Added value of Energy Storage Systems

A valuation model of ESS for industrial clusters

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A valuation model of ESS for industrial clusters

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Executive summary

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Adequate energy supply is necessary for our present complex society to operate and to thrive. To maintain economic, social and cultural development in our present society, constant energy supply must be provided. Electricity transformed into power is the energy form most commonly used for all sorts of services and productions of goods that contribute to the prosperity of our societies. To assure that the generation of electricity meets the demand it is transmitted and distributed through the electricity grid. The current trend is for more variable renewable energy (VRE) to be deployed. This is happening in either distributed generation (DG) with PV panels or VRE power plants as solar farms or wind farms. Previously, the security, control, power flows and protections of the grid design were based on a central generation model. However, with the penetration of larger amounts of VRE sources and the phasing out of synchronous (fossil) generation, there are new and other challenges for distribution system operator (DSO) and transmission system operators (TSO) to guarantee power quality and stability of the network. This will possibly affect the price of electricity and network operation costs.

Energy storage systems (ESS) are expected to be one of the main pillars for a future renewable-based power system. All sectors are electrifying and variable renewable energy (VRE) plants are being deployed more quickly than transmission and distribution operators are able to connect them to the electricity grid. To maintain the stability of the network flexible capacity is needed on multiple positions along the electricity value chain. However, the original design of the grid was not based on decentralized and variable generation. Neither are current regulations up-to-date with innovations in the grid. There are multiple barriers that the ESS needs to overcome to be widely integrated. Since investment decisions by decision-makers are not only based on technical and economic features, but also on social and environmental features better insight into the impact of different power system designs is needed.

In the first phase, identification of the problem and the subsequent literature review, showed that most research focuses either on the tech-economic modelling of singular ESS services or on the impact on the larger power system. The former often using perfect foresight for prices and market behavior for different parts of the electricity value chain, and the latter having a low level of details to grasp the operation of the larger system. The literature review showed little research is conducted at the valuation of ESS within industrial power systems. Therefore, this study explores the potential value of energy storage systems integrated into an industrial clusters power system design.

In the second phase, the work presents a basis for the valuation of ESS for industrial sites in the Netherlands in a future scenario with a large increase of VRE in the energy mix. Since energy systems are highly complex systems, modelling and simulation are used to get a better understanding of the system. Modelling helps by simplifying interactions and functional relations within the industrial power system. The power flows are simulated by tracking the following values:

- Volume electricity generated by the PV-system
- Volume generated electricity that is directly consumed
- Volume electricity consumed from the energy storage system
- Volume electricity stored in the energy storage system
- Volume electricity consumed from the grid

- Volume generated electricity fed into the grid

Hence, the model provides insights that help to reevaluate the power operation of an industrial cluster. As a result, it helps to reshape the power system investment strategy for the future.

Considering that ESSs are multi-application systems, this study analyses how different operations strategies including multiple services influence the performance of the industrial power system. Two operation strategies enhancing self-consumption (greedy) and peak shaving are compared on the following performance indicators: self-consumption, self-sufficiency, utilized and unutilized VRE, the size of the network connection, capacity for flexibility and influence of allocating transit power generation to start the back-up generator. The greedy and peak shaving operations are simulated in combination with the services of providing transit power for a back-up generator to start and the ability to provide flexibility on the imbalance market.

In the third phase, three different industrial loads (scenarios) for five different configurations of either a Photo-Voltaic (PV) system or a PV system in combination with an ESS are simulated. In all scenarios, the power system's overall performance is better when ESS is integrated in comparison to the PV-system without storage. In the scenarios, the scoring varies considerably between the configurations, primarily due to the heterogeneity of the used load profiles. Hence, allowing to identify the characteristics of industrial load profiles that are more suitable for a combined PV and energy storage system.

In the fourth phase, the results are discussed and put in a broader context. The results of this study are relevant for decision-makers considering to adapt their power system design strategy by providing a better understanding of their system. It shows how different services run in parallel allow the ESS to be operated in a way that it can add more value. Nevertheless, should decision-makers establish operational priorities since some services can be competitive and result in a sub-additive value. The results are summarized in the following bullet points.

- Clear definitions of services provided by an energy storage system are needed.
- Using peak shaving not necessarily decrease the peak load dependency on the electricity grid during times of low availability of sun and wind.
- Deployment of variable renewable energy peak power at an industrial site requires a larger size of network connection and does not diminish pressure on the distribution grid.
- Characteristics of the energy profile have a strong influence on the performance of the industrial power system design.
- To reach high levels of self-sufficiency and self-consumption large capacity of installed PV peak power relative to the peak load and storage capacity is needed.

Furthermore, the findings can help policymakers and utilities to see what the influence is of increased VRE generation at the industrial load side of the network on the larger system. This better understanding can contribute to developing clear long term policies and strategies that are needed to incentivise the deployment of energy storage. By making transparent regulations, and establishing markets for the flexibility and ancillary services, investment risks will be reduced and enable ESSs to compete with other measures. Therefore, more research is needed to assess the potential of ESSs in a holistic way. By understanding the context of the services and applications that ESS provides, policymakers can reduce barriers for the deployment. It is, therefore, crucial to get a better understanding of the interactions and functional relations of the power system to enable policymakers and utility operators to assess the relevant needs of the system in the long term.

This study is the final result of a five-month research project for the MSc *Complex System Engineering & Management* at the University of Technology Delft. It describes the role of energy storage systems integrated into an industrial power system with installed PV power. It evaluates the role of energy storage within the electricity value chain and depicts the possibilities and barriers for energy storage positioned behind-the-meter in an industrial power system. Thereafter, it evaluates the performance of different configurations of PV-systems with and without ESS integrated into various industrial power systems. The performance indicators are depicted to be interpreted without the need for perfect foresight on fluctuations of the electricity price. The performance of the system also gives insight into the influence of large scale deployment of PV at the industrial load side on the larger power system. For decision-makers of the industrial site, policymakers, and utility operators this can contribute to a better understanding of the power system.

Preface

A lot of progress has been made since I did my first research on the profitability of batteries for households with PV-systems in the Dutch power system in 2016. A lot of improvements in technology and on a policy level regarding renewables and energy storage are taking place all over the world. Every day I read more about large renewable energy plants with energy storage technology that are being researched or realized somewhere in the world. However, there is still a lot of progress to be made and opportunities to be seized. I like to think that I have experienced this same growth along with energy storage.

When I started my first study, my knowledge about performing research was close to zero as was the business-case for household batteries in the Netherlands at that moment. The TU Delft taught me how to set up a project in a proper way which made it possible to look beyond the profitability of a singular house and see the possibilities and complexities when wanting to improve the power system as a whole. The enthusiastic professors from both the TU Delft and UPC Barcelona have had an amplifying effect on my interest in both the possibilities for energy storage and flexibility in the power system. They have provided me with the same amount of answers as possibilities for new questions over the years. However, every project needs a deadline and this research project has met his. Although my name is at the front page of this thesis it has not been a lonesome ride and I would like to use these next lines to thank the individuals who have had an impact on this study.

Firstly, I would like to thank my graduation committee Martijn Warnier and Theo Fens for all their advice, support, and input during the thesis process. Each meeting was a fruitful one and helped me to see the bigger picture, see more opportunities and kept me from dwelling on temporary hick-ups. Thank you both for your enthusiasm, know-how and critical questions along the way.

Secondly, I would like to thank all colleagues of *Royal Haskonig DHV* for their explanation of the performance of a power system of an industrial site. A special thanks to Herbert Polman who has taken the time to have endless discussions on the possibilities of energy storage which helped to shape this thesis. In addition, I want to thank Mike Cantrell who helped to edit my thesis only fueled by his passion for research and renewable energy.

One of the best things about doing research on such a hot topic where everyone is curious about. Is that I had the chance to meet a lot of professionals from all over Europe who were happy to share their experiences. With every discussion, I gained new insight into the problems and possibilities that entrepreneurs, policymakers and companies are encountering. I want to thank the *EASE*, the European Association for Storage of Energy, for including me in their international workshop on Energy Storage in the future energy system where I was the only student present.
Writing this page means the end of an academic chapter in my life. Making me think about the route I took to get here and all the persons I have met all over the world who shaped me. I am curious what lies ahead but know that I got the support of my family and friends as they have been supporting every adventure I have undertaken the last twenty-six years.

Last but not least, thanks to everyone who have not been named but supported in someway and to the person that is currently reading this. I hope you enjoy it.

Alex Wittebrood
September 2019

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List of Abbreviations

TSO	Transmission system operator
DSO	Distribution system operator
HV	High voltage
MV	Medium voltage
LV	Low voltage
PV	Photo-Voltaic
VRE	Variable renewable energy
DG	Distributed generation
NG	Natural gas
DR	Demand response
ESS	Energy storage system
EV	Electric vehicle
OECD	Organization for Economic Develop and Cooperation
E-act	Electricity act
PRP	Program responsible party
ENDEX	European Energy Derivatives Exchange
EPEX:DAM	EPEX: Day-Ahead-Market
EPEX:IDM	EPEX: Intra-day market
FCR	Frequency containment reserve
FRR	Frequency restoration reserve
RR	Replacement reserves
SME	Small medium sized enterprise
ESS	Energy storage system
PRP	Program responsible party
PHS	Pumped hydroelectrical system
CAES	Compressed air energy system
FESS	Flywheel Energy storage system
FACTS	Flexible alternating current transmission system
AS	Ancillary services
PI	Performance indicators
UPS	Uninterrupted power supply
BAU	Business-as-usual
LCOE	Levelized cost of electricity
LCOS	Levelized cost of storage

1

Introduction

An adequate energy supply is necessary for our current complex society to operate and to thrive [2]. For economic, social and cultural development in our current society a constant energy supply must be maintained. Electricity is the major source for all sorts of services and productions of goods that contribute to the prosperity of our societies [49]. To assure that the generation of electricity meets the demand it is transmitted and distributed through the electricity grid. However, on 8 January 2019 the Dutch transmission system operator (TSO), TenneT [69], presented an overview of the locations in the Dutch electricity grid where maximum capacity of the transmission and distribution grid is reached. This limit is reached earlier than anticipated due to the large increase of solar or Photo-Voltaic (PV) deployment in the area. While these parts of grid are not designed to cope with this large feed-in of electricity.

In the European Union the TSO and distribution system operator (DSO) are responsible for the reliable operation of the electricity grid and electricity supply. An additional obligation is the facilitation of access and connection to the grid for generators and consumers. The generation is conventionally performed by large synchronous fossil fueled power plants. After the generation of the electricity it is transported over long distances via the (extra) high voltage (HV) transmission grid and transformed to a lower voltage in medium voltage (MV) or low voltage (LV) depending on the amount of power needed for the connection.

The current trend is for more variable renewable energy (VRE) to be deployed. This is happening in either distributed generation (DG) with PV panels or VRE power plants as solar farms or wind farms. Previously, the security, control, power flows and protections of the grid design was based on a central generation model [54]. However, with the penetration of larger amounts of VRE sources and the phasing out of synchronous (fossil) generation there are more challenges for DSOs and TSOs to guarantee power quality and stability of the network due to diminished inertia in the system [37].

The Paris Agreement and the Climate Agreement as formulated by the Dutch government [58] demonstrate political commitment to a more decarbonized pwoer system. One of the goals of the Energy Agreement is to create a system that is not dependent on natural gas (NG). In the case of heating, alternative means like heat pumps will increase. This trend in electrification, in addition to the increasing amount of e.g. electric vehicles and data centers being deployed, will probably lead to an increase of electricity demand [36, 62]. According to Panteli [52] and Singh [59] the congestion in the network will occur with high load peaks of large consumers or centralized (VRE) production but diminish with more DG. However, the current trend shows that there are large solar farms being deployed especially in rural areas where ground is cheaper but the grid is weaker: the grid is less meshed and the infrastructure in place is not designed to cope with the large peaks of the intermittent solar farms. As a result the TSO and DSOs had requested to curtail the generation of the regional power plants when transmission limitations were reached. Additionally, delays in the placement of grid connections for new VRE projects in the area are occurring [68]. Since the main limitation for transmission is the capacity of the line. It needs to be able to transmit for the maximum peak load for the required time. As a result, the capacity is oversized to make sure that the infrastructure is not operating at maximum capacity to prolong its working life. The original operation strategy of the DSOs and TSOs could be simplified to ”connect and reinforce”. However, this anticipated investment strategy for grid improvement and expansion does not match with the rapid deployment of VRE projects and electrification trend [19, 69]. Furthermore, do the TSO and DSOs have a societal responsibility to minimize the costs of transmission while contributing to the decarbonization of the electricity sector [27]. Therefore, expanding the capacity of the grid is not the only solution. Alternatives are: demand response, where the load is adapted to the availability of supply, curtailment of (renewable) production, the increase of grid flexibility and energy storage systems (ESS) [45]. ESS promises to be one of the key parts for flexibility and renewable integration.

The global demand for ESS is estimated to rise to 942 GW and 2857 GWh by 2040 according to Bloomberg [22]. With an estimated 50 GWh deployed in the year 2020 the ESS is seen a key attribute in a future power system with more renewable energy sources in the generation mix. The situation is complex since there are various storage technologies available with their own characteristics for a spectrum of applications[28].

Energy Storage systems

The increased complexities of the electricity system that are the result of the unbundling of the power sector requests different solutions of grid design. ESSs have the possibility to perform multiple services for both the owner and third parties ranging from improving self-consumption to ancillary services. Therefore, the services could be beneficial in both the public and private parts of the system. Some technologies are more appropriate than others depending on the characteristics of the services that are needed. With a large amount of VRE in the generation mix the ESSs could reduce the intermittent character of the production pattern while also creating synthetic inertia for the system, perform peak shaving and balancing [28]. The ESS is a multi-application system that is able to perform several services at the same time thus able to stack the generated revenues. However, the total value generated by the different services can not easily be assessed because some applications compete with each other. Sioshansi [60] describes this as follows:

> “Analyzing multiple applications presents modelling challenges, however, since it requires simultaneous co-optimization of multiple services. This is because different storage applications can compete with or complement one another, implying that their values can be sub- or super-additive. Thus adding values from individual storage studies is generally not appropriate.”

Investment decisions are not only based on technical and economic features: it is now widely accepted that environmental and social features are also used to determine the value of a technology [4]. Valuing criteria from the latter dimensions can be more difficult as they are not always directly quantifiable. Applications such as increasing self-consumption of VRE might not develop a positive business case but do allow for a more adequate resource utilization and less reliance of the electricity grid. The importance of different criteria also varies with different stakeholders who should therefore be consulted while selecting the criteria.

Energy storage systems in the Netherlands

The platform of Energy storage NL is used to get an overview of current projects regarding ESSs that are already deployed or are under construction. EnergystorageNL [51] is a platform that advocates for storage projects in the Netherlands. Its data shows that more than half of the battery energy storage systems (BESS) is a type of Lithium-ion technology. This is in line with the expectations of Bloomberg that BESS will be the main energy storage medium [22]. However, there are also other flexibility projects such as vehicle to building (V2B) and a virtual power plant where multiple ”home” batteries can operate as a large battery in a specific area. The majority of the projects provide services as EPEX trading, peak-shaving and frequency control: an overview of the number of such projects is given in appendix A.1.

Industrial cluster

Using the same categorization as the regional energy strategy, this research distinguishes the following energy consumption groups in the Netherlands: the residential sector, mobility, agriculture and the industrial clusters. The concept of the industrial cluster is defined by Hill and Brennan:

> ”a geographic concentration of competitive firms or establishments in the same industry that either have a close buy-sell relationships with other industries in the region, use common technologies, or share a specialized labor pool that provides firms with a competitive advantage of the same industry in other places.” [29]

An adaption of this definition is made to provide a better focus. In large industrial sites there are multiple parties connected to the same grid and sometimes this local grid is operated by the site owner and not the DSO. Industrial loads are often substantial and therefore have a large influence on the performance of the regional or national grid. Since these site are often large power consumers they are often directly connected to the MV and in some cases to the HV grid (> 10MW). With current political and societal pressure they have a strong incentive to decarbonize their process and to invest in large amounts of VRE. Furthermore, they have fewer stakeholders with conflicting interests regarding the energy consumption. The main drivers for an industrial cluster could be simplified to be: security of supply, cost-reduction, flexibility, sustainability, and innovation as stated by the research of Murrant [48] and the report on electrification of the Dutch process industry by Berenschot [19]. Therefore, this research proposes the following adaption of the definition by Hill and Brennan for an industrial cluster:

> ”a geographic concentration of (competitive) firms or establishments that either have a close buy-sell relationship with other industries in the region, use a common energy transmission grid, or have a common goal to achieve more efficient energy usage and higher penetration of renewables that provides the firms with a competitive advantage of the same industry in other places.”

This research focuses on ESS within the power system of industrial cluster with a large penetration of VRE. Other possible topics such as community battery storage systems already investigated by Parra [53], and Lucas [42] will not be part of this study.

1.1. Research problem

The amount of VRE to be deployed is increasing rapidly while there is also a social pressure to phase-out fossil generation. The intermittent character of VRE and need for flexible assets can result in more demand for ESSs. Although round-trip efficiency and high lump sum investment costs are often seen as barriers for the adoption of ESSs there are also other obstacles. Such as market design issues, uncertain regulatory measures and the unclear valuation of the services the facilities can perform. In this research the focus is on the valuation of the ESSs for industrial clusters. The goal is to help decision-makers within industrial clusters to gain more insights into the value of ESSs within their power system with a high penetration of VRE. Since an ESS is able to provide multiple services at the same time but the value generated is not easily stacked. More insight is needed in the influence of different ESS services.

1.2. Research questions

This research explores the potential added value of energy storage systems for industrial clusters in the Netherlands. Due to uncertainties in regulation and the very new role that energy storage will play as a flexible asset in the future energy system, a better understanding of the potential added-value of ESS is needed. This study focuses on how to evaluate the potential of energy storage implementation for stakeholders in industrial clusters in the Netherlands.

This is summarized in the following main research question:

> How to evaluate the added value from the services of energy storage systems to industrial clusters in the Netherlands when there is a large availability of variable renewable energy?

Sub-questions

1. What is the institutional context of the ESS within the Dutch power sector?
2. What are the services that can be performed by an ESS that are relevant for an industrial cluster?
3. What are the relevant performance indicators to evaluate the added-value of an ESS within the power system of an industrial cluster?
4. What is the influence of stacked services on the performance indicators?

1.3. Research methods and approach

This thesis is structured in four phases as illustrated in figure 1.1. Each phase helps to get a better understanding of the complex situation.

Phase I Consisting of chapter 1 and chapter 2. Chapter 1 provides the research context and defines a problem definition. It demonstrates the complexity of the energy system and provides the scope of the research. In chapter 2 a literature review is performed to determine that the study is contributing to the specified field of energy storage in the industrial sector. The literature review provides a better understanding of the theory and state-of-the-art methods within the field of study. The literature review consists of two sections. Section 2.2 gives an answer to sub-research question one by giving a description of how energy storage systems are placed within the context of the larger electrical system. In this phase the different actors within the system and their interactions are described. In addition, the relevant Dutch markets and regulations are discussed.
Section 2.3, provides an answer to sub-question two by giving an overview of the energy storage technologies and exploring and defining the relevant services for the industrial cluster. Thereafter, the state-of-the-art energy system modelling will be discussed, concluding with a knowledge gap. This is predominantly based on desk reviews.

Phase II Chapter 3 provides insight in the energy storage systems for industrial cluster through modelling and simulation. Because energy systems are highly complex systems they can be difficult to be understand. Modelling and simulation help to get a better understanding of the system by simplifying the interactions and functional relations within a specific setting [56]. A model helps to gather and structure scattered knowledge about the complex interactions and gives a structured way of thinking about changes that take place in the system. This can provide more structured insights for decision-makers to make more substantiated choices. However, by simplifying a complex system, aspects of the systems can be missed or diminished when making assumptions in the construction of the model. When interpreting a model the results are not an exact representation of the real world and vulnerable to unexpected shocks. The model demonstrates how operation strategies of the energy storage system influence the energy consumption profile and operation of an industrial site. This study analyses how the different operation strategies influence each other. Additionally, it demonstrates which performance indicators are relevant and is an answer to sub-question three. Chapter 3 conceptualizes the model and its operation and validates the concept using a testing set. These algorithms are being scored by multiple performance indicators and have been written in Python.

Phase III In phase 3 the model is used to simulate different configurations of industrial cluster energy systems for multiple scenarios. In chapter 4 the results are presented and in chapter 5 analyzed to give answer to research-question four.

Phase IV Phase 4 reflects on the results and assumptions by discussing them in the broader context in chapter 6. Lastly, the sub-questions are revisited, a final conclusion is presented and possibilities for future works are presented.

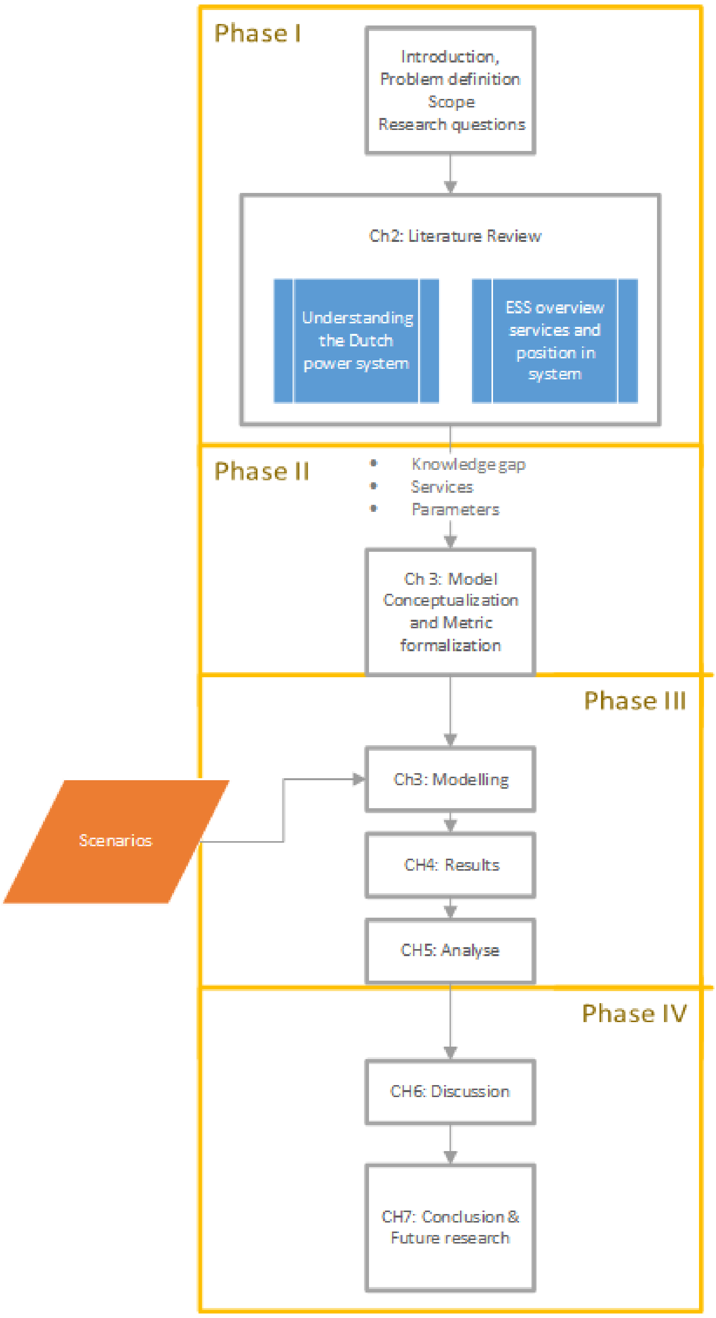


Figure 1.1: Flow diagram of the research illustrating what is described in each phase of the study.

2

Literature Review

2.1. Introduction

To demonstrate the relevance and complexity of this research a literature review has been conducted. The accumulated discoveries from the research are presented below. This review has been done by exploring the articles relevant to the evaluation of ESSs. To demonstrate the relevance and increased interest in energy storage an overview of the amount of published papers regarding the subject is presented in graph 2.1.

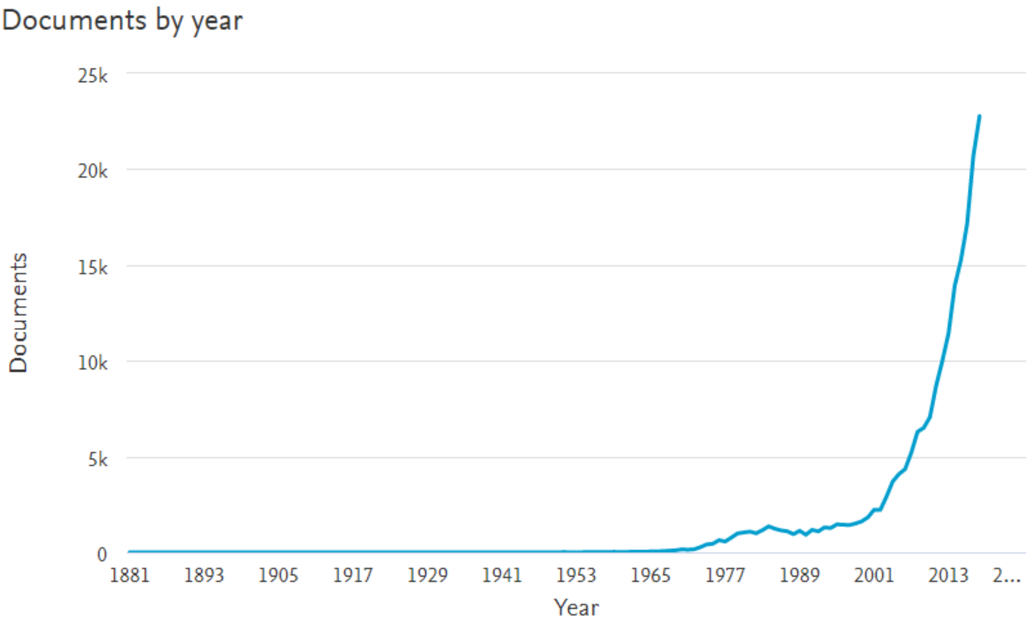


Figure 2.1: Published researches regarding energy storage from 1880 until 2018. Data retrieved from Scopus.

This has been done by formulating the following research keywords:”Energy storage”, ”renewable integration”, ”valuation”, ”evaluation”. Both ScienceDirect and Scopus have been used. The discovered articles have been scanned for relevance based on their abstract and conclusion. The first section gives a brief overview of the operation of the electricity sector. This is used to describe the different roles and interactions of the players in the market and how this has changed over the years. This gives the context for the rest of this research. Secondly, the different technologies of ESSs are presented and the different services that are relevant to Dutch industrial clusters are defined.

2.2. Electricity system

2.2.1. Introduction

In this chapter, an overview with the operation of the electricity sector is presented to show the context where ESS will partake. In section 2.2.2 the changes in operation of the electricity sector is presented. In section 2.2.3 an overview of the different roles and interactions within the system is given. Section 2.2.4 presents the mechanisms in place that facilitate the transfer of energy in the Netherlands. Section 2.2.5 presents how the electricity sector might be evolving and there-after the relevance to the industrial cluster is discussed. Lastly, section 2.2.7 gives an overview of the electricity system chapter.

2.2.2. Changes in structure of the electricity sector

The trend of electricity market restructuring started in the ’80s in the USA after the economic recession [16]. The restructuring of the electricity sector was undertaken to improve the efficiency of the operation and planning of the power system. Along with the transfer of cost risk away from the taxpayer to investors. In that day of age, the electric power system was unbundled in power generation companies (generators), TSO(s) and DSO(s). Many of the principles that are the foundation of current market designs have roots in the 80’s. However, the characteristics of power systems of today are noticeably different than the system three decades ago. The generation is conventionally performed in large centralized synchronous thermal generators that supply the energy needs. The majority of these generators are fossil-fueled. Since the world population is growing and a lot of countries experiencing economic growth the world energy consumption is expected to grow [72]. According to the United States Energy Information Administration, this increase of power consumption will mainly happen in non-OECD countries. Nevertheless, should be kept in mind that the amount of energy consumed per-capita is still significantly higher in OECD countries. Since the Paris Agreement, a lot of countries are working to maintain a maximum temperature rise of 2.0 degrees Celsius and preferably in the direction of 1.5 degrees. The facts mentioned-above combined with the strong decrease in cost for renewable generation technologies are contributing to a transformation of many power systems.

In the Netherlands, the process of liberalizing of the market started later with the established Electricity law in 1989 [47]. The Dutch government chose an incremental process of opening up the market. Before 1989 all the production and distribution companies were state-owned and even after the E-act they still had the majority of stakes in the sector. In the middle of the 90s European Commission came with three new energy-related directives (EC: 1996/92; 2003/54 and 2009/72) for the liberation of the electricity markets. Stating that the markets needed to be reorganized demanding conditions for cross-border trade and separation of core activities of the network companies at the level of the TSO. In the Netherlands this was implemented as ownership unbundling, meaning that the commercial activities are separated from the transmission and distributions operations [64]. This was implemented as the E-act of 1998 and the goal was to get a more diversified market where both consumers and producers have the ability to choose. This diversification was believed to improve the security of supply and reduction of the costs. The complete liberalization of the Dutch electricity market was achieved in 2004. The goal of the unbundling is to restrain competitive parties from having monopoly abilities.

2.2.3. Stakeholders in the electricity sector

In the original setup, the Dutch electricity market was operated by a handful of major players that generated, distributed and supplied the whole market. After the unbundling, six different roles can be distinguished in the process of delivering electricity to consumers in the Netherlands as linearly demonstrated in figure 2.2. The independent parties in the chain are generation, trading (program responsible parties), transmission, distribution, metering and supplying parties.

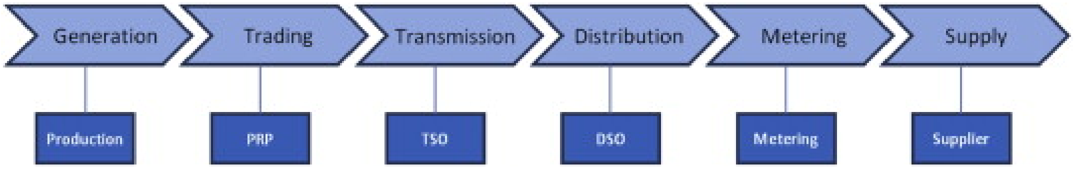


Figure 2.2: Linear representation of the Dutch electricity supply chain [63].

Generators

The generators are the group in the power system that owns the power plants where the electricity is produced. Which is currently happening in the centralized synchronous thermal plants. However, the political commitment is to move towards a power system that is less dependent on fossil fuels. Thus resulting in generation companies investing in large PV and wind parks. On the other hand, there is the arrival of distributed generation (DG). The DG changes the top-down flow of energy. Since generation is directly connected to the distribution grid at the (customer) end-user part of the electricity value chain[9]. This means consumers are sometimes also producers of electricity resulting in the new role of the prosumer. This poses the possibility for a commercial aggregator, that aggregates the generation and consumption flexibility of the prosumers to provide services to the system as described in the article of Lipari et. al [40]. Since this role has not yet been defined and acknowledged yet in European Legislation this research will not elaborate about it in here. Current market design for dispatch technology happens on the basis of the merit order. Meaning that the choice of production technology is dispatched first on the basis of lowest marginal price to meet demand. However, the TSO can demand the generation to be dispatched out of merit order to maintain system stability or diminish congestion. Demonstrating the possibility to provide flexible generation based on locations which will be elaborated on more later.

Tennet - TSO

TenneT, the dutch TSO, facilitates all transactions of the system and is owner and operator of the HV grid (110 kV, 150kV, 220kV, and 380 kV). This grid connects all regional electricity grids and the EU-grid. The task of TenneT is to guarantee grid stability by preserving the balance between electrical power injection into and withdraw from the grid, including the interactions with other countries. The main problem of the TSO is maintaining the 50 Hz frequency of the grid by balancing supply and demand. If the capacity is not matched and flows violate technical constraints it will result in irregularities in the grid. Therefore can TenneT block requests for transportation capacity. As TSO it communicates available transmission capacity with other TSOs in Europe. It is the party that controls the recognition of program responsible parties (PRPs). The main instruments are purely from an administrative nature, it handles all settlements needed to preserve the balance.

PRP

The PRP is a legal entity that has at least one physical connection to the electricity grid and interacts with TenneT [64]. These are all connected parties with an available or consuming a load of > 2MW [65]. Each connection to the grid needs to deliver a T-prognosis. The T-prognosis is the expected transmission capacity needed. In here the generators, DSOs and large consumers describe their hourly capacity need. The E-program is the net exchange of electricity per 15 minutes and is used to calculate imbalances at the point of connection. The goal of the T-prognosis is to diminish the risk of congestion problems, increase reliability and optimize transmission capacity. The E-act states that all firms can buy and sell electricity in the market. This can be with or without a physical connection. However, it is obligated to have a PRP permit or a contract with a third party that owns the permit to be able to trade electricity.

DSO

The distribution of electricity is handled by the seven state-regulated DSOs. They are compensated and regulated by the government for their performance in terms of quality of supply and transmission efficiency [64]. The DSOs are obligated to take care of the management, construction, maintenance, and development of the distribution grid between the customers and the high voltage grid. The main problem of the DSOs is the problem of congestion on the grid due to technical transmission capacity constraints. TenneT published that the costs for congestion management by DSOs increased by 16% in 2018 in comparison to the previous year[68]. The transmission capacity of the grid needs to be designed and operated to be able to cope with the largest peak load/ generation that occurs during the year. However, often this peak capacity is only reached a few times or certain periods thus not optimally utilized. Consequently, requiring relative large lump sum investments to have the capacity needed for certain periods in a year. With more VRE in the energy mix and an increase in electrification the capacities needed and volatility of the grid is assumed to increase. Facilities providing flexibility services for the grid are expected to defer the need for upgrading the distribution grid. This is currently tested by the DSOs in collaboration with the TSO in the Netherlands where a market platform is developed where market parties can provide flexibility services by demand response and injection or absorption of energy for the DSOs. The system is able to provide balancing services at transient level, in case of power shortage, it can provide power into the network (injection) from the ESS. In case of high power feed-in from other sources, the system can sink power from the network by charging the ESS (absorption). This platform *GOPACS* has been online since March 2019 and is meant to reduce the need for upgrading the grid.

Metering & supply

In the Netherlands, the metering companies are often also the DSOs which are responsible for the electricity meters. The metering company collects and sends the metering data to the supplier that supplies to the consumer. The supplier is the commercial contact with the consumer in the chain. Since the liberalization of the energy market, the amount of suppliers is growing. They are the ones that buy electricity through bilateral contracts or at the EPEX market discussed in paragraph 2.2.4 and sell it to the consumers.

Legislation

Currently, the consumer or prosumer is paying grid fees for the utilization of the electricity network to the network operator and taxes to the regulator. Before, an energy storage asset was considered both as a consumer and a producer because of lack of a clear definition for energy storage. The European Commission published a new definition in the 2017 released *Clean Energy For all Europeans package* and the *staff working document on energy storage*.

> ”Energy storage in the electricity system means the deferring of an amount of the energy that was generated to the moment of use, either as final energy or converted into another energy carrier.” [25]

The new definition set up by the EC is a start to help national policymakers to come up with regulations fitting with their electricity market set-up. The Clean Energy package also states that storage operators are allowed to provide multiple services to the system operators. The new draft version of the EU regulation on the internal market for electricity state that network operators will not demand charges to access their networks that will:

> ”discriminate either positively or negatively against energy storage.” [17]

Although this does cover the problem of operators able to apply double network fees to the owners of the energy storage. It has not solved the problem of double taxation. Since taxes are still collected during the withdrawal from and injection into the electricity grid. This is perceived as a barrier by stakeholders [17] and should be revised by the member-states themselves. Since the publication of the *Energy agenda* by the Dutch government in 2016 it has been stated that the government has strong intentions to come up with a clear policy instrument to prevent double taxation[23]. However, this has not happened in the Netherlands at the time this study was conducted.

Additionally, it is stated that TSOs and DSOs are only allowed to own, develop, manage or operate energy storage facilities in exceptional scenarios. They are allowed to invest in a storage project, under regulatory approval and oversight in a transparent way. Only if other market parties are not interested in providing specific storage services and it is beneficial for the overall social benefit [25].

2.2.4. Electricity Markets

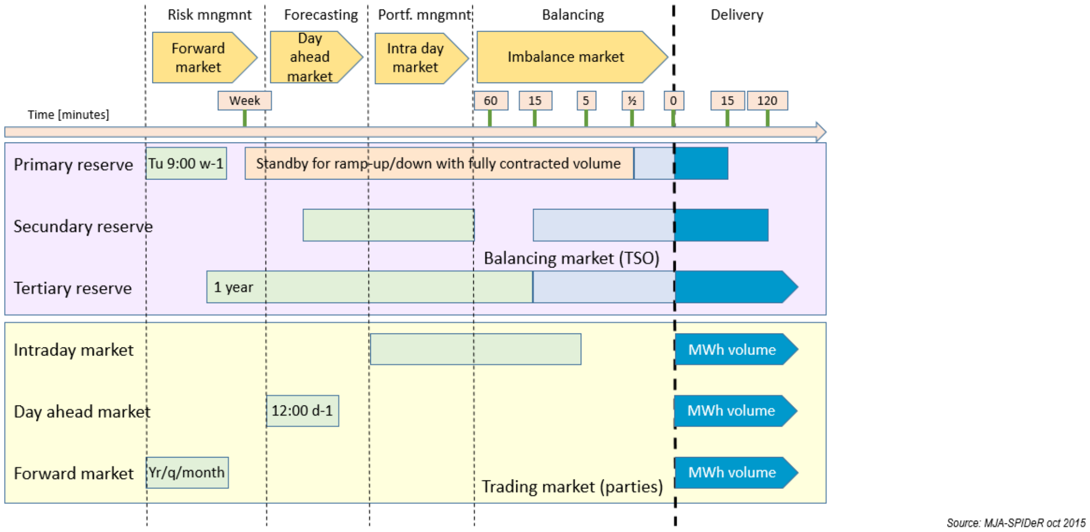
Bilateral markets

Apart from the organized markets where electricity is exchanged, the market participants are also able to trade power bilaterally without using the power exchange. This is where the largest part of the volume of electricity is exchanged in the Netherlands. In these contracts, the electricity is directly sold by the generating companies to their customers. These are large consumers, traders, or in the majority of cases the supply companies which deliver it to small medium-sized enterprises (SMEs) and domestic consumers. Bilateral contracts are non-transparent and therefore there is no public data available about the price and duration. The futures (ENDEX) and forwards (bilateral) market agreements are in place to reduce the risks for market participants, also known as hedging. For the generators, this is to reduce vulnerability to an electricity price decrease. On the other hand, it is more certainty about their electricity consumption costs for large consumers.

ENDEX In the Netherlands energy markets are differentiated in the ICE:ENDEX market, EPEX spot market, and the imbalance market [64]. The European Energy Derivatives exchange (ENDEX) market describes the contracts for physical delivery of power from/to the HV grid. The delivery is made equally each hour for the contracted period from 00:00 until 24:00. Periods are listed per months, quarters or years in parallel per 1MW [32]. The ENDEX was established to support the liberalization of the electricity market. The trades made on the ENDEX need a PRP permit because they constitute physical delivery of electricity. The contracts expire two days before delivery and can then be adjusted, if needed, as a day-ahead contract via the EPEX spot market. The EPEX is separated in the Day-Ahead-Market (DAM) and the Intra-day market (IDM).

EPEX:DAM On the DAM the electricity is traded for the next day for every hour. The parties that participate in the DAM are generation, distribution companies, large consumers, industrial end-users, brokers and traders. There is publication of baseload (all hours), peak load (08:00-20:00 GMT+01:00) and off-peak load (20:00-08:00 GMT+01:00) [1]. Each connected party whose contracted and allocated capacity exceeds 60MW is obligated to perform bids, with their excess of power to generate more or less. Smaller connected parties are allowed to put bids [70].

EPEX:IDM The IDM was introduced in 2006 and linked to both the Nord Pool and Belgium, UK, and Dutch spot markets. It is used by traders to reduce their risk for unexpected imbalance prices charged by TenneT. On the intraday market, the trades occur in 15-minutes intervals or freely definable timeslots up to 5 minutes prior to delivery. The prices can range from -9999.90 € /MWh to 9999.90 € /MWh and in the Nordic region from -99999.90 € /MWh up to 99999.90 € /MWh.



Source: MJA-SPIDeR oct 2015

Figure 2.3: Schematic illustration of the Dutch electricity market demonstrating the bidding periods in green. The grey area illustrates the period where the contracted power is able to absorb or inject, and the blue area shows the actual moment of delivery. Retrieved from Movaris[14].

The imbalance market

One of the primary tasks of the TSO is maintaining grid balance at 50Hz nominal value. This happens when supply and demand are equal in real-time. In the liberalized markets this management of reserve capacity is performed by third parties also known as ancillary services. The frequency will drop when there is a shortage of active power and will rise when there is overproduction. An increase or decrease that is too large can damage or stop electrical equipment or result in power outages. Since the practical implementation of demand response is still difficult [3] and not implemented on a large scale the adjusting is performed by ramping-up or down the generation. The imbalances are measured and compared to their E-programs. When the PRP deviates, the TSO operates as an artificial trader. The excess or shortage of electricity from the PRP is then exchanged for a price at the imbalance market. Since the accurate estimation of matching the supply and demand is very complex there is a constant mismatch. In the Netherlands and Germany, there was an imbalance volume of 1.1 TWh and 3.1 TWh respectively in 2017 [66]. In the imbalance market, there is a distinction between different types of balancing reserves; frequency containment reserve (FCR), Frequency restoration reserves (FRR) and replacement reserves (RR).

The FCR also known as primary reserve, is immediately used when needed and has a maximum response time of 30s. It is used to restore a new power balance at frequency deviating from the nominal one (50Hz). It is activated automatically and locally. Until 2014 this service was mandatory and there were no settlements, now it is auctioned by the TSO. At this moment the procurement of FCR is performed in a common market between Austrian, Swiss, Dutch, Belgian and German TSOs.

The FRR takes over the FCR when the balancing of the frequency deviation lasts longer than 30 seconds and is known as secondary reserves. It can be distinguished between automated activation (aFRR), or manual activated reserves (mFRR). The aFRR is operated and more integrated in the TSO system while the mFRR is deployed according to bids in the merit order. The FRR needs to be able to operate up to 30 minutes if the deviation has still not returned to nominal level the RR will take over [12].

The RR also known as the tertiary reserves need to be activated within 15 minutes and able to deliver power from 30 minutes to multiple hours until the balance has returned and the other reserves have restored. The average price for both FRR and RR are both commercially sensitive and due to their vital role have volatile price ranges.

The incentives for suppliers or consumers to operate on the imbalance market is saving of costs (fuel & operations) for self-consumption when absorption from the grid is needed with a surplus and can sometimes be negative in some cases. In the case of an electricity scarcity, the market price rises high and it could be used as an extra source of income by injecting power.

2.2.5. Trends in the grid

With a liberalized electricity market all actors try to maximize their profits by dispatching electricity from cheaper sources. With upfront investments becoming lower for VRE technology e.g. wind and PV and a € 0,- marginal (fuel) costs the penetration of VRE generation is getting bigger. However, when all generated electricity is sold to the grid it might overload transmission capacity and lead to congestion in areas of the grid. As a result, the TSO and DSO demand curtailment of the generator [5]. These physical constraints of the grid are due to restrictions of line flow, voltage and stability limits which influence the performance of the network. The positive influence can be reduced losses due to diminished network flows and voltage drops. The potential negative influences are power fluctuations, power factor changes, frequency regulation, harmonics, voltage rise and reverse power flow, unintentional islanding, fault currents, and grounding issues. An overview of the impacts of large penetration of DG is extensively described by Passey [54]. According to Singh [59] and Panteli [52] the congestion problems will diminish with a growing amount of DG. Nonetheless, Dutch TSO TenneT and local DSO Enexis are currently postponing the permits and development of points of connection to the grid for DG projects in rural areas where the grid is weaker [41]. This trend will only rise with more projects being developed because of cheaper land in rural areas.

The research of Staudt [62] confirms that future plans for grid expansion will not be sufficient to cope with congestion problems that will arise with a large fleet of EVs without charging in a smart way. Since the transmission capacity of the grid only needs to be as large as the maximum peak production or load. There are different solutions for congestion relief through different mediums. An overview of these solutions is presented by Mcpherson [45]: curtailing the (variable renewable) electricity production, increasing the flexibility of the grid, demand response, energy storage systems (ESS) and higher transmission interconnection. Because both TSOs and DSOs have public interests and therefore the goal to maintain grid stability and power quality while minimizing the costs of transmission. The solutions of demand response and ESS pose to be one of the key commercial parts in reaching flexibility of the grid.

In the *TenneT Annual Market Update* report of 2018 there was publicized that electricity prices have risen in central-west Europe. The price increase in the Netherlands was higher, from 39.3 € /MWh to 52.5 € /MWh, than the average west-European price increase [68]. This increase in prices is mostly due to the rise of the fuel- and emission prices with the latter reaching nearly 30 € /tCO2 in 2018 in comparison to the 5 € /tCO2 in 2016. There is also a clear rise in volumes traded on the intraday market which can be led back to the increase of VRE in the energy mix. The report also states an increase in remuneration for the balancing services: FCR, aFFR and mFFR. This increase in remuneration is the result of new regulation measures in the European electricity balancing guideline narrowing the market. It also demonstrates that the growing capacity of VRE in the energy mix resulted in more congestion managing problems. The costs for these problems were € 53 million, which is an increase of 16% in comparison to the previous year.

Lastly, a new innovation is occurring in retail markets due to developments in smart meter technology and the availability of real-time data. This better availability of information results in more efficient wholesale markets and allows the final-user to adapt their consumption on the retail price and is called dynamic pricing. A dynamic electricity price contract is defined in *the Clean Energy package* as [24]:

> ”An electricity supply contract between a supplier and a final customer that reflects the price at the spot market or at the day-ahead market at intervals at least equal to the market settlement frequency.”

Since the majority of an average electricity bill consists of non-energy components: taxes, network operation costs and policy support costs. Consequently, there is a relatively weaker price signal to shift consumption based on price volatility. Although this is seen as relevant to the decisions for the power system design for industrial clusters it is outside the scope of the research since it is strongly dependent on future electricity pricing and regulations.

2.2.6. Relevance to industrial clusters

Since industrial facilities often have a large power demand to perform their operational processes they have (multiple) large connections to the electricity grid. The costs for these point of connection are not transparent in the majority of the cases because of confidentiality in the contracts to maintain a competitive advantage. The network fee is compensation for the transmission of electricity and the point of connection to the electricity grid. These costs are paid to the local DSO to construct and maintain the regional grid. The costs of this point of connection are public until the size of 10 MW. The Dutch DSO *Stedin* asks € 197.649,00 for a 1.75MW up to 3.0 MW connection and € 270.000,00 for the construction of a 3-10 MW connection in 2018. Thereafter, a yearly amount of € 1.505,00 in the 1.75 - 3 MW range and € 7.670,00 in the 3 - 10 MW range. For a connection larger than 10 MW the design and costs are custom and most often confidential. Therefore, there is no good availability of data. The connections of industrial clusters are often larger than 10 MW especially in the case where the process of a high temperature of machinery are involved.

Next to the point of connection there is a transmission fee. This consists of a fixed and variable part. The variable part is dependent on the contracted consumed power and the month peak power. The fixed contracted part is the amount of maximum power(kW) the industrial cluster is assuming it will use at any point in the year. The DSO can also demand costs for reactive power to stabilize the grid and which cannot be used for powering of the machinery. When the fixed contracted maximum power is exceeded, this will have costs impact. Since the new contracted maximum will be imposed retrospectively for the rest of the year. The extra costs can be in the range of thousands to ten-thousands of euros at large scale. With a clear demand from society to decarbonize the processes of large industry the energy consumption will partly be electrified. Demanding larger electricity consumption and consequently larger capacity connections to the grid. As a result, the grid’s capacity also needs to be upgraded to transmit all peak consumption. In 2016 a study performed by Ecofys on the energy prices and costs per EU nation showed that the network component of the energy cost for industrial users increased from 13 € /MWh in 2008 to 17€ /MWh in 2015 [8]. Therefore, in a scenario where costs for point of connection will be higher and networks costs are more expensive. It will get more interesting for industrial connections to be less reliant on the grid and be more in charge of their own energy production and consumption.

Section 2.2.4 states that each connection to the grid that is contracted to transmit more than 60 MW is obligated by law to make bids in the imbalance market. Since 2014 it is also mandatory for capacities > 5MW that are able to be activated within 30 seconds to bid for primary control (FCR) in the market. The winning bids get a compensation based on capacity and not for the energy delivered. During the course of this study the auctions have shifted from weekly occurrence to a daily basis during weekdays. Additionally, plans are presented to have daily auctions with a 4 hour option. This will give more flexibility to the allocation of production or storage capacity. A result might be reduced prices due to lower uncertainties and more optimized allocation of production and demand.

The problem of double taxation for energy storage is only an issue for the industrial cluster when the operation strategy of price arbitrage or ancillary services are implemented. The first is the service where electricity is bought (withdrawn) from the grid at the moment when the market price is low and sold when the price is high. Staffel [61] performed the study of a combination of arbitrage and reserve balancing in the British energy market and was only profitable in the cases with perfect foresight. It stated that the dynamics of the market towards a daily dynamic price will have a positive influence. Additionally, will a more transparent remuneration for additional services help to make the ESS business case viable. In the next chapter the additional services are discussed more extensively.

2.2.7. Summary

The liberalization of the Dutch energy market has increased competition between generators and suppliers. The transmission and distribution is still state-regulated because they have monopolistic powers. There is a constant mismatch between the supply and demand of electricity resulting in imbalances of the system. To cope with this, the system operator demands ancillary services that response to these imbalances. With the trend of electrification in the society and a larger penetration of VRE the need for these ancillary services tend to be growing. However, with the large deployment of VRE, in the form of distributed generation, there is also electricity being generated at the conventional consuming side of the value chain. This new role of prosumer makes interactions and flows in the grid more complex. The original architecture of the electricity network was based on more centralized generation that would feed in the transmission system, and then transformed to the distribution systems. Therefore, the whole design for the control, security, power flows and market exchange was based on a centralized generation model with large generation nodes.

When the amount of VRE penetration will rise above the networks threshold changes in the design of the network is needed. The problem of lack of flexibility could be tackled by demand response, upgrading of the network and storage. On one hand, it has proven that demand response and ESS have not been deployed on a large scale predominantly due to lack of clear regulation, the need for stronger price-signals and reduction of technology costs. When network operation, flexibility and policy support costs will increase it will get more interesting for the industrial cluster to be more in control of their energy consumption from an economical perspective. On the other hand, is there already a lot of pressure on industrial players to integrate VRE in their energy system and therefore ESS could be of added-value to use this energy adequately. Clear regulations and remunerations for services performed by an ESS surmounts these obstacles and stimulates the industry to use ESS in an optimal way by performing multiple services in parallel. The ESS could have an impact on the generation, transmission and distribution and consumer side of the electricity value chain. The next chapter elaborates on the legislation and evaluation of services that are relevant for the development of ESS at industrial clusters.

2.3. Energy storage

2.3.1. Introduction

This chapter will elaborate on the concept of the ESS. First, in section 2.3.2 an overview with the different means of energy storage and technologies is provided. Second, in section 2.3.3 the need for storage is demonstrated. Third, in section 2.3.4 an overview of the different services that the ESS is able to provide is presented. Next, in section 2.3.5 describes how energy storage fits in the power system of an industrial cluster and its surrounding larger system. There-after is described how ESS are evaluated in different levels of the power system. Lastly, in section 2.3.6 an overview with the findings is given and demonstrated how this will contribute to this research regarding evaluating ESS for an industrial cluster.

2.3.2. Technologies

As mentioned-above, there is often a mismatch between the moment of consumption and production of electricity. Therefore, the amount of electricity must always be equal to the varying demand. The imbalance between these two can result in decreased stability and power quality affecting all appliances connected to the system. The point of production of energy in the conventional energy system is often far from the location where it is consumed [33]. Resulting in transmission losses and requires large investments. This diminishes with DG but still requests for solutions to cope with the intermittent character of DG. Solutions can be short and long-term energy storage. Energy storage is the transformation of electrical energy into an energy form that can be utilized for future operations [18, 33]. Generally, the different forms of storage are categorized in chemical, electro-chemical, mechanical, electrical, and thermal systems. An overview is given in appendix A.2. Most common benchmarks while comparing different technologies are the energy capacity (Wh), power (W), round trip efficiency (%), energy density (Wh/ M*3),specific power (W/kg), power density (W/m83) and self-discharge (due to internal resistance or side-reactions) used by Ibrahim, Lazard, Das, Zhao and Durand [18, 20, 31, 39, 76]. Some forms of storage are more developed and deployed technologies than others. In the next few paragraphs, the best-known storage technologies and their merits are described briefly.

Mechanical

The largest amount of energy storage technology capacity currently in place are **pumped hydroelectrical systems** (PHS) with around 169 GW of power, accounting for 96% of all installed ESS types operational in 2017 [34]. Conventionally the PHSs consist of a higher and lower reservoir where water is either pumped to the higher reservoir, consuming energy from the grid or vice versa by turbining, injecting power into the grid. PHS is able to store and provide energy in large quantities and provide power for hours. The technology has a long operational time and can deliver energy at a competitive cost. However, the environmental impact is often very big. Massive civil works are needed for the water reservoirs while also modifying the natural water flows. Besides are there often geophysical constraints for the construction of PHS and therefore not all locations are suitable or close to the location of energy load.

Compressed air (gas) energy storage (CAES) is a mechanical storage technique where the energy is converted into potential energy. This is performed in the form of compressed air in an underground storage cavern or above ground in pressure vessels. If the stored energy is needed it is extracted from the cavern and used to drive the expander of a turbo or piston. Before release the air needs to be heated to make sure that the expander does not freeze. Depending on the size of the cavern or storage vessel, the capacity can be very large [28]. However, the low efficiency and limitation of suitable geographic locations are disadvantages.

In the **flywheel energy storage systems** (FESS) the energy is stored in the form of kinetic energy of a rotating disk. The flywheel is rotated by an electric motor or other transmission device and the disk is supported by magnetic bearings and a vacuum to reduce friction and energy loss. The perks of the advanced FESS are a long operational life, low maintenance, and high power density. A disadvantage is its high self-discharge due to friction. Therefore, being only suitable for a small spectrum of services.

Electrical

Electrochemical double-layer capacitors (DLC), also more commonly known as **supercapacitors**. The electrochemical cells contain a conducting electrode an electrolyte and a porous membrane that allows ions to be transit between the electrodes [28]. They fill the gap between ordinary capacitors and batteries. They have very high cycle-ability and high power density, due to very low inner resistance they are characterized to have very fast charge and discharge possibilities. Other advantages are high efficiency in the range of 90% [28, 33] and are easily recycled. Although they can reach very high power density, their energy density is very low. Therefore, they are in the same operating range of flywheels with short charge and discharge time due to their high self-discharging rate.

In the **superconducting magnetic energy storage system** (SMES), the energy is stored in a magnetic field. This field is created by a direct current going through a superconducting coil at cryogenic temperature. Because the coil is kept at cryogenic temperature there is almost no resistance in the material resulting in very little energy loss. The main advantage is the high power density, fast response time and round-trip efficiency. However, its reliable output is very dependant on the functioning of the refrigeration system.

Chemical

synthetic natural gas (SNG) and **hydrogen** are secondary energy carriers and are one of the forms to storage electrical energy through the process of electrolysis of water into hydrogen. If processed further through the process of methanation resulting in SNG. Both processes are known as power-to-gas (P2G). This can then be transformed back to electricity through fuel cells by oxidizing the gas form. The production of chemical storage is often done with an excess of electricity because the efficiencies of these transformation processes are relatively low in comparison to PHS or Li-ion. On the other hand, it has the ability to store the energy in very large quantities (TWh) and for larger periods of time up to seasonal storage. Besides it is widely applicable in all sectors from transport, heating, to the large industry. Although this form of electrical energy storage demonstrates high potential the relatively low energy efficiency and the lack of large infrastructure for transport in place ensures that it has not yet been implemented on a large scale.

Thermal

In the case of thermal energy storage (TES) the electricity is transformed in high/low temperatures in the material in insulated containments. Overall round trip efficiency is considered to be fairly low (30-60%) [15]. TES can be categorized in sensible heat, latent heat, cryogen and thermo-chemical. **Sensibel heat** is the best-known with domestic water tanks as an example. A liquid such as water, oil or a solid is used as the storage medium. The capacity is characterized by the specific heat and mass of the medium. **Latent heat** is the energy that is exchanged during a phase change of for example liquid to solid state [33]. **Cryogenic** (e.g. liquid nitrogen or liquid air) is generated from an excess of electricity. When the energy is needed the cryogenic material is heated by the ambient surrounding and used to generate electricity with a cryogenic heat engine [15]. *Thermo-chemical heat storage* is energy stored in chemical substances that are the result of an endothermic reaction. The recovery of the energy is done by recombining the substances in an exothermic reaction. The amount of heat stored and recovered is dependent on the characteristics of the reaction.

Electro-chemical

This subsection describes the different types of batteries that are most commonly used. The first group and most used are the rechargeable or **secondary batteries**. They consist of an anode and cathode of specific materials with an electrolyte and a separator in between. They convert electrical energy into potential chemical energy while charging and, release electrical energy from the chemical energy during the discharge. They are all based on reduction and oxidation reactions (Redox reactions). The ions flow from the anode to the cathode enabled by the electrolyte while discharging or vice-versa while charging. The electric potential between the electrodes determines the state of charge [28]. Batteries commonly have high energy efficiency (60-95%)[15, 28] depending on the materials used. With their modular nature, they can scale in energy capacity and rated power. The majority of secondary batteries is not very suitable for high power services. However, Lithium-ion combinations have shown that they are able to provide these services and are especially used in the EV industry. Most known secondary battery technologies are: lead-acid, nickel-cadmium, sodium-sulfur, sodium nickel chloride, and lithium-ion. A disadvantage is that most secondary batteries use toxic materials and are not always easy to recycle. **Flow batteries** The operating principle is almost the same as with secondary batteries. The electro-chemical redox reactions take place in the electro-chemical cells. However, the electrolyte is not stored permanently in the cells but pumped around and contained in separate tanks instead. During charging or discharging the liquid electrolyte is pumped through the cells and reacts with the electrodes according to the redox reactions for charging or discharging. The main advantage of the flow batteries is that the energy capacity is a function of the size of the electrolyte tanks and therefore easy to expand. There is also very low self-discharge and low maintenance required. They are also characterized by high amounts of cycle-ability.

Figure 2.4 shows an overview of all discussed technologies demonstrating their rated power and energy capacity relative to each other. The comparisons are of a general nature because some technologies have a broader discharge time, power rating. However, it does give a good indication of the operation possibilities for the different technologies. Figure 2.4 was extracted from a report from Frauenhofer institute, Germany in 2019.

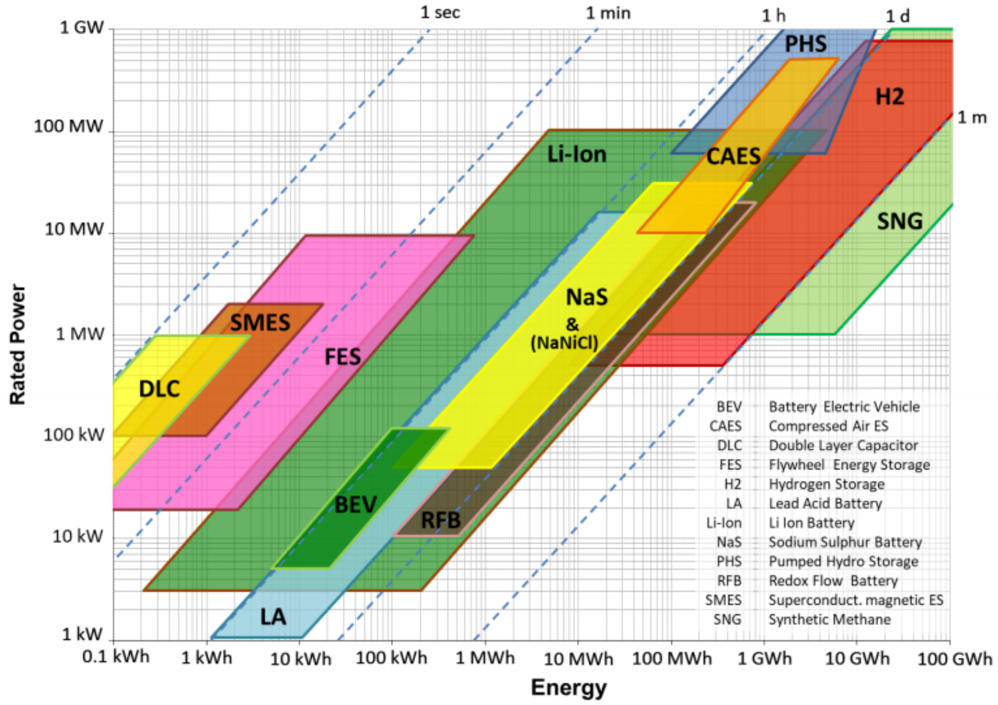


Figure 2.4: Comparison of energy capacity relative to power rating and discharging time of various energy storage technologies. This is a general overview of available data of the different technologies and gives an indication of the relative operation possibilities of the different technologies. Used with permission of Frauenhofer ISE [35].

2.3.3. Problems - demand for storage

As mentioned in section 1 the Dutch electricity grid is a complex, enormous physical and human network connecting millions of consumers to generators with both public and private enterprises. Which operates and needs to meet the minute-to-minute changes in load and output. The electricity flows through the transmission grid via the way with the least resistance from generators to the consumers. However, exact individual flows cannot be controlled with precision [44]. Restrictions of line flow, voltage and stability limits could impair the performance of the grid and therefore require central coordination of the real-time operation of the power system. With higher penetration of VRE in the grid and a diminishing amount of synchronous generators, the need for more flexible system devices is growing. There are four flexibility options that can contribute to a more stable grid with a larger amount of VRE.

This chapter focuses solely on reviewing the possible services that ESS are able to perform for the grid and an industrial cluster. ESSs are able to support both grid operators and end-users to provide a stable, and constant energy supply. In the next section, the different services are selected from the perspective of the industrial cluster and discussed more extensively. However, it should also be considered that demand response, flexible alternating current transmission system (FACTS) devices and upgrading the electricity grid in a smart way will be needed for a reliable future grid.

2.3.4. Definition and selection of services

ESS are multi-application systems since they can generate value by performing multiple services at the same time. The generated value is either by direct services performed on a contracted basis between parties or by positive external effects influencing the system as a whole. The actors within the electricity system are separated in the following groups: Generators, transmission network operators, distribution network operators, and small & large consumers. Because of the high investment costs needed for storage projects, it is stated that to maximize the social welfare generated by the technology the multiple revenues need to be stacked [21]. If these services are considered separately the ESSs will only be utilized partially and therefore not operated optimally, resulting in decreased benefits of the ESS. To be able to clearly allocate the merits and costs of the operation it is important to have a clear overview of the different services that ESS is able to provide. In table 2.1 an overview is given of the different categories of storage services along the entire value chain of the electricity grid. These services are categorized in Generation, Ancillary services, Transmission, and distribution infrastructure services and Customer energy management services also referred to as the end-users.

BESS services				
Generation/ Bulk Services	Ancillary Services	Transmission Infrastructure services	Distribution Infrastructure services	Customer Energy management Services
Arbitrage	FCR	Transmission investment deferral	Capacity support	End-user peak shaving
Electric supply capacity	Secondary frequency control	Angular stability	Contingency grid support	Time-of-use energy cost management
Support to conventional generation	Tertiary frequency control	Transmission support	Distribution investment deferral	Power quality
Ancillary services VRE support	Frequency stability of the system		Distribution power quality	Maximizing self-production & self-consumption of electricity
Capacity firming	Black start		Dynamic, local voltage control	Demand charge management
Curtailment minimization	New ancillary services		Intentional islanding	Continuity of energy supply
Limitation of disturbances	Voltage support		Limitation of disturbances	Limitation of upstream disturbances
			Reactive power compensation	Reactive power compensation
				EV Integration

Table 2.1: Overview with different services that ESS are able to perform for the different segments adapted from the roadmap of energy storage [20], Zame [75] and Diaz-Gonzalez [28].

Depending on the position along the value chain of the power grid the storage facility is capable of performing more of the services listed above. The remuneration of these services is shaped by the regulatory authorities. The services that the ESS is able to provide is often depending on the position in the value stream as presented in figure 2.2. The lower in the value stream the more services it is legally able to provide to the different levels of the power system. As mentioned in 2.2.2 the DSOs and TSOs are heavily regulated because of their natural monopolies. Along with the trend of a more unbundled grid, this research assumes that the ancillary services (AS) will stay tendered in the Netherlands. In the scope of this study, the ESS are implemented behind-the-meter within the distribution grid of the industrial cluster. Since the ESS is operated behind-the-meter there are no regulatory restrictions for providing the different services other than the physical limitations of the technological characteristics of the system. Since front-of-the-meter are more regulated assets that operate on a higher level of the value chain they need to comply with more criteria. An overview of regulatory boundaries per level along the value chain is provided by the Rocky Mountain Institute in figure 2.5[26].

With more VRE in the grid and industrial clusters also investing in their own VRE plants the internal operation of the power system will change and might influence the optimal process of the core business of the operations. However, there is a clear commitment from both the national government and the industry to include more VRE in the energy mix. Since the processes of industrial clusters are often associated with a high power demand, in-house VRE generation to supply this load might be a design solution. However, this VRE generation is often not well aligned with the energy profile that the process demands. Therefore, the implementation of a large VRE plant could result in the need for a larger point of connection to the distribution grid when the production and generation don't match. Resulting in higher costs for the end-user, the DSOs, and the TSOs. Being able to maximize production and self-consumption of the end-user may result in higher peaks for both the end-user and the DSO. While the operation strategy of peak-shaving will result in a less volatile point of connection and therefore in deferral for the need of grid reinforcement and changes in contracts.

The next ESS services are considered to be relevant at the site of an industrial cluster:

Maximizing self-consumption will help to integrate the energy generated by the owned VRE

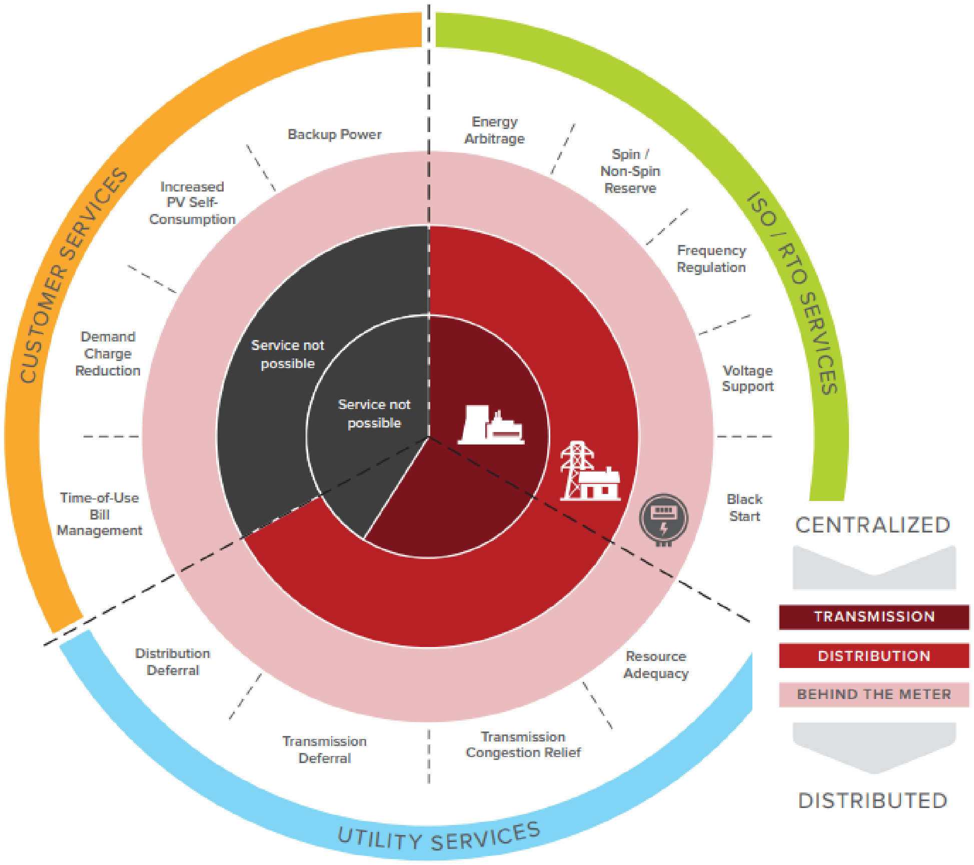


Figure 2.5: Services that ESS are able to provide in relation to their position on the value chain. Used with permission of the Rocky Mountain Institute [26].

plant in-house.

Peak-shaving will be the result of better control of reallocating the VRE generation to the moment of consumption. For the industrial cluster, end-user, the shift of overproduction of solar energy towards the end of the day can result in a less volatile energy consumption profile with lower peaks. Therefore, be eligible to reduce their month peak power and contracted power resulting in reduced costs. Additionally, the lower month power peak will result in a deferral of investment cost for the distribution operator discussed below.

Continuity of energy supply concerns the ability of the process to continue in the same or diminished operations in the case of an interruption in power supply for example during a blackout. In the conventional design, this is being performed by generator sets (gen-sets). A gen-set is a combination of an engine and an electrical generator that form a single unit that produces electrical power while consuming fuel. In this case, the ESS will provide transit power while gen-sets are being brought to operational speed. These are also often called uninterruptable power supply (UPS) units. Examples of places where UPS are in place are data centers, hospitals, and industries with processes that need to be shut down in a secure fashion. In this case, the back-up generation that facilitates the continuity of supply is often operated in spinning reserve meaning at a lower load to be able to ramp-up quickly. In other industries, it is also possible to be interrupted for a few minutes without being dangerous to the process. An example of this are water treatment plants. In this case the gen-set is stand-by heated to be able to ramp up quickly. Depending on the need for continuity of the process these set-ups are often in a N+1 (redundant) configuration. Because disruption of the electricity grid

in the Netherlands does not happen often, it occurred 24 minutes on average in the years 2012 - 2017 [50]. Although the Dutch power system is one of the most reliable in the world certain processes need to consider and be prepared for the scenario where there is a loss of grid connection. Therefore, designs including ESS, gen-sets or hybrids should be considered.
In the case, that there is a bad grid connection to the grid for the industrial site there is often electricity generation on-site. In this case, there is N+1 (redundancy) in the design. Meaning that the generator sets (gen-sets) are operated at a lower load to be able to ramp up in the case of a failure of either the grid or one of the gen-sets. It is currently researched if it is possible to reduce the number of installed gen-sets needed when designed in a hybrid system with energy storage.

Price arbitrage operation strategy: the ESS can be charged when the electricity price is low and be discharged during high electricity prices in the wholesale market.

Reactive power compensation relates to the ability of the ESS via power electronics converter to locally compensate the reactive power to control the voltage. When reactive power is injected into the system this power cannot be used for active work.

Power quality have the ability to maintain the voltage profile within acceptable boundaries. This is especially needed in the case of critical loads (operations) that need a stable supply.

Intentional islanding in the event of grid failure (black-out) the behind-the-meter ESS could temporarily provide electricity to the closed-network to mitigate downtime or ensure that the process reaches safe conditions to shut down in the case of a power outage.

The following services generate value on other levels of the power value chain when ESS is operated behind-the-meter from an industrial cluster:

Ancillary services : FCR, secondary reserve frequency, and tertiary reserve frequency. To maintain or recover balance between generation and consumption within the synchronous area. The exact details are discussed in section 2.2.4 and will be referred to as balancing services from now on. It is seen as the ability of the ESS to respond reliably, rapidly to fluctuation in supply and demand. It can be characterized along the three dimensions mentioned by Hsieh: absolute power output capacity range (MW), the speed of power output (MW/min), and the duration of energy levels(MWh)[30].

Deferral of distribution investment The ESS could aid the DSO by providing flexibility services which will diminish the need for additional transmission capacity.

VRE Support Better control of the VRE plants due to ramping limitations which will produce a more stable output which allow for higher penetration of VRE in the power system and therefore **curtailment minimization**.

This section identified the services that are most relevant for a behind-the-meter ESSs in a closed industrial network. The primary services will be performed and be measurable directly for the end-user, the industrial cluster in this case. These services will result in less dependency on the grid, better network operations, maximization of self-production and consumption of electricity and the possibility to provide flexibility services for the system operator or response to signals in the wholesale market. The planning and execution of these operation strategies can be performed in parallel but may influence the effectiveness of the services. The performance and importance of these services will also be affected by the set-up of the closed network, machinery, and processes within the network. In table 2.2 an overview is presented with the selected services relevant for an ESS facility behind-the-meter at an industrial cluster.

BESS services				
Generation/ Bulk Services	Ancillary Services	Transmission Infrastructure services	Distribution Infrastructure services	Customer Energy management Services
Arbitrage	FCR	Transmission investment deferral	Capacity support	End-user peak shaving
Electric supply capacity	Secondary frequency control	Angular stability	Contingency grid support	Time-of-use energy cost management
Support to conventional generation	Tertiary frequency control	Transmission support	Distribution investment deferral	Power quality
Ancillary services VRE support	Frequency stability of the system		Distribution power quality	Maximizing self-production & self-consumption of electricity
Capacity firming	Black start		Dynamic, local voltage control	Demand charge management
Curtailment minimization	New ancillary services		Intentional islanding	Continuity of energy supply
Limitation of disturbances	Voltage support		Limitation of disturbances	Limitation of upstream disturbances
			Reactive power compensation	Reactive power compensation
				EV Integration

Table 2.2: Overview of the selected services, highlighted in purple, that ESS are able to perform when situated behind-the-meter at a industrial cluster. Adapted from the roadmap of energy storage [20], Zame [75] and Diaz-Gonzalez [28].

2.3.5. How to evaluate

A multitude of studies has been performed on the economic prospects of energy storage. This has been done for all technologies mentioned in section 2.3.2. Multiple approaches can be used to get insight into the added value of energy storage. However, previous work has mainly focused on the optimization of singular revenue streams, different perspectives, context and tools used for specific cases. Besides they are often dependent on good or perfect foresight of the future regulations and electricity prices [61].

If the value of energy storage facilities is modeled they are often in engineering or system studies. They are often assessed as the techno-economic performance of a specific technology within a specific smaller system. These assessments are used by investors to determine if their investment will be remunerated within a specific time span. The earlier the break-even moment, the better the business case is for investors.

In the studies performed by Merei et al. [46], Luthander et al. [43] and Voulis [73] the criteria self-consumption and self-sufficiency are the common aspects to determine the performance of a power system design including PV and storage. The terms self-consumption and self-sufficiency are described by Luthander as the fraction of generated in-house electricity that is directly consumed and the fraction consumed self-generated electricity relative to the electricity demand.

The studies of Merei et al. and Bertsch et al. [6, 46] are techno-economic assessments. Optimization's of configurations of PV with storage are performed for both households and commercial buildings to analyze profitability. Both studies considered solely the optimization of self-consumption and a 2% annual increase of the electricity price. On the other hand did the *Annual market update of TenneT*, discussed in section 2.2.5, demonstrate that Day-ahead electricity prices have risen significantly more than 2% last year in West-Europe and even more in the Netherlands. Bertsch states that the costs of self-sufficiency for individual households have been quantified but that a study on the quantification of societal costs would also be relevant. The insight in societal costs could help to allocate the network and policy costs more appropriate.

In the study of Wade et al. [74] the ESS was simulated to provide services to the regional network improving voltage deviation, reverse-power-flow, and over-power. It showed that it is impractical and financially not viable to install an ESS that can provide a solution to all events within the regional network. As well they concluded that to establish the value of ESS a thorough understanding of the power system is needed on both the technical level and the stakeholders in the electricity supply value chain.

In the case of system studies, the goal is to demonstrate the impact on the larger energy system. These demonstrate the merits and demerits to society in the broader sense. An example is the study of Gissey [12] where centralized and decentralized coordination of flexibility of energy storage in the UK is simulated. Demonstrating that flexibility could reduce electricity price volatility. The largest difference between the engineering and the system studies will be the level of detail which will be included in the modelling of the added-value within the set boundaries of the modeled system.

As stated before in chapter 1 there is a need for modelling multiple services to be able to give a more appropriate valuation of ESS for an industrial cluster. However, as can be concluded from section 2.2 the value is also depended by the definition of ownership, market and contract structures.

2.3.6. Summary

To conclude, there is a large range of different storage technologies currently available. Primarily the application will determine which technology is more suitable. Hybrid solutions of technologies are also assumed to be part of future designs. There are multiple positions along the electricity value chain where ESS could be of added-value for different actors. However, not all actors are legally allowed to operate the ESS to its full potential due to certain market designs. However, for a behind-the-meter ESS at a closed network in an industrial power system, there are no institutional limitations to the performance of services. This will have fewer problems with regulations because it can perform multiple services without interaction with the grid and therefore is impacted less by the issue of double taxation when there is no closed network. When the ESS does perform services for the system operator there will be interaction with the grid should therefore be remunerated appropriately. The following services are determined to be relevant from the perspective of the industrial cluster on the electricity value chain: maximizing self-consumption, continuity of energy supply, peak-shaving, price arbitrage, ensuring power quality, intentional islanding, distribution upgrade deferral, reactive power compensation, ancillary services, and VRE integration support.

2.4. Knowledge Gap

The research for ESS has skyrocketed the last three decades. A major cost-reduction of certain technologies has taken place and regulations and market design are slowly picking up to create a policy regarding ESS. It is still difficult for decision-makers to invest in ESSs due to the uncertainty of the value of the services it can perform. Because the services are still difficult to quantify this research proposes a new addition to the existing technique to valuate the systems in a multi-dimensional way. Because not all decisions are based on the results of a techno-economic analysis. Hence, the drivers for decision-makers in industrial clusters are the security of supply, cost-reduction, flexibility, sustainability, and innovation. These drivers are not always easy to quantify. However, the investment in a large stationary ESS is a lump sum investment and remuneration of services is still very uncertain because they are very dependent on uncertain future prices. Other criteria are also variable or uncertain over time like ownership, technology performance, and change in market design or legislation. To make a substantiated decision, a trade-off between the potential benefits and shortcomings of the designs is needed. To do this, more insightful indicators are needed. Most studies focus on a singular revenue stream for determining the value of ESS due to the complexity of programming and an uncertain future. Consequently, leading to a misrepresented value of energy storage and less insight for non-technical decision-makers.
Because this research accepts that it is difficult to make hard statements about price and regulatory developments in the future it opts that the designs of ESSs should be scored differently. It proposes that the following two gaps could help decision-makers to make a more substantiated decision. Firstly, clear definitions and standards should be formulated to be able to communicate a clear scoring to the stakeholders. Secondly, this research states that a clear and well defined and commonly accepted definition of the services and criteria should be used as presented in table 2.1. Besides, there is an overall lack of energy storage studies in the Dutch power system especially focused on designs within industrial clusters.

As mentioned before, the scope of this research will be on the added-value of energy storage for industrial clusters. The industrial clusters are a geographic concentration of (competitive) firms or establishments that either have a close buy-sell relationship with other industries in the region, use a common energy transmission grid, or have a common goal to achieve more efficient energy usage and higher penetration of renewables that provides the firms with a competitive advantage of the same industry in other places.

The most important knowledge gaps that can be derived from the literature review are:

1. The definition of ESS within the larger electricity system
2. The relevant services of ESS for the industrial clusters
3. The relevant performance indicators for decision-makers to determine strategies for their local power system.
4. The influence of parallel performed services on the overall performance of the industrial power system.

3

Model

The main question addressed by this study is to give more insight into the added-value of ESSs in within the Dutch power system for industrial clusters. The focus will, therefore, be on an operational level developing metrics that are able to score the performance of a power system design without the dependency on future energy prices. The focus on the Dutch power market allowed for the model to be set-up within boundaries and regulations of the Dutch power system. However, the same model could also be used for different data-sets in different countries. On the other hand, the conclusions derived from the model need to comply with the larger technological and institutional system. Therefore, the relevant stakeholders, in this case, are the decision-makers of industrial clusters, DSOs, TSO and policymakers. In this chapter, a high-level representation of the system will be given in the conceptualization of the model.

Because the added value of the services that an ESS can perform is often still unclear this model gives more insight into the high-level operation of a closed network power system and its interaction with the grid. To determine the added value it is first necessary to get insight into the current situation of a power system in the closed network of an industrial cluster. In this simulation model, it is expected that there will be a rise of DG in the grid and that especially either industrial sites themselves or as a cluster will invest in their own VRE energy supply. Therefore, the goal of this model will be to give more insight into the results of a VRE plant with ESS within the power system in an industrial cluster. An additional objective will be the influence of different operation strategies of the battery on the performance.

The main goal of this study is to translate the quantitative data into interpretable performance indicators, which can give the foundation for substantiated strategy choices for decision-makers.

3.1. Model conceptualization

In this section, the different elements of the system and their behaviour is conceptualized to create the model of the industrial cluster power system. Following the facilities paradigm, the different interactions between the facilities are described. After-which the different operation strategies are described. Thereafter, the metrics will be explained that are used to determine the performance indicators of the model. With the remainder of this chapter discussing the data requirements.

System overview

The first part of the model is determining which components of the system are relevant for the simulation model. The clear scope will help to reduce the complexity of the total system and helps to determine an understanding of the relations and interactions within the power system. It will discuss the following five elements: the industrial load, VRE generation, the electricity grid, gen-sets, and the ESS.

In figure 3.1 a simplified overview is given of the interactions in a closed-network of an industrial cluster with their own VRE power plant.

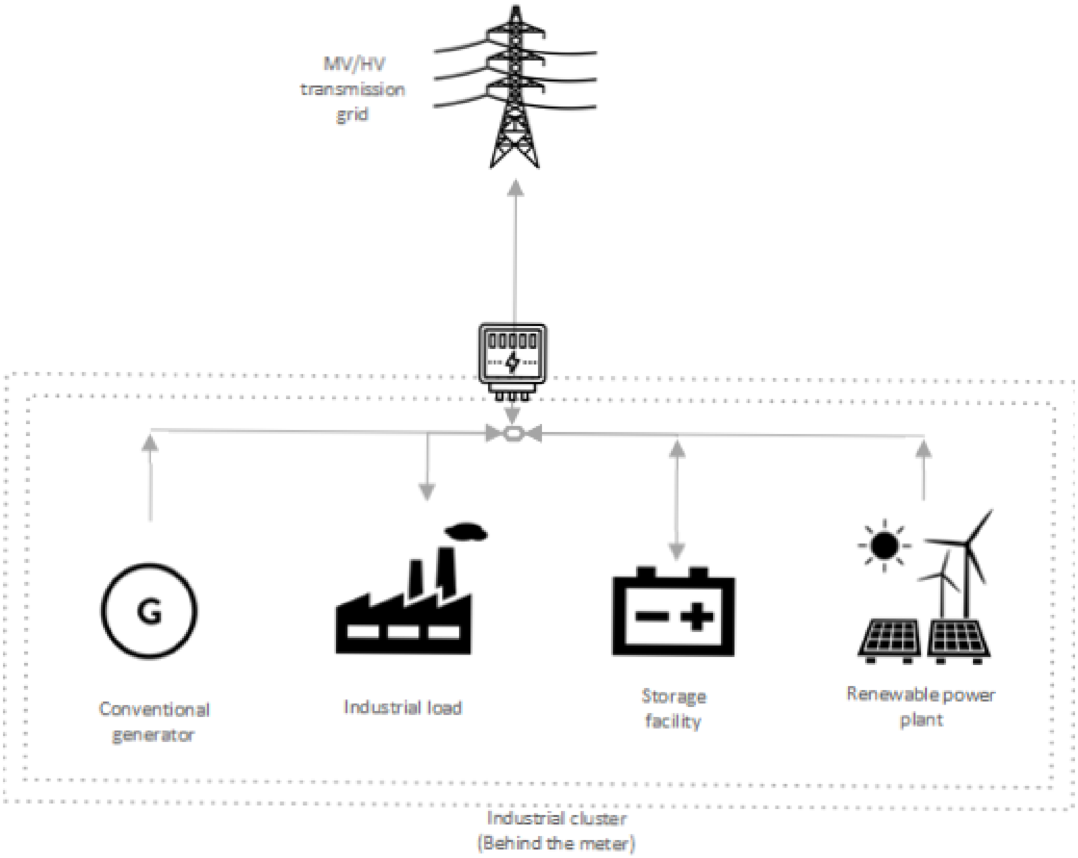


Figure 3.1: Simplified schematic overview of the power and load flows of an industrial cluster power system.

Industrial load The industrial cluster is either connected through a singular grid point of connection or multiple in the case of redundant design. Depending on the nature of the process that is being performed on-site there is a certain load-profile that can differ from being 24 hours, 7 days per week all year to batch production that occurs with a certain frequency per year. The need for continuous energy supply is also dependent on the nature of the operation. In the case of high-temperature furnaces or exothermic chemical reactions, it might be needed that processes are shut down in a safe and controlled manner. In the example of data centers, it is important that the servers have an uninterrupted power supply to make sure there is no loss of data. However, there are also examples where the production process does not need an uninterruptable power supply. The industrial load data will be an hourly consumption profile of 8760 times steps which is the equivalent of a full year (not a leap year).

The hourly consumption data resolution was chosen to match the PV-generation data. Most often consumption and generation data have an hourly or 15 minutes resolution. To build and test the model the load profile of a commercial building in the US was used. This data was retrieved from the *Open Energy Information* platform. This contains hourly load profile data-sets for 16 types of commercial buildings in the US and is published by the Office of Energy Efficiency & Renewable Energy (EERE). This data was used as a test sample for the construction and testing of the model. For the actual simulation load data of an industrial site in the Netherlands is used and was provided by a Dutch water treatment plant. Because the power consumed per hour is accumulated to a kWh per hour the assumption is made that there is a constant power consumption within the time step. This is plausible in the assumption that there is a constant process taking place. However, in the case of heavy-duty performances e.g. a hoisting crane that is hauling up a heavy load for a few minutes can result in a high peak load but would be averaged out over the hour in the data-set. Therefore, it is important to have some level of knowledge of the operation process to state that the data is appropriate for the model.

VRE Generation For the variable renewable generation plant the data from Renewable Ninjas is used. To reduce the complexity of the model it has been chosen to only simulate for a PV plant of variable size and not for wind energy. The choice to simulate PV instead of wind is the fact that there is stronger growth in installed on-land solar farms than on-land wind parks [67]. On the other hand, might it be interesting to also simulate wind power in the future because of the characteristics of solar PV production.

The data for the PV is weather data from global reanalysis models and satellite observations. The solar irradiance data that is used in the model is converted by the GSEE model (Global solar energy estimator) which is written by Pfenninger [55]. The data is a mean ratio between installed power and generated power output averaged over the time period, per hour in this case. Since this model is scoped to the Dutch power system it uses the aggregated data of the solar ratio installed power to generated power of the Netherlands. Therefore, the data for an exact location within the Netherlands could differ from the PV data that is used. The aggregated power ratio is hourly and comes with a UTC time stamp in the data-set. The choice for the averaged power ratio in the Netherlands gives a more generalized statement of the suggested power system design within the Netherlands. Additionally, the model assumes that the PV-plant is designed with power electronics which smooth the short-term power fluctuations that take place at the PV plant.

Electricity grid As extensively discussed in section 2.2 the Dutch power system is operated by the TSO and the transmission is kept at 50,00 Hz within predefined boundaries for all applications connected to the grid to operate safely. In the case of the simulation model, it is assumed that the industrial cluster is connected to the electricity grid. This is included in the design since DSOs have the obligation to provide access to the grid when requested and because the Dutch power system belongs to one of the most reliable in the world.

In the simulation, it is assumed that it is always possible to withdraw from or feed electricity back into the grid. There will be electricity exchanged with the electricity grid in the case that there is a mismatch between power generated by the PV plant and the required load at that specific time step. In the case that there is a shortage of PV and no discharge storage capacity available the electricity will be withdrawn from the grid. Electricity will be fed-in to the grid in the case when there is an overproduction of PV power and no charge storage capacity available.

The largest amount of electricity fed-in or withdrawn from the grid in kW will determine the capacity of the point of connection to the grid. As mentioned-above this assumption is only valid in the case when there is a constant process and (relatively) smooth power supply from the PV power plant. Although it is probable to assume that the point of connection/cable is able to physically withstand a sudden overshoot for a short period of time in power capacity without damaging or triggering the safety mechanisms. There might be a financial consequence as the fixed part of the power contract will be adapted and imposed retrospectively for the rest of the year as mentioned in section 2.2.6.

Gen-set In the event of power irregularities and even failure from the utility some industrial clusters rely on back-up power to guarantee continuity of power supply. Depending on the processes that are supplied there will be UPS or power supply needed within a specific time window. The design of the back-up generation is dependent on the considered emergency, legally required standby, and the amount of critical load within the studied power system. The conventional design of back-up generation is in parallel to the grid connection, as demonstrated in figure 3.1. These are often configured as an N+1 and redundancy design as opposed to the figure. This redundancy is designed to improve the reliability of the systems load when one of the generators is in maintenance or fails.

To make sure that generators are able to start within a short time window the diesel generators and gas turbines have engine block heaters. These engine block heaters add reliability to the system by preheating and maintaining the engine's temperature to make sure that the engine is capable to make a rapid and smooth performance. This is especially needed when the back-up is designed to provide a critical load at full capacity. Since the Dutch power system is one of the most reliable of the world the constant heating of the engine block could be seen as an unnecessary loss. Especially when the amount of energy (kWh) is accumulated over a full year. The size of the system is chosen to be to be 50% more than maximal demand since the optimum operational load is between 75% en 85% and there is a safety margin in the case peak load is higher.

ESS The ESS is considered to be a storage technology that is able to be charged and discharged at a high power rate. Additionally, it needs to have the characteristics to be scaled up to a high capacity to match the demanded energy profile of an industrial cluster. As discussed in section 2.3.2 battery energy storage systems pose to be a good fit with some technologies having high efficiency, power-rates and the ability to scale-up capacity. However, this research is not able to make a substantiated choice which storage system design will be the future large-scale storage technology due to the fact that the technologies are improving faster than expected [22].

The ESS will be discharged when PV generation is not able to directly provide the load of the industrial process until there is no stored energy capacity left. When the PV generation is higher than the required load the ESS will charge until maximum storage capacity is reached. Both the charging and discharging rate depends on the operation strategy. Because some technologies demand a specific minimum amount of energy stored to safeguard capabilities of the system the model assumes that the storage capacity can be utilized completely without damaging the system and that the operating management system of the ESS will safeguard these operational boundaries.

The power flows are simulated by tracking the following values:

- Volume electricity generated by the PV-system
- Volume generated electricity that is directly consumed
- Volume electricity consumed from the energy storage system
- Volume electricity stored in the energy storage system
- Volume electricity consumed from the grid
- Volume generated electricity fed into the grid

3.2. Model formalization

As mentioned in section 2.3.4 each service requires a different operation strategy from the management system of the ESS. Because services can be performed in parallel the performance of a singular operation can differ from when they are performed simultaneously. Although a considerable amount of studies have been performed on storage coordination, optimization and operation of singular services very few studies have focused on the multi-services for industrial clusters. This section will first discuss the services that are selected to be modeled. Secondly, it will describe how the operations within the power system within the model takes place. It will do this by providing a systematic overview of the algorithms that are simulated in parallel.

3.2.1. Model structure - Flow diagram

This section describes the outline of the model. The goal of the study is to provide a better understanding of the influence of combinations of different services for different configurations of energy generation and storage. Due to time and complexity restrictions, the services of greedy, peak-shaving, gen-set transit power and flexibility are simulated. The choice for these four services is primarily due to the availability of the conceptual algorithms, greedy and peak-shaving, from the dissertation of N. Voulis. Secondly, the service for flexibility is seen as a possibility to use ”idle” capacity of the ESS. Since the system is able to provide balancing services at transient level, in case of power shortage it can provide power into the network (injection) from the ESS. In the case of high power feed-in from other sources, the system can sink power from the network by charging the ESS (absorption). The ability to provide this service is derived from the interactions of the other services. As mentioned in section 2.3.4 this service is relevant for another segment of the value chain and therefore not prioritized within the operation of the ESS in this study. Nonetheless, should be considered that this is a commercial service and could have a significant impact on a potential business case. Lastly, the service to provide transit power when the gen-set is brought up to operational speed from cold-start.

The other relevant services for industrial clusters discussed in section 2.2: price arbitrage, power quality, reactive power compensation, intentional islanding and deferral of distribution investment are not included in this model. Price arbitrage has not been included since it is strongly dependent on the future electricity price. It is difficult to find literature that dares to make hard statements about future electricity price scenarios and the reports that do present them incorporate large uncertainties. Secondly, the deferral of distribution infrastructure investment is not included because numbers of this are often accumulated for the whole operation area of the DSO. As a consequence, it is difficult to quantify the impact of ESS without optimizing for a specific area. The same applies to the services of power quality and reactive power compensation. Both are location and power system specific and are considered to be out of the scope of this research. However, all of these cases should be considered as potential added value when creating a business-case for ESS in the setting of an industrial cluster.

In the next section, the services of enhancing self-consumption (greedy) and peak shaving are translated into algorithms. The concept for both the greedy and peak-shaving algorithm was based on the dissertation of Voulis [73]. The working concept was available, but a functioning code needed to be produced. Therefore, the concept of Voulis was adapted for this study and written in Python using Spyder 3.4. For the data handling, python’s Pandas library was used and to create the interactive graphs the library of Plotly. All data input was stored and read in CSV format. All data was formatted and sorted beforehand to be interpretable by the model. The model starts by loading the load- and generation profiles and operating services. Thereafter, the model will simulate the ESS operation strategy and electricity flows of the system for a whole year.

To detect what the influence is of including ESS for an industrial cluster the following operation configurations will be simulated:

1. Greedy storage operation strategy and flexibility
2. Peak-shaving and flexibility
3. Greedy storage, flexibility and gen-set energy reduction
4. Peak-shaving, flexibility and gen-set energy reduction

All configurations will be compared to a *business as usual* case and a case where PV is installed without an ESS. Additionally, there will be a comparison of different sizes of ESS storing capacity. The largest size of storage will be an *oversized* capacity that is able to provide a full day of load when completely charged. This will be compared to five smaller storage capacity configuration from 100%, 80%, 60%, 40%, 20% respectively. The difference in configuration size will help to demonstrate the influence of installed storing capacity and could help to set a scope for a specific business case.

For the determination of the different sizes of installed power of the PV park, the same sizing as in the research of Merei was chosen[46]. The size of the solar park is sized relevant to the maximum peak load of the scenario case. Meaning in the case of a 1000 kWp peak load, 100% indicates a PV park size of 1000 kWp. Because solar generation is irregular during the day this does not mean that 1000 kWp installed power provides a 100% self-consumption. Therefore, it will be tested for a 100%, 200%, 300%, 400% and 500% PV size. The overview of all compared configurations and outputs is demonstrated in figure 3.2.

To conclude, all configurations will be scored and compared according to the predetermined performance indicators which will be discussed in the next section.

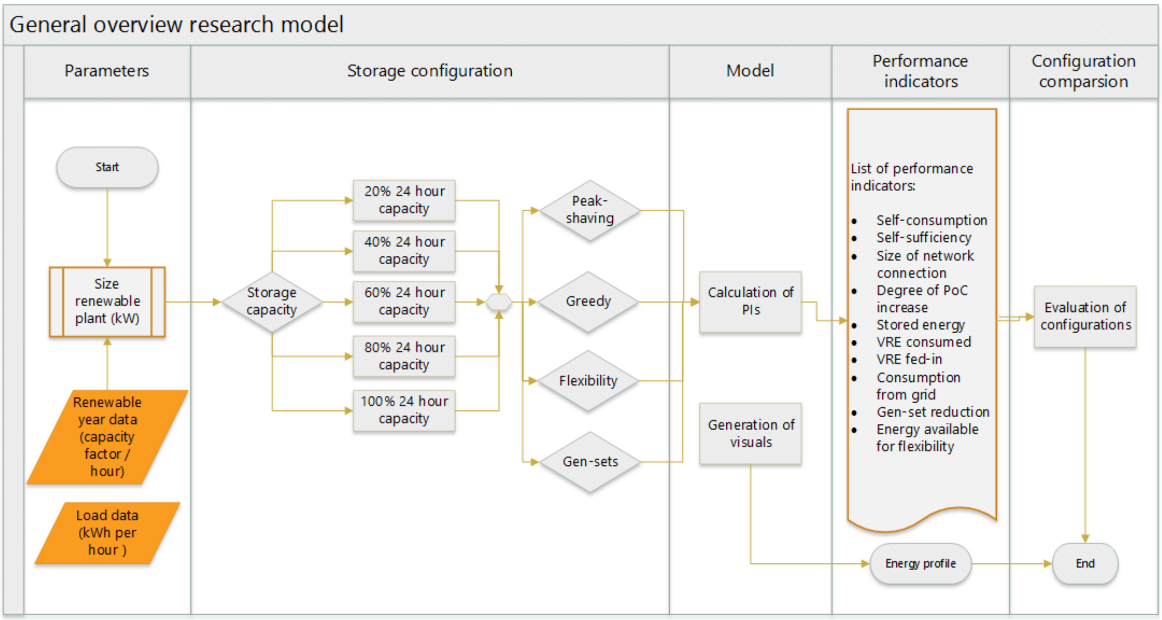


Figure 3.2: Flow diagram of the model. Illustrates the required data input in orange and provides an overview of the different operation strategies and output of the model.

3.3. Operation strategies

To get more insight into the effects of performing multiple-services this model will look at the greedy storage operation (self-consumption) strategy, peak-shaving strategy, flexibility, and gen-set reduction.

This section will address these services and operations in more detail.

Greedy-storage Is an operation strategy that perceives to fully use the storing capacity (kWh) of the battery. The operation is solely based on the mismatch between the VRE generation and the load for each time step. In the case that there is an excess of renewable production it will be stored in the ESS until the system reaches the maximum stored capacity. The available capacity is determined by the difference between the maximum storage capacity and the state-of-charge of the battery (SoC) at time step *t*. If the mismatch exceeds the available free storage capacity it will be fed-in to the electricity grid.

On the other hand, when the VRE generation comes short to provide the load the mismatch will be negative. In this case, the demand is completely met, or until all the stored energy is utilized. A systematic representation of the algorithm is shown in figure 3.3.

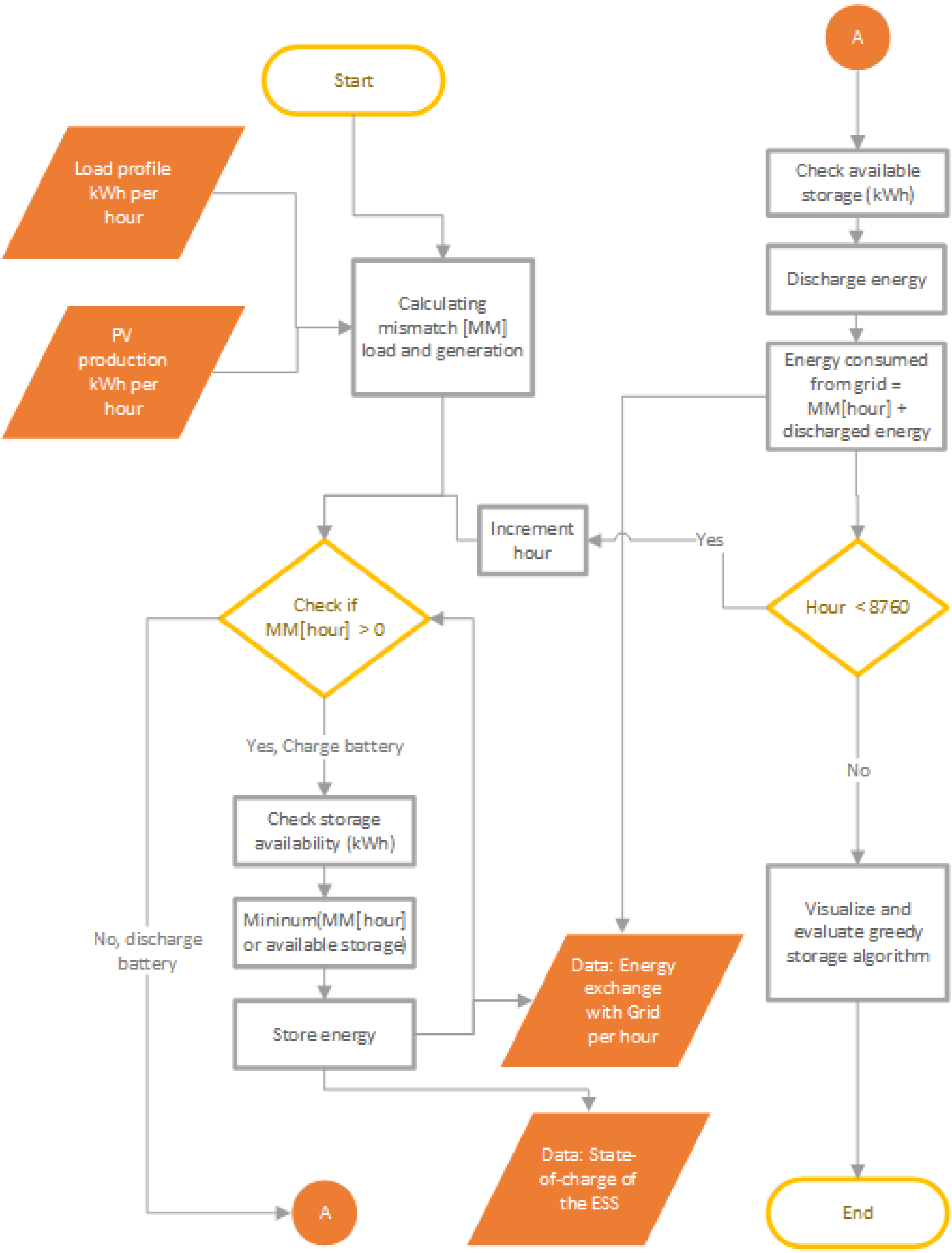


Figure 3.3: Flow diagram of greedy storage algorithm. Adapted from the dissertation of N. Voulis [73]

Peak-shaving Is an operation strategy that uses a predictable time *horizon* to forecast load and VRE generation quantities within the time *horizon* (from *t* until *horizon* in hours). It assumes that this mismatch can be predicted within the time *horizon*. In the case that there is an excess of VRE generation at time step *t* the algorithm considers the predicted mismatch and creates a vector for all consecutive positive mismatches within the assumed *horizon*. Thereafter, the *prediction* vector is sorted in descending order into a *sorted* vector while remembering the position of the original first load value in the *sorted* vector. Next, the differences between the subsequent elements of the *sorted* vector are stored in a *delta* vector. To maintain the same length the last element of the *sorted* vector is saved as the last element of the *delta* vector. The *delta* vector helps to prioritize the peaks from large to small within the time *horizon*. Based on the priority within the vector, storage capacity is reserved, *ResS*, to decrease the largest peak first proceeding to the smaller peaks. This routine is repeated until storage capacity is allocated for all mismatches (peaks) or until there is no available storage capacity left. Once all storage or peaks are reserved, the algorithm only stores the energy reserved for the time step *t*. If there is still an excess of VRE generation it is fed-in to the grid. On the other hand when demand exceeds the VRE generation at time step *t* the same routine for the allocation and reserving of energy to reduce the peaks takes place. This is all demonstrated systematically in figure 3.4

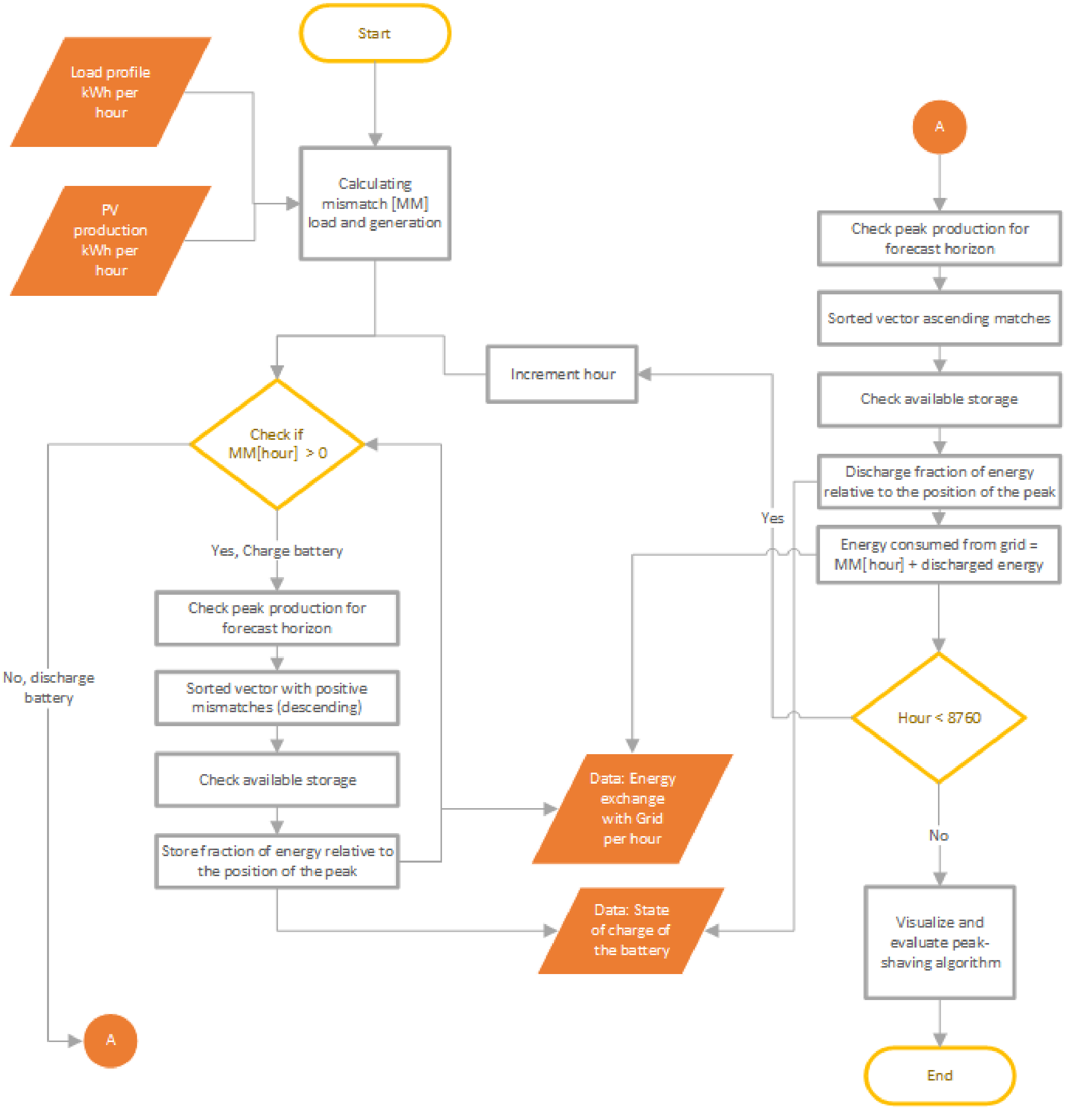


Figure 3.4: Flow diagram of the peak shaving algorithm. Adapted from the dissertation of N. Voulis [73]

Flexibility Flexibility is the ability of the ESS to either absorb power from the grid in the case of congestion or to feed-in power in the case of shortages. This ability for both consuming from and feeding-in to the grid is measured for all time steps.

Red. Gen-sets The reduced gen-sets energy service is only applicable in the configuration of the power system with an emergency diesel or gas generator. Since certain power systems are (legally) designed to have back-up generation deployable within 10 seconds after irregularities or power outages this service is relevant to an industrial cluster. To have diesel generators operable at full load within 10 seconds the engine block is constantly heated. Depending on the size of the diesel generator the energy used for heating is quite significant. By reserving a capacity from the ESS it is possible to transit the time that is needed to cold-start the diesel generator. This transition time is in the range of 20 to 30 minutes for large generators in which the ESS can provide the load from the reserved capacity and is verified with experts of which an overview is given in appendix A.4.

3.4. Output: Performance indicators

To determine the overall performance of the model multiple performance indicators (PI) were appointed. These indicators are set from the perspective of the industrial cluster. These PIs are based on the literature review and verified with actors from the sector from which summaries are given in appendix A.4. For the confirmation of the PIs derived from the literature review three experts have been interviewed. The goal of the simulations is to present the value of ESS for industrial clusters in a future scenario. This study will not focus on determining a return on investment in a specific timeframe since there is a high uncertainty on the development of future energy prices. This simulation aims to provide criteria on which decision-makers can decide how their industrial clusters fits in the market. This will help reevaluate how they operate and help reshape their business models for the future.

3.4.1. Metrics determination

The metrics are a mix of the multi-criteria decision analysis and optimization studies of Zhao, Murrant, Celli and Voulis of which an overview is given in appendix A.3. The performance indicators were chosen based on their ability to give insight in the performance of different designs with less dependence on future energy prices. Because the performance indicators demonstrate the degree of for example self-consumption, decision-makers can determine if certain configurations are more inline with the strategy of the facility. Since there is no data available for the energy consumption profile for multiple years the model only determines the performances of the configurations for one year. This model will provide more insight in the operation and added-value of ESS to the power systems from a industrial cluster perspective. Table 3.1 gives an overview of the performance indicators that are defined for this research.

#	Performance description	Explanation	Value
PI01	Degree of self-consumption	self-consumed / ttl generated PV	degree [0.00 - 1.00]
PI02	Self-consumption in MWh	self-consumed VRE	MWh
PI03	Degree of self-sufficiency	self-produced / load	Degree [0.00 - 1.00]
PI03	Degree not directly used	VRE delivered to the grid	degree [0.00-1.00]
PI04	Unused VRE in MWh	VRE delivered to the grid	MWh
PI05	Size of network connection	max exchange with grid	MW
PI06	Degree of connection	Influence on connection	degree [0.00-10.00]
PI07	Total consumption of the grid	dependency on the grid	MWh
P08	Energy reduction gen-sets	energy saved not heating	MWh
PI09	Flexibility	Capacity for absorption	MW
PI10	Flexibility	Capacity for injection	MW

Table 3.1: Overview of the performance indicators used to evaluate the power system designs.

3.4.2. Metrics explanation

In this section the established metrics will be explained. Firstly, the equations will be expressed in MWh electricity. The numbers are also transformed to evaluation scores relative to the *business-as-usual* (BAU) case. This makes it easier to interpret and compare. Next to the BAU case the configuration with solely PV, and PV with an ESS system is simulated.

The degree of self-consumption is a metric that helps to determine the amount of energy generated and consumed within the own energy system relative to the total generation of energy. In a system design without generation the degree of self-consumption is equal to 0. It gives more insight how much generated VRE is used within the energy system and an indication of the match between load and generation profile.

When a PV system is included in the energy systems, the amount of energy used directly by the load is equal to the generated power by PV-system . In when this power is lower than the load and equal to the load when there is an over-production. This overproduction is expressed in equation (3.1). In the configuration including energy storage this value is deducted by the amount of charged electricity. The quantity of directly used PV is demonstrated in equation (3.2). This formula results in an amount of electricity consumed directly within the system and is expressed in kWH. Because all metric calculations are performed for a full year with production and load available per hour the T is equal to 8760, the amount of hours in a common year (365 days).

$$UnutilizedPV = \sum_{i=t}^{T} unUsedPV(i) \tag{3.1}$$

$$Direct\ self\text{-}use = \sum_{i=t}^{T} (load(i) - Electricity\ Withdrawn\ From\ Grid(i)) \tag{3.2}$$

To determine the degree of self-consumption as declared by Luthander the accumulated directly consumed generated PV is divided by the total generated production of PV of the plant and demonstrated in equation (3.3).

$$Degree\ of\ self\text{-}consumption = \frac{\sum_{i=t}^{T} self\text{-}consumed\ PV\ electricity(i)}{\sum_{i=t}^{T} electricity\ generation\ from\ PV(i)} \tag{3.3}$$

To determine the degree of self-sufficiency, the amount of directly consumed PV generation is divided by the accumulated load. This results in a fraction and is easier to interpret and compare when looking at different designs. This is demonstrated in equation (3.4).

$$Degree\ of\ self\text{-}sufficiency = \frac{\sum_{i=t}^{T} self\text{-}consumed\ PV\ electricity(i)}{\sum_{i=t}^{T} electricity\ demand(i)} \tag{3.4}$$

To Determine the amount of unused VRE, the amount of surplus generated electricity which is fed back in to the grid relative to the configuration without storage is compared.

To determine the maximum capacity that is needed for the size of network connection to either withdraw or feed back in to the grid the maximum value of the interaction with the grid is determined.

Lastly, the total dependency on the grid is demonstrated by subtracting the amount of self-consumed PV generation calculated in equation (3.2 from the sum of the electricity consumption.

$$\text{total net consumption} = \sum_{i=t}^{T} consumption(i) - Direct\ self\text{-}use \tag{3.5}$$

To determine the capacity available for flexibility services to the DSO or TSO the stored electricity for injection and available storage capacity is captured for each hour. This will demonstrate the potential to trade on the imbalance market.

3.4.3. Data requirements and assumptions

The data requirements are based on the modelling conceptualization and operation strategies discussed in sections 3.1 and 3.2.

Both the data for load and solar irradiance needs to be transformed to hourly data if the data is expressed in 15-minute data it should be accumulated to hourly data. All data need to contain the same amount of data points, 8760. Which is the equivalent of *01:00 01/01/20XX* until *00:00 01/01/20XX+1* the subsequent year. The model is not able to handle data from a leap year. All PV data needs to be a mean power ratio between installed and generated power per hour. This makes it easier to adapt the size of the installed PV park but could be misleading when constructing a business case for a specific location. For the correct operation of the peak-shaving algorithm the load data cannot be equal to 0. If this does happen, e.g. when there is a maintenance, the load will be set to 0,1 kWh. For the efficiency, power rating and capacity of the ESS the manufacturers of the ESS technology should be contacted. In this case there is assumed that there is no physical limit to the operation, power rating and capacity of the ESS design. For the round-trip efficiency of storing the energy 90.25% will be used. Which is due to 5% energy loss during both charging and discharching. This number is conform other studies of lithium-ion technology storage systems[10].

3.5. Model Verification

To make sure that the model is working as it was conceptualized the computer code must be verified. Because computers will only operate how we tell them to operate and not necessarily what we want them to do this needs to be tested. This will be done by selecting relevant output variables that need to be monitored. The performance indicators from section 3.4 can be used for this. However, most of these indicators give a global results for the whole year and to see if the algorithms work as they were intended a closer look is needed. Therefor, all outputs for each hour and interaction between all components in the network and therefor the model is monitored and illustrated in the interactive graph. This allows the modeller to zoom in at specific moments in the data-set to make sure that the operations are performing according to the concept.

To verify the model the results of the system are plotted to monitor the behaviour of the power flows. For this purpose, all operation strategies where tested on their behaviour under extreme conditions. These test scenarios, in which parameters had extreme input values, the model should behave like expected. The following three scenarios have been tested for the greedy and peak-shaving algorithm:

Test scenario 1 where the PV-production never exceeds the load. As expected the ESS is not charged because the generated electricity by the PV is directly consumed and the rest of the electricity is withdrawn from the grid to provide the load.

Test scenario 2 where there is a small over-production from the PV, exceeding the load. As expected the ESS is charged with the positive mismatch between PV and load and discharged when there is no over-production.

Test Scenario 3 where there is a large mismatch between PV generation and load meaning that the ESS reaches maximum capacity and the exceeding amount of generation is fed-in back into the grid. Again, the model behaves as expected.

All test scenarios have been tested for all services. However, for readability of the study only the performances of a few test will be elaborated on. The test results for each independent service are presented in appendix A.5.

	Greedy	peak-shaving	gen-set reduction	Appendix ref.
TS1	✓	✓	✓	A.5.1
TS2	✓	✓	✓	A.5.2
TS3	✓	✓	✓	A.5.3

Table 3.2: Overview with the performances of the test scenarios described above.

The negative red line shows the consumption of electricity through the night when there is no sun available to provide the relatively low load at night. When the consumption starts to increase around 06:00 more electricity is consumed from the grid until PV generation starts to increase. The generated electricity is prioritized to be consumed directly by the load and only after over-production of PV will the battery commence to store energy. This process is continued until the battery is completely charged until maximum capacity or when there is no surplus. On the other hand, when there not enough electricity generated by the PV system to provide the load the ESS will discharge until the ESS is empty.

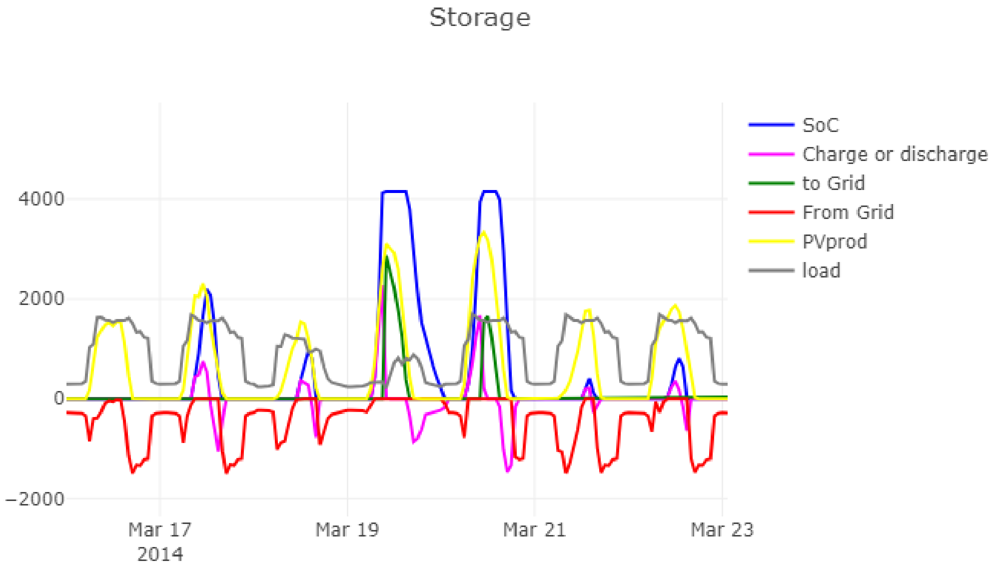


Figure 3.5: Representation of the greedy storage operation strategy for a day in March 2014. Load is illustrated in grey, generated electricity PV in yellow, State-of-Charge (SoC) in blue, charging or discharging behavior in pink, consumption in red and fed-in to the grid in green. All values are represented in kWh.

In figure 3.5 a week in March 2014 is represented and there can be noticed that the battery is not always charged only in the case of a positive mismatch between generated PV and the load.

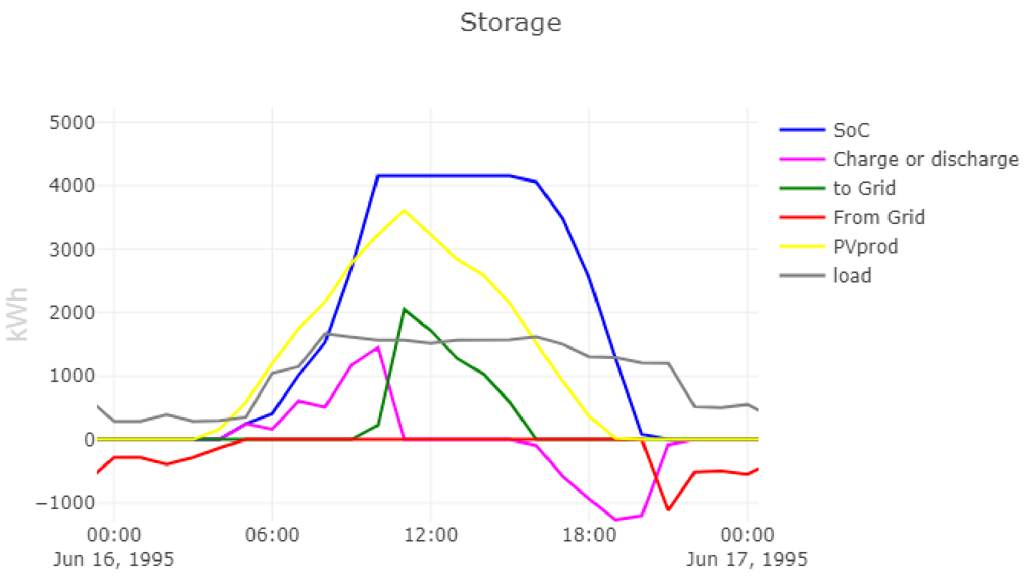


Figure 3.6: Representation of the greedy storage operation strategy for a day in June 1995. Load is illustrated in grey, generated electricity PV in yellow, State-of-Charge (SoC) in blue, charging or discharging behavior in pink, consumption in red and fed-in to the grid in green. All values are represented in kWh.

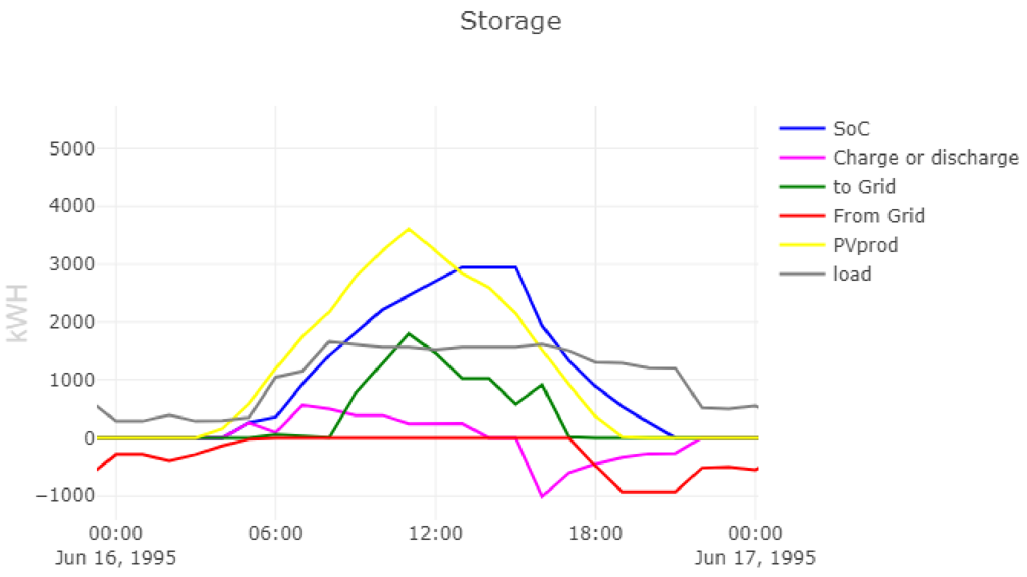


Figure 3.7: Representation of the peak-shaving operation strategy for 24 hours for a day in June 1995. Load is illustrated in grey, generated electricity PV in yellow, State-of-Charge (SoC) in blue, charging or discharging behavior in pink, consumption in red and fed-in to the grid in green. All values are represented in kWh.

When comparing figure 3.6 and 3.7 of the same date it clearly demonstrates a different behaviour of the energy storage management system. The battery is charged with at a lower rate to make sure that it is able to store energy during the peak of solar generation therefor reducing the short high peak fed back in to the grid in figure 3.7. Since the algorithm is not optimizing for increasing self-consumption but on reducing the peak-use on the point of consumption. The battery does not store until the battery is full.

The peak shaving algorithm has the possibility to adjust the amount stored based on knowledge of future VRE generation and energy consumption(load) of the assets. In the example of a five hour future time horizon with VRE surplus the algorithm allocates the amount stored to minimize the peak within that five hour horizon. This means that prioritizes the storage of larger mismatches within the time horizon. Meaning that if the largest mismatch is in 3 time steps (3 hours) it will reserve capacity for the peak in the three hours and reserve a partial amount for the time steps before. It will do this prioritization check for every time step.

3.6. Validation

Main purpose of the validation process is to show that the constructed model is suitable for its objective. Since this study aims to give more insights in the added-value of ESS for industrial clusters the question remains if the model allows to adequately address this. Hence, this study does not claim that the model can give an exact representation of the operation of an industrial power system. It was intended to give more insight in the power system to decision-makers in an interpretable manner. It will give more insights in to operation strategies and the influence on the selected performance indicators. The main source of validation was done by using existing theory on developing the operation strategies. Choices for behaviour of the specific parts (gen-sets) of the power system was validated with electrical and mechanical experts from the field expressed in summarized interviews in appendix A.4.

The model is validated through face validation by interpreting the performance indicators and plotting the behavior of the model.

Since there was no available data-set with exactly the same performance indicators used historical validation was not an option. Therefore, the outcomes of the model were validated with electrical engineers from *Eaton*, *Royal Haskonig DHV* and the TU Delft to provide confirmation on the acceptability of the generated outcomes.

The model was tested through the following two test:

1. Extreme conditions
2. Sensitivity analysis.

The extreme conditions brought a number of limitations to light. Some of these limitations could be resolved by additional programming and other needed to be resolved by adapting the data input. Due to a problem with the logic within the operations of peak shaving. The data errored when there was no availability of data or the data was set to 0. This only happened in extreme cases where the smart meter of the data is assumed to have malfunctioned, corrupted data or maintenance in the power system occured. To overcome this the 3 data points were set to 0.01 kWh load instead of 0 kWh. To cope with the problem of an exact match between amount of generated electrcity by the PV-system and the load, the data points were set to floats. As a result this exact match did not occur anymore and decreased the rounding error. Although this not increase computational time significantly for the size of dataset used in this study it could have mayor impact with larger data-sets with different resolution.

Additionally, sensitivity analysis was performed to determine that the simulation generates robust and realistic outcomes.

Next step in the validation process would be performing case studies to test the relevance of the determined performance indicators. It will also demonstrate how different processes within the industrial clusters will influence the energy profile and therefor the PIs. Additionally, the case studies with more detailed data, energy consumption and generation for 15-minute load profiles will show more accurate performance especially for processes that are more volatile.

3.7. Scenario description

To simulate how the model behaves under the influence of real-world data different scenario's are formulated. These scenarios describe the output of the simulation by changing the input variables. This section will give a short description on the approach used and the scenarios that are formulated. The simulations are run fun times for three different locations (scenarios), industrial connections to the grid.

The three scenarios are distinctive industrial connections to the grid for which iterative changes to the systems configurations within the location are applied. The different scenarios are chosen to demonstrate that different processes influence the energy consumption profile. Location A is a water treatment plant in the Netherlands and location B is a water pumping facility in the Netherlands, location C is a generic constant flat consumption profile. Figure 3.8 presents the three consumption profiles of the different locations. Both consumption profiles show that there is no seasonal influence on energy consumption patterns.

Load A has a volatile consumption profile however without very extreme peaks and within a specific range from the mean.

Load B has a more extreme volatile consumption profile with irregular peaks. In load B there are two dates: 07/04/2015 and 16/04/2015 where there is an hour where the load is equal to 0 in the original data-set and set to 0.1 kWh for the model to operate correctly.

Load C is a generic consumption profile chosen to demonstrate the influence of VRE generation with and without an ESS on a constant 24/7 energy consumption process.

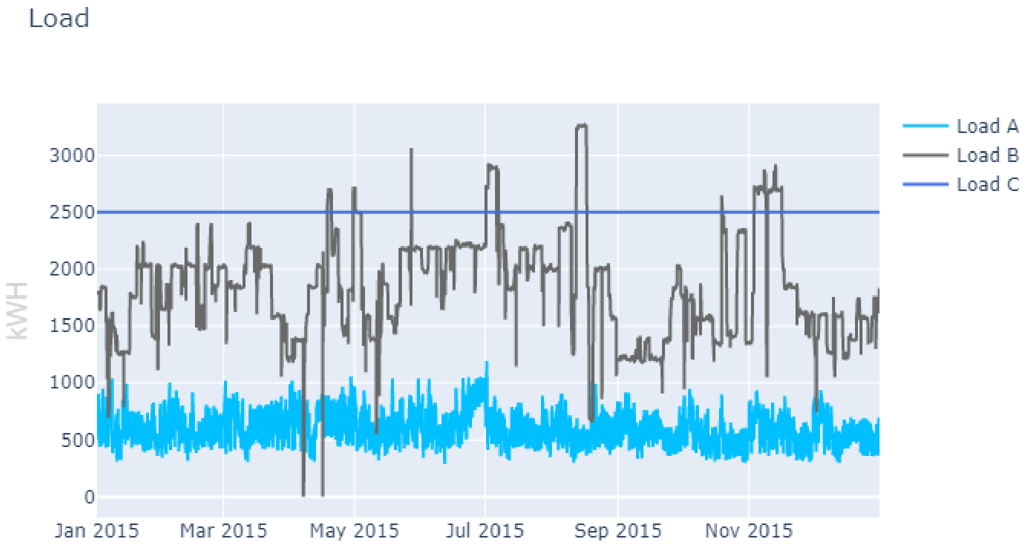


Figure 3.8: The load profile for the year of 2015 of the three scenario locations. Load A being represented in light blue, load B in grey and load C in dark bleu.

For each scenario different configurations of installed power PV and storage are compared. All configurations for the three scenarios are scored based on the performance indicators presented in table 3.1. Each configuration will be compared to *business-as-usual.* An overview of the different scenarios and configurations is presented in table 3.4. For each scenario and configurations a different combination of services will be tested to see the influence of stacking the different services on the chosen performance indicators. To keep the amount of results within boundaries the following key-performance indicators are chosen to be compared in chapters *Results* and *Analysis*.

#	**Key performance indicator**	Unit	original PI #	Neg-Neutral-Pos
KPI1	Degree of Self-consumption	[0.00-1.00]	PI01	0.45 > KPI1 > 0.75
KPI2	Degree of self-sufficiency	[0.00-1.00]	PI03	0.35 > KPI2 > 0.7
KPI3	Utilized VRE	MWh	PI02	5k > KPI3 > 10k
KPI4	Unutilized VRE	MWh	PI04	10k < KPI4 < 5k
KPI5	Degree of POC	[0-4.00]	PI06	2.5 < KPI5 < 1.5
KPI6	Capacity for absorption	MWh	PI09	100k > KPI6 > 200K
KPI7	Capacity for injection	MWh	PI10	100k > KPI7 > 200k
KPI8	Influence of gen-set service	%	PI08	binary [0-1]

Table 3.3: Overview with the KPIs that is compared in the analysis. With the scoring range described as Negative range, neutral range and the range for a positive score.

For each of the KPIs described in table 3.3 the influence of the different configurations are compared for the greedy and peak-shaving storage operations. Additionally, the impact of both operation strategies on performing flexibility service for the grid and reducing gen-set energy consumption are simulated. To compare the different operations a heatmap is created to determine which configuration scores best for the overall operation design. Since all KPIs have to be interpreted differently each KPI is interpreted differently and have different orders of magnitude. Therefore, the KPI of the configuration are compared and scored relative to performed positive, neutral or negative. The best score can either be the lowest in the case of KPI5, the degree of capacity for point of connection, or the highest as in KPI3, Utilized VRE. For the scoring a simple scoring system was used also used by Cartmell [11] to compare different scenarios for the integration of biofuels. The determination of the ranges of the independent KPIs is performed in hindsight and can be different when using other parameters. Each configuration is simulated for a system with only PV and a PV system with an ESS o see the influence and added-value of ESS to the complete power system. An overview of all simulated configuration is shown in table 3.4.

Configurations	Scenarios					
	Location A		Location B		Location C	
	PV	ESS	PV	ESS	PV	ESS
CF0	*Business-as-usual*					
CF1 PV	1.19MW	-	3.27 MW	-	2.5 MW	-
CF1 PV + ESS	1.19 MW	3.48 MWh	3.27 MW	14.15MWh	2.5MW	12 MWh
CF2 PV	2.38 MW	-	6.54 MW	-	5 MW	-
CF2 PV + ESS	2.38 MW	6.95 MWh	6.54 MW	28.30 MWh	5 MW	24MWh
CF3 PV	3.57 MW	-	9.81 MW	-	7.5 MW	-
CF3 PV + ESS	3.57 MW	10.44 MWh	9.81 MW	42.45 MWh	7.5MW	36MWh
CF4 PV	4.76 MW	-	13.08 MW	-	10 MW	-
CF4 PV + ESS	4.76 MW	13.91 MWh	13.08 MW	56.60 MWh	10MW	48MWh
CF5 PV	5.95 MW	-	16.36 MW	-	12.5 MW	-
CF5 PV + ESS	5.95 MW	17.39 MWh	16.36 MW	70.75 MWh	12.5MW	60MWh

Table 3.4: Overview with all simulated scenarios and configurations in this research.

The size of the installed peak power PV is determined to be relative to the largest peak load and then scaled from 100% up to 500% peak load. The choice for these steps was based on the research of Merei [46] which performed a optimization of PV-battery systems in commercial applications. The size of the storage capacity is also determined to be relative to the largest peak load. The capacity is then set to be enough capacity to provide electricity for 24 hours when completely charged while considering the loss during discharging. In table 3.5 an overview is given of the values of the provided data-sets. Again needs to be stated that assumed is that the process within the hour is stable and therefor the peak transmission can be expressed in MW based on the MWh value.

Scenarios	24 hour load	max. peak load	month
Location A	17393.58 kWh	1190.3 kWh	March
Location B	67211.4 kWh	3271.2 kWh	August
Location C	60000 kWh	2500 kWh	-

Table 3.5: Overview with the consumption data for the sizing of the storage capacity

4

Results

In the following chapter the results of the simulated scenarios are presented and elaborated on. The simulation consists of a set of three separate scenarios over which 10 parameters per scenario are varied. The 10 parameters represent the five configuration without and with an ESS. Each configuration is simulated for a full operational year consisting of 8760 time steps with each time step representing an hour of real-world time. Resulting in 13 outputs per parameter change. The experiment is performed in five different parts. The performance indicators are described more extensively in section 3.4.

Part 0 Influence of the choice for combined increase of PV and ESS per configuration.

Part I Influence of the different configurations for each scenario on the self-consumption and self-sufficiency.

Part II Influence of the different configurations for each scenario on the total utilized and unutilized VRE.

Part III Influence of the different configurations for each scenario on the degree of point of connection to the grid.

Part IV Influence for each scenario and configuration on the capacity providing flexibility services to the grid.

Part V Influence of the different configurations for each scenario of the service providing transit load.

During the interpretation of the outcomes of the model there should be noted that the figures offer an indication. Therefore, the results should be interpreted by order of magnitude. The results are a product of a simulation that is based on assumptions. When deriving conclusions from the model or repeating this research these assumptions have to be considered.

4.1. Influence configuration choice

Before elaborating on the specific performance indicators the influence of different configurations of installed kWp PV and MWh ESS relative to the peak load are compared. To do this different different capacities of PV and ESS on the performance indicators Self-consumption and self-sufficiency has been simulated. The influence has been tested using the parameters related to scenario A. First, the influence of different installed PV kWp relative to the peak load (1190.3 kWp) while maintaining a 60% capacity ESS (3661.81 kWh) in each configuration is simulated. Secondly, the influence of different capacities of ESS while maintaining the amount of installed kWp PV (3570.9 kWp) the same in each configuration is simulated. Lastly, the influence of the configurations that are used in the rest of the simulations on self-consumption and self-sufficiency are simulated. As mentioned-above the capacity for

ESS is designed to be a certain percentage of the capacity that is needed to deliver power for 24 hours after the peak load of the researched scenario. The outcome of the simulations is presented in figure 4.1. All simulations in figure 4.1 were performed using the greedy algorithm.

Top left					
PV=0% ESS=60%	PV=100% ESS=60%	PV=200% ESS=60%	PV=300% ESS=60%	PV=400% ESS=60%	PV=500% ESS=60%
Top right					
PV=300% ESS=0%	PV=300% ESS=20%	PV=300% ESS=40%	PV=300% ESS=60%	PV=300% ESS=80%	PV=300% ESS=100%
Bottom left					
CF1 PV=100% ESS=20%	CF2 PV=200% ESS=40%	CF3 PV=300% ESS=60%	CF4 PV=400% ESS=80%	CF5 PV=500% ESS=100%	

Table 4.1: Used ratios relative to the peak load of the scenario.

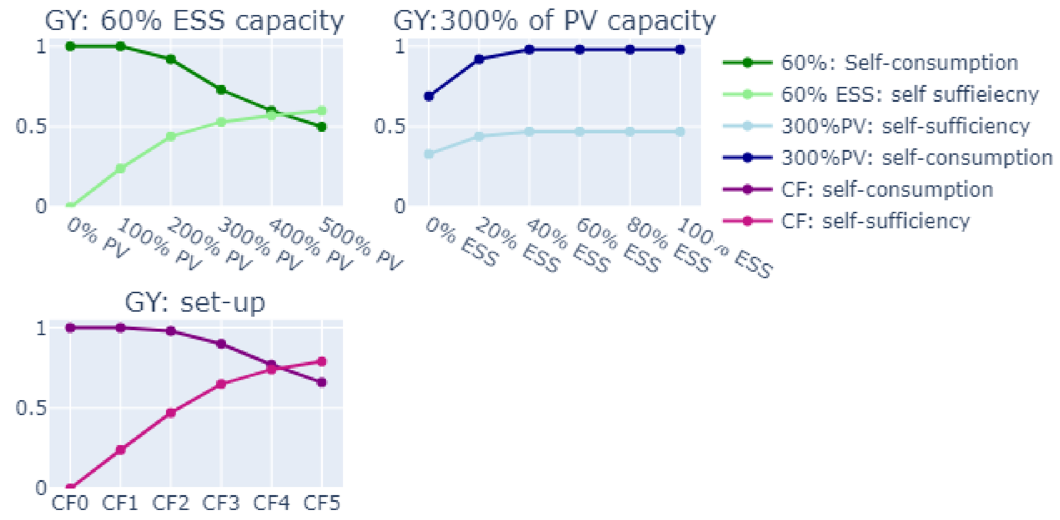


Figure 4.1: Overview with the influence of different parameters for the configurations on the performance indicators of self-consumption & self-sufficiency. Top left: a constant capacity of storage was kept while increasing the installed kWp PV. Top right: a constant installed kWp of 300% relative to the peak load while increasing the installed capacity energy storage. Bottom left: performance on self-consumption & self-sufficiency for the configurations as simulated in the remainder of the study.

The top left graph of figure 4.1 shows the influence of increased installed kWp PV while considering the same installed capacity ESS for each configuration. It demonstrated that the score for self-consumption decreases more rapidly in comparison to configurations illustrated in the bottom left graph where both capacities are increased. Which can be clarified by the fact that the top left graph there is not enough storage capacity relative to the installed peak.

The top right graph shows the influence of an increase of ESS capacity while maintaining a constant installed kWp PV. This graph demonstrates a clear maximum for both the score of self-consumption and self-sufficiency after an 40% ESS capacity. Therefore, can be stated based on these two performance indicators installing an configuration with 300% kWp PV relative to the peak load and 40% capacity ESS or more would not result in a higher score.

4.2. Greedy VS. Peak shaving

The different operational strategies of greedy and peak-shaving are compared on their measured performance. A goal of this study is to get more insight in the value of in parallel performed services. To be able to compare these different operation strategies they are first simulated independent. Therefore, the results will be presented per relevant couples of performance indicators. To maintain readability the greedy operation and peak shaving are abbreviated to *GY* and *PS* respectively. Due to the high amount of output from the model only a part of the results will be presented in this chapter. An overview with all results is demonstrated in appendix section A.7.

4.2.1. Self-consumption & Self-sufficiency

As discussed in section 3.4 the self-consumption represents the degree of directly consumed VRE in proportion to the total generated VRE. While the self-sufficiency displays the degree of directly consumed VRE proportional to the load. In figure 4.2 four graphs can be distinguished. The graphs left-above and left-below demonstrates the self-consumption scores for the different scenarios and configurations with the greedy algorithm and the right two graphs show performances with peak shaving operation. Each operation has been simulated for a configuration of installed kWp PV + ESS (line) in comparison to the same amount installed kWp PV (dashed line) without storage.

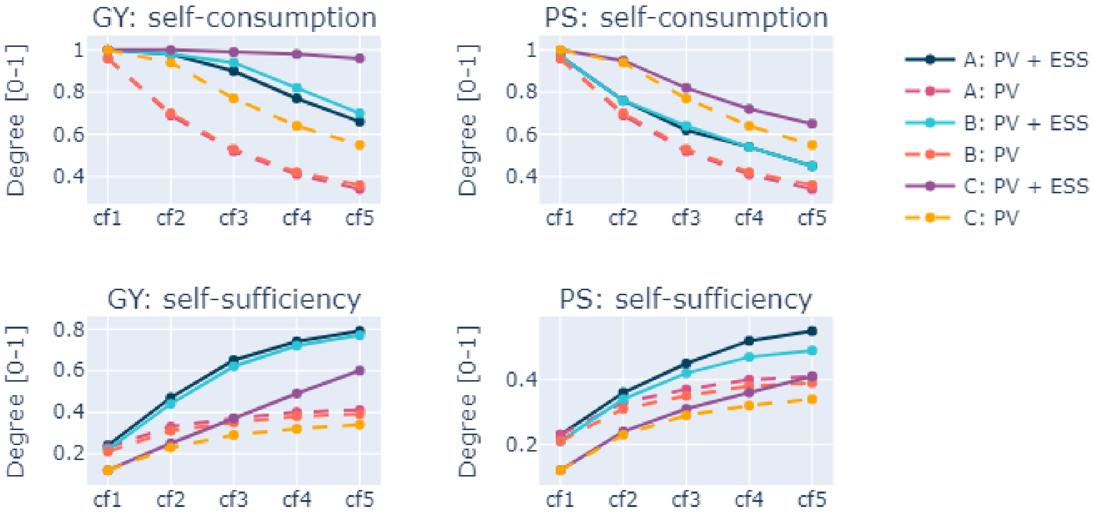


Figure 4.2: Overview of the different scenarios, operations and configurations and their self sufficiency, and self consumption performances. Straight lines represent the performance of the combined PV and energy storage systems. Dashed line represent the PV-system. Left two graphs show the performances for greedy operation and the right two graphs represent the peak shaving operation.

To enhance readability of the graphs different ranges of y-axes have been chosen. There is a clear difference between the performance of the different operation strategies. All configurations score higher on the amount of self-consumption for the greedy storage. For all three scenarios with **greedy** operation the scores for self-consumption descents more quickly with larger capacity configurations. However, scenario C with the flat load profile descents less quickly in comparison to the other scenarios for both the configurations without and with storage. This means that a load with a flat profile and a PV system sized based on the peak

capacity of the load scores better in self-consumption. The self-consumption during the **peak shaving** operation only scores 0.01 better for the *CF1* and *CF2* with an ESS in scenario C in comparison to the configurations without an ESS. Especially configurations *CF1* and *CF2* of scenarios A and B tend to decrease faster in comparison to the greedy operation.
On the other hand is the performance of self-sufficiency of scenario C significantly lower than scenarios A and B for both the greedy and peak shaving operation. This could be explained by the constant process and energy consumption during the night of scenario C and therefor larger mismatch in comparison to scenarios A and B.
All configurations score significantly lower on self-sufficiency on the peak shaving in comparison to the greedy operations. With scenario A, B and C scoring 14%, 10% and 7% higher in PV + ESS in comparison to PV only. Meaning that the energy consumption profile of scenario A is more suitable for a large capacity ratio PV with ESS in comparison to scenarios B and C when peak shaving is used. Moreover, when greedy is operated these differences for scenarios A, B and C are 16%, 38% and 38% respectively. Additionally, can be noted that the self-sufficiency for greedy operations of scenario C increase linear. Which can be explained by the constant increase of both PV and ESS in linear steps. From scenarios A and B in the case of self-sufficiency can be depicted that most

4.2.2. Utilized & unutilized VRE

Installing larger kWp PV results in larger quantities of generated kWh renewable electricity. However, not necessarily in higher quantities of utilized VRE due to the mismatch between generation and consumption. The effect of utilized VRE is strengthened when implementing greedy operation, in comparison to peak shaving. An overview of the utilized and unutilized VRE of all scenarios and configuration is illustrated in figure 4.3. There can be noted that the amount of VRE used by scenario A is significantly less than at scenario B and C. This is explained by the fact that the largest peak load of scenario A is lower than B and C resulting in a smaller capacity installed PV.

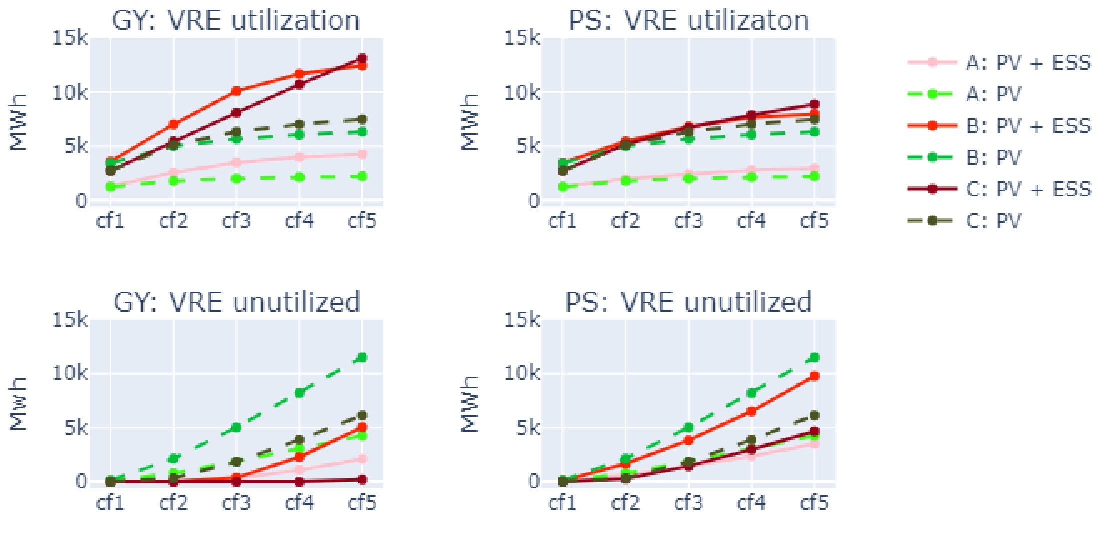


Figure 4.3: Overview of the different scenarios, operations and configurations and their utilized and unutilized VRE. Straight lines represent the performance of the combined PV and energy storage systems. Dashed line represent the PV-system. Left two graphs show the performances for greedy operation and the right two graphs represent the peak shaving operation.

Figure 4.3 shows that both scenarios A and B have the same behaviour with larger configurations. The utilization of scenario C with storage increases linear during greedy operation and tends to flatten later during peak-shaving at scenario B. This can be explained by the flat consumption profile of scenario C and the chosen design of installed PV and ESS relative to the peak. As a result more VRE is utilized due to the constant load. The graphs of

VRE utilized and unutilized give more insight in to the behaviour of the self-consumption performance indicator. In scenario A and B the steepest gain for utilized VRE is below *CF3* implying that most benefit can be achieved from these configurations. This effect is stronger in the greedy operation, in comparison to the peak shaving. In configurations *CF4* and *CF5* the quantity of unused VRE increases quickly implying that the mismatch between the PV production and load can not be covered by the installed capacity ESS.

4.2.3. Degree of capacity point of connection

Thirdly, the degree of point of connection (PoC) is compared for each scenario and configuration. The influence of each configuration for all scenarios is shown in a heatmap in figure 4.4. The color scale is from blue to yellow. Darkblue represents the size of the original peak load while yellow goes up to three times the size of the original peak load. Appendix A.9 also demonstrates the different PoC in MW for each configuration.

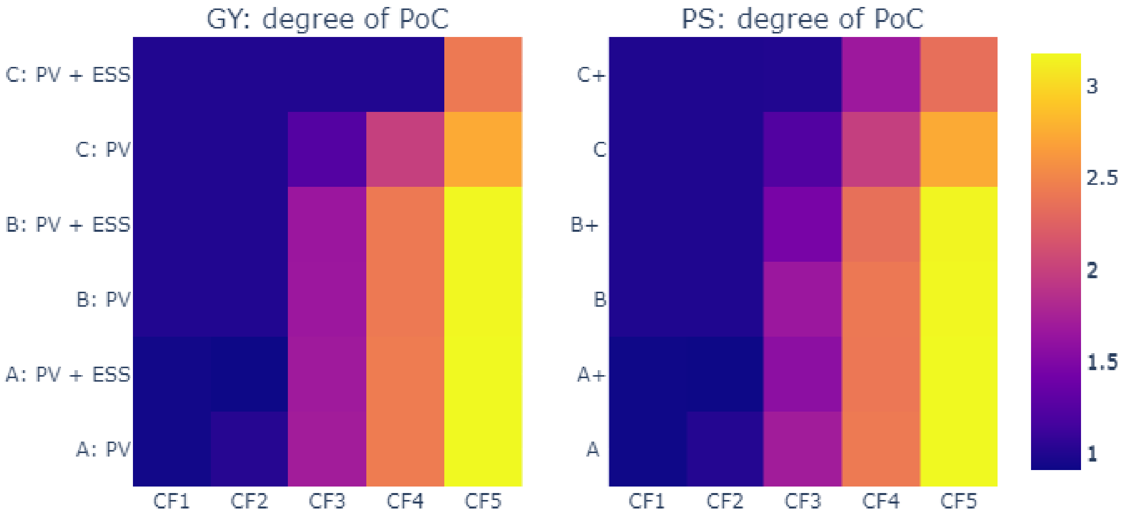


Figure 4.4: Heatmap of the different scenarios, greedy operation (left), peak shaving operation (right) and configurations and their capacity point of connection relative to *business-as-usual*. The more yellow the score the larger the PoC relative to *business-as-usual*.

Figure 4.4 reveals that the capacity of PoC stays the same or increases for most of the simulated configuration of PV or PV with an ESS. Only in scenario A for configuration *CF1* PV only and *CF2 & CF3* with PV + ESS the PoC reduces. The peak shaving operation has a reduced PoC capacity in comparison to the greedy operation for scenario A and B in the same configuration. However, one exception occurs in scenario C at configuration *CF4* the greedy operation manages to reduce the peak load more efficiently (1.0) than the peak-shaving operation (1.68) in the same configuration. On the contrary does the peak shaving score lower(better) in configuration *CF5* (2.35) in comparison to the greedy operation (2.42). The peak shaving operation outperforms the greedy operation on 6 of the 15 compared PV+ESS configurations. The greedy operation outperforms the peak shaving operation three times with two times only being 0.01 lower capacity and *CF4* of scenario scoring significantly better. Meaning that in 6 of the 15 cases the greedy and peak shaving score equal on PI of capacity of PoC.

4.2.4. Capacity for absorption and injection

Fourthly, the capacity to either inject or absorb of the system for each configuration is compared. This comparison is showed in figure 4.5. In the top two graphs the capacity for each scenario and configuration is illustrated for both operation strategies. In the bottom graphs the capacity for absorption of the two strategies is shown.

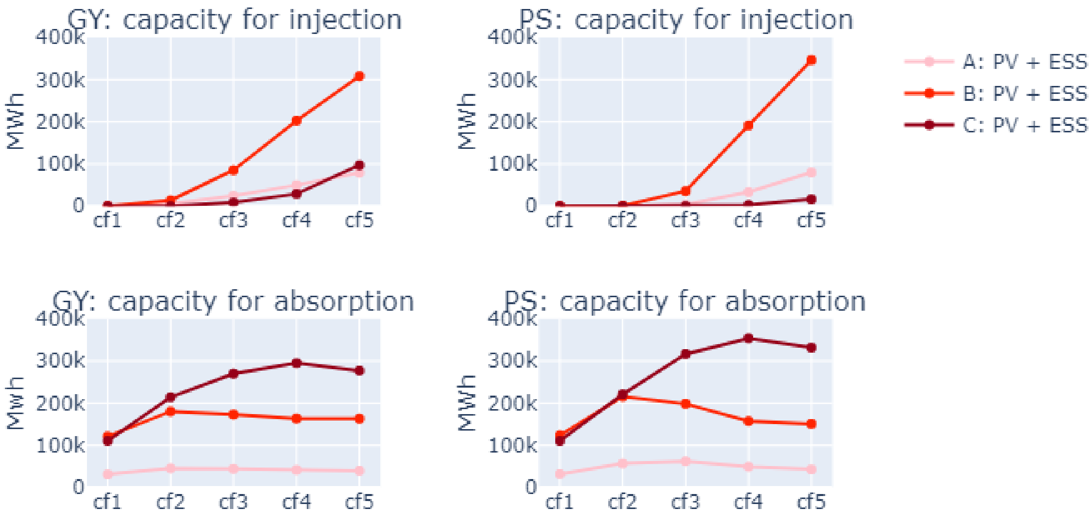


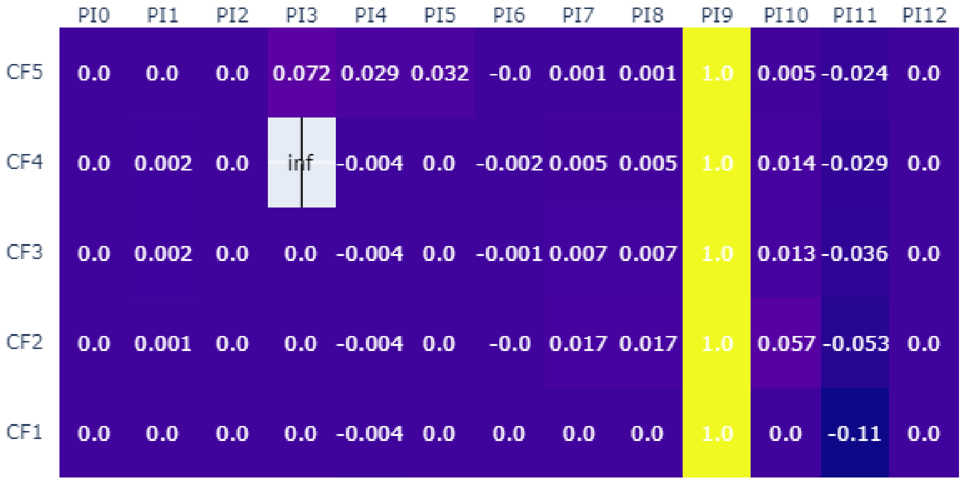
Figure 4.5: Overview of the different scenarios, operations and combined PV and energy storage configurations and their capacity to provide flexible capacity.

Figure 4.5 shows that scenario A has relatively the same available capacity for injection to the grid for each configuration. While Scenario B scores significantly higher for configuration *CF3* with greedy operation than peak-shaving. This difference is insignificant for configuration *CF4* and *CF5*. At scenario C, *CF4* and *CF5* score significantly higher for absorption when operating greedy. Meaning that the peak shaving operation does not allow for a large stored energy capacity to be able to absorb a lot of energy.

From the bottom graphs can be determined that each scenario has a certain threshold that allows for less energy being absorbed beyond a certain capacity. There has to be noted that the only interaction with the grid was based on either an overproduction of VRE where electricity was fed back in to the grid and a load demand when there was a deficit of electricity therefor consuming electricity from the grid. This means that the capacity demonstrated in figure 4.5 gives an indication of the possibilities for flexibility services of the ESS. However, the quantities that are illustrated in the graphs cannot be translated directly to quantities that can be used for this service. Also needs to be considered that using the flexible capacity might influence the performances of the other services.

4.2.5. Influence of gen-set

Lastly, including the service of reserving energy from the ESS's capacity to provide back-up energy while the back-up generator is starting. The peak power capacity of the back-up generator was set to be 150% of the peak load. This choice for over sizing the back-up generator was made to be sure to deliver the load and be prepared for future electricity consumption increase. To be certain to provide the load a capacity of half an hour is reserved from the ESS. This is very conservative and in the real-world a thermal back-up generator is believed to be able to be cold-started more quickly. The energy saved is the amount of energy that is normally used for heating the back-up generator. Therefore, the load consumption for each hour is reduced by the amount that would normally be used to heat the generator. In figure 4.6 an overview is given with the influence on all other PIs when provided allong either greedy or peak-shaving for each configuration. To maintain readability of the study the other scenarios have been illustrated in appendix A.7.1.



	PI0	PI1	PI2	PI3	PI4	PI5	PI6	PI7	PI8	PI9	PI10	PI11	PI12
CF5	0.0	0.0	0.0	0.072	0.029	0.032	-0.0	0.001	0.001	1.0	0.005	-0.024	0.0
CF4	0.0	0.002	0.0	inf	-0.004	0.0	-0.002	0.005	0.005	1.0	0.014	-0.029	0.0
CF3	0.0	0.002	0.0	0.0	-0.004	0.0	-0.001	0.007	0.007	1.0	0.013	-0.036	0.0
CF2	0.0	0.001	0.0	0.0	-0.004	0.0	-0.0	0.017	0.017	1.0	0.057	-0.053	0.0
CF1	0.0	0.0	0.0	0.0	-0.004	0.0	0.0	0.0	0.0	1.0	0.0	-0.11	0.0

Figure 4.6: Influence of allocating capacity to provide transit power during the start of back-up generation on the performance of greedy operation for scenario A for every performance indicator.

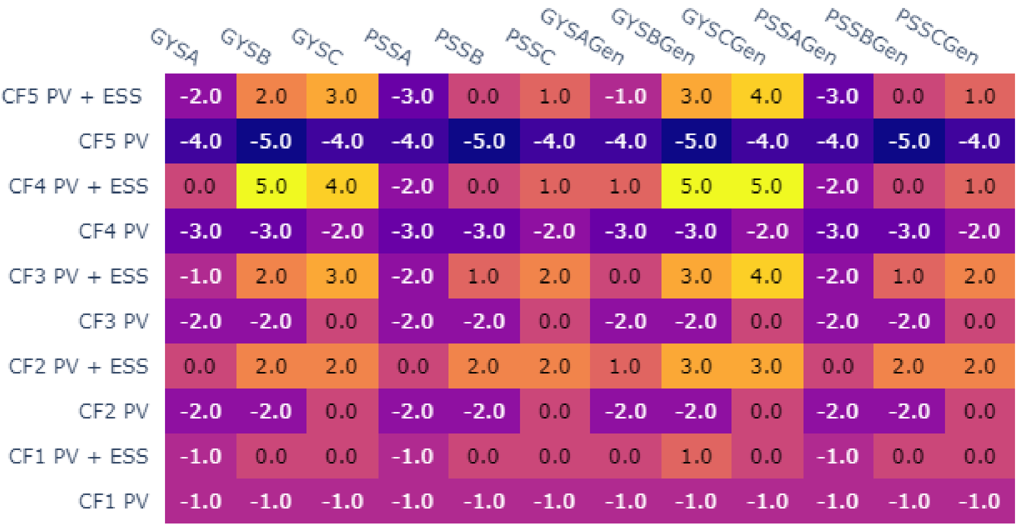
#	KPI	#	KPI	#	KPI
PI0	Self-consumption	PI4	PoC (MW)	PI8	ttl discharged
PI1	VRE utilized	PI5	PoC (degree)	PI9	genset reduction
PI2	VRE unutilized (degree)	PI6	ttl consumption	PI10	flex to inject
PI3	VRE unutilized (MWh)	PI7	ttl charged	PI11	flex to absorb
				PI12	Self-sufficiency

Table 4.2: Overview of all performance indicator used in this study in order of figure 4.6.

For each scenario and each operation strategy the score of the PI was checked with and without the service for gen-set consumption reduction. In figure 4.6 an overview of this influence shown for the greedy operation of scenario C. In table 4.2 an overview is given with all used and influence performance indicators. A negative number is a negative influence on the PI in comparison to operation without the genset reduction. *PI09* has an improvement of 100%, 1.0, in the heatmap because there was no electricity saved before. The *PI03* for configuration *CF4* gets divided by 0 resulting in an infinite better score because the VRE unutilized VRE without performance of the genset is non-zero (2kWh) while with the reserved transit electricity it is 0 due to a rounding error. Since the amounts are so small but expressed in MWh and not KWh this occurs in very little of the cases. Furthermore, it reveals that the largest influence is on the ability to absorb in configuration *CF1*. This can be explained by the reduced storage capacity due to the reserved electricity to provide transit-generation.

4.3. Overall score

The goal of this study is to give better insights to decision-makers in the added-value of ESS. In the subsection before the performances of the independent indicators have been discussed for all configurations of each scenario. This section gives an example of how an overall score can be presented based on a simple scoring mechanism. Figure 4.7 shows a heatmap with the accumulated performance for all simulated operation strategies. The first three columns represent the greedy storage operation for each scenario. Columns 4 to 6 show the peak shaving operation for all locations. Columns 7 to 12 show both greedy and peak shaving operations run in parallel with the gen-set transit-generation service. Dark blue represents the lowest overall performance and yellow the highest. The lowest score achievable is -7 since one of the kpis has a binary scoring and is not deducted when not performed.



	GYSA	GYSB	GYSC	PSSA	PSSB	PSSC	GYSAGen	GYSBGen	GYSCGen	PSSAGen	PSSBGen	PSSCGen
CF5 PV + ESS	-2.0	2.0	3.0	-3.0	0.0	1.0	-1.0	3.0	4.0	-3.0	0.0	1.0
CF5 PV	-4.0	-5.0	-4.0	-4.0	-5.0	-4.0	-4.0	-5.0	-4.0	-4.0	-5.0	-4.0
CF4 PV + ESS	0.0	5.0	4.0	-2.0	0.0	1.0	1.0	5.0	5.0	-2.0	0.0	1.0
CF4 PV	-3.0	-3.0	-2.0	-3.0	-3.0	-2.0	-3.0	-3.0	-2.0	-3.0	-3.0	-2.0
CF3 PV + ESS	-1.0	2.0	3.0	-2.0	1.0	2.0	0.0	3.0	4.0	-2.0	1.0	2.0
CF3 PV	-2.0	-2.0	0.0	-2.0	-2.0	0.0	-2.0	-2.0	0.0	-2.0	-2.0	0.0
CF2 PV + ESS	0.0	2.0	2.0	0.0	2.0	2.0	1.0	3.0	3.0	0.0	2.0	2.0
CF2 PV	-2.0	-2.0	0.0	-2.0	-2.0	0.0	-2.0	-2.0	0.0	-2.0	-2.0	0.0
CF1 PV + ESS	-1.0	0.0	0.0	-1.0	0.0	0.0	0.0	1.0	0.0	-1.0	0.0	0.0
CF1 PV	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0

Figure 4.7: Heatmap with the overall performance of all performance indicators accumulated according the simple scoring system. The highest score achievable is 8 and the lowest is -7.

Figure 4.7 shows that greedy operation scores the highest when comparing both operations with and without the transit-generation service. Additionally, it shows that for all scenarios the larger the installed PV and ESS capacity the higher the overall score. However, in *CF5* PV + ESS there is a lower score in comparison to the *CF4* PV + ESS in the same scenario. The next chapter 5 presents a more thorough explanation of the results and how they correlate to the real world.

5

Analysis

Since this research focuses on the added value of ESS for industrial clusters this chapter will discuss the results from chapter 4 in the context of the Dutch power system. Firstly, the choice for the design will be discussed and how the operation strategy affects performance. Secondly, each separate KPI is discussed in the context of a potential Dutch power system. Thirdly, a sensitivity analysis is performed to see the influence of different assumptions. Lastly, the overall scoring will be discussed as a suitable tool for decision-makers of industrial clusters.

5.1. Design choices

As discussed in section 3.7 of the scenario description the choices for sizing the capacity of both the PV and ESS were based on the largest peak of the load in the scenario. The choice for this was based on the earlier conducted research by Merei [46]. Firstly, the size of the installed PV equal to the largest peak of the load does not result in high self-sufficiency. This can be explained by the intermittent character of the solar radiation during the day and the lack of sun during the night. The geographical location also influences this result meaning using different solar data will influence this performance. Since the power generated by the smaller configurations is nearly always lower than the load the self-consumption performance indicator scores really well. There is clear evidence that without ESS the self-consumption decreases faster due to the higher mismatch between generation and consumption. However, there is a marked difference between this score when comparing the constant consumption load C to the other more volatile consumption processes. Even without the ESS, the design of PV scores almost similar to PV with the ESS for the first two configurations. This can be explained by the better match between generation and consumption when there is a flat consumption profile when using the largest peak to choose the power of the PV park. Although the peak and average energy consumption difference of load B seem larger in comparison to A it is approximately 20% bigger. Figure 5.1 shows how the average load relates to the full year profile.

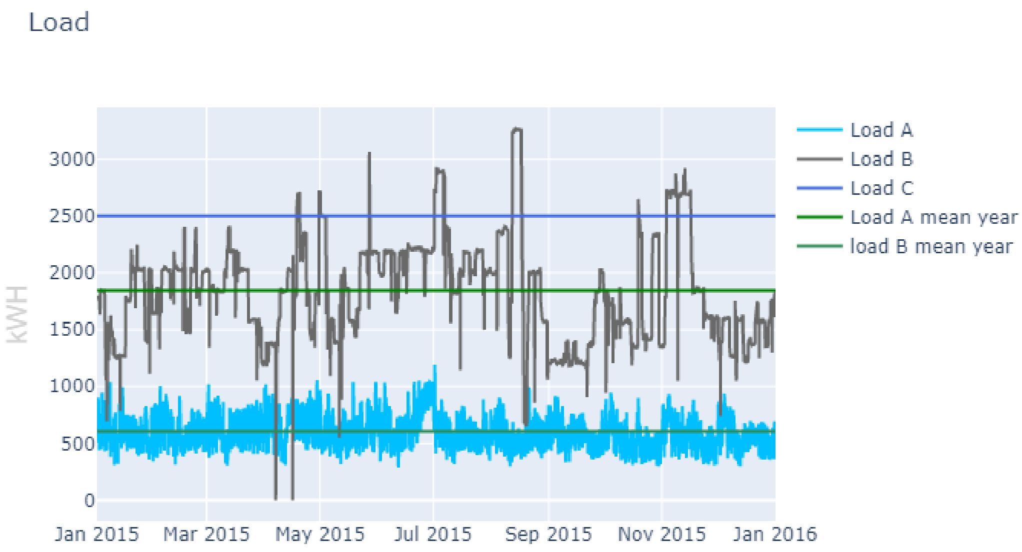
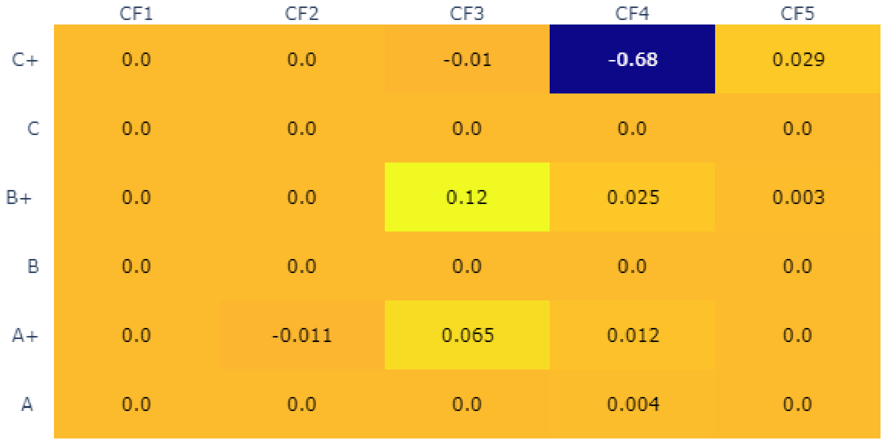


Figure 5.1: Load profiles for the year 2015 of the three scenarios with average load. Ratio highest peak load to average yearly consumption of A ≈ 1.97 and B ≈ 1.76.

The higher scores on **self-consumption** by load C can be explained by the fact that the PV capacity of load A and B are relatively oversized resulting in less VRE consumed directly and therefore a lower performance in self-consumption for the larger configurations. Secondly, the storage capacity of the ESS is also scaled on the basis of the largest peak consumption. It is sized to provide enough power and capacity for 24 hours load when fully charged based on the 24-hour profile of the peak load while considering discharging efficiency. The high amount of self-consumption of load C does correlate with scenario C scoring better on increase of PoC. Nearly all VRE is consumed behind the meter so there is no need for a larger capacity for point of connection or curtailment since the load profile C stays the same relative to the differing degrees of sizing the scoring is linear.
On the other hand, load C scores substantially lower on **self-sufficiency** in comparison to loads A and B. This is explained by the fact that the characteristics of the load profile of load A and B are similar to the characteristics of the PV generation. In other words, the electricity consuming processes at site A and B take place during the day and therefore the impact of electricity consumed during the night by load C has a higher impact on the performance of self-sufficiency.

In addition, the scoring of the performance indicators is affected by the choice of the **operation strategy** of the ESS. In almost all of the simulated scenarios and configurations, the greedy algorithm outperforms the peak shaving algorithm. However, when examining the independent performance indicators, the peak shaving algorithm does score better for some configurations. These are the degree of the capacity of the PoC and the flexibility capacity. Firstly, the impact on the capacity of the PoC is discussed. As intended, the peak shaving operation scores on 6 of the 15 simulations with storage. Figure 5.2 shows the relative performance of peak shaving compared to greedy operation for each scenario and configuration.



	CF1	CF2	CF3	CF4	CF5
C+	0.0	0.0	-0.01	-0.68	0.029
C	0.0	0.0	0.0	0.0	0.0
B+	0.0	0.0	0.12	0.025	0.003
B	0.0	0.0	0.0	0.0	0.0
A+	0.0	-0.011	0.065	0.012	0.0
A	0.0	0.0	0.0	0.004	0.0

Figure 5.2: Overview with the relative performance of peak shaving in comparison to greedy operation on the maximum size of connection used for the point of connection.

In the six cases, the PoC is reduced by 12% for scenario B with storage and 6.5% in scenario A which can result in substantial cost reduction on a yearly basis for the variable operator fee and even more when the fixed contract price is decreased. However, the operation does have a level of risk. Since the peak shaving operates with foresight of 5 hours it adjusts its charging and discharging behaviour. Reduction of PoC at configuration *CF5* and not *CF4* when comparing GY and PS can be explained by the fact that the operation works with 5-hour foresight only and not with perfect foresight. It does not always make the optimal choice. Resulting sometimes in a worse choice than without foresight. An explanation is that the algorithm allocated the wrong amount of capacity based on the foresight. This resulted in a high peak, so determining the maximum power contract for the rest of the year. The influence of different horizons will be discussed later in section 5.2.

Lastly, there is some reduction of the load by not heating the gen-set. Enough capacity of the ESS is reserved to provide transit power during a possible electricity supply interruption while the gen-sets are cold-started. Table 5.1 gives an overview of the electricity that is saved by not performing the heating.

	Scenario A	Scenario B	Scenario C
Reduced electricity	39 MWh	107 MWh	82 MWh
Total consumption *BAU*	5393 MWh	16152 MWh	21900 MWh
% load reduced	0.72%	0.62%	0.37%

Table 5.1: Overview electricity saved not preheating the gen-set

The figures presented in table 5.1 give an indication of the potential savings. Gen-sets require maintenance and testing multiple times a year to reduce the possibility of malfunction. However, the maintenance and test runs of the gen-sets have not been included in the scenarios. It is also assumed that the reserved stored electricity in the ESS is allocated efficiently and smartly by the energy management system making sure that there is little or no leakage of energy and is therefore neglected in this model.

5.2. sensitivity analysis

This section discusses the assumptions that were made while modelling the industrial power system. Multiple operation strategies were simulated with different variables. Firstly, the foresight horizon of the peak shaving will be discussed and secondly the impact of using different solar data.

Foresight horizon In all simulations with peak-shaving operation that have been run there has been a foresight of VRE generation and demand for the oncoming 5 hours. To see the influence of using different foresight horizons a sensitivity simulation is performed. The peak-shaving is run with 1 up to 24 hours foresight on scenario B with configuration *CF3*. The influence of the different foresight capabilities is presented in figure 5.3.

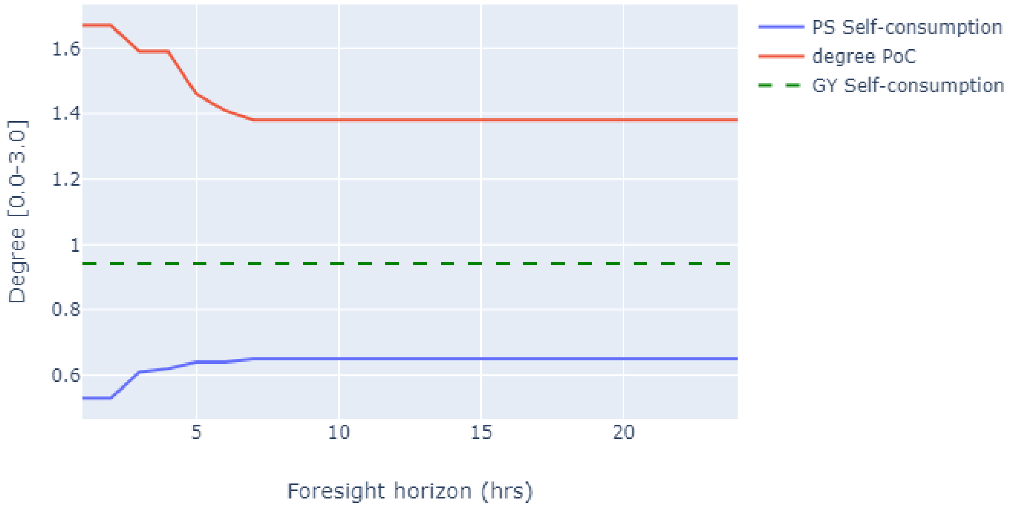


Figure 5.3: Influence of using different hours foresight on the performance of the peak-shaving algorithm on self-consumption and degree of point of connection on configuration *CF3* of scenario B.

Figure 5.3 shows that with more hours of foresight, the peak-shaving behaves better on both the performance indicator of degree of point of connection and on self-consumption. Nonetheless, the Greedy operation scores better on self-consumption for all hours of foresight.

Round-trip efficiency In all simulated configurations for each scenario the round-trip efficiency has been 90.25%. This has been derived from 95% energy conversion during charging and vice versa during discharging. To see the influence of this assumption, simulations have been performed where different charging and discharging efficiencies are analyzed. The results of these simulations are shown in figure 5.4.

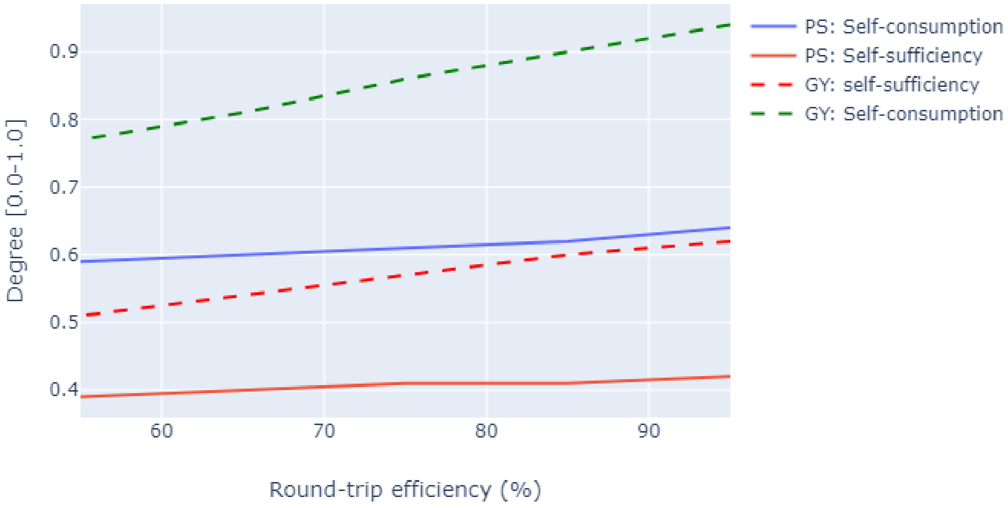


Figure 5.4: Influence of different charging and discharging efficiency on the performance of self-consumption and self-sufficiency for both Greedy and peak shaving operations.

Figure 5.4 shows that a decrease of 95% to 55% results in an 18% decrease in performance of self-consumption for the Greedy operation. On the other hand, does peak shaving performs 8.5% worse on self-consumption with a 40% decrease in efficiency. Note that the peak shaving algorithm does not react linearly to the efficiency decrease while the greedy operation does. This is expected since the efficiency is not considered during the allocation of the storage capacity for the hours of foresight. The efficiency is only considered in the model during the moment of transfer of energy. This affects the operation of peak shaving and should be further researched in future optimization research. A 40% decrease in efficiency results in a 17.74% decrease in self-sufficiency for the greedy operation and 7% decrease of self-sufficiency of the peak shaving operation. To conclude, on the basis of the data the impact of efficiency on the performance of the peak shaving operation is significantly smaller than on the greedy operation. This can be explained by the fact that the peak shaving operation already scores significantly lower than the greedy operation on these two PIs. Nevertheless, the figure shows that other (cheaper) technologies with lower efficiency than some lithium-ion batteries might be more suitable for an operation that is focused on peak shaving an issue for future research.

6

Discussion

Since a model is a simplification of reality, assumptions and choices were made to be able to perform this study. This chapter evaluates how design choices have influenced the results. Firstly, the limitations of the model are discussed and secondly, the possibilities for future research are presented.

6.1. Limitations of the model

The first and largest assumption is that none of the design and scoring choices are dependent on EUR/MWh. While a commercial entity is more likely to maximize profit and make sustainable investments to ensure profitability in the future. Since future electricity, carbon, and technology costs are difficult to predict, this study was performed without. The insight into the performance of the power system without directly expressing it in economic figures results in more substantiated strategic choices for the decision-maker. The performance indicators used in this study can be used as marketing tools by the management and contribute to higher goodwill of the company. However, very little research has been found on the valuation of ESS within industrial clusters. The possibilities for future research are discussed in section 7.3.

Capacity sizing In the model the sizes of installed PV and ESS were not optimized but instead based on the largest peak consumption of the load. For the volatile energy profiles, this meant that the choices for installed PV and capacity storage were in some cases based on an exceptional peak in the year. Therefore, it might be better to adjust the size of the configuration based on multiple years of energy consumption.

Round-trip efficiency The round-trip efficiency that corresponds to some lithium-ion technologies was used since it is presently deployed in half of the projects. However, it is also one of the more expensive technologies even though the cost per MWh is decreasing rapidly. Since the 90.25% round-trip efficiency used is a generalized efficiency, it might differ in real-world power system designs. Therefore, the influence of different efficiencies and technologies should be considered when simulating different power systems. The degradation of charging and discharging capabilities during the operational lifetime of an energy storage technology has not been included in the modelling of the industrial power system. This will affect the ability to provide certain services during operational life. An example of decreasing round-trip efficiency is researched by Byrne [10]. In the case of price arbitrage, a decrease of 20% in round-trip efficiency requires a 31% increase in the ratio high/low price to be cost-effective. In this study the service of price arbitrage has not been included, it does demonstrate that efficiency does not necessarily have a linear influence on the performances of the system.

Load profiles In this study, two real-world energy profiles are used with hourly consumption kWh resolution. The choice for hourly data was to match the available hourly solar data, reduce the number of data points and computational time. However, most consumption data is currently available in 15-minute resolution and could impact the outcome of the performance indicators. The assumption that a process is constant within the hour, and therefore represents the maximum capacity for transmission of point of connection is also influenced by this. In the case of a large crane levying a heavy cargo, it might use a large amount of power for a few minutes resulting in a brief high transmission peak in MW, but a lower kWh usage when interpreted for the hour. Therefore, when interpreting the values of this model in other cases there should be a thorough understanding of the process before making statements. This effect is expected to be less strong when using 15-minutes data.

Furthermore, the load profiles in this study that are simulated, are constant processes without any temporal coincidence between solar generation and load peaks. The profiles do not show a clear day and night consumption pattern or reduced activity in the weekend as in the test profile of the Miami office building.

Section 5.1, the analysis, shows that the characteristics of the electricity profiles have a large influence on the performance indicators. Hence, further research should be performed including more consumption profiles to give more reliable statements about the specific characteristics that are more suitable for a PV system in combination with an ESS. Examples of different processes; are batch processes and constant processes with reoccurring peaks.

In addition, research on wind energy in combination with an ESS may well result in different performances of the industrial power system. Further, is a combination of wind and PV systems interesting.

Finally, more extensive validation can be performed. Using the same data-sets as previous studies to determine the performance of the modelled operation strategies and test with similar real-case data of already installed combined PV and energy storage systems.

Geographic location The focus of this study is on industrial clusters within the Dutch power system. Assumptions of a strong electricity grid with little chance of irregularities in the power supply and stable electricity prices were made. On the other hand, outside of the Netherlands are industrial sites that have a connection to a weaker, more unstable, grid or have no connection at all. In these scenarios, the cost of electricity is higher and the need for flexible and secure energy supply differs from the situation in the Netherlands. As these smaller systems are often more reliable of fossil fuel thermal plants and more susceptible to irregularities within the grid due to lower interconnectivity.

Number of services This study is performed to show the influence of different services provided in parallel by a combined PV and energy storage system on the performance of the industrial system. In this study, the greedy, peak shaving and providing transit energy for back-up operations are simulated. The services of price arbitrage and flexibility services have not been included due to the scope and time restrictions of this research. The study did include the ability to provide flexibility for the DSOs, resulting in a capacity either to consume or inject power from/to the grid. No real interaction

with the grid, based on signals from either DSOs, TSOs or markets have been included in the research. To model the services of FCR and price arbitrage, there needs to be perfect foresight on prices and remuneration for these services. Without these, it is difficult to develop substantiated scenarios for the future. From the literature review was concluded that is difficult to make statements on these prices will develop.
However, the annual market report of TenneT of 2018 shows that electricity prices are increasing in the European central western region and there is an increasing trend in remuneration in the reserve markets. These services are relevant to the model since they could strengthen a potential business case. It is also believed that the provision of flexibility services to the grid will impact the performance of the industrial power system since the volume that is traded on the imbalance market is increasing and the deployed *GOPACS* congestion platform has come online.

Simple scoring

The scoring method used in this study is an accumulation of performance indicators. The range that determined whether a design scored -1, 0 or +1 is based on the extreme values of the performance indicators metric; i.e. the compared scenarios determined the range. However, since the model did not include economic and societal features, the scoring can only be indicative of certain performance based on the indicators that were used. To provide a more holistic result more performance indicators should be included.
There is no weighting of the importance of each performance indicator when deriving the final score. Thus the performance of reducing the electricity that was conventionally consumed for heating the generator set has the same impact on the final score as self-sufficiency. In determining the best design, a decision-maker should weight the different performance indicators, either based on the relative impact or other means.

6.2. Economic indication

The scope of this study excluded statements about the possible economic gain of an ESS for an industrial cluster in the Netherlands in the future. Due to the lack of substantiated evidence about trends in prices of electricity and the remuneration of services. However, this section will try to give an indication of some of the remuneration ranges based on the performance indicators and current prices. These figures should not be used for financial or any other advice.

The data of the report of *Fraunhofer* from 2018 is used [38] for the cost of solar power. This report shows the *levelized cost for electricity*(LCOE) for a ground-mounted utility-scale power plant >2MWp. The LCOE represents the price of the generated kWh. It incorporates the economic life of the plant, the construction, maintenance, operations, and fuel costs and is usually expressed in units of cents per kWh or Eur / MWh) for the complete lifetime of the project. The report states that utility-scale power plants in Northern Germany already achieve 50 EUR/MWh with a solar irradiance of 950 kWh/(m^2a) are able to achieve an LCOE of 50 EUR/MWh and that prices will keep on decreasing with modules getting cheaper. For an indication of the *levelized cost of storage*(LCOS), the yearly report of Lazard was consulted and a publication of BloombergNFE. Lazard's report from November 2018 uses an LCOE around 280 EUR/MWh as a lower bound for a Lithium-ion ESS for commercial industrial applications, while the BloombergNFE report from March 2019 states that an LCOE of 165 EUR/MWh is already feasible. However, the context of these studies is not fully known and the figures should, therefore, be interpreted with caution.

Since scenarios B and C, configuration *CF4* both include the service of providing transit energy to start the gen-set they scored best in the overall testing. Scenario B is presented because it has real-world load data. Appendix A.8 shows an overview of the numbers that were used to give an indication of the economic impact. An overview of the result is presented briefly below. Note that the analysis is based on a configuration of 400% Wp load PV installed and an ESS capacity to provide 80% of the 24-hour load.

Reduced consumption costs Since there is a combined PV and storage system available the industrial cluster is able to provide a part of the load itself. This results in a positive business case for the PV the only configuration with an electricity price of 50 EUR/MWh but always a negative business case with the prices from both BloombergNEF and Lazard for storage.

(Partly) Dispatchable VRE Since it is possible to control the output of the VRE with the ESS the PV park does not have to curtail when there is a significantly lower or even negative electricity price. The same would be in the case where the DSO request for curtailment due to congestion.

Point of Connection Since there is an oversized PV park in the configuration the capacity of the PoC will increase approximately 2.5 times the size of *BAU*. Assuming that curtailment of the plant is not an option the capacity will need to increase 2.5 in size. Due to a lack of data on the prices of large PoCs the costs are assumed to increase relative to the upgrade.

Flexibility services The current market price for flexibility per MW for the year 2018 in the Netherlands was on average 3500 EUR/MW as illustrated in figure 6.1. With a total volume of 1.1 TWh traded in 2017, this shows great market potential [66]. On the other hand, the amount of flexible power needed from the Netherlands is currently 34 MW. Hence, the market capacity is small and a lot of competition will probably result in a lower average price. However, it is also possible to bid on the German, Belgium, Austrian and Swiss imbalance markets. Providing flexibility services or responding to spot prices in the market will influence the performance of other services.

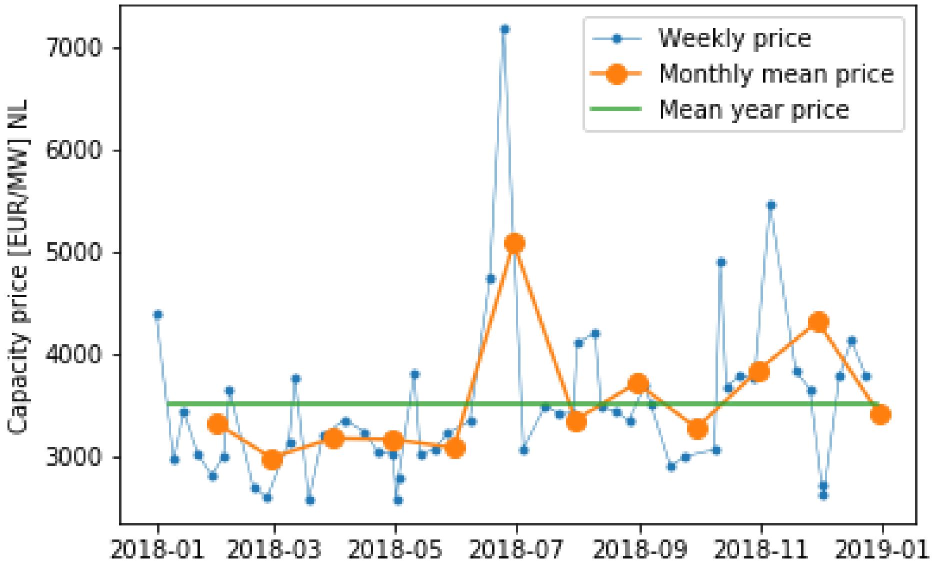


Figure 6.1: Possible remuneration per available MW per week in 2018. Included are monthly and yearly mean of the remuneration for primary control in the Netherlands. Data retrieved from Regelleistung [57].

6.3. To integrate or not to Integrate?

The results show the benefit for the industrial cluster to integrate both VRE and ESS in their power system. It also shows that a good understanding of the power system's characteristics is needed to determine which design and operation is most beneficial or in line with the strategy of the industrial cluster.

An example of ESS operation is peak shaving. This operation reduces the peak power flows and therefore determines the grid capacity connection. Conversely, it will also reduce the self-consumption and self-sufficiency of the system in comparison to greedy operation. Thus a strong incentive in the form of subsidy, remuneration or cost-reduction may be provided by the network operator to make this specific operation attractive.

Moreover, the possibility of feed-in electricity back into the grid determines which operation is more favorable. In a scenario where there is a very large integration of VRE and there is dynamic pricing for the electricity fed back into the grid might be sold at a negative price. Implying that there is a strong incentive to curtail the energy that would be fed-in to the grid and result in negative business scenarios.

The current political climate shows a strong commitment to the increase of VRE in the energy mix. This, together with geopolitical effects on the oil and gas price, can drive decision-makers of industrial clusters to want to be more in charge of their energy consumption and production. Even in a stable and reliable grid with relative cheap availability of energy, as in the Netherlands, it is worth reducing the carbon energy consumption when CO2 is increasingly taxed and thus influence the return on the investment.

Furthermore, this study shows that more distributed generation in the form of PV at the industrial load side does not result in a reduced dependency of the grid. It decreases the volume consumed from the grid, but not the peak load or peak generation fed back into the grid. Firstly, the peak load is difficult to be provided by VRE during the periods where there is little wind available or overclouding, also known as "Dunkelflaute" [7]. Even in combination with a large capacity of ESS it is difficult to transit this period. Based on the assumptions made in this research, the cost for transmission and distribution will only increase with more VRE deployed at the load side of the electrical value chain. Due to the intermittent nature of the VRE, the availability of energy is expected to be more volatile. It is unsure if the electricity prices and remuneration for the imbalance market will either rise or decrease and in the long run, it is assumed that they will change with more VRE in the energy mix. Since industrial sites are often characterized by being risk-averse, this is an argument to be more in control of their own power system and energy supply through the integration of VRE and ESS.
To span, the so-called "dunkelflaute", period with low availability of sun and wind, different long term "clean" energy carriers like hydrogen could help to provide the energy load in a future scenario with large penetration of VRE in the energy mix. However, hydrogen still faces considerable challenges. The production of hydrogen from renewable or low-carbon energy is still costly, and the development of infrastructure is slow and represses the adoption. Clear long term policies and strategies from governments could reduce the risks that come with the required cross-sectoral investment coordination that is needed for this new development of a new network infrastructure.

This same clear long term policies and strategies are also needed to incentivise the deployment of energy storage. By making transparent regulations, and establishing markets for the flexibility and ancillary services, investment risks will be reduced and enable ESSs to compete with other measures. Therefore, more research is needed to assess the potential of ESSs in a holistic way. By understanding the context of the services and applications that ESS provides policymakers can reduce barriers for the deployment. It is, therefore, crucial to get a better understanding of the interactions and functional relations of the power system to enable policymakers and utility operators to assess the relevant needs of the system in the long term.

7
Conclusion

7.1. Introduction

This last chapter presents an overview with the main conclusions of this study based on the predefined research question and sub-questions in chapter 1. This study explores the potential value of energy storage systems integrated into an industrial cluster power system. From this perspective, the following research question is formulated.

> How to evaluate the added value from the services of energy storage systems to an industrial cluster in the Netherlands when there is a large availability of variable renewable energy?

This research question is answered by answering four sub-question which are the backbone of this study. These four sub-questions are answered in the remainder of the chapter.

What is the institutional context of the ESS within the Dutch power sector?

The generation of electricity needs to match the consumption at the same time for a stable network operation. Therefore, the appropriate amount of electricity always needs to be provided while matching the varying demand. The imbalance between the generation and the demand results in reduced power quality, damaging machines, or even resulting in a blackout. It is more challenging for TSOs and DSOs to match the generation and demand since is the amount of variable renewable energy in the energy mix is increasing and electrification of processes in all sectors is taking place. In addition, the costs of congestion in the electricity grid have significantly increased from 2017 to 2018. The strategies for upgrading the electricity grid do not match the rapid deployment of VRE and the trend of electrification. Since the transmission capacity is based on the peak load or peak generation of VRE there is an increasing demand for flexible capacity in the grid. This could be met partially by grid expansion, demand response, and energy storage systems (ESS). Integrating ESS with VRE plants could reduce the fluctuating output of VRE.

Energy storage systems are defined by the fundamental ability to store electricity in some form which can be used to deliver power and energy to the network at another time. An ESS is an asset that is able to deliver and consume power from the grid and thus the regulator perceived it as both a consumer and generator. As a result, the system was charged for network fees, taxes and levies during charging and discharging. Although this has been partly solved in the new definition by the European Commission by defining ESS as a separate entity. Therefore, excluding the ESS from double net tariffs, where levies are paid both during absorption and injection from/into the grid. The double taxation of the electricity during consumption and injection from/into the grid is still occurring. This legislation still needs to be updated on a national level in the Netherlands. The ESS could be of added-value at the position of the generator, distribution & transmission and end-user along the electricity value chain.

What are the services that can be performed by an ESS that are relevant for an industrial cluster?

Energy storage systems consist of a large range of different storage technologies. The application determines which technology is more suitable. Each technology has different operating characteristics and response times. Nevertheless, are they mostly simplified by their ability to deliver power at a certain rate to the system and the duration, energy capacity, of this supply. An ESS positioned within the power system of an industrial cluster is able to perform multiple services in parallel. These include distribution support, end-user and commercial services at the same time. When the ESS is situated behind-the-meter of the industrial grid is able to perform the following list of services categorized based on the electricity value chain.

- Generation
    - Price arbitrage
    - Ancillary services
- Distribution infrastructure services
    - Distribution investment deferral
    - Intentional islanding
- End-user
    - Peak shaving
    - Power quality
    - Maximize self-consumption
    - Continuity of electricity supply
    - Reactive power compensation

By performing multiple services at the same time the viability of projects increases. However, the total value generated by the different services cannot be assessed by stacking the values because some of the services compete with each other.

What are the relevant performance indicators to evaluate the value of an ESS within the power system of an industrial cluster?

When making an investment decision it is not solely based on the technical and economic features. It is widely accepted that social and environmental features also influence the value of a project. It is especially difficult to make assumptions on the future price of electricity and the cost of technologies. Therefore, this study has provided some performance indicators which could be translated to economic figures but also gives indications to strategies for power system design for decision-makers in industrial clusters. Since more processes are electrified and the distribution grid is sometimes behind upgrading their distribution capacity it is more interesting for an industrial cluster to be more in charge of their own energy system. The performance indicators that are used in this study are based on previous research regarding the operation of renewable energy systems and are presented below.

- Degree of self-consumption [0.0-1.0]
- Degree of self-sufficiency [0.0-1.0]
- Utilized variable renewable energy [MWh]
- Unutilized variable renewable energy [MWh]
- Capacity of the network connection [0.0-10.0]
- Capacity for absorption [MW]
- Capacity for injection [MW]

- Influence of gen-set service [%]
- Electricity saved not heating gen-set [MWh]

The key performance indicators presented above aim to provide insight into the potential operation of different industrial cluster power system design. Simulations based on these KPIs help to reevaluate the operation of industry and could help reshape their consumption strategy for the future.

What is the influence of stacked services on the performance indicators?
The operation strategy of the ESS affects the performance of a power system in different ways. The larger the configuration of installed PV peak power and capacity of the ESS, the larger the impact on the majority of the performance indicators. However, only in the smaller configurations the size of network connection was able to be reduced in comparison to the *business-as-usual* configuration. Therefore, this study states that for the ratio installed PV, ESS, and peak load the industrial power system peak transmission capacity through the point of connection is more likely to increase than to decrease.
In the case of operating multiple services and therefore allocating the capacity of the storage, the performance of the different services is influenced since some services are competitive. By reducing the capacity to be used for one of the services the capability to perform others is influenced. How big this influence is, is relative to the amount of capacity that is allocated to the service and the moment of utilization. In this study, the influence of providing transit energy and an indication of the ability to perform flexibility services is simulated in parallel to the greedy and peak shaving operations. Since the capacity of storage is allocated differently for peak shaving, in comparison to greedy operation. Thus influencing the ESS capability to inject power into the grid more strongly than allocating capacity to provide transit power for the back-up generation.

> Answering the main question: **How to evaluate the added value from the services of an energy storage systems to an industrial cluster in the Netherlands when there is a large availability of variable renewable energy?**

The primary drivers for decisions regarding the design of a power system for an industrial cluster have been simplified to be: security of supply, cost-reduction, flexibility, sustainability, and innovation. The security of supply has been expressed in self-sufficiency, the cost-reduction in the capacity of the point of connection to the network and utilized VRE. The flexibility is expressed in the ability to provide flexible capacity to the grid by either absorbing energy in the case of congestion due to high power feed-in from other sources and injecting power in the case of shortage. Sustainability is also related to the volume of utilized VRE. To get a better insight into how a power system scores on these indicators a better understanding of the system is needed. A tool to get more insight into the power system is through modelling. This study uses modelling of the industrial power system to simplify a complex system and simulate different designs to see the impact of alternative design choices.

Deploying an ESS behind-the-meter in the Netherlands using current technology prices and market design is often considered too costly in comparison to *business-as-usual.* This is in combination with the difficulty to predict future energy prices and technology costs have made this study choose different indicators to provide information on the performance of a power system design. Decision-makers of industrial clusters can use these indicators as a start for the foundation of future strategies for power system design.
The integration of large quantities of VRE both with and without ESS at the industrial cluster side of the electricity value chain also impacts the larger power system. The scenarios of combined PV and ESS result in lower feed-in to the grid, in comparison to PV-systems without an ESS. The feed-in of electricity to the grid increases with larger amount of VRE deployed in all simulated scenarios. Thus, giving information to both policymakers and utility operators on the impact of the integration of a large amount of kWp VRE.

The institutions in the Dutch power-system have not been developed yet to support the integration of ESS. This is mainly due to uncertain or unclear legislation regarding the role of ESS in the power system. In the scenario that an ESS is placed behind-the-meter at an industrial cluster only performing a single service, the system is only partially utilized and often idle during the operational lifetime. Therefore, multiple services should be provided in parallel to use the capabilities of the ESS more optimal. Nevertheless, operational priorities need to be made by a decision-maker since some services can be competitive and result in a sub-additive value.

From the simulations, it is apparent that the characteristics of the energy profile have a strong influence on the performance indicators. The two most promising designs are configurations with a large PV peak power relative to the peak load including ESS capacity. Therefore, demonstrating that the most volatile load is not the best performing design considering the following performance indicators: self-consumption, self-sufficiency, utilized and unutilized VRE, the size of network connection, capacity for flexibility and influence of transit power generation.

7.1.1. Societal contribution

The amount of VRE to be deployed is increasing rapidly while there is also social pressure to phase-out fossil generation. The drivers for decisions of commercial industrial sites are often either profit maximization or cost minimization. This research shows that the integration of a PV-system is attractive in each simulated scenario. With no restrictions in feeding back into the grid and a relative high feed-in tariff, it is always beneficial to install the largest kWp possible. However, this should be nuanced since there are costs of a larger connection to the grid with a large PV park. Additionally, there is a considerable chance that not all generated is allowed to be fed-in to the grid at peak production by the DSO due to congestion problems. This request for curtailment is already taking place at some locations in the Netherlands. This research contributes to a better insight into the consequences of large capacity deployment of large PV with or without energy storage behind-the-meter of industrial loads. The study shows the impact of large PV deployment and show the volume risk of curtailment. This could incentivise decision-makers to integrate energy storage in possible future power system designs as it would reduce the risk of present business-cases for large scale PV parks. Since a lot of investment is already in place for the procurement of large scale PV, including ESS could improve the installation process.

The different prices to sell back to the grid has been touched lightly in this study but should be covered more thoroughly in the future. Since the large deployment of VRE is likely going to affect both the electricity price and network operation prices and therefore the business case for the configuration of new energy systems designs. Finally, ESSs are expected to be one of the main pillars for a future renewable-based power system. However, there should be considered that due to low solar irradiance in the winter the dependency of the industrial system does not necessarily decrease dependency on the grid. Thus, a larger deployment of distributed renewable generation does not automatically result in less peak power demand from the regional or national electricity grid.

7.1.2. Scientific contribution

The amount of studies performed on the topic of energy storage has been increasing rapidly in the last three decades. The majority is conducted as either engineering or system studies. They are often assessed as the techno-economic performance of a specific technology within a specific smaller system. In the case of system studies, the goal is to demonstrate the impact on the larger energy system. These demonstrate the merits and demerits to society in the broader sense. This study contributes to insights into the engineering design of relatively smaller power systems. This study focuses on industrial loads with various characterized loads. It demonstrates the complexity of parallel programming of the provision of services by the ESS, and the sub- or super-additive value to the system. It demonstrates that a more holistic approach is needed to show the real potential of energy storage systems. This will contribute to the correct valuation of energy storage in energy systems and could contribute to further optimization as an asset within the system. In addition, more research can give a better understanding of the influence of a large deployment of VRE in combination with ESS. This can help researchers to build better predictions of a future power system design. In addition, this can contribute to a better definition of the ESS within the future power system and thus help policymakers.

7.2. Conclusion

This study explores the potential value of energy storage systems integrated into an industrial clusters power system. It simulated the power system of three industrial loads in combination with different configurations of either a PV-system without storage or a PV-system combined with an energy storage system. An energy storage system is able to perform multiple services along the electricity value chain. An overview of these services is presented and a selection is depicted that is relevant for a behind-the-meter energy storage system implemented in an industrial power system with own generation. The performance of a selection of these services is researched by simulating different storage operation strategies for various configurations of the loads.

This study is conducted to gather insight into the institutional, economic and technical barriers of an energy storage system integrated into the power system of an industrial site in the Netherlands. Energy storage systems have not been widely implemented within the Netherlands, and this study provides a better understanding of the multi-service added value of energy storage system within an industrial power system. By simplifying the system the study contributes to a better insight into the performance of providing multiple services in parallel by the system. These insights can be beneficial for both successive research and policymakers responsible for the larger power system.

It has done so by researching the influence of different configurations of installed power PV and the capacity of energy storage within different industrial power systems. It demonstrates that the parallel performance can be both sub- or super-additive value to the system. In addition, demonstrates that the energy profile, and thus the process, has a strong influence on the performance of the system. Through the simulation of multiple energy storage operation strategies, a decision-maker of an industrial power system gets a better insight into the added-value of a combined PV and storage system. This can contribute to a more substantiated choice for future strategies on power system design.

7.3. Future research

This thesis assesses the potential added-value of an energy storage system in an industrial cluster power system in the Netherlands. The model provides a start in understanding the different designs of power systems of industrial clusters in the Netherlands. However, more extensive modelling of interactions of the industrial system with the larger power system is necessary. For this, more insight is needed in the different load profiles and processes of different industrial clusters. Since the heterogeneous load profiles strongly affected the performance of the system, more case-specific studies could validate the relevance of the performance indicators that are used in this study.

The accumulated scoring of the designs can be improved by using multi-criteria decision analysis. In this study, all performance indicators have the same relative importance in the overall scoring of the power system design. However, not all performance indicators have the same impact on the performance of the system or perceived equally important by a decision-maker. Thus, in a future study, there could be incorporated a difference in importance and impact between the performance indicators that are used. Therefore, including more relevant experts from the sector could improve the quality and quantity of the used performance indicators to assess a power system design more holistically.

Furthermore, would a different geographic location be interesting for the scope. Industrial sites at remote places like islands and desserts are known to have a less reliable grid connection which makes it more attractive for decision-makers to be less dependent on the grid. At the moment, this energy is often provided by large gas turbines or diesel generators. These power system configurations are already established in other locations in the world. Often multiple generators (gas or diesel) are configured in parallel when there is no or a weak connection to the electricity grid. Often they are running on e.g. 60% load as a spinning reserve to be able to ramp up in the scenario when one of the generator malfunctions. The amount of redundancy installed is dependent on the amount of risk the facility is willing to take. However, it could be possible to constantly run fewer generators at a more optimal load e.g. 85-100% and let the ESS provide the power during transit when the other generator is starting. This would make it interesting to include the performance indicator of saved diesel or gas by running the generators at a more efficient load.

Since the impact of different load profiles is determined to be very strong, further research should also be performed on the impact of demand response management(DSM). Or even a combination of ESS and DSM as the two can be distinguished as a technology that is able to store energy to be consumed at another time and a service that adjusts the moment consumption. Lastly, would it be interesting to determine the impact of using wind data as the variable renewable energy source. Since the wind is not bound to a day and night generation pattern which might be more suitable for certain industrial energy consumption profiles.

7.4. Reflection

This study is the result of a five-month research project to get more insight into the valuation of energy storage systems integrated into the power systems of industrial clusters. The research contributes to a better understanding of the role of energy storage in the power system. During this process, there were multiple obstacles and intersections that shaped the thesis. This chapter discusses the lessons learned in the past five months.

During the start of this research in January 2019, my focus was more on the distribution network itself and the possibilities of ESS to relieve congestion and help deferral of grid upgrades. However, during iterative brainstorming with both the supervising Professors and input of *Royal Haskoning DHV* the scope shifted towards behind-the-meter power-system simulation, with a focus on industrial size connections to the electricity grid. During the scoping process and literature review, it came forward that there was a lot of uncertainty about the correct valuation of the multiple services that an ESS is capable to perform in parallel. The creation of an overview of services relevant to industrial clusters helped to narrow down the scope. The interviews and discussions with mechanical and electrical engineers contributed to the technical feasibility of additional services relating to the use of back-up generators. The original plan was to combine modelling techniques in combination with multi-criteria decision-making methods. The multi-criteria decision method could have given insight into the importance of the performance indicators. However, this was assumed to be outside the scope of this research and is perceived as the next step for this research. While using the model to simulate flows of energy of the power system and expand the model by increasing the number of performance indicators. This study contributes to a better understanding of different power system designs. The better understanding of the context of ESS behind-the-meter at industrial sites could help policymakers to come up with clear and transparent regulations. Additionally, the model leaves with a lot of opportunities for future researchers to further verify, expand and calibrate the model.

Finally, in terms of personal reflection, the author believes that the process of the thesis was both adventurous and challenging. By investigating the project the author was able to deepen his knowledge in the area of the energy sector and improve his skills in modelling power systems. In addition, knowledge of project management and communication within an engineering consulting company was gained. In summary, the thesis enabled me to combine the methods, tools, and knowledge that were introduced to the author by the MSc *Complex System Engineering and Management* at the University of Technology Delft and the specialization courses in electrical engineering at the Universidad Politecnica de Cataluña in Barcelona. The author believes that contact with an international network of experts in the field had an amplifying effect on his enthusiasm regarding the possibilities of flexibility services in the future power system. The experience of being in a surrounding where real projects are actually designed contributed to a more realistic and better-scoped study. Besides, the experience of gathering the relevant information, data, scientific writing, modelling and company dynamics. The experience of communicating the process and relevant information to people that are not directly involved in the project is perceived as extremely beneficial.

A

Appendices

A.1. Overview Energy storage projects the Netherlands

Total of 49 projects on the website	Technologies
45	stationary storage
39	non V2B
3	h2bromide
4	Thermal storage
24	Lithium-ion
3	Hydrogen projects
1	chemical storage (Elia project)
3	Virtual power plant (Homebatteries)

Table A.1: Overview of deployed storage projects in the Netherlands [23].

Amount	Service
10	APX Trading
4	Unbalancing
8	Peakshaving
13	FCR
8	Self- consumption
7	distribution support
14	Pilot

Table A.2: Overview of services performed by the energy storage facilities [23].

A.2. Overview of different forms of energy storage and their technologies

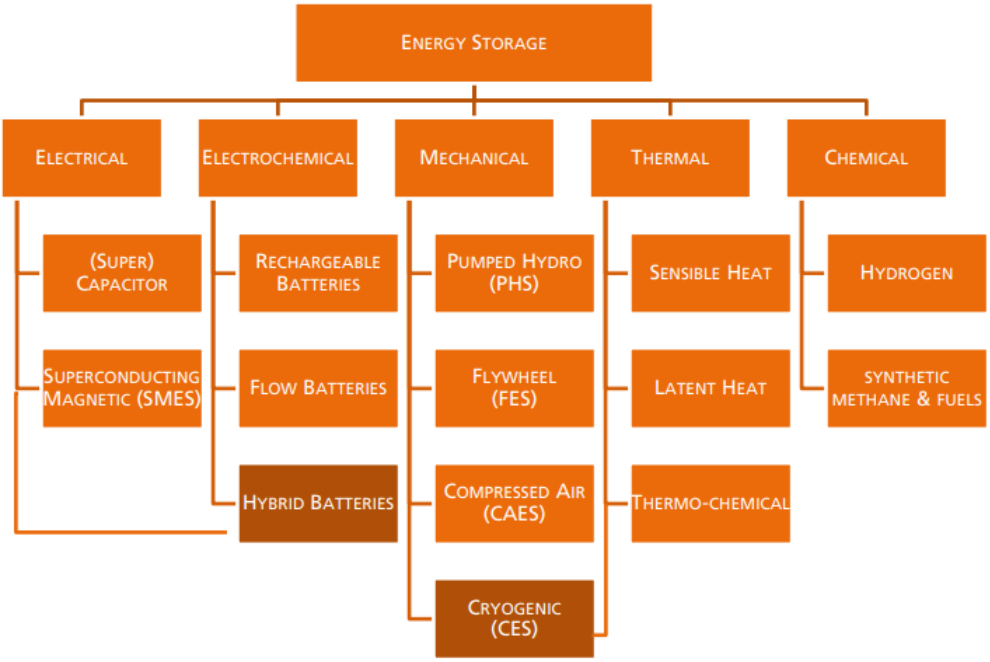


Figure A.1: Different types of ESS technologies suitable for grid connection [35]

A.3. KPIs

A.3.1. KPIs Zhao

Perspectives	Original Sub-criteria
Technology	Cell Voltage
	Storage Capacity
	Charge and discharge frequency
	Discharge time
	energy density
	cycle life
	Maximum charge and discharge efficiency
	specific capacity
	specific power
	self discharge rate
	specific energy
	safety
Economy	capital intensity
	battery capacity cost
	battery power cost
	operation cost
	cost recovery time
	energy storage system profit
	increase revenue of combining wind plants to the power grid
	benefit of terminal recovery
Environment	energy saving and emission reduction effectiveness
	CO2 intensity
Performance	Energy efficiency
	Energy intensity
Sociality	Delay of power grid construction
	Reduction of system reserve capacity
	Reduction of power grid loss

Table A.3: Overview with the KPIs from Zhao comparing different ESS technologies [76]

A.3.2. KPIs Troncia

Perspective	Sub-criteria
Economic criterion	NPV
Smart grid criterion	Operational flexibility
	Power system Stability
	Duration of interruption
	Voltage variations
	Energy losses

Table A.4: Overview with the KPIs from Troncia focus on different designs of ESS in a rural network with a focusto enhance grid stability. [71]

A.3.3. KPIs Murrant

Attribute	Definition
Deferral of grid upgrades	The ability of the project to defer upgrades to the electricity network (distribution or transmission)
Economic Co-benefits	Economic benefits to the owner/host of the project as a result of the ES project
Economic Growth (Innovation)	The ability of the project to stimulate economic growth through innovation within the region
Economic Viability	The ability of the project to secure funding, usually dependent on the economic profitability of the project
Environmental Co-benefits	Environmental benefits as a result of the ES project, such as improved local air quality
Increasing Self Consumption	The ability of the project to increase the self-consumption of energy generated in Cornwall rather than relying on exports
Technology Viability	The ability of the technology to perform as required over the lifetime of the project

Table A.5: Overview with KPIs used by Murrant to different technologies for different locations in the UK [48].

A.3.4. KPIs Celli

KPIs	Metric value
Network costs	[k€]
Energy losses	[MWh]
Reactive power exchange	[k€]
Black start	[MW]
Distributed Energy storage cost	[k€]
Average interruption duration	[h \year]
Average interruption frequency	[Occurrences \year]
Voltage regulation index	[p.u.]
Voltage dips index	[Vdips \year]

Table A.6: Overview with the KPIs of the research of Celli where is optimized for a ESS in a rural system.[13].

A.3.5. KPIs Voulis

KPI	Metric value
Renewable energy utilization	GWh
Maximal annual power peak	MW
Self-consumption	%
Self-sufficiency	%

Table A.7: Overview with the KPIs used in the dissertation of Voulis to score the impact of increasing storage penetration and coordination in neighborhoods in Amsterdam, the Netherlands.

A.4. Interview summaries

All of the contacted experts have been interviewed regarding the following problem:

Gen-set reduction

The first assumption was that an ESS would be able to reduce the amount of redundant back-up generators in a power system design for industrial clusters. E.g. reduce the amount of four to three since the ESS is able to provide flexibility and the gen-sets would be able to operate more efficiently and would be worn out less quickly. The assumption is that they are operated at spinning reserve and therefore not efficient.

Secondly, assumed is that in the case that the back-up generation is not operated at spinning-reserve it is in stand-by mode. Meaning that the engine block of the generator is constantly heated. To be able to ramp-up with a short response time. However, the generator-set could also utilized from cold-start. But this takes more time and depending on the operation the electricity supply needs to be uninterruptable or within a specific time window. Therefor, the ESS could allocate some capacity to provide power during the time the gen-set is activated from cold-start. How long does the generator-set need to be sure to provide the energy supply?

A.4.1. Email contact: Professors TU Delft

Dr.ir. H. Polinder
Biography: Henk Polinder holds a PhD (1998) in electrical engineering from Delft University of Technology, the Netherlands. Since 1996, he has been an assistant or associate professor at Delft University of Technology in the field of electrical machines and drives. He worked part-time at Lagerwey (1998/99), at Philips (2001) and at ABB Corporate Research (2008). He was a visiting scholar at the universities of Newcastle-upon-Tyne (2002), Quebec (2004), Edinburgh (2006) and Itajuba (2014).

Summarized and translated response: No hard evidence but half an hour would be more than enough to start a big diesel generator from cold-start. Dr. Ir. P. de Vos

Summarized and translated response: No conclusive answer. There are scenarios where the generator can be started within the half hour. This is dependent on the characteristics of the generator and the ambient temperature. However, there will be a possibility of failure or rupture of material in the engine under large thermal stress. This could result in a cancellation of the warranty of the generator by the manufacturer.

A.4.2. Interview Eaton

Martijn Imming - electrical engineer - Business Development Manager Data centers - Eaton INudstries B.V.
Specialist on grid design for data centers and industrial and utility distribution systems.

Summarizedand translated repsonse:
In the Netherlands there are very few industrial sites that have large CHP generators operating at spinning reserve since the Netherlands have a very reliable grid. In the case data centers the power system is already designed including UPS with batteries. Although in the US due to weaker grid there is often local generation by either diesel generators or gas turbines. State of mind of data centers are changing the capacity of the installed batteries is also considered to provide ancillary services. However, does not know of pilot cases. Also new design of data centers only with batteries and without conventional back-up generation. States that diesel-generators are very mature and can be operated efficiently at most loads and would result in very little gain combining it with ESS.
States that in the second case a large diesel generator is able to provide full load within half an hour after cold-start without issues. Probably also able to do this within 15 minutes.

A.4.3. Electrical engineers: Ir. Herbert Polman, Ir. Luc van Dort - *Royal haskoning DHV*

Ir. Herbert Polman - Senior Electrical Engineer at Royal Haskoning DHV - former head electrical engineering, power generation & distribution at Shell.
Ir. Luc van Dort - Specialist electrical facilities at Royal Haskoning DHV

Summarized and translated response: In the Netherlands the operation of spinning reserve is not performed. More likely to happen in more isolated places like islands or oil refineries in the dessert. Diesel generator is very mature technology with high efficiency. Able to provide different loads and ramp up and down easily when operated above certain threshold without compromising efficiency significantly. Diesel generators and CHP are heated constantly to make sure that the oil and moving parts are within certain temperature range. This makes it possible to ramp up quickly without damaging the moving parts. Since the Dutch grid has very low down time the constant heating of the generators can be seen as a waste. However, some operation require by law that back-up generation is available within a specific time frame. Most ESS technologies are either to expensive or technically not able to completely deliver the service of the back-up generator. However, the power during the time to start the generator without preheating could be provided by the ESS.

Table of PIs used

All 12 performance indicators from table 3.1 have been presented to all interviewees. Responses were:

- Appropriate list of performance indicators.
- Uninteruptable power supply is missing.
- No need for back-up generators for one of the interviewees and therefor no gain to be made.

A.5. Model verification

A.5.1. Greedy

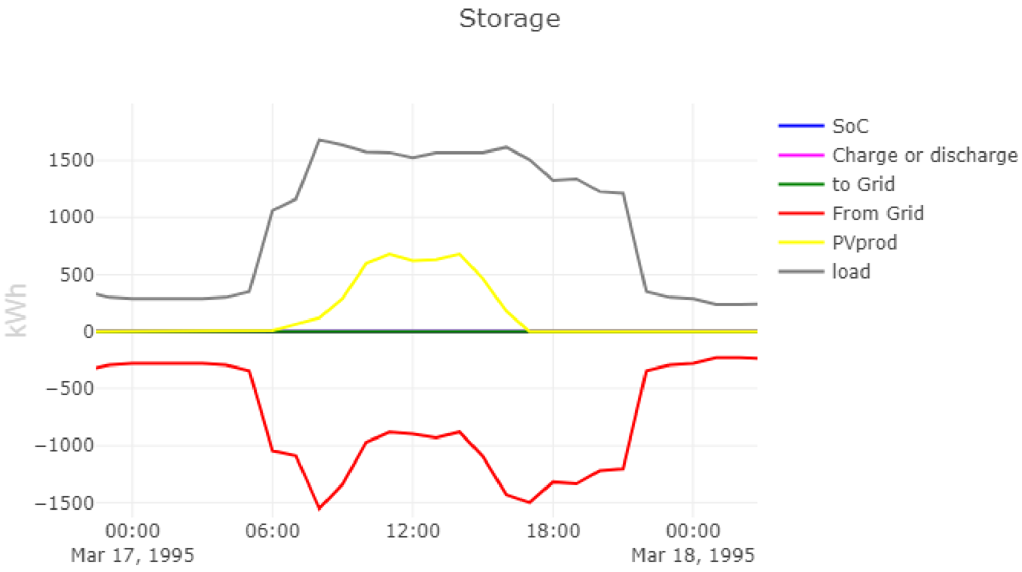


Figure A.2: Test scenario 1 greedy algorithm. Load is illustrated in grey, generated electricity PV in yellow, State-of-Charge (SoC) in blue, charging or discharging behavior in pink, consumption in red and fed-in to the grid in green. All values are represented in kWh.

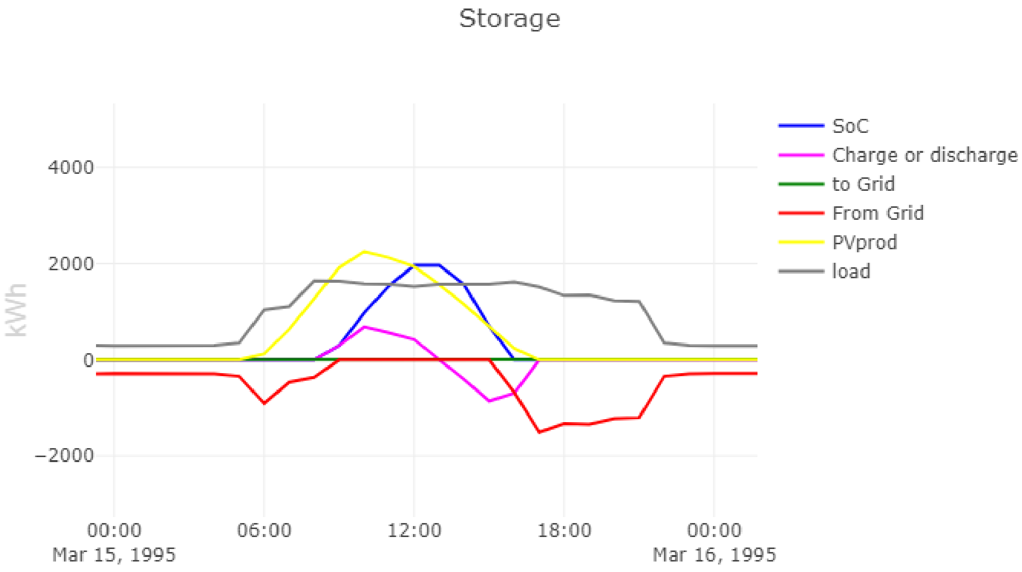


Figure A.3: Test scenario 2 greedy algorithm. Load is illustrated in grey, generated electricity PV in yellow, State-of-Charge (SoC) in blue, charging or discharging behavior in pink, consumption in red and fed-in to the grid in green. All values are represented in kWh.

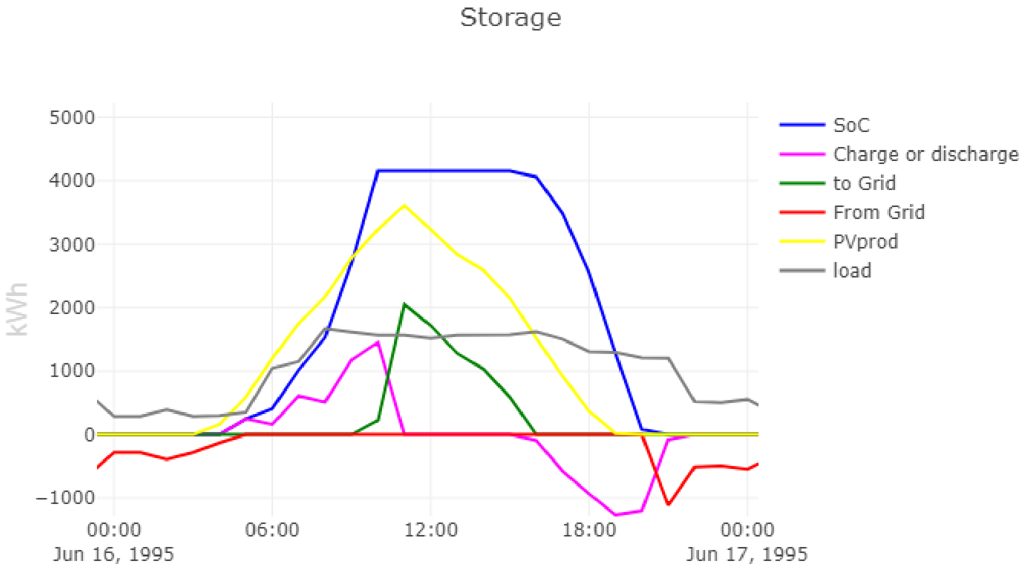


Figure A.4: Test scenario 3 greedy algorithm. Load is illustrated in grey, generated electricity PV in yellow, State-of-Charge (SoC) in blue, charging or discharging behavior in pink, consumption in red and fed-in to the grid in green. All values are represented in kWh.

A.5.2. Peak-shaving

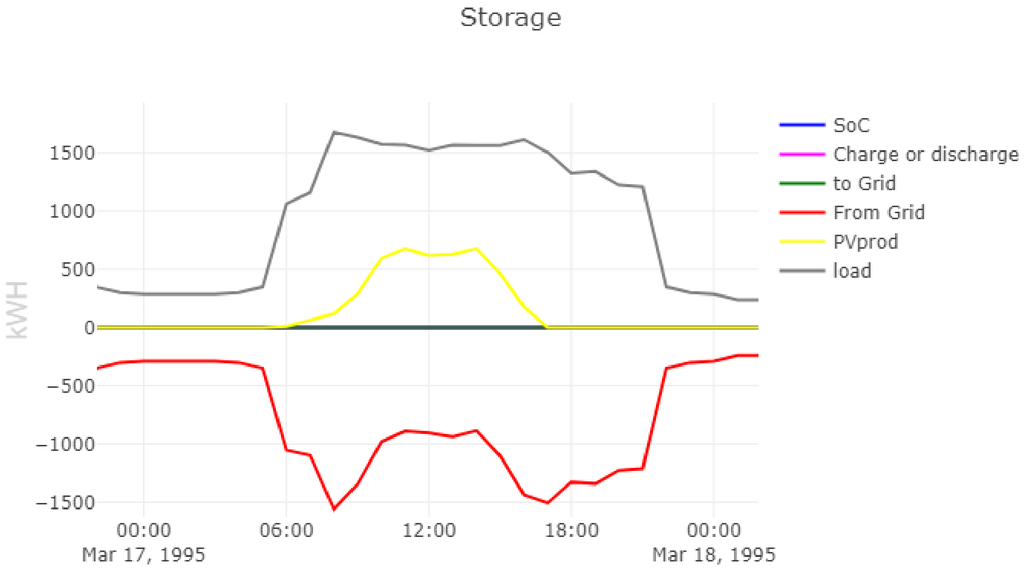


Figure A.5: Test scenario 1 peak shaving. Load is illustrated in grey, generated electricity PV in yellow, State-of-Charge (SoC) in blue, charging or discharging behavior in pink, consumption in red and fed-in to the grid in green. All values are represented in kWh.

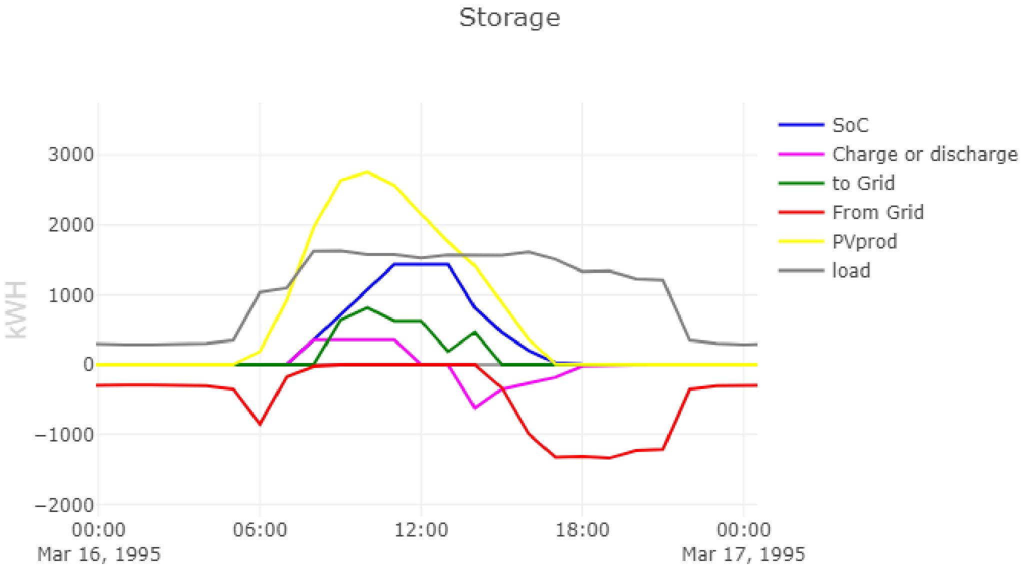


Figure A.6: Test scenario 2 peak shaving. Load is illustrated in grey, generated electricity PV in yellow, State-of-Charge (SoC) in blue, charging or discharging behavior in pink, consumption in red and fed-in to the grid in green. All values are represented in kWh.

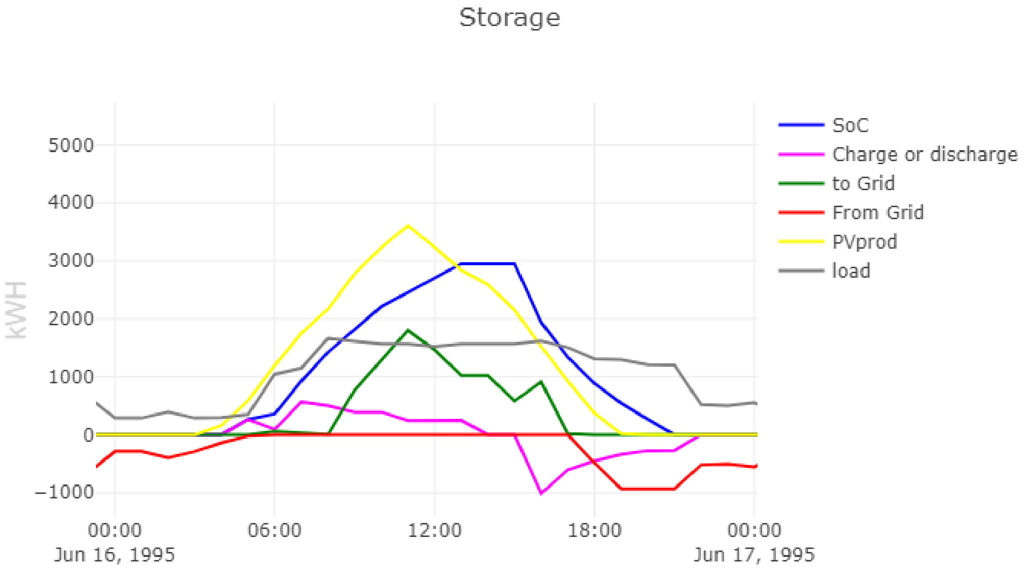


Figure A.7: Test scenario 3 peak shaving. Load is illustrated in grey, generated electricity PV in yellow, State-of-Charge (SoC) in blue, charging or discharging behavior in pink, consumption in red and fed-in to the grid in green. All values are represented in kWh.

A.5.3. gen-set testing

A.6. Performance Graphs

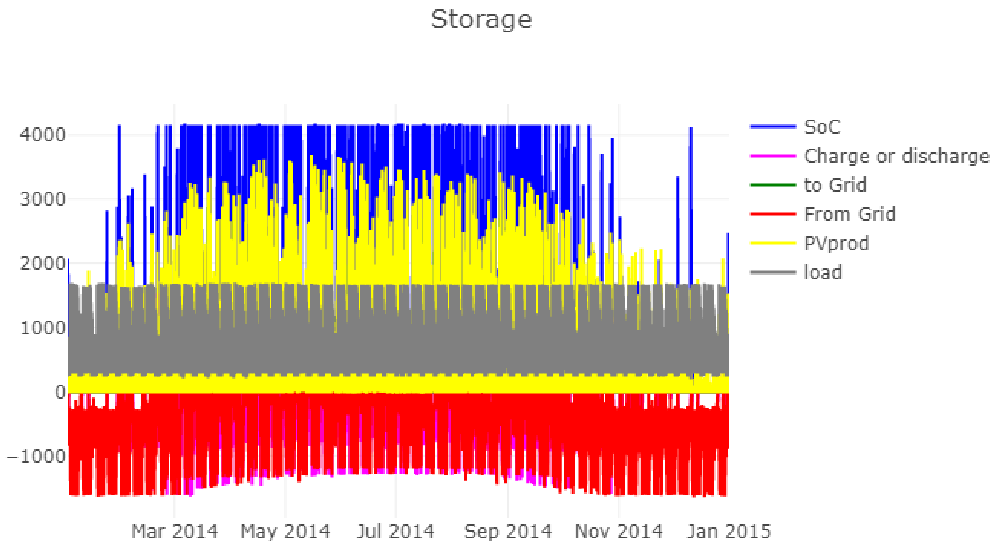


Figure A.8: Representation of the greedy storage strategy for 8760 hours (1 year)

A.7. Results

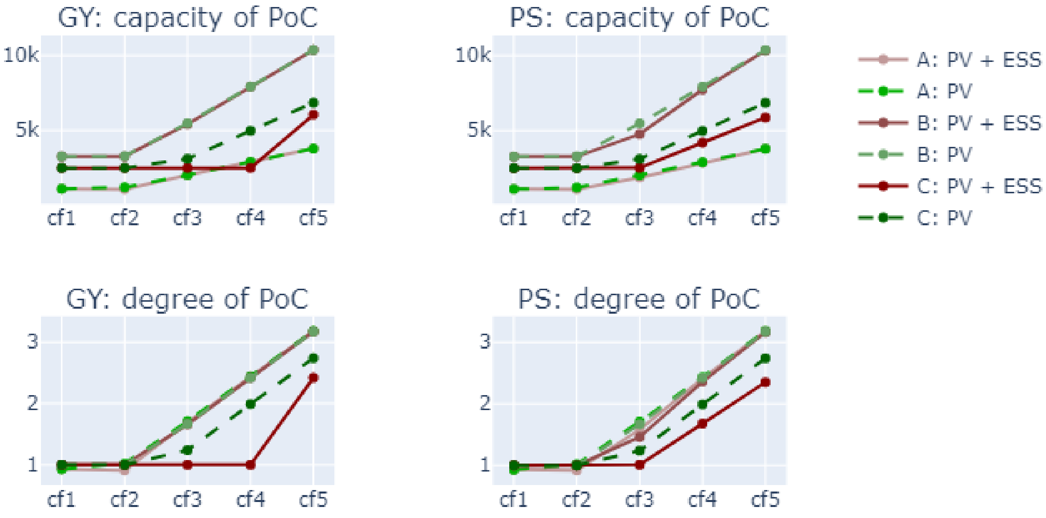
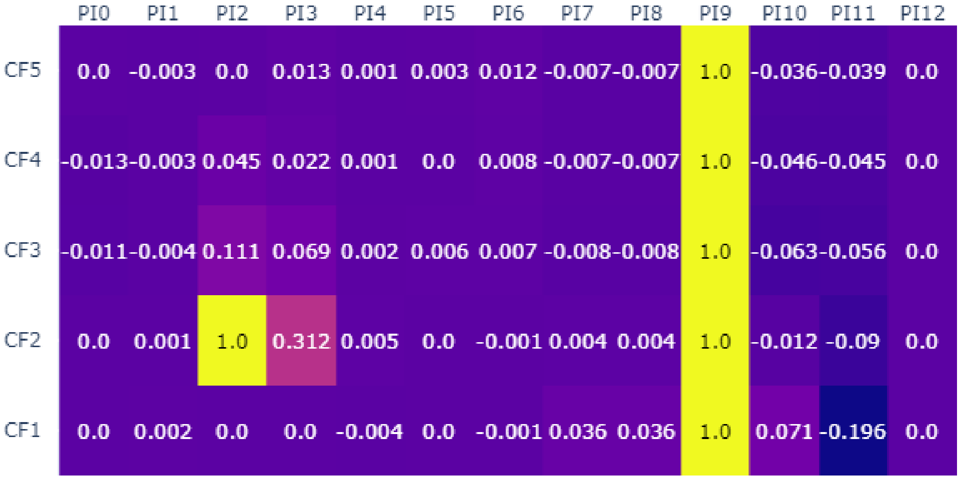


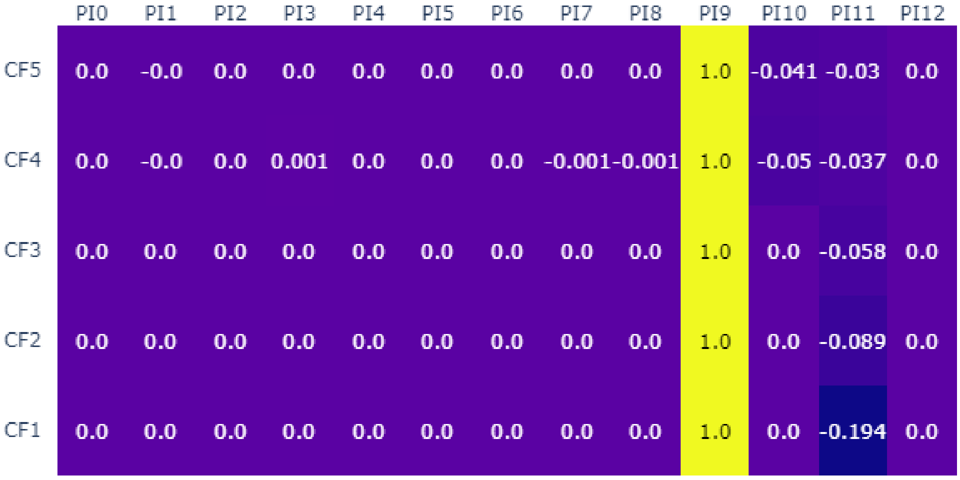
Figure A.9: Overview of the different scenarios, operations and configurations and their capacity for Point of Connection.

A.7.1. Gen-set influences



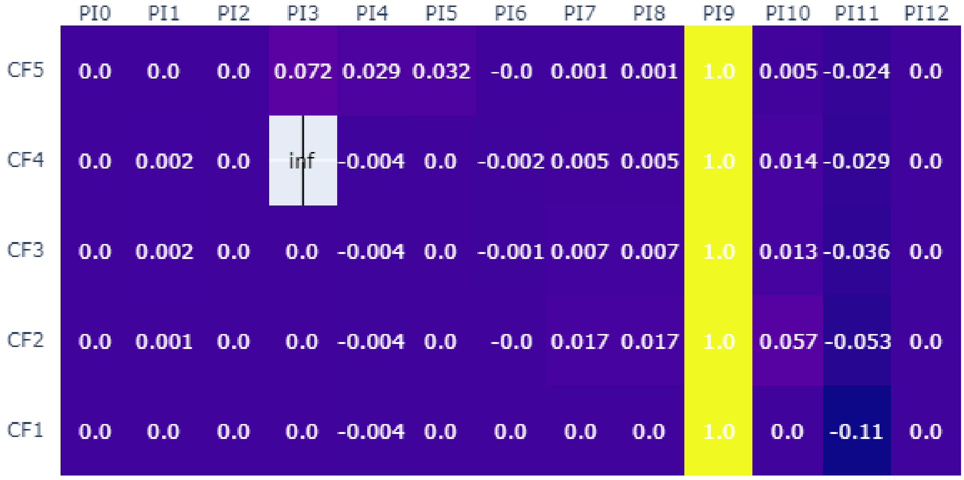
	PI0	PI1	PI2	PI3	PI4	PI5	PI6	PI7	PI8	PI9	PI10	PI11	PI12
CF5	0.0	-0.003	0.0	0.013	0.001	0.003	0.012	-0.007	-0.007	1.0	-0.036	-0.039	0.0
CF4	-0.013	-0.003	0.045	0.022	0.001	0.0	0.008	-0.007	-0.007	1.0	-0.046	-0.045	0.0
CF3	-0.011	-0.004	0.111	0.069	0.002	0.006	0.007	-0.008	-0.008	1.0	-0.063	-0.056	0.0
CF2	0.0	0.001	1.0	0.312	0.005	0.0	-0.001	0.004	0.004	1.0	-0.012	-0.09	0.0
CF1	0.0	0.002	0.0	0.0	-0.004	0.0	-0.001	0.036	0.036	1.0	0.071	-0.196	0.0

Figure A.10: Gen-set transit energy influence greedy algorithm scenario A on other performance indicators.



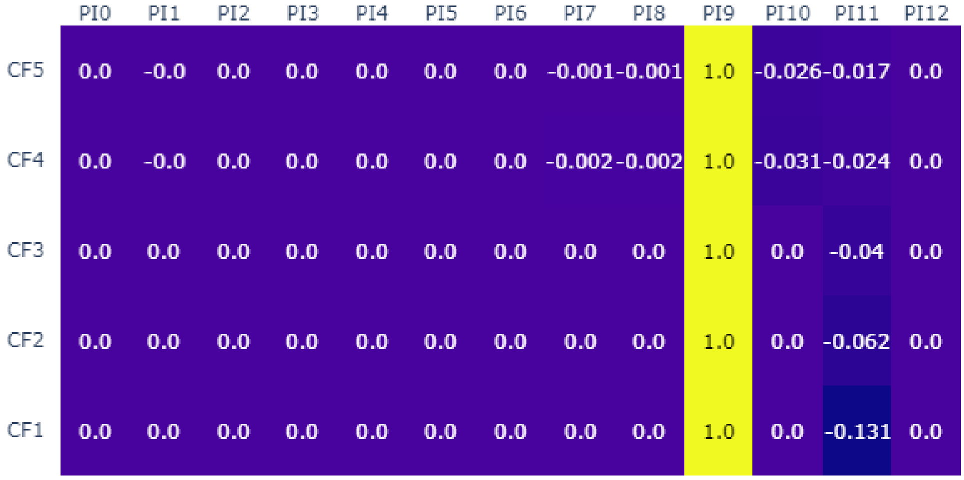
	PI0	PI1	PI2	PI3	PI4	PI5	PI6	PI7	PI8	PI9	PI10	PI11	PI12
CF5	0.0	-0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	-0.041	-0.03	0.0
CF4	0.0	-0.0	0.0	0.001	0.0	0.0	0.0	-0.001	-0.001	1.0	-0.05	-0.037	0.0
CF3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	-0.058	0.0
CF2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	-0.089	0.0
CF1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	-0.194	0.0

Figure A.11: Gen-set transit energy influence peak shaving algorithm scenario A on all performance indicators.



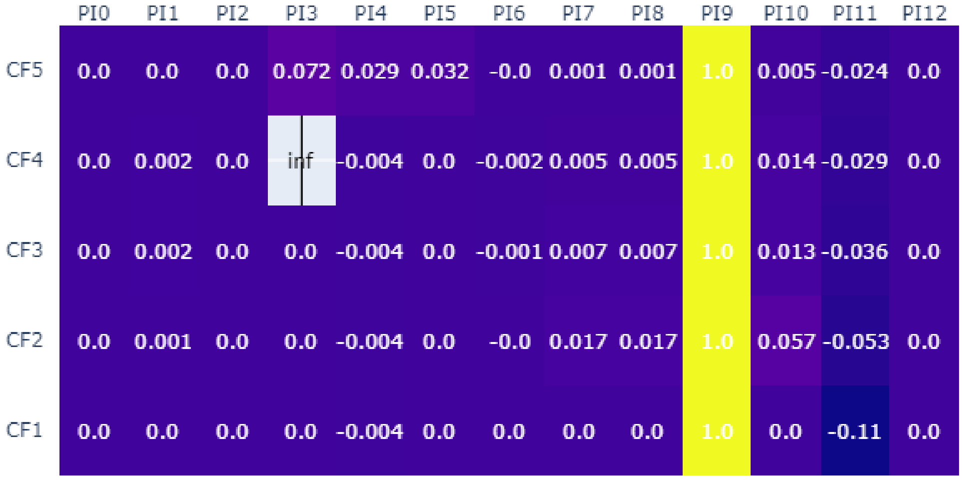
	PI0	PI1	PI2	PI3	PI4	PI5	PI6	PI7	PI8	PI9	PI10	PI11	PI12
CF5	0.0	0.0	0.0	0.072	0.029	0.032	-0.0	0.001	0.001	1.0	0.005	-0.024	0.0
CF4	0.0	0.002	0.0	inf	-0.004	0.0	-0.002	0.005	0.005	1.0	0.014	-0.029	0.0
CF3	0.0	0.002	0.0	0.0	-0.004	0.0	-0.001	0.007	0.007	1.0	0.013	-0.036	0.0
CF2	0.0	0.001	0.0	0.0	-0.004	0.0	-0.0	0.017	0.017	1.0	0.057	-0.053	0.0
CF1	0.0	0.0	0.0	0.0	-0.004	0.0	0.0	0.0	0.0	1.0	0.0	-0.11	0.0

Figure A.12: Gen-set transit energy influence greedy algorithm scenario B on other performance indicators.



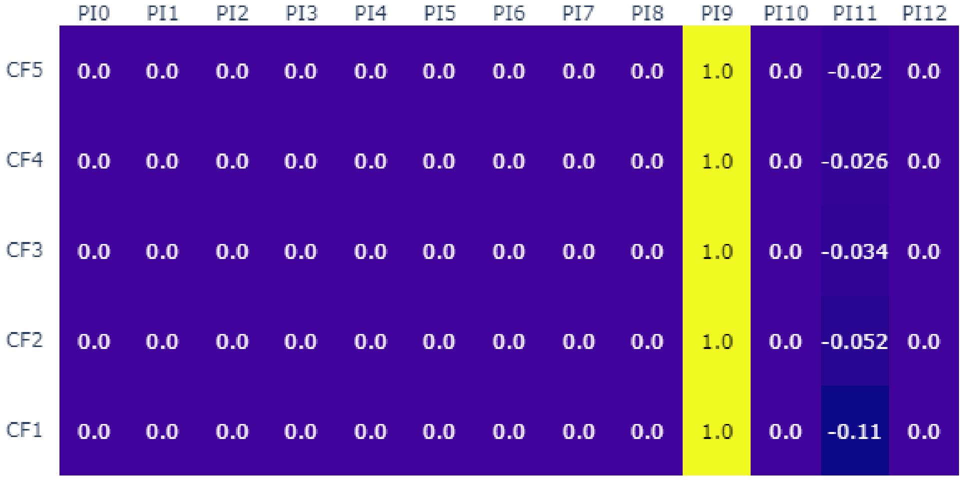
	PI0	PI1	PI2	PI3	PI4	PI5	PI6	PI7	PI8	PI9	PI10	PI11	PI12
CF5	0.0	-0.0	0.0	0.0	0.0	0.0	0.0	-0.001	-0.001	1.0	-0.026	-0.017	0.0
CF4	0.0	-0.0	0.0	0.0	0.0	0.0	0.0	-0.002	-0.002	1.0	-0.031	-0.024	0.0
CF3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	-0.04	0.0
CF2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	-0.062	0.0
CF1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	-0.131	0.0

Figure A.13: Gen-set transit energy influence peak shaving scenario B on other performance indicators.



	PI0	PI1	PI2	PI3	PI4	PI5	PI6	PI7	PI8	PI9	PI10	PI11	PI12
CF5	0.0	0.0	0.0	0.072	0.029	0.032	-0.0	0.001	0.001	1.0	0.005	-0.024	0.0
CF4	0.0	0.002	0.0	inf	-0.004	0.0	-0.002	0.005	0.005	1.0	0.014	-0.029	0.0
CF3	0.0	0.002	0.0	0.0	-0.004	0.0	-0.001	0.007	0.007	1.0	0.013	-0.036	0.0
CF2	0.0	0.001	0.0	0.0	-0.004	0.0	-0.0	0.017	0.017	1.0	0.057	-0.053	0.0
CF1	0.0	0.0	0.0	0.0	-0.004	0.0	0.0	0.0	0.0	1.0	0.0	-0.11	0.0

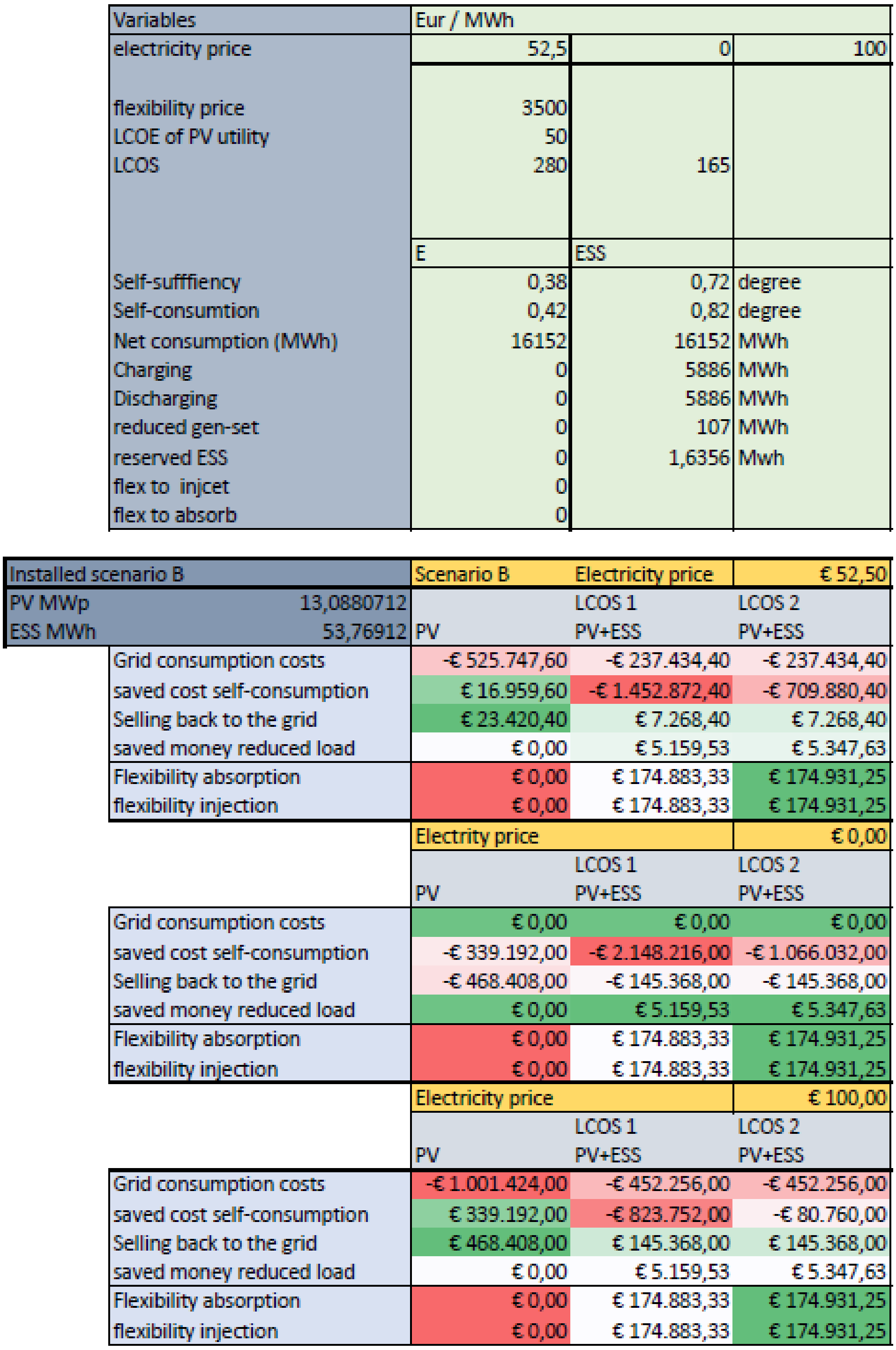
Figure A.14: Gen-set transit energy influence greedy algorithm scenario C on other performance indicators.



	PI0	PI1	PI2	PI3	PI4	PI5	PI6	PI7	PI8	PI9	PI10	PI11	PI12
CF5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	-0.02	0.0
CF4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	-0.026	0.0
CF3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	-0.034	0.0
CF2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	-0.052	0.0
CF1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	-0.11	0.0

Figure A.15: Gen-set transit energy influence peak shaving algorithm scenario C on other performance indicators.

A.8. Economic analysis



Variables	Eur / MWh		
electricity price	52,5	0	100
flexibility price	3500		
LCOE of PV utility	50		
LCOS	280	165	
	E	ESS	
Self-sufffiency	0,38	0,72	degree
Self-consumtion	0,42	0,82	degree
Net consumption (MWh)	16152	16152	MWh
Charging	0	5886	MWh
Discharging	0	5886	MWh
reduced gen-set	0	107	MWh
reserved ESS	0	1,6356	Mwh
flex to injcet	0		
flex to absorb	0		

Installed scenario B		Scenario B	Electricity price	€ 52,50
PV MWp	13,0880712		LCOS 1	LCOS 2
ESS MWh	53,76912	PV	PV+ESS	PV+ESS
	Grid consumption costs	-€ 525.747,60	-€ 237.434,40	-€ 237.434,40
	saved cost self-consumption	€ 16.959,60	-€ 1.452.872,40	-€ 709.880,40
	Selling back to the grid	€ 23.420,40	€ 7.268,40	€ 7.268,40
	saved money reduced load	€ 0,00	€ 5.159,53	€ 5.347,63
	Flexibility absorption	€ 0,00	€ 174.883,33	€ 174.931,25
	flexibility injection	€ 0,00	€ 174.883,33	€ 174.931,25
		Electrity price		€ 0,00
			LCOS 1	LCOS 2
		PV	PV+ESS	PV+ESS
	Grid consumption costs	€ 0,00	€ 0,00	€ 0,00
	saved cost self-consumption	-€ 339.192,00	-€ 2.148.216,00	-€ 1.066.032,00
	Selling back to the grid	-€ 468.408,00	-€ 145.368,00	-€ 145.368,00
	saved money reduced load	€ 0,00	€ 5.159,53	€ 5.347,63
	Flexibility absorption	€ 0,00	€ 174.883,33	€ 174.931,25
	flexibility injection	€ 0,00	€ 174.883,33	€ 174.931,25
		Electricity price		€ 100,00
			LCOS 1	LCOS 2
		PV	PV+ESS	PV+ESS
	Grid consumption costs	-€ 1.001.424,00	-€ 452.256,00	-€ 452.256,00
	saved cost self-consumption	€ 339.192,00	-€ 823.752,00	-€ 80.760,00
	Selling back to the grid	€ 468.408,00	€ 145.368,00	€ 145.368,00
	saved money reduced load	€ 0,00	€ 5.159,53	€ 5.347,63
	Flexibility absorption	€ 0,00	€ 174.883,33	€ 174.931,25
	flexibility injection	€ 0,00	€ 174.883,33	€ 174.931,25

Figure A.16: Overview with economic gain.

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