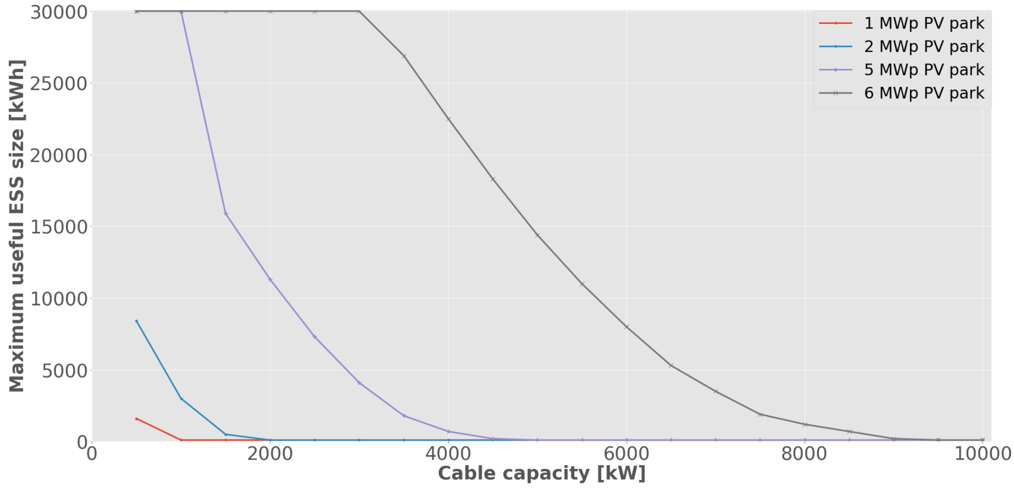


Figure 60: Maximum useful Ideal ESS size given the generation and cable capacity.
With a DG capacity of 1 MWp (red with dotted markers), 2 MWp (blue with dotted markers), 5 MWp (with star markers) and 10 MWp (with x markers).

Summary

In this section a hybrid system, with cable capacity limitations, was designed to optimally profit from a storage system.
First the best performing and most profitable energy storage system technologies were identified. A PV solar energy system with a small grid connection. The overall best energy storage system for a DG is a LFP Li-ion battery energy storage system. However, it has high capital costs. For applications which do not require fast response times a PHES thermal energy storage system is the most profitable.
It was already concluded that energy storage still is too expensive. So it was investigated when energy storage would be economically feasible for the PV solar park with small grid connection. The costs of both the energy storage system as the storage's transformer need to reduce drastically. This is more important than improving the performance of the storage technologies. It is predicted that by 2030 the capital cost of a Li-ion BESS would decrease to half of the current costs, however, with these circumstances this would

still not be sufficient.
Subsequently the type of decentralized renewable energy generation system was reviewed. Energy storage was more beneficial to the energy output and revenue for PV solar energy than for wind energy.
Additionally the connection system of the hybrid generation system was explored to determine the required energy storage size given the cable capacity. In this section the most profitable hybrid system was a system with a suitable connection and without energy storage. This was subsequently used to determine when energy storage would be economically as interesting as connection reinforcement. This depends on the storage technology of course, but seemingly there are situations where the connection system could become so expensive that a hybrid DG system with a small connection and an energy storage system would be more profitable than a hybrid system without energy storage and an adequate connection cable capacity.
Finally, the boundaries of the technical usefulness of energy storage was investigated for a given generation size and cable capacity. For a 5 MWp PV park with an Ideal ESS and a 1 MW connection system this boundary is over 30 MWh.

6 Operating strategies results and analysis

In the previous section the design of the hybrid system is discussed, this section is about the operation of the hybrid system. There are several strategies identified in section 3.4 to charge and discharge an ESS in the decentralized hybrid system. These are mentioned again in table 24. In this table also two systems are introduced. System A is the hybrid system frequently used until now, a 5 MWp PV solar park and 1 MW connection cable. System B is a hybrid system with a 5 MWp PV solar park and 5 MW cable, which has also been briefly discussed in section 4.3. So in the first system the strategies relating with transport limitations can be evaluated. In the other the potential of trading when the limitations are resolved.

Table 24: Charging- and discharging strategies and hybrid system

#	Charging strategy	#	Discharging strategy	-	System
1	No charging	1	No discharging	A	5 MWp PV & 1 MW Cable
2	From supply, limiting cable capacity	2	Cable capacity not limiting	B	5 MWp PV & 5 MW Cable
3	Supply, Price is not favorable	3	Price is favorable		
4	Grid, Price is favorable & no supply	4	Price is favorable & no supply		
5	Grid, When no supply	5	When no supply		
6	Supply, Until ESS is full	6	When (partly) full		

The following charge- and discharge strategies and system combinations are attributed to a storage application, table 25. This charge and discharge combination represents an 'operating strategy'.

Reasoning behind the different combinations for system A
No charging and discharging, 11, are the base cases for both systems. Charging and discharging strategies 2 (22 in the table) is the default storage operating strategy that is used in most of the sections thus far. This operating strategy is only applicable for system A, as in system B the cable capacity is not limiting the energy export. The peaks of over-generation are curtailed or 'shaved' and stored to be exported when the cable allows again.
Strategies 24 and 25 are also only applicable for system A, but the energy is not only exported once it is able, but also exported when there is no power supply at all, at night for instance. So the energy supply is shifted in time to moments with no other solar energy generation. With strategy 24 the energy is not only time shifted but also waited when the electricity price is favorable.
Strategies 23 and 33 are the last strategies deemed applicable to system A and only export energy when the price is favorable, during the day or night. The difference is at 23 only the supply is used for ESS charging, but for 33 the ESS is also stored from the supply when the electricity price is low. Noted is that for system A, charging strategy 2 always applies with storage, as explained in section 3.4.
The other charging and discharging strategies are not applied in system A because charging the ESS with energy from the grid limited the energy output of the systems' own produced energy. This is further explored in section 6.0.1. Although with charging strategy 6 energy is not bought from the grid, in preliminary tests this charging strategy did not yield good results for a similar reason as strategies 4 and 5.

Reasoning behind the different combinations for system B
For system B charging and discharging strategies 2 are not applicable. The other strategies are examined.

Table 25: Different operating strategies and applications. The first digit is the charge strategy, the second the discharge strategy and the letter represents the hybrid system.

Combination	Application
11A, 11B	Base cases
22A	Peak shaving
24A, 25A	Time shifting
23A, 33A	Trading with capacity limitations
33B, 34B, 35B	Time shifting with trading
43B, 44B, 45B	Trading
36B, 46B, 56B	Trading with high ESS use
53B, 54B, 55B	Unregulated trading
63B, 64B, 65B	Time shifting

With charging strategy 3 there are three combinations surveyed: 33, 34 and 35. With these combinations power produced at moments with a low electricity price are sold at other times with more favorable electricity prices. Except for 35, which does not adhere to energy prices to discharge. With these strategies it is expected that the total amount of energy that is exported, decreases with the increase of the ESS size, because the energy is not directly exported from supply to grid, but some is stored with some efficiency losses.

With 43, 44 and 45 the storage system is purely utilized for trading, buying energy at a low price and selling at a higher price.

The goal of discharging strategy 6 is to be able to utilize the storage unit more frequently, as the storage system is partly discharged when it is fully charged. In combination with charging strategies 3, 4 and 5 the discharging strategy is explored.

Charging strategy 5, explored in combination with discharging strategies 3, 4 and 5, is trading without regarding the electricity price, only when there is no supply, thus no counter electric current.

Finally charging strategy 6, which is a variation on charging 3, but it always charges from the supply until the storage system is full, so without adhering to the electricity price. This strategy is combined with discharge strategies 3, 4 and 5.

Model parameters and Buy/Sell price points

For both systems, A and B, the following (other) model parameters apply, table 26. The Ideal ESS is used for storage. For the trading operating strategies a buy/sell price point needs to be chosen. The buy price is set at 0.05 €/kWh, the sell price point at 0.058 €/kWh. These values were found, using a exhaustive search, to result in the highest combination of energy output and revenue. The operating strategies will only be compared based on their energy output and revenue.

Results

In the preliminary results for each application listed in table 25 the most promising operating strategy combination was identified, table 27. This was based on the energy output and revenue.

The results for system A and B are shown in table 28.

Table 26: Model parameters ESS technology comparison, *decision variable

Parameter	Unit	Value
ESS size*	MWh	0 - 15
PV solar capacity	MWp	5
Cable capacity	MW	1, 5
Dynamic DAM price	€/kWh	-
Transformer efficiency	-	0.97
Interest rate	-	0.06
Buy price point	€/kWh	0.05
Sell price point	€/kWh	0.058

Table 27: Operating strategies and applications performed best in preliminary tests. The first digit is the charge strategy, the second the discharge strategy and the letter represents the hybrid system.

Combination	Application
System A	
11A	Base case
22A	Peak shaving
25A	Time shifting
23A	Trading with capacity limitations
System B	
11B	Base case
33B	Time shifting with trading
43B	Trading
56B	Trading with high ESS use
53B	Unregulated trading
64B	Time shifting

For a system with cable capacity limitations trading improves upon the base case, but the improvement compared to peak shaving or time shifting. A note to this trading strategy is that the energy output gain is mostly due to the amount of energy imported from the grid instead of the energy generated from the DG. This is further explored in following section, section 6.0.1.
Peak shaving adds to most value, in terms of energy output and revenue, for a system with cable capacity limitations.

The base case for a system without cable capacity limitations is already very competitive, because all the energy that is produced by the generation system, is able to be exported to the grid. Of the proposed operating strategies purely trading is the most profitable strategy. Trading with high ESS use more energy energy is exported overall, but the revenue gain is negative. An additional drawback from the more utilized ESS with this strategy is that the yearly cycle lifetime is exceeded for ESS sizes smaller than 7 MWh, even with the Ideal ESS. So this strategy is not suited for the ESS operation.
Time shifting with trading, is also a viable operating strategy to improve the revenue of the system, without

losing a significant amount of energy. This loss is due to transformer losses during charging and discharging. The values are expected to be lower when realistic energy storage systems are utilized. So this strategy was also calculated with a LFP Li-ion battery system. The revenue gain was still higher than the energy loss.

Table 28: Operating strategies compared based on relative energy output gain and revenue gain, from 0 MWh ESS to 15 MWh ESS.
Base values for System A (11A) are Energy output = 2.76 GWh and Revenue = €151,000.
Base values for System B (11B) are Energy output = 5.19 GWh and Revenue = €283,000.

Application	**Combination**	**Energy output gain** [%]	**Revenue gain** [%]
System A			
Peak shaving	22A	77	74
Time shifting	25A	71	67
Trading with capacity limitations	23A	34	43
System B			
Time shifting with trading	33B	-2.2	8.5
Trading	43B	68	22
Trading with high ESS use	56B	80	-16
Unregulated trading	53B	69	-8.6
Time shifting	64B	-2.8	6.6

So peak shaving is the best operating strategy for a hybrid system with cable capacity limitations. And buying electricity from the grid when the price is low and selling it when price is more favorable, is the best operating strategy for a hybrid storage and decentralized PV solar energy generation system without cable capacity limitations.

6.0.1 Trading with cable capacity limitations

As mentioned in the previous section, charging strategies 4 and 5 are not applied to system A. This is when the ESS is charged with energy from the grid, the energy produced over the capacity of the cable cannot be stored in the ESS because it is already full. In this section an example of this will be shown for a hybrid system with cable capacity limitations and a trading operating strategy (43A):
- Charge from grid when price is favorable & there is no supply.
- Discharge when price is favorable.

In fig. 61 the total amount of energy supplied from the PV park, the amount of energy exported to the grid and the amount imported from the grid are plotted. The total energy output gain is 49%. This gain is for the most part, 73%, due to the amount of energy imported to the grid and only 27% is gain of the energy generated by generation system. This compared to the standard, peak shaving operating strategy (22A) where the energy output gain is 77% and a 100% of this gain is energy produced by the PV park.
So it is proven that trading an operating strategy for a system with cable capacity limitations is not beneficial for the penetration of renewable solar energy from its own park.

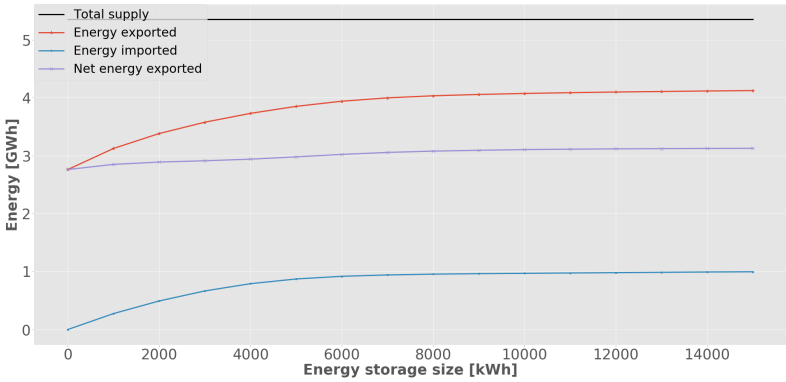


Figure 61: Total energy supplied, exported and imported as a function of the ESS size.

Results of the 5 MWp PV solar park, cable capacity of 1 MW and Ideal ESS. In black the total amount of energy supplied to the system. In red, marked with stars, is the amount exported to the grid. In blue, marked with dots, is the amount imported from the grid. In blue, marked with x, is the net energy exported.

7 Discussion

In this section some results and research choices are discussed.

Power capacity as model output

The first results I like to discuss are the first results with storage, Case 1 in section 4.2, and in particular the power capacity of the ESS. The profit curve, fig. 32, has a large bend upwards at an Ideal ESS size of 4 MWh. This bend is so extreme that at this point the profit is at its minimum. This bend in the profit curve is also present for the other storage technologies (fig. 52), but for these systems it does not cause a local minimum. This bend is due to two design choices in my simulation model:

1. The power capacity is a model output rather than input.
2. Only one value was used for the power capacity capital cost coefficient.

1. As described in section 3.4, it was chosen to make the power capacity of the ESS, a model output. The necessary power capacity of the ESS is defined as the maximum charge or discharge rate that occurred in the entire simulation, eq. (22). The resulting power capacity, fig. 29a, is dictated by the cable capacity, C-rate and supply data. It is possible to include the power capacity as a decision variable by rebuilding the simulation model with Mixed-integer programming.

2. The bend is more extreme for the Ideal ESS as the energy capacity capital cost coefficient of the Ideal ESS is relatively low in comparison to the power capacity capital cost coefficient. This value is assumed to be equal for all storage technologies, as discussed in section 2.5. So for the Ideal ESS the cost of the power system is substantially higher than the storage system cost, fig. 31. The bend in the profit curve is less extreme for the other storage technologies because the storage system costs are higher.

Power capacity as model output in section 5.3

In section 5.3 the power capacity curve, fig. 56b, also has an unusual shape. It has two lumps in the middle of both the curve of the Ideal ESS and the LFP BESS curve. As mentioned in the paragraph above, this is because of how the power capacity is defined. The shape of the curve is subsequently dictated by the cable capacity, C-rate and supply data. The power capacity lumps are a result of a singular coincidence of a low point in the power supply and the cable capacity limit at which time the ESS is able to discharge a large amount energy. The resulting cost and profit curves for the Ideal ESS system have local minima. It has a lesser effect on the cost and profit curve of the LFP BESS system.

The power capacity lumps could be smoothed out with more supply data from various years.

Wind on AC bus

The simulation of the wind generation system is incorrect. As explained in section 2.5 a wind farm should be connected to the AC bus. However, in the simulation model a wind farm is not simulated differently from a PV park. In this way the energy exported directly from the wind farm to the grid has to go through an AC/DC transformer, but in reality the wind farm system is directly connected to the grid without the additional transformer. This AC/DC transformer should actually be positioned between the DG and the ESS. This means that the base case, without storage, of wind energy is slightly better than depicted in section 5.2. And the storage case is slightly worse. Yet this does not alter the conclusion that a PV solar park benefits more from the addition of storage than wind energy. As a matter of fact it strengthens this claim.

Moreover, a FES should also be connected to the AC-bus according to some sources, but this is contradicted by other papers where these systems are connected on the DC-bus [45, 23]. As this does not change the conclusion that FES is not as suited for mitigating cable capacity limitations on the MV-grid as other storage technologies, the connection difference was neglected.
It was not found on which bus the thermal storage systems should be connected.

Energy output- and revenue gain
The energy output- and revenue gain are not equal, as first seen in section 4.2, but more noticeable in table 15. In this table, depending on the storage technology, sometimes the energy output gain is higher than the revenue gain and vice versa. With a fixed electricity price these gains are equal, but due to the variation of the price over time, the revenue gain turns out lower or higher than the energy output gain. To solve this, more financial data from various years would be necessary.

Operating strategies
The system is optimized based on one operating strategy of an entire year. However, the revenue, could have been higher when the seasonal or even daily variations of the electricity price would have been taking into account. For example, only one fixed buy/sell price point was used for the entire year, whereas the DAM market price is higher in the summer than in the winter. This seasonal difference could have been utilized better, by choosing a different buy/sell price point based on the season, or possibly month, week or even day. As the electricity price is set a day in advance, if the weather prediction for the next day is good enough, an optimum operating strategy, including buy/sell price points and choice of financial market, could be calculated a day in advance.

Standard hybrid system design
In the first results, the standard storage case in section 4, a hybrid generation system design with cable capacity limitations was chosen: a 5 MWp PV park, a 1 MW connection cable and an Ideal energy storage system. This system was arbitrarily chosen, but it was also used for most other cases and calculations. It is unlikely that there is a real world scenario that has the exact same generation and connection system and the Ideal ESS is fictional, so the results gathered in these calculations cannot be directly implemented. However, the conclusions drawn from these results are relevant. The results are scalable to different hybrid system sizes and for different electricity prices. Furthermore, most calculations were used to determine the potential energy storage or to compare various operating strategies. So also for the economic feasibility the conclusions are applicable.

One way transport constraint
The seventh constraint, one way transport, dictates that the battery cannot be charged and discharged at the same time. It also applies to the connection cable so that energy is not exported and imported at the same time. This constraint influences the charging strategies in two ways. Firstly, there are two charging strategies defined that import energy from the grid. These charging strategies only import energy when there is no power being generated. Secondly, the default charging strategy, charge from supply when limited by cable capacity, is always in use. This is, for both, to prioritize energy generated by the DG. This is eventually the goal of the addition of energy storage to the DG. These design choices affect the operating strategy results, especially trading in a hybrid system with cable capacity limitations, section 6.0.1.

One general hydrogen fuel cell system

In this thesis only one general hydrogen fuel cell technology was included for consistency and simplification. However, as also discussed in section 2.4, the different HFCS's have different advantages and disadvantages. For mitigating cable capacity limitations the PEMFC would probably be the best suited HFCS, as it is a relatively mature technology and dynamic enough to follow the power supply.

Sensitivity analysis

The sensitivity analysis of section 4.3, was mostly a qualitative analysis to validate the correctness of the simulation model. For instance, it was concluded that results of the simulation model is scalable for different hybrid system sizes. However, this was only examined in the comparison of two hybrid systems: the standard hybrid system, 5 MWp PV park, 1 MW connection cable and Ideal ESS, and a hybrid system 10 times larger. This is not very extensive. The same can be said for the sensitivity of the power supply size and the cable capacity.

OPEX, Interest rate and subsidies

There are three aspects that are very case specific and are, for that reason, neglected or simplified in this study, but they have a big influence on the economic feasibility of a hybrid DG system.

The operational costs (OPEX) were not included in this thesis, as addressed in section 2.4. The OPEX highly depends on the assumptions of what constitutes to the operation and maintenance of a system and where the system is located. I do recommend to further research the operational costs.

For the most part in this study an interest rate of 6% was maintained. The effect of altering the interest rate was examined in section 4.3. Increasing the interest rate from 5% to 15% resulted in an annualized cost 2.5 times higher. This signifies how important it is against what interest rate it is possible to loan. 6% is low for a commercial party, but it is on the safe side for Alliander (section 3.4). However, recently an energy storage project in the Netherlands was found that got an interest rate of 5.5% [73], which is fairly similar to the 6% used in this thesis.

This energy storage project has more similarities to the cases discussed in this study. In this project two 6 MW Li-ion BESS's in connection with a wind farm are used to trade on the FCR market. This project does have an extra aspect to make it economically feasible, that is not yet mentioned in this thesis; subsidy. This is also a very case specific aspect and a bit political, because of this, it has not been taken into account in this thesis, but I recommend to research the possibilities to be qualify for subsidies when realizing an energy storage project.

Perfect forecasting

A perfect forecast is not fully realistic for any study involving renewable energy generation, as also discussed in section 2.3. The results of this study would realistically come out lower than presented now. The operation strategies should also be optimized to minimize forecasting errors and subsequent penalties.

Furthermore, the cost of trading on the electricity markets are not included to simplify the computations. These costs are the responsibility of the PRP connected to the DG. When included the results would become slightly worse than depicted now, but should not be so high that this would significantly influence the outcome of this study.

Demand side

In this study the demand of electricity is not directly included, as stated in section 3.1. This is to simplify the programming of the model. The demand is, however, included in the electricity price, because the electricity price is affected by supply and demand, as discussed in section 2.3. When the supply is high the electricity price will drop and when the demand is high the electricity price increases. This said, including the demand can introduce more storage operating strategies, like matching supply with demand. The system could also be optimized to maximize the renewable fraction, as discussed in section 2.6.

Blind power

In section 2.2 the rated power capacity of a cable was stated to be different to the real power capacity of a electricity cable. A cable of 1000 kVA would actually have a power capacity of 850 kW. This is not included in this study as it would cause more complexity, but it is important to consider. The power output of a hybrid DG system could potentially be 15% lower. This would make the base case without storage worse and when storage is applied the reliance on the ESS greater. Or the other way around, a larger connection system would be necessary to maintain the same power output. This would make the connection system costs higher, lowering the profitability of the system, but making the case for energy storage vs grid reinforcement better.

Real storage systems capacities and costs

The revenue, costs and profits are only an indication of the possible results. In real life of course, the results can differ from these outcomes. The results of the simulation model are smooth and continuous. This makes it easier to read out, but also to calculate the maximum profit in the simulation model. This is partly because the cost coefficients of the subsystems are fixed and do not jump. As a result the optimum ESS could be a very precise size, for example, 12.3 MWh and 3.6 MW. However, this is only an indication. Sizes and prices are often standardized, maybe there is an ESS already on the market with a capacity of 12.5 MWh and 4 MW at 3.99 M€.

Future uncertainties

Finally I want to address is the uncertainties of the future of renewables. It is expected that the electricity markets will completely change in the future. Now renewable energy is considered free, however, this can create very low electricity prices and sometimes even negative prices. This is unsustainable for the electricity market and needs to be reformed. Additionally, with an emerging CO2 market and circular economy, these reforms are inevitable. Nevertheless, it is hard to predict how the markets will be operating in the future. This has not been researched in my study.

8 Conclusion

In this section conclusions are drawn from the results from the previous chapters. This is done by answering the following research questions:

Research Question

- Under what conditions can energy storage for decentralized renewable energy generation be economically feasible to mitigate connection scarcity on the medium-voltage grid?

Sub Questions

∗ How to build a simulation model to optimize the use of energy storage in a decentralized renewable energy generation system?

∗ What are characteristics of a hybrid generation and storage system to optimally profit from the storage system?

∗ What are beneficial operating strategies to optimally use the energy storage system in the hybrid system?

The goal of this research is to be used as a framework for adding energy storage to aid in the connection of decentralized renewable energy generation in areas with limited connection availability to the electricity grid.

How to build a simulation model to optimize the use of energy storage in a decentralized renewable energy generation system?

The model that simulates energy storage in a hybrid DG system, should consist of different black boxes which can be switched to simulate different hybrid system designs and energy storage operating strategies. The hybrid system consists of three subsystems: the generation system, the connection system and the energy storage system. The generation system can be either a PV solar park or a wind farm. The size is characterized by the power capacity in kW. The boundaries for a DG on the MV-grid are 0.3 MW - 10 MW. The connection system is characterized by the cable capacity in kW. The boundaries are the same for the generation system. Different storage technologies can be used for the energy storage system: BESS, FBESS, FES, TES and HFCS. The ESS is characterized by the energy storage capacity in kWh and the power capacity in kW. The boundaries for an ESS in a hybrid DG system are 0 MWh - 15 MWh and 0 MW - 10 MW.

Additionally, there are three interesting electricity markets for energy storage on this scale that should be implementable in the simulation model: the Day Ahead Market, the Frequency Containment Reserve and the automatic Frequency Restoration Reserve.

The simulation model needs abide by seven technical constraints:

1. Conservation of Energy, system
2. Conservation of Energy, storage
3. Maximum depth of discharge
4. C-rate
5. Cable capacity
6. Self-discharge
7. One-way transport

The inputs for the model are power supply, financial data, a decision variable and model parameters. The outputs are the ESS size, the energy output, revenue, system costs and the objective of the model is to maximize profit of the system. The profit is defined as the difference between the yearly revenue and the annualized cost.
To find the optimum ESS size, the profit can be maximized by exhaustive search and with direct search-based mathematical optimization.

This model was applied on a standard storage case to verify the model performance. Additionally the model was validated by varying different model parameters. It was concluded that the proposed model could accurately simulate the behaviorisms of energy storage in a hybrid DG system connected to a MV-grid.

What are characteristics of a hybrid generation and storage system to optimally profit from the storage system?

As in literature, the results of the simulation model has shown that energy storage is still very expensive. Even with cable capacity limitations, it is currently more profitable not to invest in energy storage for a DG. The capital cost of the energy storage system is the most important factor in the profitability of the hybrid system. Nevertheless, improving the performance of storage technologies is very useful, as is reducing the power capacity cost of the power system of the ESS. The best performing energy storage technology is the LFP Li-ion BESS and the most profitable is the Pumped Heat Electrical Storage TES, although, this technology is not suitable for applications that require a fast response time. In the first results it could be concluded that the added value from an ESS is larger in the smaller volumes. For instance, between 0 MWh and 3 MWh, the energy output gain was 13% and between 12 MWh and 15 MWh this was only 3%. Energy storage was more beneficial to the energy output and revenue for PV solar energy than for wind energy. This is most likely because solar energy has a more constant diurnal cycle than wind energy, which results in a better daily operation of the ESS.
In most situations grid reinforcement is currently more profitable than energy storage to combat cable capacity limitations. However, in locations that are badly accessible, energy storage could be an interesting option. Although, such a situation does not benefit the profitability of the project.

What are beneficial operating strategies to optimally use the energy storage system in the hybrid system?

The operating strategies are applied to two different hybrid DG systems, one with cable capacity limitations and one without. The most beneficial ESS operating strategy for a system with energy transportation limitations is peak shaving of over-generated energy to sell when the connection cable is not at full capacity anymore. Trading on the electricity markets is not beneficial for the penetration of the renewable energy generated by the DG system. For a system without these cable capacity limitations trading, buying electricity from the grid at a low price to sell at a later moment with a more favorable electricity price, is the most profitable operating strategy.

Under what conditions can energy storage for decentralized renewable energy generation be economically feasible to mitigate connection scarcity on the medium-voltage grid?

In this study it has been shown that energy storage can improve the energy output and earnings of a DG system on the MV-grid. Especially for a system experiencing connection capacity limitations. Nevertheless, not adding energy storage or adding grid reinforcement are still more profitable options. With the improvement of storage technologies and particularly the capital costs, energy storage can become economically feasible. The improvements that are predicted for 2030 alone would unfortunately not be sufficient. The results are more promising for energy storage for a hybrid PV solar park than for wind energy. For locations where grid reinforcement is costly or not possible, energy storage could become more interesting.

Apart from answering these research questions, the goal of this thesis was also to be used as a framework for new energy storage projects in the Dutch medium-voltage grid. In this report the appropriate information is gathered to be used in the selection of an energy storage system and an operating strategy for a hybrid DG system. A detailed description of the Dutch electricity system is given, including the MV-distribution grid. The electricity markets that are accessible for a hybrid DG plant are identified and a comparison of the different energy storage technologies is provided. Additionally, some alternative congestion mitigation methods to grid reinforcement and energy storage are discussed.
Furthermore, with the proposed simulation model it is possible to size the storage system and get an indication of the costs, revenue and profit of the hybrid system. So the model can be used for further studies about energy storage applications for decentralized generation.

8.1 Recommendations

With the proposed simulation model it is possible to compute some more interesting results. These are listed in this section. There are some interesting fields also worth exploring for future research.

8.1.1 Recommendations for this research

Accessible electricity markets
The first thing I recommend is to compare the potential of trading on the three accessible electricity markets: the Day Ahead Market, the Frequency Containment Reserve and the automatic Frequency Restoration Reserve. For all simulations in this report the Day Ahead Market has been used, but it is also possible to sell to and trade on the frequency balancing markets, as discussed in section 2.3. All the necessary information, data and programming to compute and analyze the results, are already facilitated.

Additional operating strategies
With more time I would have liked to investigate more operating strategies in section 6. For instance, peak shaving for system B to maintain a constant power output. As stated in section 1.1, the growing availability of decentralized generation is not the only cause of congestion in the MV-grid. The erratic nature of the renewable energy sources aggravates this congestion. So if the storage system could be operated in such a manner that the power supply could be smoothed out to produce a constant power output, this would increase the predictability of renewable energy to the grid, which is beneficial to manage grid congestion. Although, I do not expect that this is a more profitable operation strategy, I believe it is a valuable strategy for the deployment of energy storage.

Furthermore, I recommend investigating the effect of curtailing the power supply on the systems performance in the sensitivity analysis and as an operating strategy. The operating strategy would be a combination of curtailing the outer most peaks of the power supply and energy storage, to see whether this has a positive effect.

Three additional case studies

I also recommend investigating three additional case studies.

A case in which grid reinforcement takes several years to realize and whether it is interesting to invest in energy storage in the time it takes to wait for the realization of the grid reinforcement. A case to investigate the impact of multiple small energy storage systems on multiple DG's vs one large ESS on one DG.

A case to evaluate how the cost and benefits of a hybrid DG system are divided between the developer and the DSO.

8.1.2 Recommendation for future research

Reduce capital costs of energy storage

I concluded that energy storage and the auxiliary power system need to become cheaper in the future, so I recommend to research how to reduce the capital costs of the energy storage technologies and the power system.

Demand side

To improve the simulation model I recommend including the demand side of electricity. In this study the demand of electricity is only indirectly included in the electricity price, but if included, it is possible to optimize the energy storage system to match the erratic supply of renewable energy storage and the demand. For instance, by maximizing the renewable fraction.

Adding operational and maintenance costs

I would also recommend investigating the operational and maintenance costs associated with the energy storage systems to improve upon the system's costs calculations.

Data from various years

In section 7 it was mentioned that some conclusions could be further substantiated by including more supply- and financial data from various years.- and financial data from various years. I recommend reviewing the reason why PV solar energy benefits more from the addition of energy storage than wind energy, because it could have several explanations. It is unlikely, but possible, that this is just random. A more logical reason is that solar energy has a more constant diurnal cycle than wind energy, which results in a better use of the ESS. Solar energy also has a lower capacity factor than wind energy, in the Netherlands. This could possibly also be a cause. Furthermore, it could be beneficial to look at the effect of different capacity factors in the sensitivity analysis. To study this further more supply data, from various years, would be required.

Imperfect forecasting

This study had mostly focused on the potential of energy storage for DG in various circumstances, so assuming a perfect forecast was justified. It is interesting, though, to investigate the influence of imperfect forecasting. Reducing the forecasting errors and optimizing the operating strategy per day.

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