LUTMDN/TMHP-19/5439-SE
ISSB 0282-1990

Demand-side flexibility in shopping centres

A case study on Väla shopping centre

LUND UNIVERSITY

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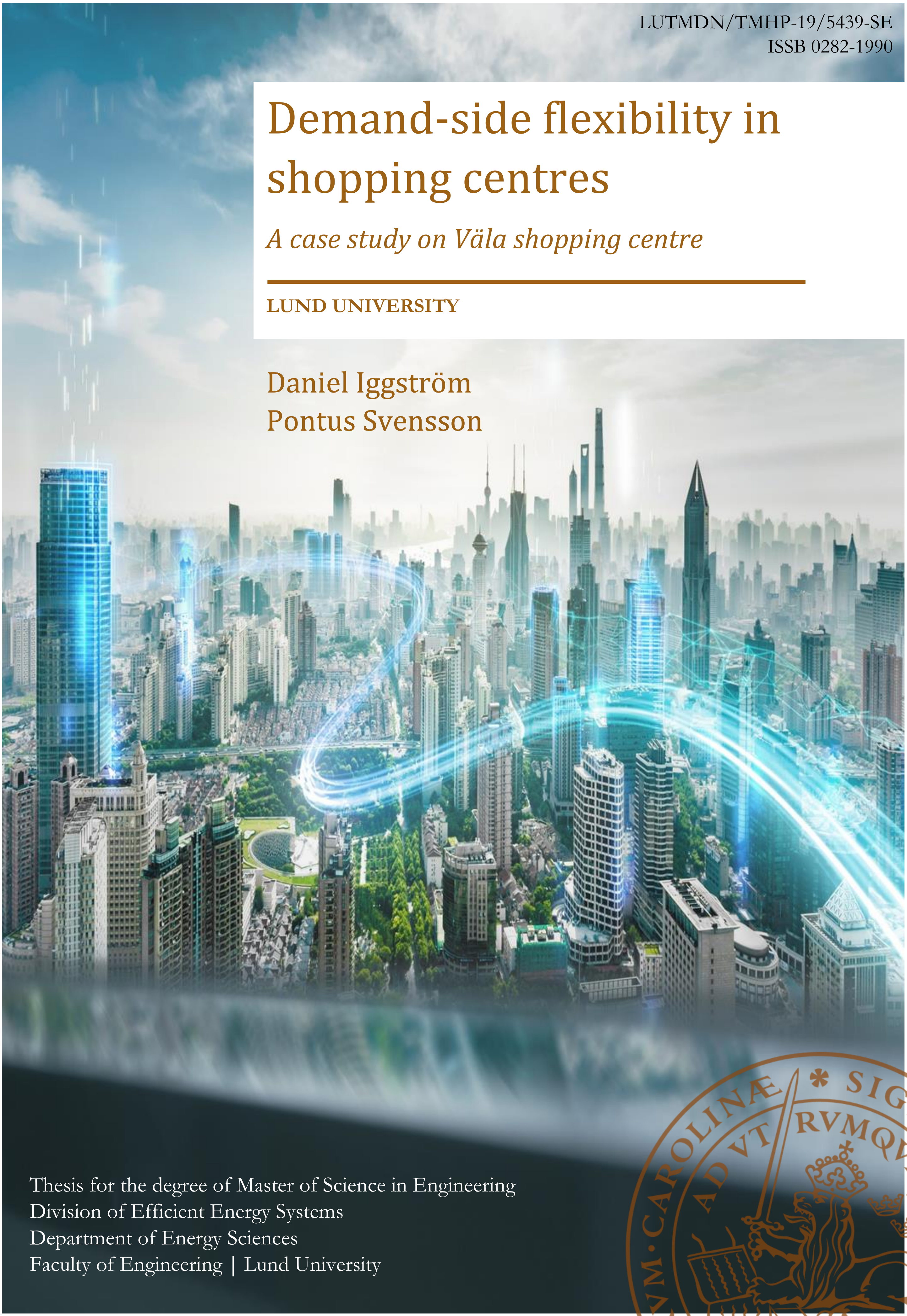

Thesis for the degree of Master of Science in Engineering
Division of Efficient Energy Systems
Department of Energy Sciences
Faculty of Engineering | Lund University

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12 June 2019

LUND UNIVERSITY

LTH
FACULTY OF ENGINEERING

In collaboration with:

SIEMENS
Ingenuity for life

This master thesis for the degree of Master of Science in Engineering has been conducted at the Division of Efficient Energy Systems at the Faculty of Engineering, Lund University, in collaboration with Siemens AB, Malmö.

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ISSN 0282-1990

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Acknowledgements

First and foremost, we would like to thank the Smart Infrastructure division at Siemens AB for providing us the opportunity to work with such an interesting topic. We hope that this thesis will be the take-off towards many successful implementations of demand-side flexibility in commercial buildings in Sweden and internationally.

We want to express our greatest gratitude to our Siemens supervisor Annah Håkansson. Thank you for all the useful comments and remarks. To all colleagues at Siemens, we wish you the best and remember all the joyful times in the office. In particular, we would like to thank Mats Jönsson. Your knowledge has been crucial to our work. Further, we want to thank numerous people at Skandia Fastigheter, AirSon, and personnel at Svenska kraftnät. You have all been vital pieces of this master thesis puzzle.

To our LTH supervisor Kerstin Sernhed, your advice, guidance and engagement have been invaluable for this thesis to be finalized. Further, thank you to all the professors, lecturers and supervisors that we have met during our five years at LTH.

Finally, we want to express our profound gratitude to our families and friends for always providing us with continuous encouragement and unfailing support.

Malmö, May 2019

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Abstract

Sweden is heading towards an energy system with less nuclear power and more intermittent energy sources. Together with the coming electrification of the transport and industry sector, this challenges the future stability of the Swedish power system. However, a part of the solution could be that consumption of electricity temporarily is adjusted to facilitate the operation of the power system, recognized as Demand-Side Flexibility (DSF). The purpose of this thesis has been to investigate the prerequisites for Väla shopping centre to offer DSF with strategic load control and operation of a Battery Energy Storage System (BESS).

A technical assessment of loads has been carried out using four important characteristics of consumer flexibility: sheddability, controllability, availability and acceptability. The ventilation system, comfort cooling system and indoor lightning were qualitatively evaluated using these flexibility parameters. In the BESS assessment, simulations of peak power reduction were conducted using a software System Advisor Model. The technical potential was evaluated for two BESS dimensions and was translated into savings using grid fee agreements from both Öresundskraft and E.ON. This analysis was complemented with a qualitative analysis of the prerequisites to also use the BESS for frequency regulation.

The results show that DSF with loads at Väla shopping centre constitutes a complex technical challenge, since existing control chains and systems would have to be retrofitted to serve new purposes. It was concluded that the ventilation system was best suited for DSF applications out of the three investigated loads. The reasons for this were the presence of controllable variable frequency drives, the predictable availability pattern with respect to operating power and the large installed nominal capacity.

The BESS simulations show that yearly peak power demand potentially could be reduced by 12-14% with BESS dimensions of 1600 kW/2000 kWh and 1200kW/1500 kWh. These BESS dimensions would generate average yearly savings of 333-284 TSEK with E.ON's grid fee and 198-178 TSEK with Öresundskraft's grid fee. The calculation of Pay-Back Time (PBT) and Net Present Value (NPV) indicate that E.ON's grid fee and the smaller BESS would be more economically favorable, but that an investment in a BESS would not be profitable, neither with the current circumstances nor with a future lower BESS price. The base case indicates that the PBT of the investigated BESS dimensions lies between 33-63 years. In a hypothetical scenario with a future lower BESS price and significant price development of power components in the grid fee, the PBT becomes 10-12 years.

From the analysis of the prerequisites for providing frequency control, it was concluded that the BESS legislatively could be qualified as a balancing resource on the reserve market. Furthermore, the operational performance analysis indicated that the BESS would be available for frequency regulation during longer periods of time even if reducing peak power would be prioritized throughout the year. The main limitation for providing frequency control is the risk of increasing the yearly costs towards the network operator during a down-regulation at times when the power demand at Väla shopping centre is close to its cost determinative power level.

Keywords: demand-side flexibility, shopping centre, load control, battery energy storage system, peak power reduction, frequency regulation.

Sammanfattning

Förutsättningarna för Sveriges energiförsörjning håller på att förändras i takt med att kärnkraften gradvis fasas ut och ersätts med intermittent elproduktion. Detta sker samtidigt som elektrifieringen av transport -och industrisektorn, vilket för med sig växande problem som äventyrar den framtida stabiliteten i elnätet. Ett sätt att hantera kommande utmaningar är att elkonsumtion temporärt anpassas för att gynna driften av elnätet, vilket brukar benämnas som efterfrågeflexibilitet. Syftet med denna studie var att undersöka vilka förutsättningar det finns för Väla köpcentrum att erbjuda efterfrågeflexibilitet dels genom styrning av laster dels genom att installera ett stationärt batteri.

En teknisk analys av lasterna har genomförts genom att titta på flexibilitetsparametrarna frånkopplingsbarhet, kontrollerbarhet, tillgänglighet och accepterbarhet. Ventilationssystemet, kylsystemet och belysning utvärderades sedan kvalitativt utifrån dessa parametrar. I analysen av möjligheterna med en stationär batterilösning genomfördes simuleringar av topplastutjämning i mjukvaran System Advisor Model (SAM). Den tekniska potentialen för att reducera toppeffektbehovet utvärderades för två batteristorlekar och räknades sedan om till besparing med priskomponentera från både Öresundskrafts och E.ON:s nättariffer. Denna analys kompletterades sedan med en kvalitativ analys av förutsättningarna för att också erbjuda kapacitet på Sveriges balansmarknader.

Den tekniska analysen av lasterna visar att efterfrågeflexibilitet är en utmaning eftersom befintliga kontrollkedjor inte är anpassade för att styras med avseende på effekt. Detta medför att ytterligare kontrollfunktionalitet och mätning skulle behöva implementeras. Den last som bedöms ha bäst tekniska kvalifikationer för efterfrågeflexibilitet är ventilationssystemet. Anledningen till detta är att aggregaten styrs via kontrollerbara frekvensomriktare, driftseffekter är förutsägbara och att den installerade nominella effekten är stor.

Simuleringar av effektreduktioner med batterilösning visar att årliga toppeffekten på Väla köpcentrum kan reduceras med 12–14 % för batteristorlekar motsvarande 1500kW/2000kWh och 1200kW/1500 kWh. Dessa batteristorlekar möjliggör en teoretisk årlig besparing på 333–284 TSEK med E.ON:s nättariff och 198–178 TSEK med Öresundskrafts nättariff. Återbetalningstiden och nuvärdet visar att E.ON:s nättariff och den mindre batteristorleken är mer finansiellt gynnsam. Investeringen skulle dock inte vara lönsam varken med nuvarande förutsättningar eller med en kombination av ökande priser på effektkomponenter och framtida lägre batteripriser. I grundfallen beräknades återbetalningstiden till 33–63 år och i ett hypotetiskt fall med ett framtida lägre batteripris och prisökning av effektkomponenterna i nättariffen, blir återbetalningstiden 10–12 år.

Analysen av förutsättningarna för att bidra med frekvenshållning visar att en batterilösning såväl tekniskt som juridiskt skulle kunna kvalificeras som en balansresurs på reservkraftsmarknaden. Analysen av batteriets operativa drift visar dessutom att det finns tillgänglig kapacitet för frekvenshållning är om batterilagret skulle reducera toppeffektbehovet på årlig basis. En begränsning är den prisbestämande effektnivån i nättariffen, då det finns risk att öka den årliga kostnaden mot nätägaren om driften av batterilagret skulle orsaka en effekttopp i samband med att det deltar i frekvensregleringen.

Contents

List of abbreviations

aFRR	Automatic Frequency Restoration Reserve
BEMS	Building Energy Management System
BESS	Battery Energy Storage System
cRSP	common Remote Service Platform
DSF	Demand Side Flexibility
EI	Energy market Inspectorate
FCR-D	Frequency Contaminant Reserve Disturbance
FCR-N	Frequency Contaminant Reserve Normal
HVAC	Heating, Ventilation, and Air Conditioning
mFRR	Manual Frequency Restoration Reserve
MVHR	Mechanical Ventilation with Heat Recovery
NPV	Net Present Value
PBT	Pay-Back Time
PV	Photovoltaics
RPM	Revolutions Per Minute
SAM	System Advisor Model
SoC	State of Charge
TSO	Transmission System Operator
UPS	Uninterruptable Power Supply
VFD	Variable Frequency Drive

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1. Introduction

This chapter aims to introduce the thesis. Firstly, a short background of the research areas handled in this thesis are given together with a presentation of the collaboration partner. This is followed by a problem discussion which then leads into the thesis purpose and the research questions.

The Swedish energy system is heading towards a phase of transformation, induced by political decisions such as the *Agreement on Swedish energy policy* (Regeringskansliet 2016). The agreement states that Sweden's energy supply is to rely entirely on renewables by 2040, which means that the share of wind and solar power must increase (Svenska kraftnät 2017c). However, the implementation of more intermittent power production, together with the potential phase out of nuclear power and electrification of the industry and transport sector, entails several challenges that must be handled in future power system. These challenges include short- and long-term balancing of the power system, shortage of grid capacity on all voltage levels and handling of overproduction from renewable electricity generation (EI 2016; NEPP 2016).

The most difficult challenge is probably that all these complications need to be addressed at the same time. Consequently, this creates the need of a diverse and innovative portfolio of solutions that could be combined to ensure stability and reliability of the power system. However, for this to be realistically feasible it requires that not only producers and grid owners take action, but also that consumers are a part of the solution.

Historically, increasing consumption of electricity in Sweden has been solved by either increasing production capacity and/or transfer capacity. However, with the emerging challenges in the power system this solution might become untenable, which means that the attitude towards consumption of electricity might have to be changed on a societal level. A first step in this process would be that some consumption temporarily is adjusted to facilitate the operation of the power system, which typically is recognized as Demand-Side Flexibility (DSF).

DSF is a measure that both technically and cost effectively could assist the transformation of the power system. It could be used for multiple balancing services, handling grid scarcity on all voltage levels and contributes to a more efficient use of productions resources (EI 2016). In summary, DSF could compose a societally and environmentally beneficial solution to many of the impending challenges in the power system.

1.1 Collaboration partner and reference project

This thesis is written in collaboration with Siemens ABs operating company Smart Infrastructure (SI) in Malmö. In April 2019, the former divisions of Building Technologies (BT), the low and medium voltage part of Energy Management (EM) and the control products division of Digital Factories (DF) were fused to the operating company SI (*see Figure 1*). The fusion was conducted to better reflect the needs and trends of the society. An interest of the new division is how infrastructure can become a larger part of the energy system, an interest which is shared by the thesis authors.

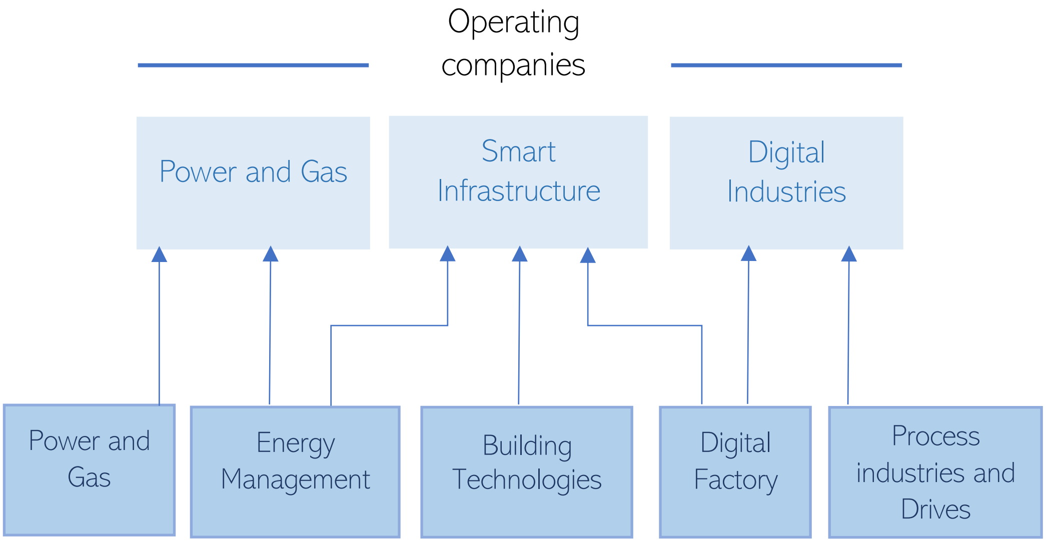


Figure 1. New organisational structure of divisions within Siemens operating companies.

The purpose of the new organizational structure is to enhance cross-divisional collaboration and carry through projects where knowledge and experiences could be shared. This increased collaborative capability has already shown to be successful in a project conducted by Siemens in Finland (Siemens 2018b). The Sello project initially purposed to improve the energy efficiency at the shopping centre Sello but developed into a significantly more innovative project. Sello is conceptually changing its role in the energy system from being a consumer to become a small Virtual Power Plant (VPP), used for balancing the power system. The term VPP does still not have a strict definition in the literature, but will in this thesis be defined as the combination of various small generation and consumption assets to form a single "virtual" power plant (Saboori, Mohammadi & Taghe 2011). At Sello this is achieved by strategic control of a reserve generator and multiple loads in the building including ventilation system, cooling systems, lightning, heat pumps, electric ground heaters and car chargers. Additionally, a large onsite Battery Energy Storage System (BESS) has been installed in connection to the large photovoltaic plant situated on the roof.

The vision for the project is that the flexibility resources at Sello could be collaboratively controlled to provide balancing power, which then could be offered on the reserve markets. This has already been partly achieved since the BESS and reserve generator currently is taking part on the reserve markets. The loads are being and will continue to be prequalified by the Finnish power system operator Fingrid in the coming years, but functional tests have been conducted which indicate that several of the loads technically should be able to qualify for applications such as frequency control.

The Sello project is considered an ongoing success story and has sparked interest both nationally and internationally. Naturally, this induces an interest for Siemens to expand this concept into more potentially successful cases in Sweden.

1.2 Problem discussion

The future challenges in the energy system are both many and complicated, which means that measures must be invented, researched and tested before problems in the power system become too severe. DSF is a subject which has been researched for many years already, but currently stands in more focus than ever before. It is the thesis authors perception that most studies published in Sweden the last few years enlightens the general benefits and challenges of DSF combined with estimative quantitative numbers of technical potential. One such example is study from North European Energy Perspective Project (NEPP), where the potential for DSF from several studies have been collected and possibilities and limitations are discussed for multiple consumer types (NEPP 2013). Another study requested by the Swedish Energy Market Inspectorate (EI), enlightens similar problems as in (NEPP 2013), but also highlights different consumer types subjective opinion towards realising DSF (Sweco 2016).

These and other similar studies successfully give an overview of benefits and challenges of DSF, which are partly differentiated for various customer types. However, there is a lack of studies that on a detailed technical level investigate the prerequisites for DSF in actual buildings (Aduda et al. 2016). Furthermore, evaluation of flexibility in buildings has to be done on a case-by-case basis due to the large amounts of factors that play a role in deciding what flexibility that can be utilized and during what times (IEA 2017). Thus, conducting a case study is motivated since it generates both valuable case specific details of a certain building and contributes to increasing the general knowledge about what challenges that must be handled to realise DSF in practise.

1.3 Finding a case study object

The working process to find a suitable case study building took basis in what previous studies have identified regarding technical prerequisites for DSF. In NEPP (2013) it is stated that the aggregated technical potential for DSF in Sweden is largest for electrically intensive industries (2600-3600 MW). There are, however, uncertainties how much of this that practically could be realised with respect to the activities in the buildings.

Electrically heated households have the second largest potential, but where a significant challenge is to coordinate these flexibility resources properly and obtain acceptance. Further, for office buildings, the aggregated potential is estimated to 150 MW and for schools 15 MW. For shopping centres, the technical potential is estimated to 140 kW per object and 45 MW if all shopping centres in Sweden are aggregated. (NEPP 2013)

Even though the aggregated potential for commercial buildings are rather low in comparison to the aggregated potential of electrically intensive industries, they have a significant advantage in that there usually already is a Building Energy Management System (BEMS) implemented from which the loads in the building can be controlled. This makes strategic control of loads easier to technically realize in commercial buildings than in both industries and households. Also, it is likely that commercial buildings in general have lower shares of crucial electricity loads that must be operated continuously through the whole day. This statement could be motivated by the fact that the majority of loads in commercial buildings are related to customer comfort, while industries typically relies on machines and electricity driven tools, which need electricity to be functional. Towards typical households, commercial buildings have the advantage that they are larger with respect to power demand, thus offering an easier aggregation of loads, which could generate a greater value for the power system.

From a feasibility perspective, it was considered important to find a building where a lot of data could be easily accessed and where the general knowledge about the building is good. A building which fitted into this description proved to be Väla, located outside Helsingborg in the south of Sweden. Väla has been working together with Siemens for several years with the focus on improving energy efficiency to make Väla more environmentally sustainable. Additionally, a positive attribute that already exist at Väla is a large photovoltaic (PV) plant located on the roof.

The reference case Sello in Finland includes a large BESS, which is why the prerequisites of a similar installation would be interesting to investigate within the framework of this thesis. Thus, it was considered suitable to use Väla as object for a case study and then investigate what value a BESS could generate in combination with the large PV-plant. However, in order to enable other applications than just storing potential overproduction from the PV-plant, it was considered reasonable to also allow charging of the BESS from the grid.

The benefits of using a BESS as flexibility resource in comparison to loads is that no consideration has to be taken to the activities in the building, thus eliminating any risk for causing climatic discomfort. Typical applications of behind-the meter installed BESS is peak shaving, energy arbitrage and frequency control (Gitis, Leuthold & Sauer 2015). The prerequisites for all of these applications was considered interesting to include in the scope of the thesis.

Summarized, the scope of this thesis is a case study at Väla with a broad formulated purpose, but with two categories of research questions which more in detail describes what is aimed to be answered.

1.4 Purpose and research questions

The purpose of this thesis is to investigate the prerequisites for Väla to offer DSF. The thesis will focus on technical aspects of loads as a flexibility resource, evaluation of the potential to reduce peak power demand and provide frequency regulation using a BESS. The first category of research questions is linked to the technical aspects of the loads, and the second to the BESS assessment. The research questions of this thesis are:

What loads at Väla could be used for DSF applications?

- What loads are sheddable?
- How are the loads controlled?
- When are the loads available for DSF?
- What acceptability is there for using loads as DSF resources?

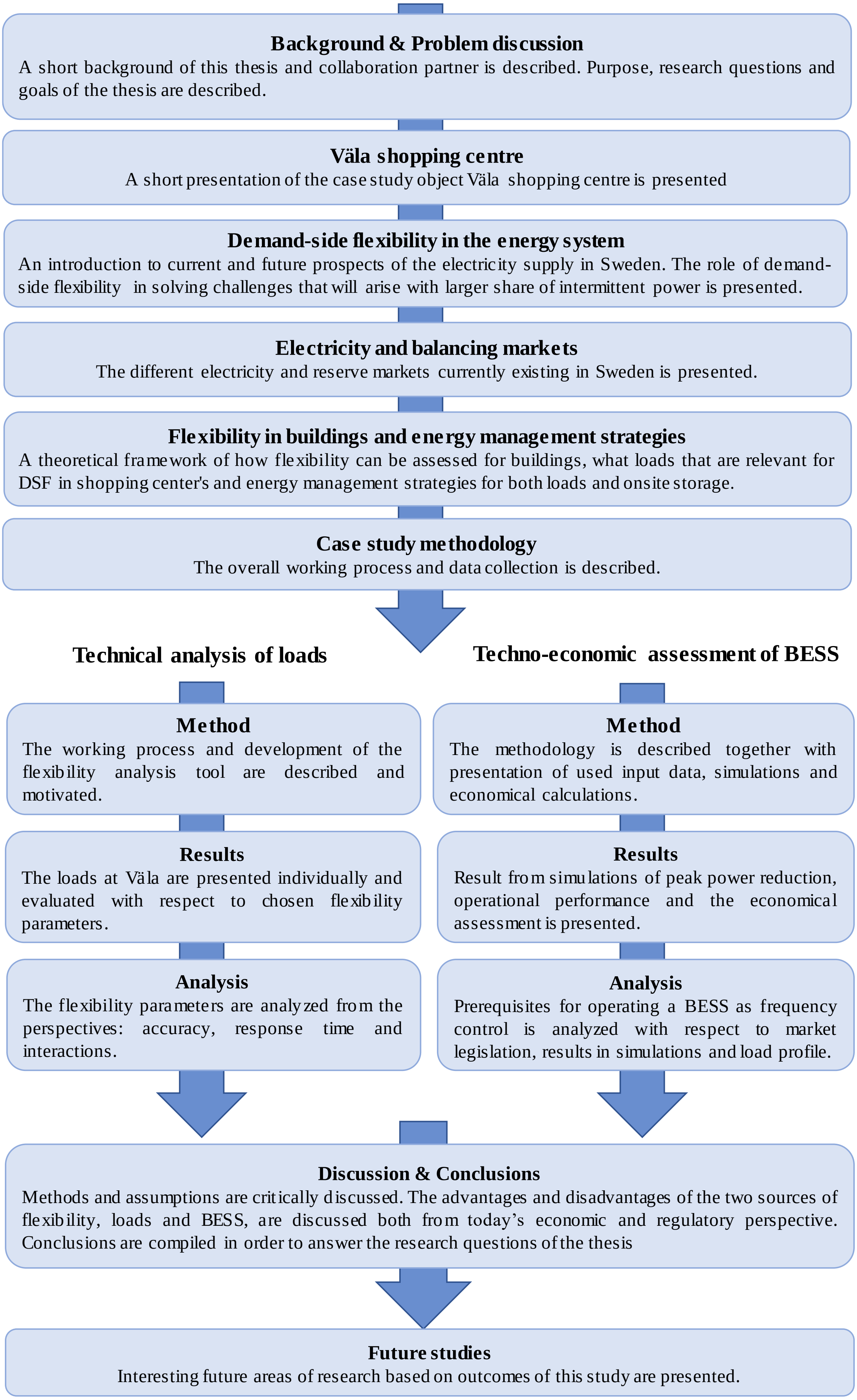
What are the prerequisites for operating a BESS at Väla?

- What is the technical potential for reducing peak power demand?
- Would it be profitable to reduce peak power demand?
- What are the prerequisites for enabling both peak power reduction and frequency regulation?

The goal of the study is to establish a framework containing important technical aspects that should be regarded when assessing the potential for a building to offer DSF through load control and to investigate if an onsite energy storage solution at Väla would be beneficial both from technical and economical perspectives. This knowledge is of value both for Siemens, which are aiming to implement DSF in their business portfolio. Also, the knowledge is of value to other stakeholders in the energy sector such as energy companies, transmission and distribution system operators and building owners, since implementing DSF in practise could create value for all these stakeholders.

1.5 Structure of the thesis

The initial six chapters of the thesis aims to frame the scope of the thesis and to provide the reader with the necessary theoretical background. The study is then divided into two parts where methods, results and analysis are presented individually for technical assessment of loads at Väla and for the techno-economic assessment of the BESS. The last two chapters aim to combine outcomes from both parts by presenting summarizing and concluding discussion chapters. A visual illustration of the structure is presented on *page 6*.



Background & Problem discussion
A short background of this thesis and collaboration partner is described. Purpose, research questions and goals of the thesis are described.

Väla shopping centre
A short presentation of the case study object Väla shopping centre is presented

Demand-side flexibility in the energy system
An introduction to current and future prospects of the electricity supply in Sweden. The role of demand-side flexibility in solving challenges that will arise with larger share of intermittent power is presented.

Electricity and balancing markets
The different electricity and reserve markets currently existing in Sweden is presented.

Flexibility in buildings and energy management strategies
A theoretical framework of how flexibility can be assessed for buildings, what loads that are relevant for DSF in shopping center's and energy management strategies for both loads and onsite storage.

Case study methodology
The overall working process and data collection is described.

Technical analysis of loads

Method
The working process and development of the flexibility analysis tool are described and motivated.

Results
The loads at Väla are presented individually and evaluated with respect to chosen flexibility parameters.

Analysis
The flexibility parameters are analyzed from the perspectives: accuracy, response time and interactions.

Techno-economic assessment of BESS

Method
The methodology is described together with presentation of used input data, simulations and economical calculations.

Results
Result from simulations of peak power reduction, operational performance and the economical assessment is presented.

Analysis
Prerequisites for operating a BESS as frequency control is analyzed with respect to market legislation, results in simulations and load profile.

Discussion & Conclusions
Methods and assumptions are critically discussed. The advantages and disadvantages of the two sources of flexibility, loads and BESS, are discussed both from today's economic and regulatory perspective. Conclusions are compiled in order to answer the research questions of the thesis

Future studies
Interesting future areas of research based on outcomes of this study are presented.

2. Väla shopping centre

This chapter purposes to give the reader a short background of Väla including, previous work, future ambitions and how electricity supply contract and grid fee agreements currently are formulated.

Väla is situated in the south of Sweden, northeast of Helsingborg. The buildings that together make up Väla shopping center are owned by Skandia Fastigheter. The shopping centre is composed of a large commercial zone recognized as Väla retail area and includes Väla Centrum, Väla Volym and Väla Park. The building is located at Marknadsvägen 9 and house more than 100 shops and restaurants. Although the building can be considered as one unit, it is comparted into several sections. From now on, the case study object Väla centrum (section A-L) will be referred to as Väla, since it is the largest coherent building in Väla retail area (*see Figure 2*).

Figure 2. Case study building (Väla, section A-L) at Väla retail area (Google Maps 2019).

The building covers an area of around 50,000 m^2 and has a large electric consumption, due to extensive lightning, ventilation and cooling loads. Consequently, it was decided in 2012 that a collaboration with Siemens AB should be proceeded with the focus to significantly lower the energy consumption. This collaboration turned out to be very successful and the energy consumption was lowered with more than 15% just by replacing old equipment and by optimizing the operation of the loads in the buildings. The next goal, formulated by the chief energy operator at Väla retail area, is the shopping centre should be a zero-zone by 2023 (Siemens 2018a). This means that the retail area should be self-sufficient in energy viewed from a yearly perspective.

As a part of the work with increasing the energy efficiency of Väla it was also decided to install a photovoltaic plant (PV), which until recently was Sweden's largest PV plant. It was commissioned in 2016 and covers one sixth of the entire roof area of Väla Centrum. The PV plant is positioned in the east-west direction and has an installed nominal power of 1.1 MW, which means that it theoretically could cover the power demand from the electrical comfort cooling during the summer.

2.1 Electricity supply at Väla

The local grid owner that supplies Väla with electricity is Öresundskraft, which is the second largest grid owner in the area. Väla is considered as a large consumer (>250A) and has a supply voltage of 20 kV. The current grid fee agreement for Väla includes several price components such as the momentary outtake of power, energy consumption and reactive power outtake (Öresundskraft 2019).

Further, the large yearly electricity consumption enables the establishment of other types of electricity supply contracts than what smaller consumers and private persons typically can subscribe to. However, the exact details in the contract could not be shared by Skandia Fastigheter since these are confidential according to a business agreement. Still, the conceptual structure of price components could be provided including a description how Väla is exposed towards the physical electricity markets.

2.2 Electricity supply contract

The electricity supply contract at Väla could be recognised as a combination of traditional flat rate and market dependent rate. Excluding taxes and certificate costs, it consists of three price components, which are listed below:

- Energy price
- Transfer charge
- Service and measurement costs

The transfer charge and service costs cannot be influenced in any way by Skandia Fastigheter. However, the energy price, which is a yearly price in SEK/kWh that Skandia Fastigheter pays for the consumed electricity, can be controlled to some extent. The agreement in the contract states that the supplier buys in a yearly energy volume in accordance to a power trading instruction that has been negotiated. A yearly energy price is then determined depending on the prices of the physical markets and how successfully the supplier trades during the year. Thus, this means that the portfolio price is exposed towards the price variation on the physical markets and that it reflects in the yearly fixed energy price.

3. Demand-side flexibility in the energy system

The purpose of this chapter is to give the reader a background of the power generation situation in Sweden, impending challenges with intermittent power generation and the value of DSF. The concept DSF is also decomposed into more specific definitions.

3.1 Power production in Sweden – current situation and prospects

The share of renewable electricity production in Sweden has increased during the last decade (*see Figure 3*) and this has two main explanations. Firstly, the successively increased taxation of fossil fuels has strengthened the competitiveness of biofuels. Secondly, the implementation of economical instruments, such as the electricity certificate system, has promoted implementation of renewable energy for several years. The proportion of renewable electricity generation in relation to total electricity production was 58% during 2016. (Energimyndigheten 2018)

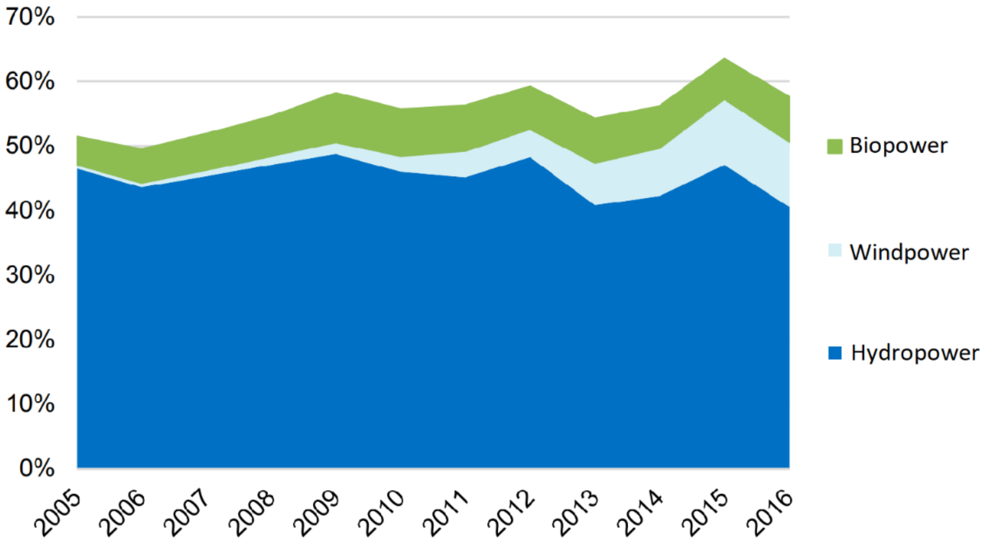


Figure 3. The proportion of renewable electricty generation in Sweden 2005-2016. (Energimyndigheten 2018)

In *Figure 4*, the total electricity usage and the development of electricity production from 1970 to 2015 is shown. The proportion of fossil fuel in Swedish electricity production is not included in *Figure 4* but corresponds to approximately 1-2% of the total electricity production. The share of solar power is still very small (0.06%), but is expected to rise since installed capacity is increasing rapidly. (Energimyndigheten 2018)

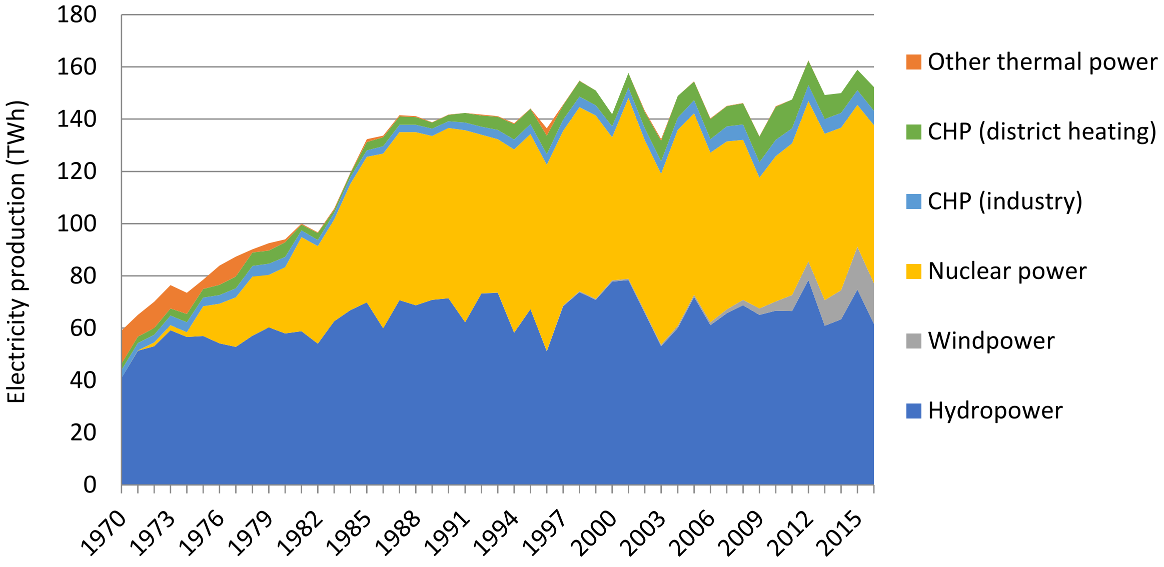


Figure 4. Development of electricity production resources 1970-2015.(Energimyndigheten 2017)

Nuclear power represented 34% of the total electricity production in 2016, making it the second largest source of electricity in Sweden (Energimyndigheten 2017). The prospects of nuclear power in Sweden are, however, very uncertain, which naturally causes worries for the long-term power supply. In 2015, the nuclear power plant owners released a decommissioning plan declaring that the four oldest nuclear reactors (O1 and O2 in Oskarshamn and R1 and R2 at Ringhals) will be taken out of service by 2020 (Energikommisionen 2017).

The main reason for these shutdowns are profitability problems, induced by low electricity prices as well as increased fees in the nuclear waste fund, power taxation and increased security demands (Energikommisionen 2017). The prevailing unfavourable conditions for nuclear power make new investments improbable, which implicate that the electricity generation in Sweden likely will include a significantly lower share of nuclear power in the future (Svenska kraftnät 2015).

The decreasing amount of electricity generation from nuclear power affects the operation of the electrical power system significantly, especially if it solely is replaced by intermittent electricity production (Svenska kraftnät 2015). In a scenario analysis made by Svenska kraftnät it is assumed that nuclear power will be replaced by wind and solar power by 2040 (*see Figure 5*).

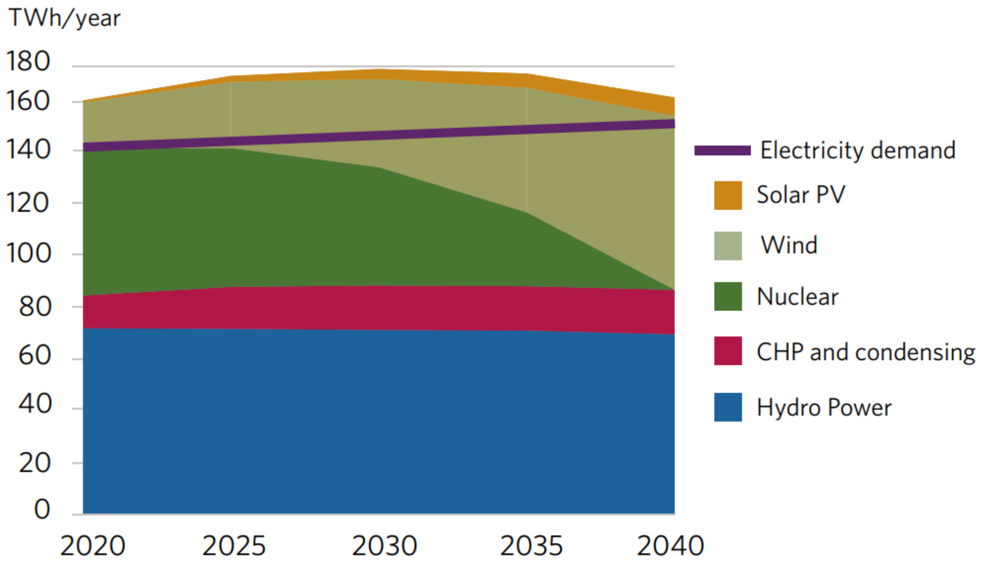


Figure 5. Development scenario of electricity generation and use in Sweden until 2040. (Svenska kraftnät 2017c)

It is important to keep in mind that this is a scenario based on assumptions regarding the technical lifetime of currently operating nuclear power plants and current pace of development for wind power (Svenska kraftnät 2017c). The real outcome will be revealed with time, but it is clear that challenges with intermittent power generation must be handled in the near future.

3.2 Challenges in the future power system

There are several challenges in the transition towards an energy system with large share of intermittent power generation:

- The intermittency of wind and solar power makes it significantly more complicated to maintain the balance in the system.

- With the phase-out of nuclear power, both mechanical inertia and voltage regulation capacity decreases, which complicates how the power system must be operated to maintain stability.

- The risk for power shortage increases since power production capacity rapidly could change as a consequence of unforeseen changes in weather condition.

- There will be an impending risk for overproduction, which is a challenge both from technical and energy market perspectives.

In the following subchapters these challenges will be further explained and exemplified in order to give the reader perspective on how the implementation of intermittent power production affects the operation of the power system.

3.2.1 Balance in the power system and scarce grid infrastructure

Balancing the power system will be a challenge for the future, which has become apparent already in the past few years. The complexity originates from the fact that variations in generation from wind and solar power naturally does not follow the typical cycles in consumption, resulting in more frequently recurring unbalances in the power system.

In *Figure 6*, the development of minutes per week outside the normal frequency band in Sweden is illustrated. From this illustration it becomes clear that the number of intra-hour imbalances are increasing which can be interpreted as a deterioration of the balance capability. It is expected that more intermittent power generation in the Nordic system will increase the occurrence of forecast errors, resulting in a further worsening of the frequency quality in the coming years (Svenska kraftnät 2016a).

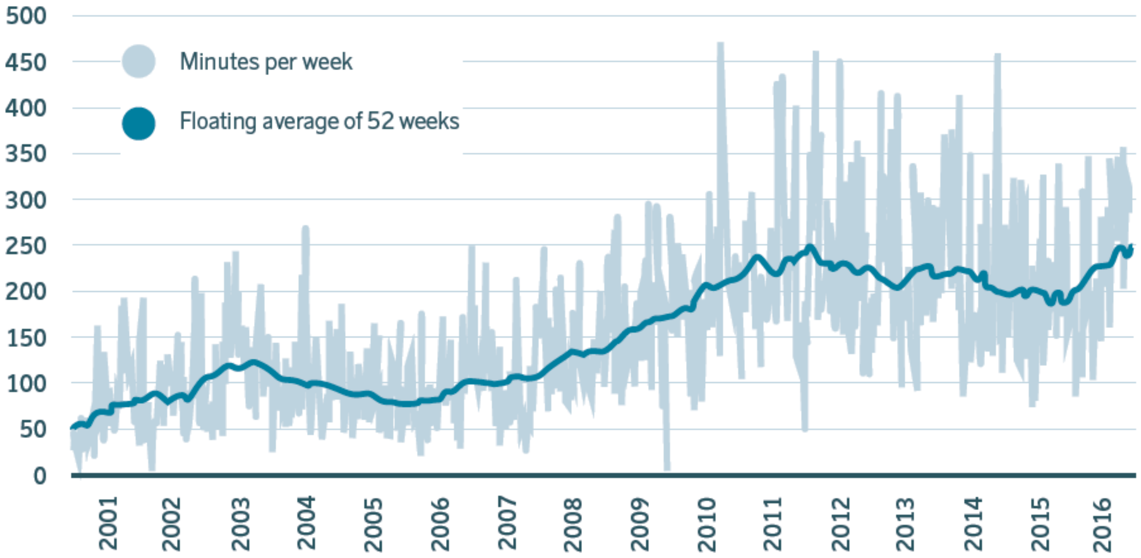


Figure 6. Minutes per week outside the normal frequency band in Sweden 2011-2016. (Svenska kraftnät 2016a)

Further, intermittent power generation also increases the number of situations where the grid infrastructure is functionally inadequate. This is due to the fact that the existing grid infrastructure is dimensioned to handle fluctuations from consumption and not the combined variation from both consumption and production. This is a concern especially affecting grid parts on a regional and local level since intermittent power generation to a large extent is connected at this level (EI 2016). As an example, it is likely that the direction of energy flow will be the opposite from what it is today. This could typically be caused by PV systems that momentarily produces more than the local demand, which then implicates that overproduced electricity must be transmitted to overhead grid parts. This is a scenario that current distribution networks are not designed for (EI 2016).

Further, the expected establishment of electric vehicles is another concern that must be considered in the lower levels of the grid infrastructure (Power circle 2018). During 2018 there were almost 70 000 registered electrically chargeable vehicles in Sweden, and a continuous strong growth is expected. This ongoing trend has partly been induced by the bonus-malus system that was implemented during 2018 and partly by the decision to introduce environmental zones in city parts where air quality is a concern.

In an analysis from Power Circle it is estimated that by 2030, there will be 2.5 million electrically chargeable vehicles in Sweden (Power circle 2018). This puts high demands on power grid capacity since extensive charging infrastructure will be needed. This is a concern from a power supply perspective as well as from a local balancing perspective. Consequently, the increased integration of renewable energy and the expansion of electric vehicles set new requirements on the lower voltage levels of the power system.

3.2.2 Mechanical inertia and voltage regulation

Both the problems with balancing the power system and the problems with an under-dimensioned infrastructure to withstand power peaks are key challenges in the development of future power system. However, there are additional complications that also need to be addressed.

With the phase-out of nuclear power, the amount of mechanical inertia in the power system decreases, thereby making the system more sensitive to momentary disturbances (NEPP 2016). Furthermore, maintaining the voltage level at the high levels of the grid will become more difficult as a consequence of the phase out of nuclear power (Svenska kraftnät 2015). This creates the need for the implementation of resources capable of delivering reactive power that are strategically placed in the power grid (Svenska kraftnät 2015). As the share of nuclear power decreases, these technical issues will become more tangible and the need for actions will continue to increase until sustainable solutions are in place.

3.2.3 Power shortage

As already stated, balancing the power system will become more difficult as the share of intermittent electricity generation increases. Additionally, occasions when there is a risk for shortage of power will become more frequently recurring in the future (NEPP 2016).

The risk for power shortage is greatest during cold days and periods of high consumption. Yet, it is not unlikely that shortage might arise at other times in the future since significant production capacity might be lost due to unforeseen changes in weather condition (EI 2016). According to the scenario analysis made by Svenska kraftnät there will be on average 400 hours of power shortage in south of Sweden in 2040 if no measures are implemented (Svenska kraftnät 2017c). In another scenario analysis made by Sweco in collaboration with EI, it was estimated that the shortage of power in 2030 might become 2200 MW in their reference scenario and as large as 8150 MW during a cold winter day. This prognosis was based on that 35% of yearly electricity consumption would be covered by wind and solar power (EI 2016). What could be interpreted as positive in this context is that the need for power on a nationally aggregated level is not expected to rise significantly until 2030. In a report published by IVA, it is described that the demand for power likely will follow the development of electricity usage (IVA 2016a).

Currently the power usage in Sweden varies between 8500 MWh/h during a warm summer night and up to 27000 MWh/h a cold winter day. What mostly matters from a capacity perspective is the maximum outtake of power. In the prognosis for 2030, assuming that the development of power need follows the development of electricity usage, it is expected that maximum power need will be in the range of 23600 - 28700 MWh/h (IVA 2016a). This is in the range of what the power supply in Sweden currently would manage, which means that situations of maximum load will not become an escalating problem. However, it should be remembered that the capacity situation most likely will be entirely different, which means that the risk of power shortage not only will depend on the load situation, but also of prerequisites for wind and solar generation.

3.2.4 Overproduction from intermittent power sources

A scenario which does not get as much attention as the risk for power shortage is when renewable electricity generation is high but electricity consumption low. With large shares of intermittent electricity generation, there will be an impending risk for overproduction, which becomes even more critical if nearby countries have a similar situation (NEPP 2016).

Overproduction problems are already experienced in Denmark where wind power supplied 43.4% of electricity consumption in 2017 (Dansk Energi 2018). This is expected to increase to 51% by 2020 (Svenska kraftnät 2015). Overproduction from wind power in Denmark is currently regulated by Swedish and Norwegian hydro power, but during situations when interconnectors are overloaded this makes the electricity price fall. At one such occasion, Christmas Eve in 2012, the price fell to -200 €/ MWh, which is the minimum allowable price at Nord pool spot (Svenska kraftnät 2015).

From this experience it becomes clear that occasions of overproduction are problematic both from technical and market perspectives, especially if nearby countries apply the strategy to use interconnected countries for regulation purposes. It is likely that problematic scenarios of overproduction will become more recurrent in the Nordic countries given the removal of nuclear power in Sweden, the continuous expansion of wind power in Denmark and the Energiwende in Germany where the goal is to reach 80% renewable energy generation by 2050 (Fores 2018).

Summarized, the transformation of the energy system entails several difficult challenges. The hardest challenge is maybe that all these complications need to be addressed at the same time, creating the need for a diverse portfolio of solutions that could be combined to ensure stability and security of supply of the power system in the future. This requires that all parts of the society take responsibility and adjust to make the transformation of the energy system as beneficial as possible. One way of doing this is to adapt consumption to facilitate the operation of the power system, typically recognized as DSF.

3.3 Definition of demand-side flexibility

The definition of DSF varies among different sources in the literature. There are also several terms recurring in literature that essentially refer to the same thing, such as demand-side management, load management and demand response. Therefore, it is necessary to present a definition of DSF that will be used in the framework of this thesis. According to the Council of European Energy regulators (CEER), DSF is defined as:

> *The capacity to change electricity usage by end-use customers from their normal or current consumption patterns in response to market signals, such as time-variable electricity prices or incentive payment or in response to acceptance of the customer's bid, alone or through aggregation, to sell demand reduction/increase at a price in organised electricity markets or for internal portfolio optimisation.*
>
> (CEER 2014, p.8)

This definition enlightens several dimensions of DSF and gives perspective on the complexity of the concept. However, in order to put it into context the definition needs to be decomposed into more interpretable parts.

3.3.1 Implicit demand-side flexibility

Implicit DSF, also recognised as price-based flexibility, refers to a situation where consumers can influence their electricity cost by adapting their electricity consumption (EI 2016). This adaption can be induced by varying market signals such as time-of-use tariff, real time pricing or when the cost of using electricity increases because of the current load situation on the grid typically known as critical peak pricing (CEER 2014).

3.3.2 Explicit demand-side flexibility

Explicit DSF, sometimes referred to as incentivised DSF, means that flexibility is offered to an organised market, e.g. (intra-day market or market for power reserves) or for other purposes such as facilitating local grid balancing. The need for explicit DSF often originates from situations when load on the grid is heavy or when there is an impeding risk for bottlenecks. Explicit DSF typically puts higher demands on reliability since capacity must be guaranteed according to requirements on the relevant market. (EI 2016)

3.4 Demand-side flexibility – applications and benefits

As described previously, there are many challenges that need to be addressed in the transition towards a power system that relies on intermittent energy sources. DSF is a solution that potentially could assist the implementation of intermittent energy sources in the power system. DSF has the following applications and benefits:

- Balancing services
- Local grid benefits
- Efficient use of production resources
- Handling shortage of power

In the following subchapters these applications will be further explained and exemplified in order to give the reader perspective on how the implementation DSF could facilitate the implementation of intermittent power production in the power system.

3.4.1 Balancing services

Conceptually, consumption variation affects the frequency in the grid similarly as production variation and should therefore be considered as a potential resource for frequency control (EI 2016). However, DSF originating from load control varies in characteristics depending on the load, which affects the suitability for providing balancing services. Important characteristics that must be considered are capacity, repeatability, endurance and response time (Svenska kraftnät 2017c). A functional combination of these is decisive for the flexibility resource to be accepted as a balancing resource on the reserve markets. However, also the geographical location in the grid is important. Keeping the frequency is a challenge, where balance providers are insufficient, which is the case in middle and south of Sweden (EI 2016).

Particularly critical scenarios would be during low wind and solar production and high consumption or high wind and solar production during low consumption (NEPP 2016). At these scenarios it would be possible to apply DSF by allowing temporary increases of consumption during overproduction and reductions when there is deficit of power. Using DSF as a measure for frequency control could potentially also release capacity from hydro-power, consequently increasing the total power system regulating capacity (Svenska kraftnät 2017c).

3.4.2 Local grid benefits

Large parts of the regional and local grid in Sweden are relatively old and are dimensioned after the conditions that existed at that time (IVA 2016b). Considering the arising challenges that follow with increased share of intermittent power generation and electric vehicles it is very likely that reinforcements in the grid infrastructure soon will be needed. However, DSF could potentially be used to even out the aggregated load-curve which would release capacity in the existing grid infrastructure (IVA 2016b). Consequently, this could postpone costly investments in grid reinforcements or, even more beneficially, remove the need (EI 2016).

Functional use of DSF could also result in lowering the total transferred power on the distribution grid, which is positive both from a load perspective and for lowering transmission losses (NEPP 2016). Furthermore, if DSF through load reductions could be used during hours of maximum power outtake, this could be economically beneficial for the local grid owner since it could enable a lower power component in the price paid against overhead grid parts (NEPP 2016).

How beneficial DSF would be locally depends on the prerequisites at the specific location in the grid. At locations where establishment of intermittent energy sources are extensive, it could be cost-efficient to implement DSF, while it would be less valuable at locations where grid capacity already is sufficient (Tekniska verken 2017).

3.4.3 Efficient use of production resources

Considering the challenges in the future energy supply, it becomes even more important to use production resources efficiently. Implementation of DSF could be beneficial for this purpose if the flexibility is proactive, which means that flexibility is included in the pricing of electricity (EI 2016). Societal benefits could thus be accomplished if consumers systematically reduced their consumption during hours of high price and moved it to hours of lower price.

To reach completely efficient use of production resources, from a socio-economical perspective, the value of the last used MWh according to the customer should be the same as the current price on the market (EI 2016). Paradoxical is that increased DSF would decrease the volatility in electricity price, resulting in a lower economic incentive to change consumption patterns (NEPP 2016). Hence, an equilibrium point will be reached when the cost for moving consumption is the same as the benefit of utilizing price differences on the market.

3.4.4 Handling shortage of power

Challenges with power shortage in the future will mostly originate from losses of production capacity rather than increased power demand, as explained in previous subchapters. This makes power shortages both harder to predict and more likely to emerge in the future.

The current solution to shortage of power mainly consists of stand-by production reserves. This is a solution that is controllable and secure, but at the same time socio-economically inefficient considering that the cost for maintaining production capacity is relatively high and that the reserves very rarely are activated in practice (NEPP 2013). DSF could potentially constitute a more cost-efficient solution. Load reductions from electricity intense industries are already prepared for this purpose to some extent but it is expected that DSF solely should be able to cover the need for power reserves already in 2025. (Svenska kraftnät 2017c).

4. Electricity and reserve markets in Sweden

In this chapter different electricity and reserve markets currently existing in Sweden are presented. The purpose of this chapter is to give the reader a thorough background of how different markets are structured and why they exist.

4.1 Electricity price areas

In the northern parts of Sweden, the production of electricity always exceeds the consumption of electricity. In the south of Sweden where the largest cities are located, the situation is the opposite. Thus, there is a need for transmission capacity from the northern parts of Sweden to the southern parts. For most of the time the transmission capacity is sufficient, but during times of high consumption or low production, bottlenecks in the transmission grid arises due to the physical limitations of the used components. To incentivize investment of electricity production in the southern parts of Sweden as well as upgrades and extensions of the transmission grid where the bottlenecks usually arise, Sweden was in 2011 divided into four electricity price areas *(Figure 7)*. The production and consumption of electricity together with the need for transmission within each area together decides how much the electricity price will differ between the areas. (EI 2014b)

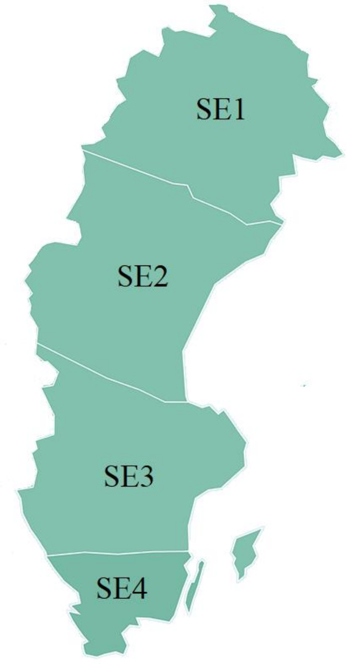


Figure 7: Electricity price areas in Sweden.

4.2 Trade of electricity

Apart from the physical flow of electricity that is delivered to the consumer, electricity is also traded through power markets. Within the Swedish power system, electricity can be traded on three groups of markets; physical markets, financial markets and reserve markets. (Svenska kraftnät 2017a)

4.2.1 Financial

On the Stockholm Stock Exchange, Nasdaq OMX, long-term trade of electricity is done. Using contracts for future delivery of electricity, this market allows players to manage risk that comes with a varying spot-price with respect to both time and regions. The contracts are not linked to any physical supply of electricity. (Swedish Smartgrid 2018).

4.2.2 Physical markets

Contrary to financial markets, trading of electricity on physical markets always result in real delivery of electricity. Apart from the 10 % of electricity which is traded through bilateral agreements between generators and suppliers, the rest is traded on the marketplace Nord Pool. Except from Iceland’s Transmission System Operator (TSO), Nord Pool is jointly owned by the TSO: s in the Nordic and Baltic countries. On Nord Pool, electricity generators and suppliers meet to trade electricity for each hour. The price that the consumer pays will largely be reflected by the agreed price on Nord Pool for each hour. (EI 2018; Nord pool 2017).

Day-ahead market

The day-ahead market, recognized as *Elspot* or the spot market, is the main market for electricity trading on Nord Pool. The operation of the market is applicable to the following day’s delivery of electricity, and buyers and sellers of electricity must submit their bids before 12 AM the day before. A bid is specific for every hour and must contain both information about the quantity (MWh/h) and price of the bid (EUR/MWh). The buyer is usually a utility and may also be a balancing responsible party. Thus, the size of the bids of the utility must be estimated from its customers expected consumption.

The offered bid price of the buyer on the other hand is decided from what the buyer is willing to pay for the quantity at that hour. The seller, or producer of electricity also submit their bids and consider parameters such as what production resources that will be available at the delivery hour. When the marketplace closes, the buy and sell bids are agreed upon and a final quantity and price is established for every hour that day (see *Figure 8)*. All sell bids below the established price must deliver the promised quantity that hour and all buy bids above the established price must buy the promised quantity that hour. Irrespective of what the buy and sell bids were before market closure, the electricity will be traded at the established market price, thus the day-ahead market applies marginal pricing. (EI 2018; Nord pool 2017)

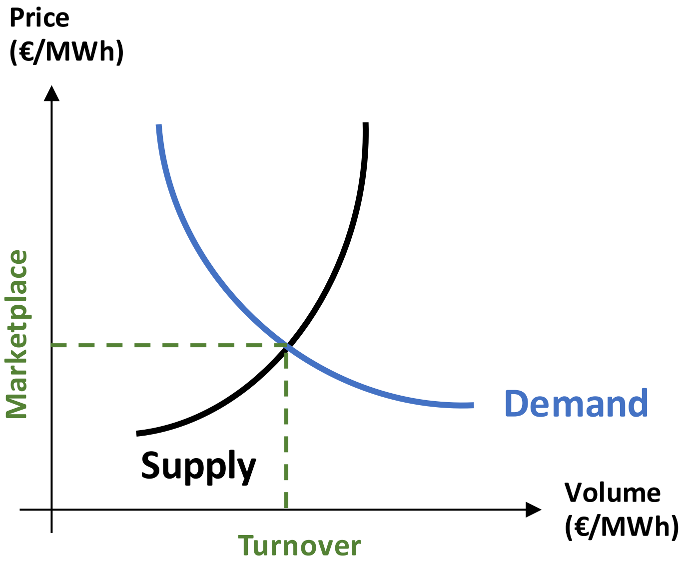


Figure 8. Visualization of how the market price on the day-ahead market is established. (Nord pool 2017)

Intraday market

Estimations of both the following day's consumption and production of electricity are followed by insecurities. Factors like changing weather prognoses and unplanned incident plays a role in determining what the final consumption and production will be, and therefore conditions may change from the opening hour of the day-ahead market, to the delivery hour (Copenhagen Economics 2016). Because of this uncertainty, also an intraday market named *Elbas* exists on Nord Pool to adjust for potential errors in estimations.

The intraday market opens two hours after the closure of the day-ahead market and closes one hour before the delivery hour (EI 2018). The main participants of this market are the balance providers since they face an economic risk if they were to cause imbalances during the delivery hour. The volumes that are traded on Elbas are only around 1 % of the volumes traded on the day-ahead market (EI 2018).

4.3 Balancing and frequency regulation

The production and consumption of electricity must constantly be balanced. If these are not in balance, the frequency in the Nordic synchronous area, 50 Hz, will diverge from its normal value (EI 2014a). Major deviations from this frequency can infer damage to components due to heat generation and increased wear and tear. Derivations may also adventure the stability of the electrical grid, potentially causing black-outs and a collapse of the entire system (DTU 2008).

4.3.1 Balancing

It is expected that the balance service providers maintain balance between electricity production and consumption before the delivery hour. They have strong economic incentives to do so since they are financially accountable for eventual imbalances. Imbalances are evaluated from reported data from the balancing responsible providers. (Svenska kraftnät 2019a)

On both the day-ahead and the intraday market, the balance service providers have had the opportunity to make sure that there is balance between electricity production and consumption. From the closure of the intraday market to 45 minutes before delivery hour the balance service providers should report preliminary operation plans and possible changes (Entsoe 2016). This must be done because the balance responsibility is surpassed to Svenska kraftnät during the delivery hour. Only seldomly, can the responsible balance providers exactly match production and consumption of electricity. One reason for this is that electricity is traded on an hourly basis, whereas consumption of electricity changes instantaneously. Svenska kraftnät has prepared for imbalances during the delivery hour by procuring frequency and power reserves by the balance service providers. These reserves are divided into primary, secondary and tertiary frequency regulation and fill different functions, have different requirements for participation and are compensated for in various ways. (Svenska kraftnät 2019a) The function and the requirements of each reserve will be further explained in coming subchapters. A summarizing table is also presented in *Table A (see Appendix A).*

4.3.2 Primary frequency control

The primary frequency regulation consists of automatically activated resources which function is to stabilize the frequency as quickly as possible in events of imbalance. The participating resources constantly measure the frequency in the electric grid and adjust their production or consumption depending on the need for up or down regulation. Today the primary regulation almost exclusively consists of hydropower. The primary frequency regulation consists of the products FCR-N (Frequency Containment Reserve – Normal) and FCR-D (Frequency Containment Reserve – Disturbance). Both products can be traded two days before the delivery hour (D-2) at 15:00 PM the latest and the day before the delivery hour (D-1) at 18:00 PM the latest. For both markets the bids placed must specify capacity (MW), requested compensation (EUR/MW) and which electricity area the resources are in. The requested compensation must reflect the actual cost of regulation, in addition allowing a small margin for risk and profit. Historically only production resources have been allowed to participate on the two FCR markets. However, in 2019 consumption resources will also be allowed to participate. (Svenska kraftnät 2018a)

Frequency Containment Reserve – Normal

FCR-N is activated for frequency derivations within 49,9 to 50,1 Hz, a range denoted as normal operation. The purpose of FCR-N is to adjust for small imbalances that arise during the delivery hour. The imbalances arise mainly due to the stochastic behavior of electricity demand at small time scales and small variations in wind power production. The Nordic TSO:s have decided that 600 MW FCR-N should be available in the Nordic power system. The capacity that should be provided by each country is based on the electricity consumption of the previous year. This means that around 200 MW is allocated to Sweden. (Energimyndigheten 2014)

The product FCR-N is both a power and an energy product. This means that compensation is given both for the capacity provided and the energy delivered. When all bids are placed, Svenska kraftnät arranges the bids from the cheapest to the most expensive. The cheapest required capacity for every hour is called-off and compensation will be given to the winning bids. However, the compensation for the energy is not decided until the end of the delivery hour, since it cannot be known before the delivery hour how the frequency will vary, and what need there will be for an up or down regulation from the participating resources. (Svenska kraftnät 2019c)

The lower limit for participating on the FCR-N market is 0.1 MW and the resource must be activated to 63 % within 60 seconds, and 100 % within three minutes. Bidding is done in steps of 0.1 MW. (Svenska kraftnät 2019c)

Frequency Containment Reserve – Disturbance

If the frequency goes beyond the boundaries defining normal operation state (49.9-50.1 Hz), FCR-D should help stabilizing the frequency as quickly as possible. Variations this large usually comes when a large production facility or power line is unexpectedly disconnected from the power system. The volume of FCR-D is dimensioned for the largest dimensioning incident recognized as the N-1 criteria. This means that the capacity of FCR-D should be equal or close to the largest production unit in the synchronous area, or a HVDC link with a deduction of 200 MW. This unit is usually the nuclear reactor Oskarshamn O3 with the capacity of 1360 MW. As for the FCR-N, the capacity is divided between the countries, where Sweden has around 400 MW. (Entsoe 2016)

For FCR-D it is required that 50 % of the imbalance should be restored after five seconds and within 30 seconds all the imbalances should have been restored. This is the case because the primary regulation resources must be available if another major disturbance where to happen shortly after. The FCR-D is only a power product, and the compensation is usually less than for the FCR-N. (Energimyndigheten 2014)

4.3.3 Secondary frequency control – aFRR

The secondary frequency control is also part of the automatic frequency control. The product is called automatic Frequency Restoration Reserve (aFRR) and was introduced in 2013 as a response to a worsened frequency quality (Entsoe 2016). The aFRR aims to quickly restore the frequency in the power system. It is usually purchased only for morning and evening hours during weekdays, times when maintaining the frequency at 50 Hz is particularly challenging (Svenska kraftnät 2018d). The function of aFRR is to restore the frequency back to 50 Hz after it has been stabilized by the primary frequency control, and thus release the capacity of the primary regulation. Contrary to the primary frequency control, the aFRR is controlled by a centralized controller, rather than locally controlled as is the case for the primary frequency control. The minimum requirement for the aFRR is currently 5 MW with a required activation time of maximum 2 minutes and the product is both a power and an energy product. (SEDC 2015)

4.3.4 Tertiary frequency regulation

The capacity of the automatic primary and secondary resources should constantly be available to adjust for potential future imbalances. However, when primary and secondary reserves are activated, they are no longer available. The tertiary frequency control is composed of two products, the regulating power market and the fast-active disturbance reserve, with the function of releasing capacity from the primary and secondary frequency control (Bang, Fock & Togeby 2012). Also, a third product, the power reserve, is included in the portfolio.

Regulating Power Market

The regulating power market consist of manually activated reserves that are activated through voluntary bids submitted to the market by the balance responsible actors. The market is denoted manual Frequency Restoration Reserve (mFRR) or Regulating Power Market and opens 14 days before the supply day and closes 45 min before the delivery hour. (EI 2018)

The requirement for activation of the mFRR is much slower than both the primary and secondary frequency control. Within 15 minutes the resource must be fully activated. mFRR is an energy product and the bidding activation process is a bit more complicated than for the primary and secondary frequency control. Factors such as limitations in transmission capacity, bid volumes and activation times are all taken into consideration by Svenska kraftnät with respect to the current needs. To facilitate bids in SE4, the minimum volume is 5 MW compared to the SE1, SE2 and SE3 where the minimum volume is 10 MW.

Power reserves

During cold winter days there may be situations where the production capacity is insufficient to meet the consumption needs. Therefore, a power reserve has been purchased since 2003 by Svenska kraftnät. In the power reserve, a minimum of 25 % must be reductions in consumption

(Miljö- och energidepartementet 2016). This is usually done through bilateral agreements with individual industries. According to the law of the power reserve (2003:436), it should be available from the 16th of November to the 15th of March (Miljö- och energidepartementet 2003). The minimum volume is 5 MW in all electricity price areas and compensation is given for administrative costs, energy during hours of activation and capacity (Svenska kraftnät 2019b). As for all the above markets participating players must be balance service providers and thus have an agreement with Svenska kraftnät (Svenska kraftnät 2013b). The objective was that the Power reserve should be replaced with a market-based solution after 2015. However, since progress for such a solution has been slow, the law of the power reserve is prolonged to the winter of 2025/2026 (Svenska kraftnät 2016b).

Fast-active disturbance reserve

The function of the mFRR is vital since it helps to restore the automatic frequency control. However, the mFRR is composed of voluntary bids and there is no requirement of what the total volume of this market should be. Therefore, there are sometimes situations where submitted bids on the mFRR are insufficient both with respect to volume, response time and grid bottlenecks. As previously mentioned, the FCR-D stabilize the frequency when there is large disturbance in the power system. To ensure that the frequency can be brought back to normal operation in the required time, Svenska kraftnät procures capacity in the form of gas turbines. The dimensioning of the fast-active disturbance reserve follows the same criteria as for the FCR-D. They are placed in SE3 and SE4 to minimize the risk of bottlenecks in transmission capacity. (Svenska kraftnät 2013a)

5. Flexibility in buildings

In this chapter a decomposed terminology typically utilized in studies of DSF is presented together with a framework of how flexibility resources could be characterized. Later in the chapter, energy management strategies for both loads and BESS are described from a theoretical perspective but is also complemented with results from empirically oriented previous studies.

5.1 Flexibility resources and flexibility reserves

Quantifying the flexibility that buildings can provide to the energy system has to be done on a case-by-case basis (IEA 2017). The reason for this is due to the large amounts of factors that play a role in deciding what flexibility that can be utilized and during what times. A number of these are: type of activity in the building, climate at the location of the building, occupancy patterns and the physical nature of different loads. There is no international well-established methodology for assessing flexibility in buildings; instead this process typically relies on expert analysis (Connell & Riverso 2017). This is partly because there are several definitions for energy flexibility, and thus several methodologies for quantifying it (Lopes et al. 2016). However, recent efforts are under way for developing a standard definition of energy flexibility, a standard terminology and a standard methodology (IEA 2016).

Irrespective of the many methodologies, most processes of quantifying the flexibility of a building can be visualized as in *Figure 9*. The outmost circle is the starting point and the potential is often determined from the nominal power of the installed loads in the building. The second outermost circle is smaller because now regards have been made to factors such as whether the loads in the outermost circle can be controlled. The second innermost circle is even smaller because some flexibility resources might not be economically beneficial to use. For example, the benefits of running a backup generator might not be economically beneficial when also considering the fuel costs that come along running the generator. The innermost circle is smallest since all flexibility might not be allowed to participate on physical or reserve markets due to legislations or technical requirements. (Ulbig & Andersson 2014)

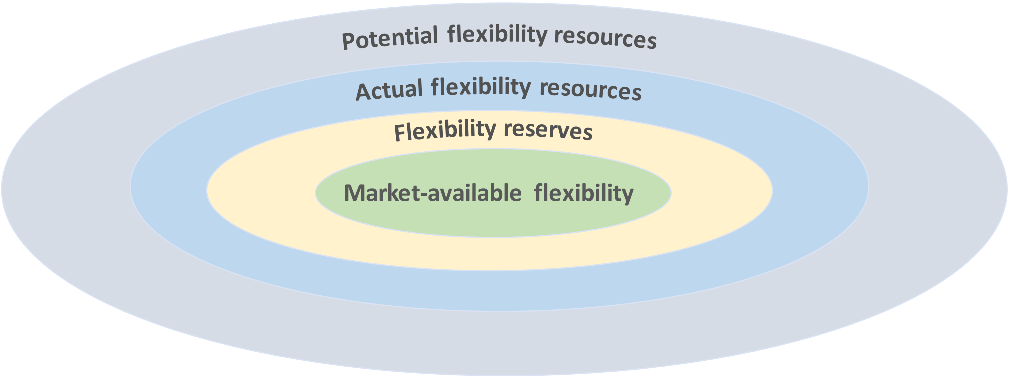


Figure 9. Classification of operational flexibility resources and reserves. Illustration based on (Ulbig & Andersson 2014)

5.2 Flexibility terminology

Many studies are lacking a common terminology of descriptors on DSF characteristics (Aduda et al. 2016). This can be problematic since comparison between loads and buildings becomes more difficult to do as well as establishing a common methodology of how to assess prerequisites for DSF.

In one of the available terminologies available for DSF classification loads must be *sheddable, controllable* and *acceptable* to be flexible (Olsen et al. 2013). These descriptors will be explained below. This terminology is useful for achieving a broad understanding of what parameters are important in determining flexibility. However, it fails to incorporate a detailed understanding of other factors and dimensions that also are important to evaluate when estimating the DSF potential, such as potential rebound effects (Connell & Riverso 2017).

5.2.1 Sheddability

Firstly, loads can be categorized to whether they are sheddable or not. This grouping is associated with the physical function and constraints of the loads. Loads that are sheddable are non-essential and will not affect the comfort or productivity in the building if they would be disconnected for a short time (Thumann & Younger 2003). These can for example be non-essential lightning. Loads that are non-sheddable cannot be disconnected even for a short time. These loads are for example elevators, computers and escalators.

5.2.2 Controllability

The term controllability refers to hardware and software control systems that are available in the building (Ma et al. 2013). If DSF should be able to replace and complement production resources, it is required that the building has the required communication and control possibilities (Olsen et al. 2013). Building control systems for energy is typically recognized as Building Energy Management Systems (BEMS). Other functions such as lighting, fire and safety control may also be included in these systems. When estimating the DSF potential, it is required that these systems are thoroughly examined.

(Callaway & Hiskens 2011) emphasize two requirements for load control schemes. First, they should be “fully responsive”, meaning that they should enable control that have high resolution in different time scales. Also, they should be non-disruptive, meaning that the operation of the scheme should have little effect on building performance. Relevant parameters to consider for non-disruptiveness are for example building temperature and lightning levels. Thus, even though a load is classified as sheddable with respect to physical constraints, it might not be controllable due to a lack of physical control units or software control schemes.

5.2.3 Acceptability

In contrary to sheddability and controllability, which entirely refers to objective load characteristics, the descriptor acceptability also has subjective dimensions. Acceptability aims to characterize DSF characteristics from the perspective of the building operator (Olsen et al. 2013). The descriptor can be defined as the percentage of load that the building operator are willing to accept being used for the flexibility event (Aduda et al. 2016), also considering corresponding financial incentives (Olsen et al. 2013).

Acceptability is dependent on several factors. It varies over different time scales, both daily and yearly. It is dependent on where the building is located, patterns of building occupancy as well as the general perception towards DSF activities. (D'hulst et al. 2015) also include the concept of *availability* as a descriptor relevant for evaluating acceptability. Availability consider both what hours the load is available and how large share of the load that is available for DSF applications during those hours (Aduda et al. 2016).

5.2.4 Shiftable and curtailable

Another terminology that aims to classify loads presents five classes of loads which gives more specific information on the DSF characteristics of loads. A visualization of the concepts is presented in *Figure 10*. If the actual energy use must be the same as the forecasted energy use, the load is classified as non-flexible. If the total energy use must be met, but it is acceptable that the shape of the energy profile is either changed or moved in time, the load is classified as *shiftable loads*. Loads where the energy profile is fixed but can be moved in time are named *shiftable profile loads*. Loads where the volume is fixed but where the profile may change are named *shiftable volume loads*. Loads that have an energy need which can be reduced without being replaced are called *curtailable loads*. Curtailing loads may however have come at the cost of for example worse comfort. *Curtailable loads* are further divided into *reducible loads* which can be reduced without being switched off and *disconnectable loads* which only are on/off-controlled. (Ottesen & Tomasgard 2015)

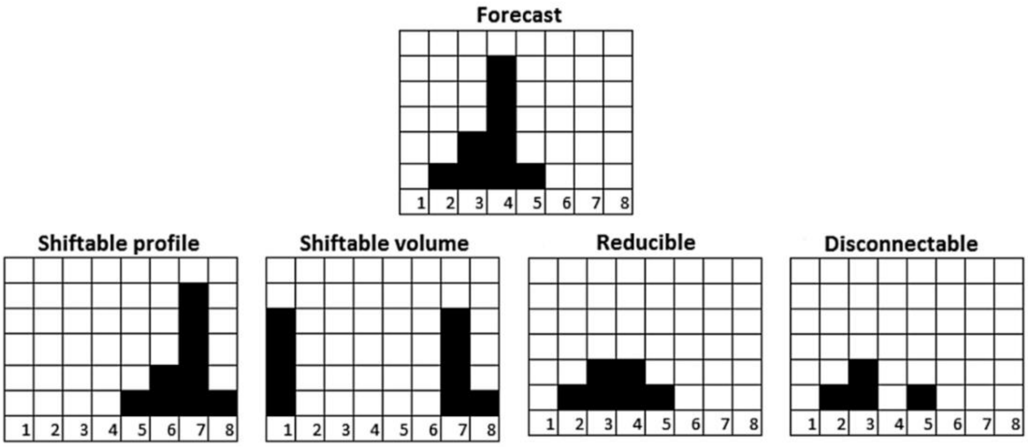


Figure 10. Visualization of load flexibility classifications. (Ottesen & Tomasgard 2015)

5.3 Flexibility characterization process

The two terminologies and ways of classifying loads for DSF potential do not contradict each other, rather they complement each other. (Connell & Riverso 2017) combine these two terminologies into a classification method for DSF load characteristics. The classification framework is then used in a flexibility characterization process. The task of evaluating the flexibility parameters also with respect to availability is an untrivial task. Flexibility parameters vary throughout different time scales due to weather, occupancy and operation schedules of the building (Olsen et al. 2013). Apart from access to data and developing a methodology, a flexibility evaluation requires energy audits as well as expert analysis with specific knowledge about the building in question (Connell & Riverso 2017).

(Connell & Riverso 2017) aims to classify flexibility for a whole building, and thus include energy storage and on-site generation as well. The process is visually presented in *Figure 11*. The result from the flexibility characterization process is a flexibility matrix. For every load, a selection of parameters, such as flexible power (kW), availability time of event (h), time it takes to shed the load (s or min) and the time in advance that is required for notification (h), are chosen and quantified. These parameters are then used as input to an aggregator or a BEMS.

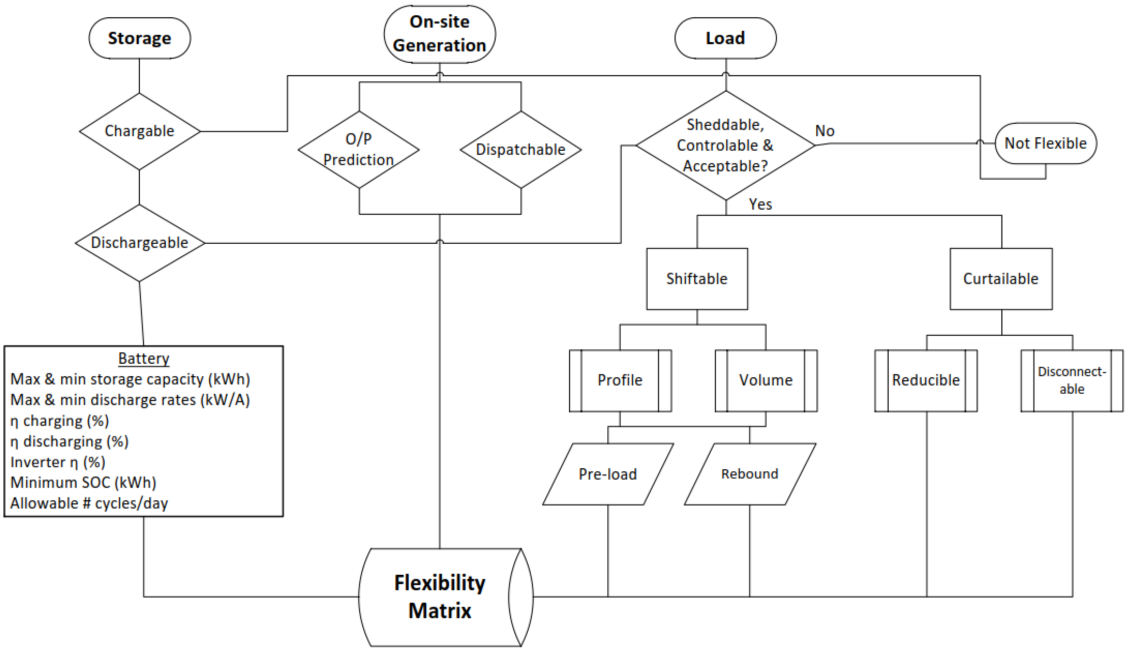


Figure 11. Flexibility characterization process. (Connell & Riverso 2017)

The aim of the flexibility characterization process is to eliminate non-flexible loads and identifying loads, on-site generation and storage for DSF. The results from a flexibility characterization process might be presented as in *Figure 12*. Sheddability, acceptability, controllability and the overall flexibility is presented as a percentage of the total load at specific times. The overall flexibility is then achieved by multiplication of the three descriptors.

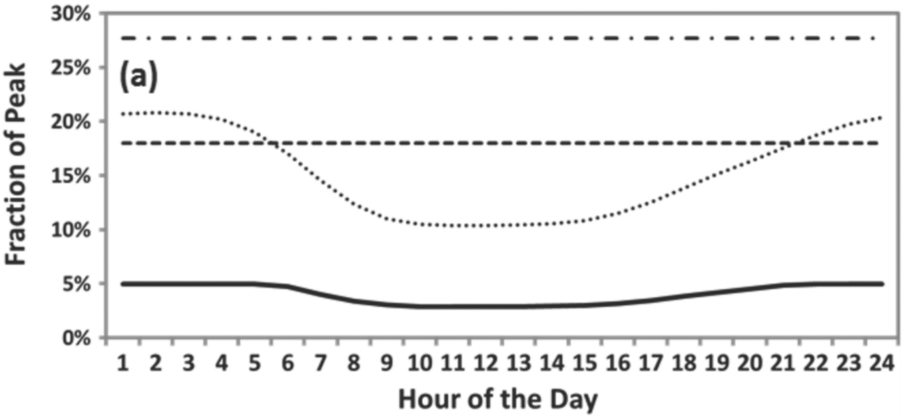


Figure 12. Visualization of sheddability, controllability, acceptability and overall flexibility. (Ma et al. 2013)

Apart from evaluating the flexibility parameters, it is also necessary to consider market constraints, load forecasting and grid signals that depend on the current need when evaluating what loads that should participate on what markets and at what times. Thus, flexibility becomes a scheduling problem that needs to be optimized (Connell & Riverso 2017). As price and market constraints differ from country to country, this too becomes an argument that the flexibility characterization process must be conducted on a case-by-case basis.

Lastly, there are several other aspects to consider when evaluating flexibility. (Hao et al. 2014) and (David et al. 2012) identify the response time of the load as an important parameter. (Alcázar-Ortega et al. 2015) also list additional factors such as duration of recovery period and eventual rebound effects which are important to consider when classifying loads for DSF applications. Further, potential interactions between loads and a need for integration of loads into the building automation system might also be needed to consider (Yin et al. 2016).

In summary, it can be stated that there are a number of interesting parameters to evaluate. However, three general properties of energy flexibility return in literature; shiftable capacity, time and cost (IEA 2017). These properties, together with their limitations, summarize what is crucial to know when estimating flexibility.

5.4 Energy management strategies

Demand-side flexibility, demand-side management, load management and demand response are frequently recurring terms in the literature and typically have overlapping definitions for similar concepts. The definitions typically include manipulation of the shape of load-curves, but also applications of energy storage solutions (Yumak et al. 2016).

What complicates the identification of a conventional terminology further is that these terms are frequently used with different perspectives. From a grid owner perspective, they often refer to activities that serves to influence the consumption patterns of customers on an aggregated level in order to facilitate the operation of the grid both technically and economically. From the consumer perspective, they typically refer to adaptive consumption in order to take advantage of financial incentives provided by the local grid company or from different energy market places. (Javor & Janjic 2016)

While there are ambiguities regarding what context different terms should be used and what specific actions they include, they collectively cover a variety of strategies that could be beneficial from both customer and grid perspectives.

5.4.1 Load-curve management

In theory, a load-curve could be arbitrary manipulated. However, (Gellings 1985) specifically defines six main categories of load-shape objectives. The same division of categories are found in more recent publications (Sinha & De 2016) and (Javor & Janjic 2016). They include *peak clipping, load-shifting, Valley filling, strategic conservation, strategic load growth and flexible load shape.* However, since the focus of this thesis is short-term flexibility on a building level, only the first three strategies will be explained more thoroughly.

Peak clipping refers to a strategy where loads in a building are temporary curtailed without later compensation (Sinha & De 2016). The aim of the strategy is to reduce the peak power demand from the building and could be economically incentivised by critical peak pricing or to reduce costs from grid tariffs. *Valley-filling* is a strategy where electricity consumption is increased during off peak periods when electricity price typically is lower (Sinha & De 2016).

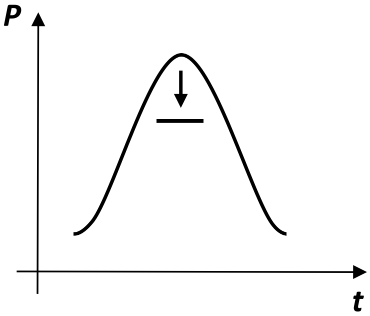


Figure 13. Conceptual illustration of peak clipping. (Javor & Janjic 2016)

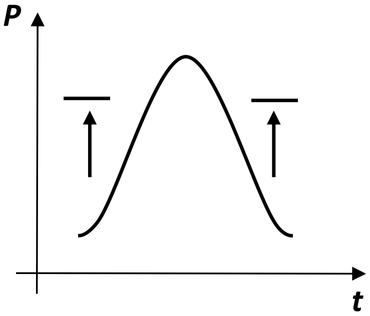


Figure 14. Conceptual illustration of valley filling. (Javor & Janjic 2016)

The consequence of both peak clipping and valley-filling is that variation in demand is reduced which means grid capacity could be more efficiently utilized (Sinha & De 2016). A strategy which combines the benefits of both concepts is load-shifting. Load-shifting means moving of load from periods of peak consumption to periods of lower consumption (see *Figure 15*).

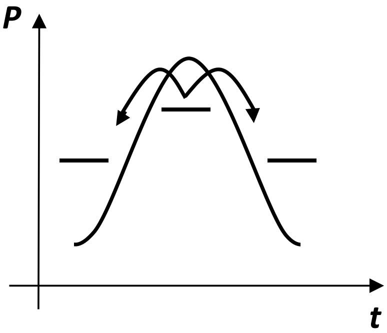


Figure 15. Conceptual illustration of load-shiftning.
(Javor & Janjic 2016)

The possibility to implement these strategies varies a lot in practice and depends on several factors such as the characteristics of loads and the types of activities which take place in the building. A solution that minimizes the risk of negatively influencing activities in the building and still conceptually could accomplish all these strategies would be to implement a BESS (Gitis, Leuthold & Sauer 2015). With adjusted control of charge and discharge a BESS could change the shape of the load-curve profile as seen from the grid, consequently accomplishing the same benefits as previously explained for load management strategies (*see Figure 16*).

From a techno-functional perspective, BESS is a well-functioning alternative for load management strategies. However, slow operation requirements and large-scale load shifting does not take into account the best characteristics of BESS, which might reflect in financial outcome of an investment (Chen et al. 2009).

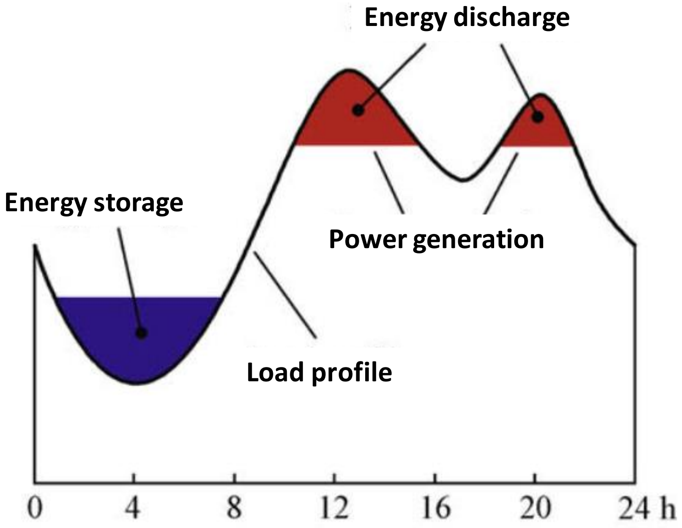


Figure 16. Conceptual load-cuve management from strategic operation of a BESS. (Chen et al. 2009)

5.4.2 Energy arbitrage

In load levelling and peak shaving applications of BESS the focus is on the time structure of a specific load, while with energy arbitrage the focus solely lies on price volatility on the electricity market. Conceptually, energy arbitrage implies buying electricity at one time and then selling it back to the market at another time (Gitis, Leuthold & Sauer 2015). Thus, revenue is gained if the operator buys electricity at a low price and then sells at a higher price.

A strategy which conceptually is the same as energy arbitrage is scheduled charging. Both strategies use the same margin on the market, but the difference lies in the physical flows of energy. Energy arbitrage typically means that the BESS is charged from the grid and then discharged back while in scheduled charging and discharging this does not have to be the case (Gitis, Leuthold & Sauer 2015). An example could be price-controlled charging of electric cars or batteries charged through overproduction from residential PV-systems where the energy is stored until periods of higher electricity price.

Concerning energy arbitrage through operation of a BESS, the potential revenue naturally scales with number of completed charging and discharging cycles. This could be problematic, especially for electrochemical BESS, since they degrade as a consequence of charge and discharge cycles (Xu et al. 2016). In a study conducted in 2017, it was shown that degradation of the battery has a strong impact on profitability for energy arbitrage (Wankmüller et al. 2017). The results indicate that battery degradation solely could reduce the revenue from a BESS conducting energy arbitrage with 12-46% depending on end of life criteria and battery degradation model.

Another concern is that revenue through energy trading scales with the size of the energy storage rather than the with the power rating. In the case of electrochemical batteries, they require a chemically active storage medium which makes the specific cost for increasing the size of the energy relatively high in comparison to the cost of increasing the power rating (Gitis, Leuthold & Sauer 2015). This makes electrochemical batteries from a cost perspective less attractive for energy arbitrage.

Previous studies on energy arbitrage

Several studies have been conducted examining the economic potential of energy arbitrage in different electricity markets around the world. Typically, these studies include formulation of an optimization algorithm, which then is applied on historical times-series of electricity prices to evaluate the economic potential at the specific marketplace.

A study that was conducted in 2016 at Aalto university in Finland, the value of energy storage systems in the Nordic power market was analysed and included the potential benefits of price arbitrage (Zakeri & Syri 2016). In the study revenues of a general electrical energy storage (EES) employing price arbitrage on the day-ahead market and intraday were calculated and compared with the cost of different (EES) technologies. Their results for the day-ahead market indicated that the potential revenue from energy arbitrage was the highest in Finland and

Denmark while Sweden and Norway showed significantly lower profitability potential. For 2015, the potential revenue in Finland was estimated to 35 000 € per installed MW while corresponding value was just below 15 000 € /MW and 7 000 € /MW in SE4 and SE1. However, when comparing these results to the costs it was concluded that cost-to-benefit ratio never exceeded 30% in any region for pumped hydro storage (PHS) and for batteries the results show that less than 5% of the investment is returned each year. In the analysis of the intraday market, the Danish market showed the best profitability of all Nordic countries, however, profits were still lower than in the day-ahead market. For Sweden, the potential revenue was calculated to less than 500 € / MW in both SE1 and SE4 which is significantly lower than in the day-ahead market. Conclusively, this study shows that the current price volatility in the Nordic power markets is too low to make energy arbitrage through storage of electrical energy profitable.

A study showing the trends in the German intraday market was published in 2018 (Metz & Saraiva 2018). In this study the storage dispatch of a Li-Ion was optimized with respect to both 15- and 60-min auctions typically used for the intraday market in Germany. The results showed that no business case exists for pursuing energy arbitrage by using Li-Ion batteries. Furthermore, in the sensitivity analysis it was shown that price volatility must increase by a factor 7 to make an investment profitable within the technical lifetime of a BESS.

5.4.3 Ancillary services

Ancillary service is a collective term that refers to various functions which are fundamental for maintaining a stable power system. Functions that are typically included within the definition is reactive power control, voltage control, black-start capability, frequency control and various types of power reserves (Svenska kraftnät 2017c). Their functionality in the power system is very time dependent which is why they are typically categorized by response time (Hesser & Succar 2012).

Further, reactive power control, voltage control and black-start capability are all services that technically could be provided from a BESS. They will not be analysed in this thesis. These applications are commonly considered as secondary uses and the investment in a BESS typically need other types of revenue streams to make it economically attractive. (Gitis, Leuthold & Sauer 2015)

However, frequency control which is handled through the reserve markets is interesting to explain further. As described in the *chapter 3*, the frequency quality in Sweden has already begun to decrease and the need for balancing power will only increase as more intermittent power is introduced in the power system. Furthermore, frequency control could technically be provided from controlled operation of both loads and BESS which means that there are many potential resources that currently are not utilized for these purposes, but that could become valuable in the future power system.

5.4.4 Frequency regulation

Maintaining a stable frequency is a vital part for operating a power grid. Being part of frequency regulation is however technically challenging since there are strict technical operation requirements that must be met (Svenska kraftnät 2018a). These include fast response times and capability to follow frequency in real time. Consequently, this means that there is only limited amount of reserve units capable of delivering the service.

BESS typically offers a combination of fast activation time, accurate capability to follow frequency variations and good efficiency (Chen et al. 2009). This makes participation on the reserve markets, specifically FCR-N and FCR-D, attractive since they have technical requirements which well matches the characteristics of BESS.

However, even if a BESS technically could manage the requirements on the reserve market, there are still legislative barriers that limits the possibility for BESS to participate on the reserve markets in Sweden. According to the new requirements, which are being effectual during the spring of 2019, a resource active on the reserve market must either be considered as a production or consumption resource, which implicates that there either must be net input or output of energy during the activation hour (Svenska kraftnät 2019c). This means that BESS operation, with both input and output of energy during the same hour, cannot be offered as a resource on the reserve market even with the updated legislation.

Further, the upcoming changes on the reserve markets comprises new rules for reporting bids, but the more relevant part for this thesis is that also bids from adjusted consumption could be accepted (Svenska kraftnät 2018a). This means that balancing services through load control could be offered on the reserve market if the technical requirements are met.

Accomplishing frequency regulation through load control is however technically challenging and naturally entails several complications, but also has some advantages compared to traditional generation units (Olama et al. 2018). Firstly, it potentially reduces the overall emissions since less fossil-based production units will be needed to balance the power system. Secondly, loads could provide instantaneous response compared to the slower response time of larger generators. Lastly, it could also give better capacity resilience since many small loads could be more accurately controlled than the output of a few large generators (Olama et al. 2018).

Frequency regulation from load control

In a pilot study that was conducted in 2017, it was investigated how capacity from water heater systems could be controlled to participate on the FCR-N market (Svenska kraftnät 2017b). The project was a collaboration between Svenska kraftnät and Fortum and included 100 households located in Stockholm. The goals with the project was firstly to evaluate how well consumption flexibility could manage the technical requirements for participating on the market, secondly to investigate how a pre-qualification phase could be designed for consumption resources, and lastly give indications on how legislation could be changed to make participation from consumption resources possible.

The results of the study showed that control of load from water heater systems managed to meet the technical requirements for response time with good margin and therefore could be qualified to participate on the market. Analysis of data from the test period also showed that the households electricity consumption followed the variation in frequency accordingly.

What proved to be the main complication during the test period was reporting of measurement values where the requirements from Svenska kraftnät were not met. They also had some problems with reaching the minimum allowable capacity of 0.1 MW on the FCR-N market which then had to be compensated in the balancing portfolio. Even though there were some complications it was considered a very instructive study and specifically positive was that the impact on comfort in the household was not notably affected during the test period.

Further, testing the suitability for consumption resources to take part in the reserve markets have been an area of research for many years internationally. Several studies have focused on HVAC systems and their capability to provide frequency control.

In a study that was conducted during 2014 in the United states it is shown how fans in HVAC systems can provide frequency regulation without impacting the indoor climate significantly. (Hao et al. 2014). The results were established through modelling and parameters were taken from a commercial building located on the University of Florida Campus. The numerical outcome from the simulations indicated that 15% of rated fan power could be used for regulation purposes without impacting the indoor climate notably. The analysis showed that indoor temperature was lowered by less than 0.1 C° and the system could respond within 8 seconds after request.

This study was then followed up by an experimental study on the same building later the same year (Lin et al. 2015). The results from this practically oriented study confirmed that the fan motors in the HVAC system could provide frequency regulation without causing discomfort. The technical capacity for the investigated units was estimated to be 5.8 kW which if used during all its operational hours could generate up to $1400 as yearly revenue on the reserve market according to 2013 prices.

In another paper, the demand response potential of ventilation fans in the Nordic countries was evaluated. The study was conducted at Aarhus university in the Department of engineering during 2016 and used the ventilation system in a 12-storey building as test bed (Rotger Griful et al. 2016). The analysis was conducted using a validated model based on the fan affinity laws (*see Equation 1, subchapter 6.3*) and with specific considerations taken to the impact on the indoor climate of the building. The results indicated that the ventilation system technically could provide frequency control but that the requirements for indoor climate is a limiting factor. The analysis showed that indoor climate was more impacted by short power reductions than by power increases. The conclusions stated is that aggregation of several buildings of this type would be needed to meet the requirements of lowest bid power (0.3 MW) on the Danish ancillary service market but that ventilation systems technically could be an attractive asset for providing frequency control.

All previously mentioned studies have focused on the ventilation fans in HVAC systems, but there are other parts of these systems that also could be used for different ancillary services. An experimental study that was conducted at MIT in 2015 shows that HVAC chillers could provide secondary frequency regulation (Su & Norford 2015). The demonstrations showed that the technical requirements from the system operator were met with margin and that the control system performed technically very well. The results indicated that ± 25% of nominal power could be used for frequency control up to several hours.

Frequency regulation with BESS

As stated previously in the chapter, it is possible to provide frequency control through operation of a BESS. How this conceptually could be done is illustrated in *Figure 17*. When the grid frequency goes above the tolerance interval the BESS should charge and correspondingly discharge when the frequency goes below the tolerance level.

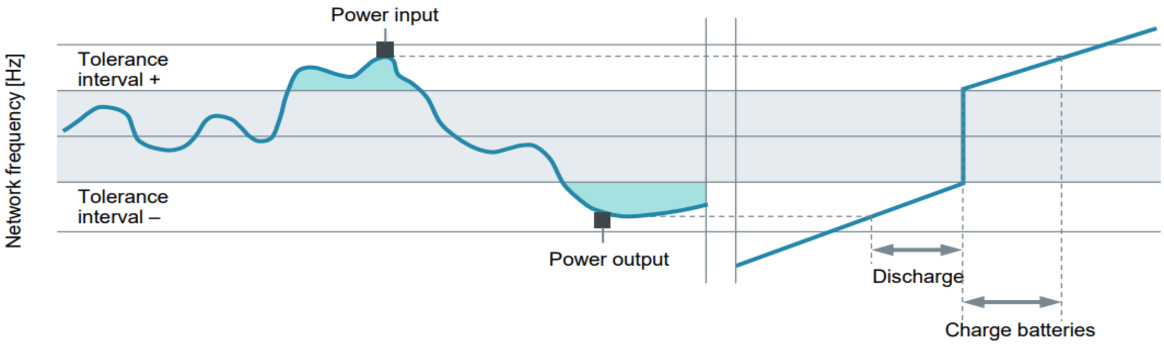


Figure 17. Conceptual control strategy of BESS for providing frequency regulation. (Siemens 2017)

The adequacy of providing frequency control from BESS has been practically proven in a pilot study conducted by Svenska kraftnät and Fortum during 2018 (Svenska kraftnät 2018b). The objective of this project was to investigate whether energy storages could take part on the FCR-D market. Both technical and market aspects were considered in the study since Fortum wanted to evaluate if the solution would be commercially functional.

The test was proceeded using an Uninterruptable Power supply (UPS) with its belonging energy storage which could provide 0.1 MW for both up- and down regulation. Normally the UPS system is used to ensure energy supply to critical functions in a data centre during shortage of power, but according to Fortum they often over-dimension these systems, which means that there often is spare capacity which could be used for ancillary services.

During the study period two control methods were tested: local and central control. In central control the frequency was supervised at Fortum’s operating centre and if frequency deviations arose a commando was sent to the UPS system via an integrated interface. In local control, the frequency was supervised directly by the UPS system and automatically reacted based on the bid that was placed on the FCR-D market.

The results showed that the UPS system managed the prequalification for FCR-D during both central and local control with margin and therefore technically could be suitable for the service. However, with central control it was shown that the UPS-system was not always activated when it was supposed to and there was an undesirable time-delay for the activation. With local control of the frequency, the UPS system could respond significantly faster both to small and large deviations. The power output from the UPS system followed the deviations in frequency as desired, consequently supporting the balance in the power system.

Concerning the pricing of bids at the FCR-D market it is stated in the legislation that pricing should be cost-based with a small risk supplement (Svenska kraftnät 2018a). During the test period of this study this rule was ignored, and the bid prices were chosen so that the UPS system always would get activated. This means that no conclusions regarding profitability could be drawn from the results of the study.

Conclusively, the study showed that UPS-system with belonging energy storage could be suitable as a resource on the FCR-D market, but also entailed some concerns that must be further researched. One of these was that the charging of the energy storage must be controlled to ensure that the grid stability is impacted as little as possible during periods when frequency control couldn’t be provided by the system. Another is that accurate measurements, data quality and functional communication systems are challenging to accomplish yet necessary when providing this type of service.

Further, the study conducted by (Zakeri & Syri 2016) contains some results that is discouraging from a profitability perspective when it comes to providing services on the reserve markets with BESS. In the analysis of this paper the theoretical revenue from both energy arbitrage and ancillary services is stacked and compared to the Life Cycle Costs (LCC) of several Electrical Energy Storage (EES) technologies including Li-Ion batteries (*see Figure 18*).

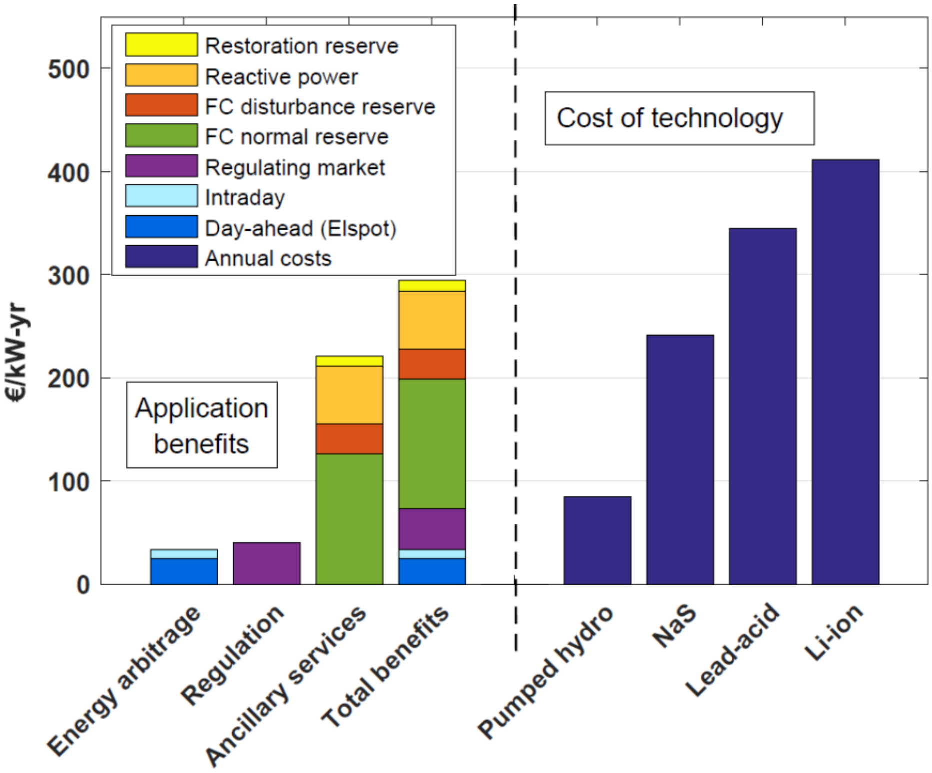


Figure 18. Comparison of possible benefits with cost of four EES systems. (Zakeri & Syri 2016)

From interpretation of *Figure 18,* it can be concluded that aggregated theoretical revenues from all markets not would cover the costs for neither Lead-acid nor Li-Ion batteries. However, it was also stated in the conclusions that optimization and proper capacity allocation for simultaneous participation on several markets would generate higher revenue than calculated in the study made by Zakeri & Syri (2016).

6. Demand Side Flexibility in shopping centers

In this chapter, an overview of previous work concerning DSF in shopping centers will be presented. Electric loads that are common in shopping centers will be presented with respect to their DSF characteristics. (Olsen et al. 2013) define commercial building end-uses as space heating, comfort cooling, ventilation and indoor lightning. Since Väla uses district heating to satisfy its space heating needs, only the three latter will be presented.

6.1 DSF suitability

As previously mentioned, there are several benefits to using commercial buildings for DSF applications. According to (Maasoumy et al. 2013), more than 30 % of commercial buildings have introduced BEMS. Such systems ease the connection between the building operator and the grid operator. (Maasoumy et al. 2013) also states that because most ventilation fans in commercial buildings are equipped with Variable Frequency Drives (VFD), it is possible to control the power need of ventilation systems within the order of seconds. HVAC systems in commercial buildings are in general also larger than in residential buildings, thus consuming more electricity. Ventilation fans use about 15 % of the building's total electricity consumption and together with the fact that they can be easily controlled, they are well suited for ancillary service applications (Maasoumy et al. 2013).

6.2 Energy consumption in shopping centers

There are about 350 shopping centers in Sweden, of which 160 are indoor malls (SP 2011). Except for grocery stores and sports centers, shopping centers is the type of building in Sweden where most energy is used per square meter. The actual energy use in shopping centers is difficult to estimate, since energy performance certificates conducted for this building type only consider the energy use of the property, and excludes the energy used by the tenants (Chalmers 2012). However, for the category retail buildings to which shopping centers are included, the largest electricity end-uses are lightning (42 %), electricity used for cooling foods (26 %) and ventilation (12 %). For all these loads there has been an estimated technical potential for energy reduction of 20 %. (Energimyndigheten 2010). However, the different end-uses for electricity and their potential for energy reduction say little about the potential for flexibility of the load, though it can give an idea which loads that may be most interesting to start evaluating. Apart from ventilation, cooling and lightning common loads for the shopping centers are for example escalators, elevators and electric doorways.

(Cronholm, Forsberg & Stenkvist 2006) studied the potential for temporary power reductions in shopping centers. The study looked at two buildings with winter peaks of 0.8 MW and 2.8 MW. It was found that the peak power for a year arose during summer months, when the need for electric cooling was the largest. The energy use during nighttime was lower since many systems, such as ventilation and most of the lightning were shut down, since the building typically would not be occupied at these times. Further, the electricity consumption was divided into two categories; the electricity used for the property and the electricity used by the tenants. The grid fee agreements were usually based on the maximum power needed, rather than for what safety fuses the building has. Electricity that was bought either had a variable price or a flat rate determined by power purchase agreements (Cronholm, Forsberg & Stenkvist 2006).

To make sure that air quality and thermal comfort standards were achieved, the ventilation was usually started two hours in advance before businesses. A strategy for temporarily reducing the need for power was to delay the start of the ventilation. However, an obstacle to this strategy that was identified was that the building operator risked committing a breach of contract with respect to the building tenants, since standards for air quality and thermal comfort were regulated in the rental agreements. A potential for delaying electric cooling loads was also proposed. (Cronholm, Forsberg & Stenkvist 2006)

6.3 Ventilation systems

HVAC is a shortening for *Heating*, *Ventilation* and *Air-Conditioning*. HVAC systems usually accounts for a large share, usually more than one third of the electric load in commercial buildings. Due to the large air volumes and system inertia HVAC systems can usually be temporarily turned off without an instant impact to occupants in the building. (Yin et al. 2016)

The air handling units are equipped with motors to where the fans are attached. The theoretical electric power consumption is related to the air flow through one of the fan affinity laws, presented in *Equation 1*, where RPM is a shortening for revolutions per minute of the ventilation fan. (ASHRAE 2012)

Equation 1

$$Power_{New} = Power_{Old} \times \left(\frac{RPM_{New}}{RPM_{Old}}\right)^3$$

From *Equation 1* it is seen that there is a cubic relationship between fan speed and fan power consumption. Thus, a small reduction in fan speed can have a significant reduction on fan power consumption.

HVAC systems are often considered to be sheddable and controllable, since they usually are connected to a BEMS. However, the acceptability might differ substantially from case to case (Connell & Riverso 2017).

Ventilation systems are usually classified into two main groups. The first group, natural draught ventilation, is achieved by a natural circulation due to temperature differences of indoor and outside air. The second group, mechanical ventilation, is achieved with the help of fans. In commercial buildings, MVHR (Mechanical Ventilation Heat Recovery) systems are most common. In Swedish, these are denoted as FTX systems. They have two fans, one supply fan (T) and one exhaust fan (F). In between those a heat exchanger (X) is placed, potentially saving 50-60 % compared to systems without heat recovery. (Energimyndigheten 2015)

Ventilation systems can have three types of air flow characteristics: Constant Air Volume (CAV), where the air flow is constant, Variable Air Volume (VAV), where the air flow can be regulated and finally Demand Controlled Ventilation (DCV), where the air quality is measured continuously and the air flow modified accordingly to retain air quality and comfort requirements (Hesaraki & Holmberg 2013).

VAV and DCV systems can be achieved using valve-regulation. This means that the air flow is regulated by a valve that opens or closes. However, since this type of control mainly alter the air flow and not the energy use of the ventilation fan, valve systems are sometimes coupled with control systems for the ventilation fan as well. Such systems can either be voltage controlled or frequency regulated, where the latter have better control options but are more expensive (Bioenergiportalen 2011).

Further, ventilation fans can be controlled differently. They can either be on/off-controlled, thus being *disconnectable* and/or have the option to be operated at a reduced fan setting, thus being *reducible*. Depending on the nature of the ventilation system and the type of fan, operation at reduced fan setting is limited to ventilation fans either being voltage or frequency regulated. Ventilation fans that are frequency regulated have VFD's, allowing the fan speed to be controlled which results in higher efficiencies, especially for low speeds. However, they are often limited to operate at frequencies over 20 Hz since cooling problems may arise at lower frequencies, and magnetization problems may occur below 10 Hz (Akron 2016).

Regulations that concern the design and operation of ventilation systems in Sweden come from the administrative authorities of National Board of Housing *(Boverket),* Building and Planning, Public Health Agency of Sweden *(Folkhälsomyndigheten)* and Swedish Work Environment Authority *(Arbetsmiljöverket)*. These deals with the topics of allowed energy use of ventilation systems, requirements for air exchange rates and requirements for CO_2 levels and temperature. For example, regulations state that a building should be ventilated with at least 0.35 liters per second and square meter. If there are people inside the building, the minimum air supply flow rate must be an additional 7 liters per second and person that can be expected to be present in the building. (Boverket 1998)

Controlling ventilation for achieving desired power deviations can be done in several ways. However, HVAC systems are nonlinear, time-varying and dependent on several variables. Poor control can result in an increased energy use, a worsening in thermal comfort and even damage to systems. Further, HVAC systems are often facing large disturbances such as varying occupancy rates and changes in outdoor temperature (Zaher, Counsell & Brindley 2011). (Beil, Hiskens & Backhaus 2015) showed that changing room temperature set-points for achieving desired power fluctuations for ventilation fans proved to be both non-linear and uncertain.

6.4 Lighting

Compared to HVAC systems, lighting systems are less automated in general and are therefore less easy to shed automatically. However, shedding of lighting have the benefit of not affecting occupant thermal comfort, having short response times and are both predictable in their response as well as repeatable (Francis & Sila 2007). The sheddability level of lighting differs depending on the use of the place where lighting provides the service. Studies in commercial buildings have shown a potential sheddability level of 33 % (David et al. 2012), but these numbers are not general for the whole building segment. In retail facilities for example, which often have lighting requirements, a maximum sheddability of 25 % have been estimated. Further, since buildings are usually internally sub-divided into areas that have different illumination requirements, representative numbers for sheddability of lighting in commercial buildings are difficult to achieve (Husen et al. 2012).

Lighting is usually not considered to be shiftable since this would have a direct effect on the service that the lighting provides (Jamasb & Pollitt 2011). Depending on the lighting technology used, lightning may be reducible, equivalent to dimming, or only disconnectable. The controllability of lighting differs substantially depending on for example lighting technology and wiring schemes. The two ways of controlling a light source, dimming or on/off control, are both interesting from a DSF perspective since both strategies provide a load reduction. Lighting load may also be coupled to occupancy sensors and solar irradiation sensors.

6.5 Comfort cooling

Comfort cooling can either be produced locally or be provided through district cooling. For locally produced comfort cooling, the most common technology is vapor-compression refrigeration. (Cronholm, Forsberg & Stenkvist 2006) found that approximately 11 % of the yearly electricity need in shopping centers came from space cooling, assuming an availability of 1100 hours per year. However, the need for space cooling is season dependent with consumption normally distributed around late spring to early fall. If the space cooling is achieved with vapor-compression refrigeration machines, this could be in the order of 1 MW. If shopping centers make use of district cooling, no major monthly trends in the power demand can be seen (Cronholm, Forsberg & Stenkvist 2006).

Pre-cooling refers to that the HVAC system is started in advance, before occupants arrive to the building. (Becker & Paciuk 2002) found that for buildings with high internal loads, intensive pre-cooling during nighttime, resulting in a lowering of the temperature of the internal mass, can be used as an effective strategy to reduce the peak power during daytime. However, this strategy contributed to a higher energy use. This study was conducted on office buildings, but they are similar to shopping centers with respect to high internal loads and operating hours. (Naoya et al. 2007) found that controlling the valve coupled to the piping system for the coolant had a direct effect on the power needs of the chillers. However, this strategy resulted in a rebound of the cooling demand at the end of the shed period, which was larger than the baseline.

7. Method

In this chapter the work procedure of the thesis and the methodologies used to answer the research questions are presented and explained. Firstly, the overall case study and data collection process is described. Secondly, the working process of the load assessment is presented. Thirdly, the methodology applied in the Techno-Economic BESS assessment is described together with a presentation of the used input data.

7.1 Case study methodology

To answer the different research questions several methods were used. The concept of using several methods to study a phenomenon is called triangulation and involves both quantitative and qualitative data. Triangulation tends to give a more detailed and complete picture compared to only using one method (Eliasson 2010). Triangulation strengthens validity (Jacobsen 2002; Patel & Davidsson 2011) by gathering both quantitative and qualitative information about the same phenomenon from several sources.

An explorative approach has been used in mapping, retrieving and compiling necessary information. The process of finding right in gathering information and finding the right people to talk to have been similar to the *snowball method*. Starting with interviewing one person, that person recommend other people to talk to. This recommendation is based on that person's beliefs of who would be the right person to contribute to the work (Larsson, Lilja & Mannheimer 2005). The first people were employees at Siemens, who gave recommendations of people at AirSon and Skandia Fastigheter, who had more site-specific knowledge about Väla. This helped both retrieving the results and the design of the conducted ventilation experiment.

The case study was divided into two parts. This breakdown was done with respect to the two main sources of flexibility that lay within the scope of the thesis, loads and BESS. The working process for the two parts were conducted separately, and neither the methods used nor results from the two parts influence each other.

7.2 Data collection

To answer the first group of research questions, information about the loads at Väla were needed. This data had to be collected and compiled from several different sources. The main sources used were:

- Product data sheets and operating instruction sheets for hardware.
- Previously collected and compiled data from Siemens as well as the results from experiments that have been done on the HVAC system.
- Siemens Navigator. The software platform developed by Siemens AG, is a cloud-based energy and sustainability management platform that aims to optimize building performance. Historical load data as well as aggregated load data for the buildings are compiled and can be visually presented in the platform(Siemens 2019).
- Siemens common Remote Service Platform (cRSP). The software platform developed by Siemens AG, allows remote access and control over the BEMS.

Also, continuous contact has been held with the following people that have site specific knowledge about Väla.

- Lars Pellmark (Skandia Fastigheter) - Responsible for installations and energy technology at Väla.
- Martin Karlsson (AirSon Engineering AB) - Energy advisor for Väla.
- Mats Jönsson (Siemens AB) - Energy controller at Väla.
- Tim Hellström (Siemens AB) - Service technician responsible for Väla.

Some information that specifically relates to Väla, such as occupancy patterns is confidential and could therefore not be used in this thesis. Consequently, all data and information that will be presented have been approved by relevant responsible parties.

From the data collection process, it was concluded that only some loads at Väla were possible to include in the scope. This selection was based on the energy use of the load and the possibility to retrieve data from the load. It was concluded that ventilation, cooling and indoor lighting should be included in the scope. The three loads together account for 85.6 % of the electricity need of the property. It was also decided that the electricity use of the tenants was to be excluded, since this cannot be influenced by the building operator. Tenants at Väla refer both to stores and restaurants.

7.3 Technical load assessment

From the literature review of methods for assessing flexibility and what loads that are interesting for DSF it was concluded that there are several parameters that are relevant when evaluating the flexibility of a load. Only some of these were chosen to be included in our tool for assessing flexibility. The selection of these emanated from those considered by the authors to be most widely used in literature and those most central in evaluating flexibility of a building. Since the purpose of this thesis was to investigate the prerequisites for Väla to offer DSF and not quantifying this flexibility, research areas and methodologies have been selected with the purpose of mapping and qualitatively discussing rather than quantifying the parameters. The chosen parameters and its sub-areas of interests used to evaluate the flexibility of different loads have been identified by the authors with support from literature (*see subchapter 5.2*).

Sheddability

Sheddability is used to remove essential loads that can be considered non-flexible and of no interest in any kind of DSF application. Apart from identifying the non-flexible loads, the sheddability parameter also aimed to classify those loads that are flexible into categories. Both the names and definitions of the four groups are identical to those presented in the theoretical framework. Thus, *shiftable loads* can either by *shiftable profile loads* or *shiftable volume loads* and *curtailable loads* can either be *reducible* or *disconnectable loads*. It is possible that a load can be classified into more than one of these groups.

Controllability

For any DSF application, it is essential that one can control the participating loads. The controllability parameter primarily incorporated load specific criteria. The sub-areas researched are presented below.

- What parameters determines the power demand of the load?
- What parameters are used to control the load?
- How is the control chain designed for the load?
- How accurate can the load be controlled?
- What is the response time from a change in control parameters, to a change in the power output of the load?
- What interactions are there between the different loads?

Availability

Availability is chosen to map daily and seasonal variation in the availability of the load both with respect to operating times and operating power. The flexibility that can be offered for any DSF application will be influenced by eventual daily and seasonal variations of the availability of a load.

Acceptability

For participation in any DSF application, the building operator must be aware of what downsides the participation of different loads for DSF applications may generate.

Using a load as a flexibility resource may, depending on the load, have different effects on building performance parameters. Therefore, different parameters must be considered depending on the load in question. Indoor temperature was chosen as an indicator for ventilation and space cooling since the thermal comfort is largely dependent on this parameter. Also, Väla have agreements with the tenants in which Väla is obligated to maintain the indoor temperature within certain limits.

7.3.1 Mapping and evaluation of loads with respect to flexibility parameters

To evaluate loads with respect to the chosen parameters, several methods and sources of information have been used. The choice of methods to evaluate the different parameters have been dependent on what has been considered to be the most just and viable method. The following sources and execution methods have primarily been used:

- First-hand sources, either by deriving the information through people with site-specific knowledge about Väla, or through site-visits at Väla. A site-visit at Väla was conducted on 2019-03-26.

- Experiments for those parameters that cannot be evaluated with current knowledge.

- Previously conducted experiments or measurements when the option of conducting experiments did not seem viable or favorable.

The flexibility parameters used in this thesis have been taken from literature. This is also true for the flexibility evaluation process which largely have been inspired by Connell & Riverso (2017). The flexibility evaluation process developed and used in this thesis is presented in *Figure 19*. It starts with identifying, selecting and quantifying loads. The loads are then evaluated from the flexibility parameters one by one. After every flexibility parameter there is either a yes or no-option. If one load has a single no, then the load is considered non-flexible. Thus, for a load to be considered flexible, it requires a complete chain of yes-options. Due to the complexity and extensiveness of evaluating the flexibility parameters, a simple yes or no does not capture the whole picture. However, the flexibility evaluation process illustrated in *Figure 19* is conceptually accurate.

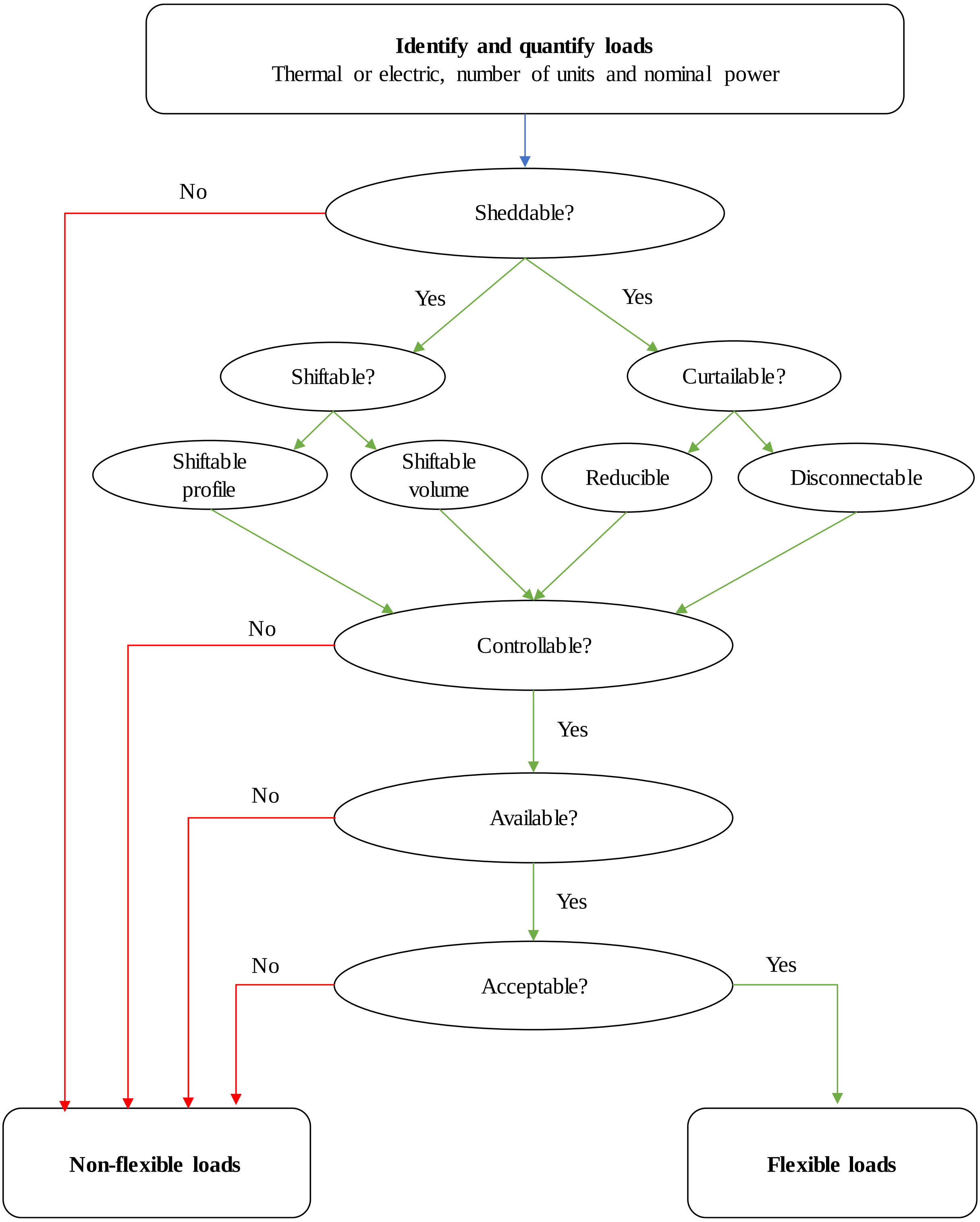


Figure 19. Flexibility evaluation process. The process starts with identifying and quantifying loads. The loads are then assessed with regards to chosen flexibility parameters. For every parameter, there is either a yes or no alternative. Loads that passes every parameter are considered flexible loads, while those who get one or more no, are considered non-flexible loads.

7.3.2 Controllability evaluation for ventilation

An experiment was conducted to evaluate the controllability of the ventilation. The experiment aimed to evaluate how exact the ventilation could be controlled with respect to a desired power output and what the response time was from a set-point change to a change in power-output. The argument for conducting an experiment was that the current BEMS does not log the live power consumption for the ventilation fans. Thus, there were three ways to find out the live power consumption from the ventilation units at Väla. Firstly, it could be read from the display of the VFD next to the ventilation fans. Secondly, the theoretical fan law (*Equation 1, subchapter 6.3*) could be used. This method requires that there are measurements for the fan where the power consumption and RPM of the fan have been measured. Thirdly, one could use a fan curve to estimate the power consumption. However, this require that product sheets for each fan are available, since these are product specific. These were not available. The first method of reading the live power consumption from a display was considered superior since this method gave actual and live values of the power consumption of the fans.

Due to the many similarities of the physical setup of the HVAC units at Väla, it was concluded that conducting an experiment of one of the HVAC units would be enough, why ventilation unit TAFA-06 was chosen. The only criteria for choosing a ventilation unit were that it was not to have ventilation ducts connected to another ventilation unit. Thus, there were several ventilation units to choose from.

The experiment was conducted during the site visit at Väla 2019-03-26 in company with the service technician Tim Hellström. The experiment included four tests. Three tests included changing the pressure setpoints since this is a parameter that regulates the power need of the fans. The fourth test was a fan signal test where the setpoint to the fan signal of the exhaust fan was changed to 100 %. Setpoint pressures and fan signal were changed by remotely accessing the BEMS system via cRSP.

7.3.3 Availability evaluation for ventilation

It is important to evaluate the availability of ventilation fans with respect to operating power, since this indicates what flexibility there is for both increasing and decreasing power demand. From previous measurements conducted for Väla it has been found that most of the ventilation units do not operate at their rated power. Such measurements have been made for 20 out of the 33 ventilation units at Väla. This data is presented in *Table B* in *Appendix B*. For 16 of the ventilation units there were fan frequency and corresponding power measurements from one occasion. Using this data, it is possible to calculate the power consumption from any other frequency with help of *Equation 1*.

However, this is a theoretical relationship and physical parameters such as friction may hinder practical use of the formula. Thus, to validate the fan frequency and fan power data two of these data points are needed. For ventilation unit FTX-39, FTX-40, FTX-41 and FTX-42, two data points were available. Also, assuming that the fan signal is 100% at rated power, and the fact that rated power was available for several fans, two data points were available for 20 of the ventilation fans. The supply fan of FTX-40 was found to have two measurements that corresponded well with the theoretical relationship, why it was chosen with the purpose of exemplifying the availability with respect to operating power. Using fan signal data that were measured every 10 minutes from the variable frequency drive belonging to the supply fan of FTX-40, it was possible to calculate how the active power varied during 2018. This knowledge is important to evaluate how much flexibility the fan has with respect to its operating power.

7.3.4 Acceptability

Even though the ventilation and cooling system at Väla are two separate physical systems, they are connected and interdependent of each other in such a way that the acceptability parameter is difficult to evaluate solely for one of the two systems. Previous experiments by Siemens had already been conducted with respect to the thermal comfort for parts of Väla.

Since a key function of the ventilation and comfort cooling system is to maintain a good thermal comfort, the experiments could be used to evaluate the acceptability parameter for ventilation and comfort cooling. Acceptability was therefore evaluated using previously conducted experiments at Väla. This was motivated since the tests were extensive and the opportunities for conducting similar experiments again was not considered feasible.

7.4 Techno-economic assessment of BESS

The assessment made for a hypothetical BESS at Väla was divided into two parts. The outcome of the first part constituted the basis for the analysis made in the second part.

The purpose of the first part was to evaluate the technical potential for peak power reduction and what economical value this would generate at Väla. Two different sizes of BESS were analysed in order to evaluate how dimensioning affects technical performance and outcomes in the economic analysis. The assessment was conducted through simulations using System Advisor Model (SAM) followed by economical calculations in Excel.

In the second part the purpose was to establish a theoretical framework in which ways it would be possible to use the BESS for both peak power reduction and frequency regulation. The procedure for doing this consisted of the following steps:

1. Identify what the current market legislation states regarding participation from BESS on the reserve market. This was considered as the natural starting point since it constitutes the fundamental basis for determining how a BESS must be operated to be accepted as a balancing resource.

2. Evaluate how often the BESS would be available for frequency regulation throughout the year. In this evaluation it was assumed that reducing peak power would be prioritized, which implicates that the BESS only would be available for frequency regulation during periods when reducing power demand from the grid not could be economically reasonable.

3. As a last step, the difference between average monthly power demand for Väla was compared with the power components in the grid fee agreement. The purpose of this was to evaluate what capacity that could be used for frequency regulation, without causing additional costs towards the grid operator.

The first step was accomplished by researching Svenska kraftnäts’s homepage where several documents regarding market participation rules were available. The second step was carried out by analysing the operational performance in the previously conducted simulations with focus on the degree of utilization of both capacity and energy. Also, the average State of Charge (SoC) and the number of activation days and hours were analysed in order to give a time perspective of how regularly the BESS was operated for reducing peak power demand. The third step included calculation of the monthly average power demand during hours when Väla was open and closed. These values were then compared with the power demand levels that determines the price paid towards the grid operator.

Conclusively, by coupling limitations originating from the grid fee with the outcomes from the operational performance evaluation, it was possible to estimate what capacity that would be reasonable to offer on the reserve markets during periods a year.

7.4.1 Assumptions and delimitations

The conducted BESS simulations and associated economical assessment included the following assumptions and delimitations:

- Simulations were based on historical data of PV production and aggregated load. Thus, no forecasting model reflecting stochasticity from PV-production and load profile has been formulated or considered in the analysis.

- Only load data from 2017 and 2018 was used since energy efficiency measures have been implemented during the years before, which means that those profiles are not representative of how it looks with the current equipment and system settings

- Degradation of the BESS module has not been considered, neither in the simulations, nor in the economic evaluation. The SAM software offers this opportunity, but due to insufficient functionality of the software, it could not be used in the applications investigated in this thesis (*see subchapter 7.4.5*).

- Operation and maintenance costs were not included in the economical assessment.

7.4.2 Load profile and data from photovoltaic plant

The production data from the onsite PV-plant and four seasonal load profiles from Väla is presented in *Figure 20* respectively *Figure 21*. The electricity production during 2017 was 861 MWh with a peak hour power of 837 kWh/h.

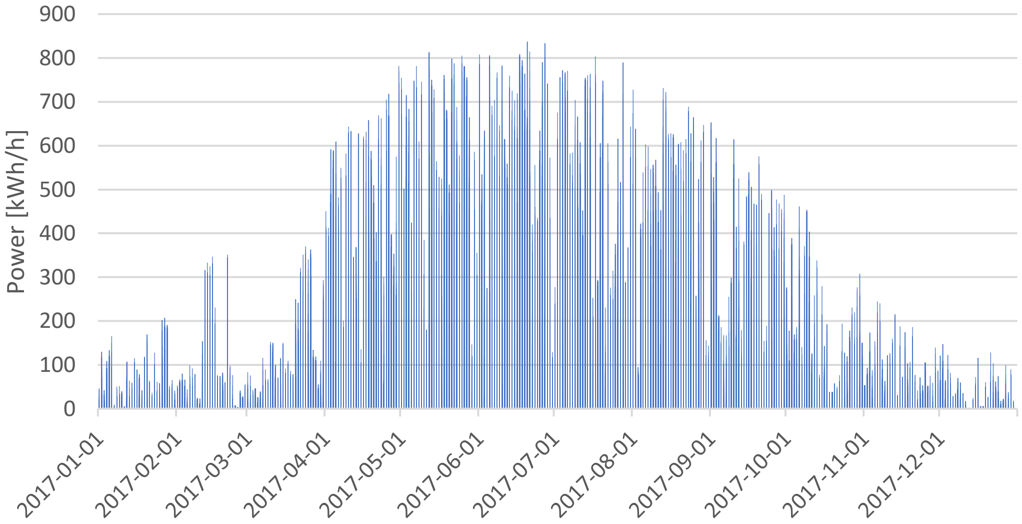


Figure 20. Delivered power from the PV-plant at Väla during 2017.

From analysis of the aggregated load data it was concluded that the PV-plant never produces more electricity than Väla consumes. This means that a BESS at Väla never could be charged from overproduction of the PV-plant. Thus, it would be necessary to charge the BESS from the grid at all times.

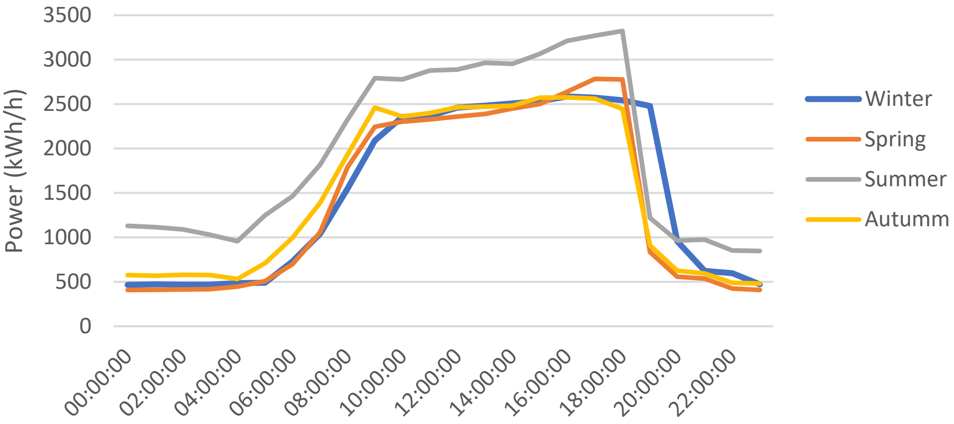


Figure 21. Load profiles at Väla from the four yearly seasons.

Further, as can be observed in *Figure 21*, the aggregated load from the building has a very similar profile during winter, spring and autumn while in the summer it is slightly higher. The main reason for this is the addition of cooling load during the warmer periods of the year.

7.4.3 Price components in grid fee agreement

The local grid owner that physically supplies Väla with electricity is Öresundskraft. The currently valid grid fee agreement for Väla has several price components and depends on both the momentary outtake of power and energy consumption during the year. All price components in the agreement are shown in *Table 1*.

Table 1. Price components in Väla's grid fee agreement (Öresundskraft 2019)

Fixed yearly fee (SEK/yr)	14000
Subscription fee (SEK/kWh/h, yr)	332
Power fee (SEK/kWh/h, yr)	274
Transfer fee (SEK/kWh)	0.028
Allowed reactive power outtake (%)	50
Reactive power fee (SEK/kVar, yr)	100

The price components that affects the outcome in the economic assessment is the subscription fee and the power fee, since they depend on the momentary power outtake. The power demand level for the subscription fee is set at the beginning of each calendar year and should correspond to the highest outtake of power in kWh/h during the year. If this limit is exceeded, the property owner gets penalized by a double price for those kW above the subscripted power level. The power fee is applied from November to March and depends on the highest value of power (kWh/h) during the individual month. The fee is then divided over the period, which means that only one fifth is paid each month.

In *Figure 22* the development of price components in Väla's grid fee during the last four years is illustrated. The price components, which depend on the momentary outtake of power, have increased in the last years and specifically notable is that the subscription fee has increased by 60% in four years. In the same time period, the power fee has increased by 14% while the transfer fee has been lowered by 22%.

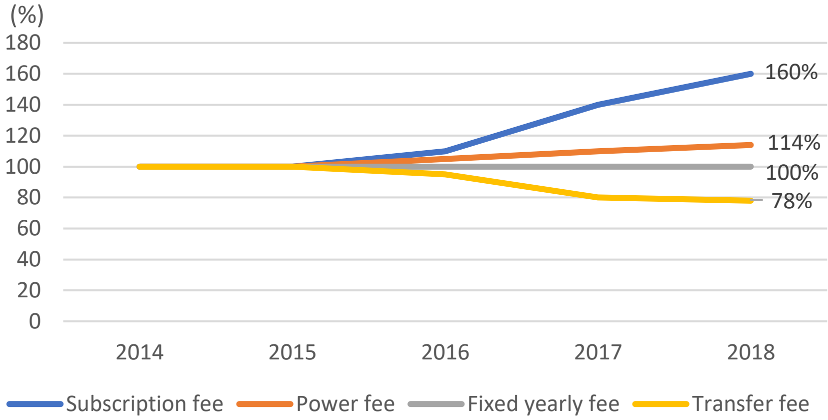


Figure 22. Price developement of components in Väla's grid fee agreement from 2014- 2018.

Furthermore, a comparison on what savings similar BESS operation would have enabled if Väla would have been situated in E.ON's grid was also conducted. A comparative grid fee, that typically is applied for high voltage connections at a local grid level and which includes a power dependent price component was found among E.ON's grid fee agreements (E.ON 2019). The details of the price components in E.ON's grid fee are shown in *Table 2*. Price components regarding outtake of reactive power are not included in the table since it was redundant for the comparative analysis. Yet, it exists in the actual agreements.

Table 2. Prices components in E.ON's grid fee agreement.

Fixed fee (SEK/month)	2100
Power fee (SEK/kWh/h, month)	81.60
Transfer fee (SEK/kWh)	0.04

As can be seen in *Table 2*, the grid fee applied by E.ON includes a monthly fixed fee and has a higher transfer fee than Öresundskraft. The price for the peak power component depends on the highest hourly outtake of power in kWh/h during each month.

7.4.4 BESS technology and configuration

The BESS technology that was used for the technical and economic analysis was Li-ion batteries. Li-ion batteries is nowadays the dominant technology among the electrochemical storage solutions regarding both growth and market share when it comes to applications of stationary storage (Tsiropoulos, Tarvydas & Lebedeva 2018). Consequently, this was considered as the natural choice of battery technology.

Another important parameter for the analysis was how the BESS should be configured with regards to the power capacity, typically known as the c-ratio. The high capital costs of Li-ion batteries entails a significant financial risk, which means that an optimal configuration for the desired application could be necessary to obtain long term profitability (Hesse et al. 2018). Several studies have analysed the optimal sizing of BESS for peak shaving applications (Hesse et al. 2018; Xu et al. 2019). The outcome of these studies show that sizing and configuration is a complex problem and that the optimal solution typically varies depending on the profile of the load. Consequently, to circumvent this optimization problem, it was decided to use similar BESS configuration and dimension as used in the reference case in Finland. This was motivated by the fact that the results from this study easily can be compared with outcomes in the Sello project which could be useful for coming work at Siemens.

The BESS installed at Sello have a power capacity of 2000 kW and storage capacity of 2100 kWh. However, this configuration is larger than what was originally intended and is the result of a mistake from the supplier. The actual desired configuration was a power capacity of 1600 kW and storage capacity of 2000 kWh, which is the reason to why this configuration was used in the simulations of this study. A smaller BESS with the same c-ratio, 1200 kW/ 1500 kWh, was also simulated in order to create a comparative result on how the technical and economic value changes if a smaller BESS would be chosen for Väla.

7.4.5 Simulations in SAM

To conduct simulations of the described BESS operations, the software SAM was used. SAM is a free software developed by the American National Renewable Energy Laboratory (NREL) and is often used for technical and financial modelling of renewable energy systems (Lopez 2016). SAM enables high temporal resolution quasi-steady state photovoltaics coupled with energy storage performance models (Nelson et al. 2015).

The conceptual setup of components in the model can be seen in *Figure 23*. The BESS is placed behind the meter and via a power converter connected to an AC bus. The building load, PV-plant and the grid are connected to the same bus. Together these components conceptually compose a small microgrid. The power converters connected to the BESS does not have any physical model, but are estimated using single point efficiencies, which applies for both charging and discharging of the BESS. In the simulations these values corresponded to 96% for both charge and discharge.

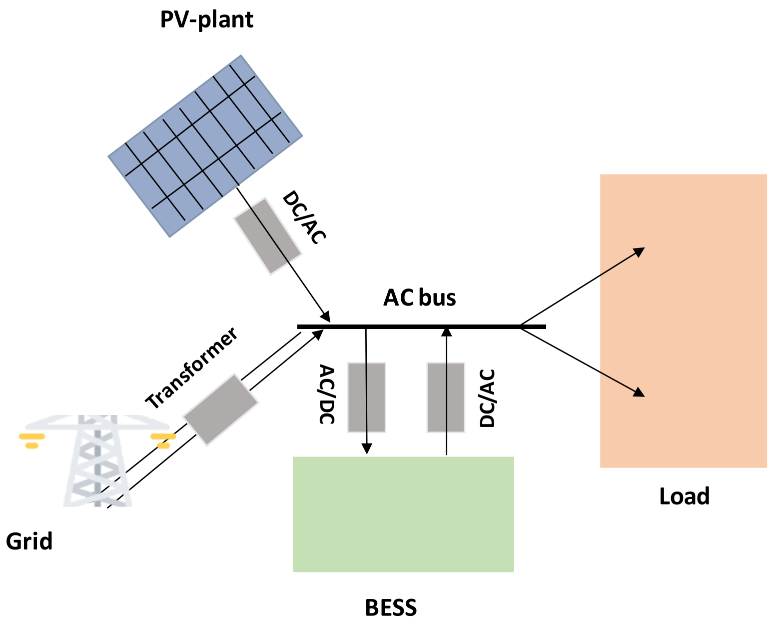


Figure 23. Conceptual setup of components in the SAM model.
The illustration was collected from (Nelson et al.2015), but has been edited by the thesis authors.

The software enables accurate modelling of photovoltaics, but this was not used in the simulations since the production from the real onsite plant already was included in the load data. Thus, the only interesting application was the BESS modelling part. However, in the available version of the software it was required that PV production was simulated in order to access the BESS applications. This problem was solved by simulating one solar cell positioned in the north direction, which naturally gave almost non-existent production, but enabled usage of the battery model. A detailed explanation of how the SAM simulation works can be found in *Appendix F*.

Degradation of BESS

Regarding degradation of the BESS, it is possible to customize a model based on several input parameters in SAM. Another alternative is to use a Li-Ion model with predetermined degradation coefficients. However, after several hours of attempts to include a multi-year BESS degradation in the simulations, it was concluded that the functionality in the software could not be adapted to the applications investigated in this thesis. The main complication was that the simulations had to be adapted to the price components in the grid fee agreements, which made the financial tool in SAM unusable. This resulted in that it was impossible to relate the reduced technical performance to the financial calculations. Consequently, it was determined to neglect degradation of the BESS since it could not be accounted for in a justifying way in neither the technical nor the economical assessment.

7.4.6 Economical assessment

An economical assessment was conducted in order to evaluate the profitability of a BESS investment at Väla. Calculations were based on the results from the simulations of peak power reduction, average costs of BESS and prices in the grid fees. The purpose of the economical assessment was to give an idea on what the income would need to be to make a BESS profitable and if an investment would be reasonable given the current circumstances.

The analysis was initiated by calculations of the yearly savings that come from reducing the peak power with consideration to the grid fee structures of both Öresundskraft and E.ON. This could be accomplished by subtracting the reduced peak power from the original peak power and then calculate what cost saving this would generate using the price components in the grid fee agreement. The next step was to identify what the BESS would cost with the current market prices.

Cost of BESS

The complete cost of a BESS consists of several components that all have to be in place to make the system functional and secure. The average price for a complete installation could, nonetheless, be found in the literature, which makes it possible to roughly estimate what a BESS of a certain dimension would cost.

Prices on Li-ion battery systems have decreased significantly the last few years, but exactly how much varies in different sources. In the report written by (Tsiropoulos, Tarvydas & Lebedeva 2018) results regarding the BESS market development from several qualified studies have been gathered. This report indicates that the estimated cost for a BESS during 2017 stretched from a high 1200 €/kWh to remarkably lower 250 €/kWh. However, this interval was valid for both utility and behind-the meter applications of Li-ion battery systems. For behind-the-meter applications the cost-variation was lower and stretched from 1000 €/kWh to 550 €/kWh, with an average of around 600 € / kWh. Consequently, 600 €/ kWh was considered as the reasonable value to use in the economical assessment. In the future, the prices are expected to be lower and prognoses indicate that by 2040, the cost for a stationary storage system will be in the range of 165 €/kWh to 410 €/kWh (Tsiropoulos, Tarvydas & Lebedeva 2018).

Further, operation and maintenance were neglected in the economical assessment. The estimative operation and maintenance costs for a BESS vary among different sources in literature, which makes it hard to fairly estimate. It depends on the degradation of the battery module, labour costs and age of the facility (Anvari-Moghaddam et al. 2017). Thus, due to this complexity, it was considered more reasonable to neglect these costs in the economical assessment.

Calculation of Pay-back time and Net Present Value

The profitability of a BESS investment at Väla was evaluated by calculating the Pay-back time (PBT) and Net Present Value (NPV). These are two basic methods in financial calculations and are suitable for initial assessments of an investment. The PBT puts the repayment time in focus and considers only how long time it would take to get back invested capital (*Equation 2)*.

Equation 2

$$PBT = \frac{Investment\ cost}{\sum Yealy\ savings}$$

Concerning the yearly savings, these were calculated separately for 2017 and 2018 since the potential for peak power reductions depends on the load profile, which in itself differs between years. However, in the calculation of pay-back time, the average yearly saving was used, since this was considered to be more representative than the results from one year solely.

For the calculation of NPV, *Equation 3* was used. C_0 corresponds to the initial investment cost, C_s corresponds to the yearly capital savings, r is the discount rate and T is the calculation period. In order to calculate the necessary yearly income to get a positive NPV, *Equation 3* was rearranged in order to solve for C_s.

Equation 3

$$NPV = -C_0 + \sum_{i=1}^{T} \frac{C_s}{(1+r)^i}$$

Calculations were conducted for a discount rate of 5% and 10%. Concerning calculation period this was set to ten years based on the expected technical lifetime presented in Lazard (2017). The technical lifetime in Lazard (2017) refers to general useful economic lifetime of the technology. However, the actual useful lifetime of a BESS varies from case to case and depends on how the BESS is operated during its lifetime, sub-technology and construction factors.

8. Technical assessment of loads

In this chapter, the results from the load assessment are presented. Firstly, ventilation, comfort cooling and indoor lighting are presented with respect to details such as rated power. Secondly, the results from the flexibility evaluation process are presented.

8.1 Electricity consumption at Väla

A mapping of the energy use at Väla was conducted in 2014. It included both electricity and heating and is presented in *Figure 24*. Electricity used by the tenants represents 58.6 % of the total electricity consumption and electricity used by the property represents 41.4 %.

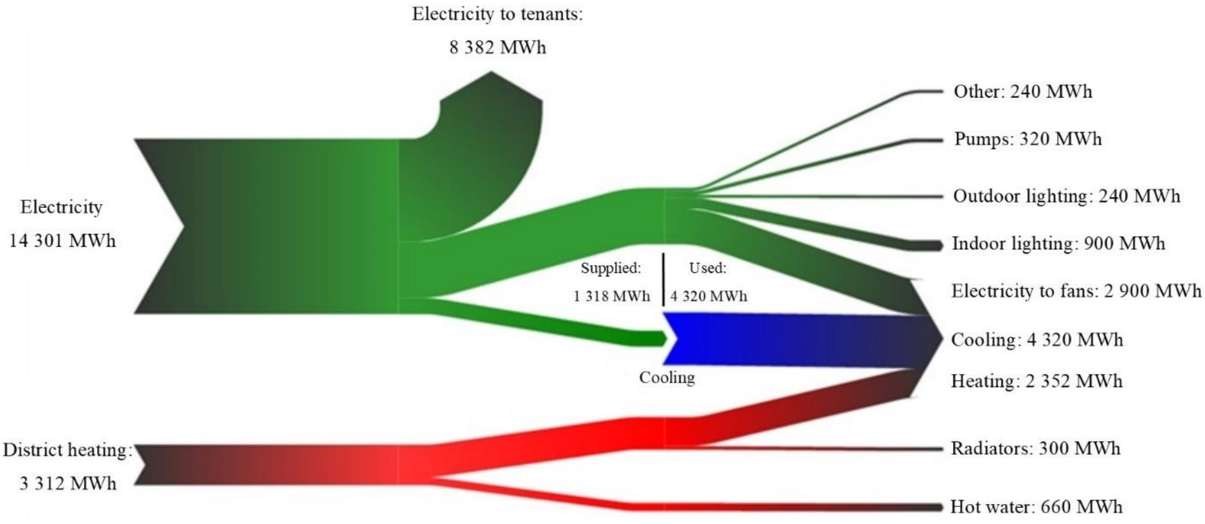


Figure 24. Energy end-uses at Väla in 2014.

8.2 Loads at Väla

Excluding the electricity that is used by the tenants, *Figure 24* shows that the three largest loads at Väla with respect to electricity use are ventilation (49.0 %), chillers (22.3 %) and indoor lighting (15.2 %). Together they sum up to 86.5 % of the electricity use of the property, leaving 13.5 % consumed by outdoor lighting, pumps and other loads such as escalators, elevators and electric doors.

8.2.1 Ventilation

There are 33 HVAC units in total at Väla with a total rated fan power of 935 kW. As can be seen in *Table A* (see *Appendix A)*, the rated fan power values differ both with respect to different ventilation units and with respect to supply and exhaust fans. The HVAC units are placed on the roof, in fan rooms and in ventilation corridors. With exception for air-handling unit TA-29, all HVAC units are of FTX-type with VFD's. However, they differ both with respect to their age, manufacturer and product type. Values for the four air handling units FTX15, TA-13, TA-31 and TA-29 are not available, why the values of aggregated power for the ventilation fans are higher than those presented in *Table A (see Appendix A)*. It has been estimated that the total supply of air provided by the ventilation supply fans is 260 m^3/s.

8.2.2 Comfort Cooling

Väla produces their comfort cooling locally with the help of chillers using vapor compression cycles. Each chiller is composed of three major components that consume electricity. Except for the five compressors (VKA01-VKA05 in *Table 3*) that account for the highest power needs, there are also one coolant cooler connected to each compressor. The purpose of these are to remove the heat absorbed by the coolant in the cooling batteries. Each coolant cooler unit is composed of 12 fans, each fan with a rated power of 1.6 kW each. To each compressor and coolant cooler, there are one circulation pump, thus ten in total. Specifics about the three component types is presented in *Table 3.*

Table 3. Details about the chiller components at Väla. VKA01-VKA05 are the compressors. Product name, commission date and rated electric power is presented.

Chiller components	Product	Commissioned	Rated electric power (kW)
VKA01	Trane HCCH1D2F0J0	2004	209
VKA02	Trane HCCH1D2F0J0	2004	209
VKA03	Carrier 30HXC-310	2011	265
VKA04	Carrier 30HXC-310	2011	265
VKA05	Carrier 30HXC-310	2011	265
Pumps			139
Coolant coolers	Refrion	2011	96
Total			**1448**

Except for ventilation unit TA-01, which only utilizes the heat exchanger as a source of energy for the supply air, each air-handling unit is connected to one cooling battery and one heating battery. All cooling batteries are in turn connected to a single piping system to where all compressors are connected. The coolant is a glycol-water mix with a total volume of 90 m^3. The piping system at Väla is presented in *Figure 25*.

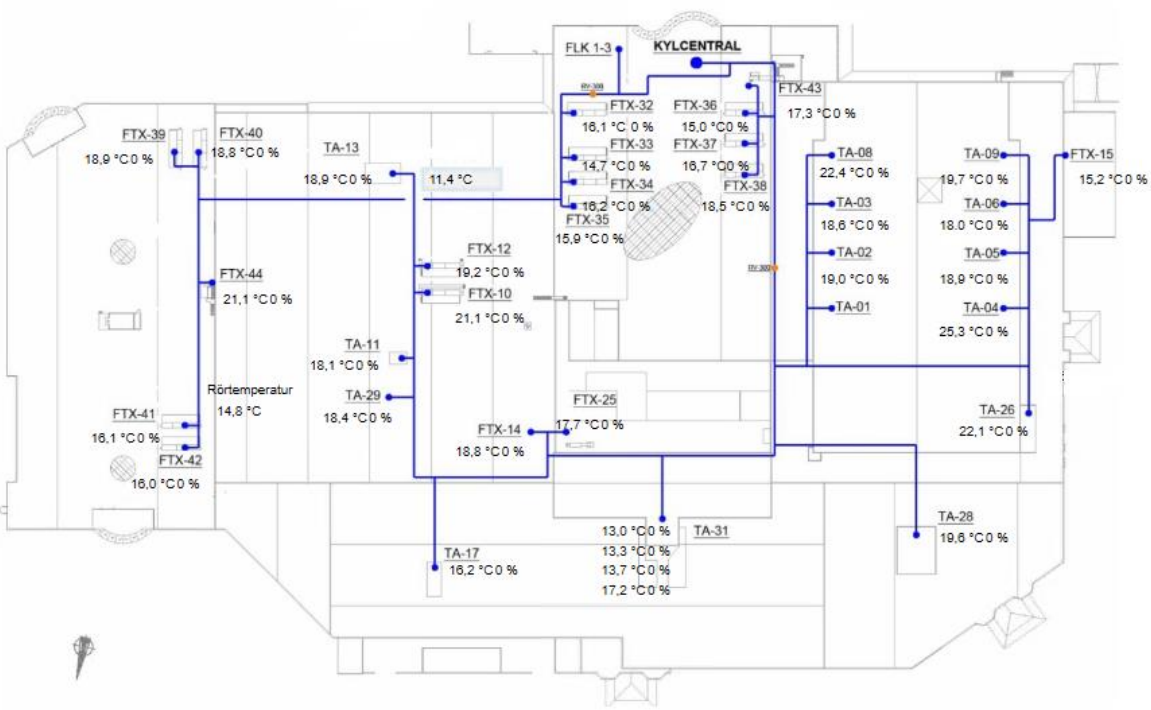


Figure 25. The piping system for the coolant that connect the chillers to the cooling batteries. The locations of each ventilation unit are also seen.

8.2.3 Indoor lighting

During the site visit at Väla, it was concluded that mapping of the indoor lighting at Väla is very challenging. Hallway lighting composes the largest share of indoor lighting and is located in the ceiling, making it difficult to assess what lighting armatures and lighting sources that are installed. No information or documentation have been found that could provide this information. The only details found that regard the light sources is that they are not dimmable.

8.3 Building Energy Management System

The BEMS installed at Väla is called Desigo CC, an Integrated Building Management Platform developed by Siemens AG. The BEMS can be controlled via remote access in cRSP or directly via computers at the site. In Desigo CC, it is possible to monitor, model and control the loads that are connected to the system. As an example, setpoint values for controllable parameters can be manually changed.

8.4 Sheddability of loads at Väla

In *Table 4*, the sheddability of the loads within the scope of this thesis are presented. Regarding the ventilation, there are legal requirements of a minimum air flow per second. Thus, ventilation cannot be considered shiftable. The ventilation can be considered curtailable as long as the minimum air flow is kept, thus the ventilation is reducible but not disconnectable.

Due to the thermal inertia of buildings, comfort cooling can both have a shiftable profile or shiftable volume load. The comfort cooling at Väla can to some extent be considered curtailable. However, a reduction of the chiller load or a disconnection of the chillers would result in a change of the thermal comfort.

Indoor lighting is usually not shiftable since there is an instant need for lighting together with an instant physical behavior of the load. Considering the indoor lighting as one system, it is reducible. This could be achieved by shedding half of all the lights. It cannot be disconnectable on a system level since this correspond to no indoor lighting at all.

Table 4. Sheddability classification of the three largest electric loads at Väla. Cells that correspond with a certain characteristic are marked.

	Shiftable		***Curtailable***	
Load type	**Profile loads**	**Volume loads**	**Reducible**	**Disconnectable**
Ventilation fans			🟩	
Comfort cooling	🟩	🟩	🟩	🟩
Indoor lighting			🟩	

8.5 Controllability of ventilation and comfort cooling

Even though the ventilation and comfort cooling systems at Väla are two separate systems, they are integrated both when it comes to the hardware and software control systems. Therefore, controllability aspects for the two systems will be described and analyzed together.

For the ventilation fans, locally measured parameters are sufficient for accomplishing accurate control. This is not true for the comfort cooling since it is dependent both on central and local control. Central control refers to how the chillers themselves are controlled and local control refers to how the cooling batteries are controlled.

8.5.1 Physical setup

Nearly all HVAC units deliver air to several different stores and areas through a network of ventilation shafts that belong to its respective HVAC unit. However, HVAC units FTX-39 to FTX-40, FXT-41 to FTX-42 and FTX-33 to FTX-35 share ventilation shafts and are mutually controlled to some extent. Due to the large number of sections within Väla (A to L), only building C is presented to give a presentation of the physical setup of the ventilation system. In *Figure C (see Appendix C)* an overview of building C is presented. It can be seen that different ventilation units serve different zones, indicated by red lines.

The physical setup of the different HVAC units differs substantially when it comes to the physical configuration of individual ventilation ducts that transport the air to stores and areas that are served. These differences are for example the length of the ducts, how many outlet valves that are connected to the ventilation ducts, how many stores these valves are connected to and how many m^2 each HVAC unit serves. One major difference between the outlet valves in the different stores are that only some are motorized, meaning that the ventilation system at Väla is partly CAV and partly VAV. Even if an area has VAV, there will always be a minimum air flow even for VAV-valves, since the control range of these do not stretch to fully closed valves.

There are also differences between what components that each HVAC unit are composed of, even though they are smaller compared to the differences of the ventilation shafts. Such differences are for example if the ventilation units have CO_2-sensors.

8.5.2 Local control parameters

Despite the differences, a conceptual view, which is valid for most HVAC units at Väla, is presented in *Figure E (see Appendix E)*. *Figure E* is a modified screenshot of the HVAC unit FTX-39 from the BEMS Desigo CC. Live values for different parameters can be seen as well as setpoint values for some of the parameters.

Parameters that relate to the control of ventilation shafts and comfort cooling are presented in *Table 5*. Additional parameters that are seen in *Table 5* are for example supply and exhaust air flow and efficiency of the heat exchanger. However, these are only measured and cannot be directly controlled and are therefore not included in *Table 5*. All parameters in *Table 5* can be controlled by setpoints changes, meaning that it is possible to assign parameters new values manually.

A parameter can also have setpoint ranges that define acceptable values. When a new setpoint is assigned, the system will try to achieve that setpoint if it lies beyond the setpoint range. As can be seen in *Figure E* (see *Appendix E)*, the actual value differs from the setpoint value for several parameters, such as the supply and exhaust fan pressures. Further, some parameters have operating constraints which are also presented in *Table 5*. For example, the output signal from the VFD that goes to the ventilation fans cannot be lower than around 40%. This fan signal would increase the wear and tear of the fan and the risk of fire due to excessive heat generation.

Table 5. Parameters that relate to ventilation and comfort cooling that both are measured and can be controlled.

Load	Parameter	Limits	Unit
Ventilation	Supply and exhaust fan signal	40-100	%
	Supply and exhaust fan pressure	Specific for fan. Correlated with fan signals.	Pa
	CO_2-level	Maximum limit 1100	ppm
Comfort cooling	Supply and exhaust air temperature		°C
	Room temperatures		°C
	Cooling battery valve position	0 (closed) - 100 (open)	%
	Heat exchanger valve position	0 (closed) - 100 (open)	%
	Ambient temperature		°C

Even though there are several parameters that are controllable it is those that relate to the power needs of the ventilation and comfort cooling that are more interesting to describe further. Concerning the ventilation, these parameters are the *supply and exhaust fan signal* and *supply and exhaust fan pressure*. Regarding comfort cooling, interesting parameters are the *supply air temperature* and *cooling battery valve position*. Further, even though the parameters have a direct connection to its respective load, only two out of these four parameters are used in practice. These can be called primary parameters and are *supply and exhaust fan pressure* for ventilation and *supply air temperature* for comfort cooling. The two other parameters, *supply and exhaust fan signal* and *coolant valve position to cooling battery* can be called secondary since these are not used directly to control the loads. Rather, a change of the primary parameters infers a change on the secondary parameter through the programmed software scheme in the controller.

8.5.3 Central control parameters

From *Table 3 (subchapter 8.2.2)* it is seen that the chillers are made from different manufacturers. They are also not using the same compression technique. The two compressors from Trane are of screw-type, meaning that when the comfort cooling demand increases the electric load of the compressors increase evenly. The compressors of Carrier type are of scroll-type with 10 power steps, each increasing the electric load with 10 %.

The compressors are programmed to power up depending on the ambient temperature. As can be seen in *Table 6* each chiller power up with increasing ambient temperature. However, they are programmed in such a way that VKA02 will not start if not VKA01 is operating at full capacity. They are also programmed to maintain a supply temperature of the coolant that depends on the ambient temperature. The higher the ambient temperature, the lower the setpoint temperature of the supply coolant. The coolant coolers are programmed to maintain a constant forward temperature. These all have VFD's.

Table 6. The ambient temperature at which the different chillers power up.

Chiller	VKA01	VKA02	VKA03	VKA04	VKA05
Start at ambient temperature [°C]	> 14	> 17	> 20	> 22	> 25

8.5.4 Local control chain of ventilation and comfort cooling

Depending on the disturbance, the control chain will look differently. However, the most common disturbance to the HVAC system is an increase in occupancy or ambient temperature. As an example, if a temperature sensor registers a higher temperature than the setpoint temperature, the system can react in several ways to counteract this.

If the store has motorized supply air valves that regulate the supply airflow to the stores these will open more and increase the air flow to the store. This response influences both the power needs of the chillers and the ventilation fans. With a higher air flow passing through the cooling battery, there will be a higher need for cooling to maintain the supply air temperature. This can be accomplished in two ways. Primarily, this demand is satisfied by utilizing more capacity of the heat exchanger. The exhaust air is then used to pre-cool the ambient air.

However, when the heat exchanger valve position is at 100 % and there is still a need for cooling to maintain a desired supply air temperature, the cooling battery is used. The flow needed to maintain the *supply air temperature* corresponds to a certain value of the *coolant valve position to the cooling battery*, meaning that the valve will open. This would in turn create a need for a higher flow rate through the chillers, causing an increase in the power needs. When a motorized supply air valve to a store opens, this also creates a pressure drop in the ventilation channel. Since the power needs of a fan and the fan pressure is correlated, a pressure drop in the ventilation channel would infer a decrease in the power consumption of the fan.

If there are no motorized supply valves coupled to the ventilation shafts, an increase in temperature would only infer a change in the power needs of the chillers. This is under the assumption that the heat exchanger is operating at 100 %. This would again be achieved by an increased valve position to the cooling batteries.

8.5.5 Central control chain of comfort cooling

Both ambient and local changes at the coolant batteries will affect the local control parameters and thus have implications for the power needs of the different chiller components. If the ambient temperature increases, the compressors will power up due to the new and lower setpoint temperature of the forward coolant corresponding to that ambient temperature. Larger comfort cooling needs due to opening of valve position or higher temperature of the intake air will result in higher return temperature. This will also cause the coolant coolers to increase their power demand since the return temperature back to the HVAC units is to be maintained.

8.5.6 Controllability experiment on ventilation

The results from the four experiments on ventilation unit TAFA-06 are presented in *Table 7*. The new setpoints for fan pressures and fan signals are presented with the corresponding power. From *Table 7* it can be seen that for the tests that included increasing and lowering pressures, the power of the fans did not achieve a single value. The size of the power fluctuations differed depending on the test and fan, ranging from 0.1 kW to 0.6 kW. For the fourth test, the power need of the exhaust fan was fixed at its rated capacity, 7.5 kW.

Table 7. Test results from ventilation unit TAFA-06. Setpoint values of fan signal, fan pressures and its corresponding power are presented. Supply fan = SF and Exhaust fan = EF.

	Fan	**Pressure [Pa]**	**Power [kW]**
Initial values	SF	70	5.1 – 5.5
	EF	205	4.8 – 5.3
Test 1: lowering pressures	SF	54	4.5 – 4.9
	EF	160	4.1 – 4.2
Test 2: 100 % fan signal	EF	300	7.5
Test 3: increasing pressures	SF	80	5,9 – 6.0
	EF	215	4.9 – 5.5
Test 4: lowering pressures	SF	45	3,8 – 4,0
	EF	140	3.7 – 4.3

After the experiments, the fan signal values before, during and after the experiments were extracted from the BEMS. These are presented in *Figure 26*. From *Figure 26* it is seen that the fans start at 09:15 according to the time schedule (see *Figure D* in *Appendix D*) and then increase quickly to their operating points.

1. At 09:51, when the first test was conducted, it is seen that the fan signals drops for both fans.

2. At 09:56, when the second test was conducted, a small increase of the exhaust fan and a small decrease of the supply fan signals can be seen. The reason for the large drop in exhaust fan signal that shortly follows is that when a 100 % fan signal setpoint was applied, the exhaust fan pressure increased substantially as well as the fan achieving its rated output. An output signal of 100 % cannot be seen in *Figure 26* since fan signal values are only logged in the BEMS with a time interval of five minutes.

   However, it was observed in the live interface of Desigo CC. The following drop in signal for the exhaust fan down to 10 % was a response of the exhaust fan shutting down as a protective measure due to an excessively high pressure of 300 when the fan signal was changed back to its original value of 88 %. Therefore, the exhaust fan had to restart which resulted in a recovery period, which also is seen in *Figure 26* at around 10:01.

3. At 10:10, it is seen that the fans have recovered to their initial signal values. This is when test three started which resulted in a small increase of the exhaust fan signal and a larger increase in the supply fan signal.

4. At 10:15 and it is seen that both fan signals decrease. This is when the fourth test started. It is also seen that the supply fan has a slower response time compared to the exhaust fan.

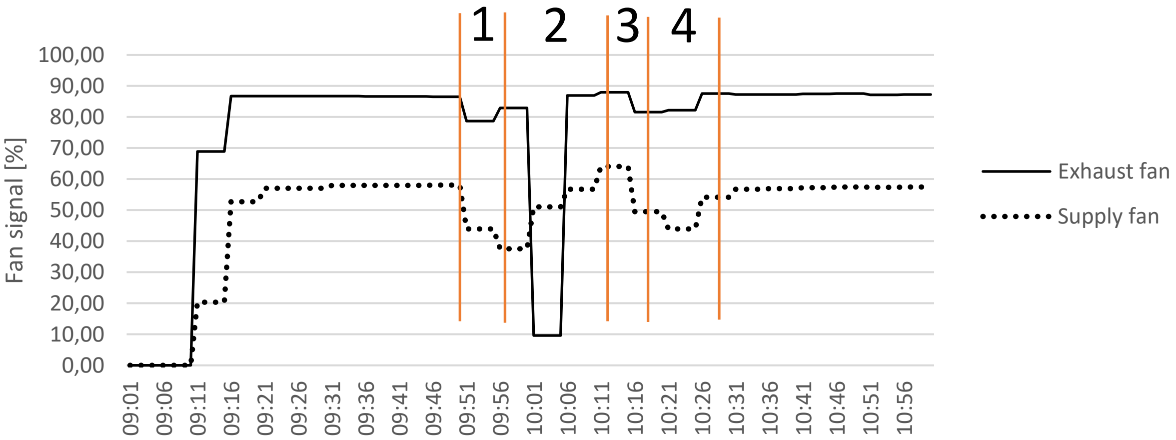


Figure 26. Experimental results from TAFA-06 conducted at Väla 2019-03-26. Resulting exhaust and supply fan signals of TAFA-06 before, during and after the experiments are seen. On the top, markings of when the different experiments occurred are presented.

There were other important observations during the experiments which were not captured by the results in *Table 7* and *Figure 26.* The following was seen in the experiment:

- The actual pressures were not the same as the setpoint pressures. This is valid both before the tests during normal operation as well as when the tests were conducted.

- The fans had a very fast initial response from the time that the new setpoints were applied. Within seconds from that the new value was applied, there was a prominent change in the sound of the fan, indicating an acceleration or deceleration of the fan.

- Even though the fans had an initial fast response, this effect was not maintained since it took minutes to achieve a new setpoint pressure. Also, during test four it is seen in *Figure 26* that the supply fan signal was higher than that in test one.

8.6 Acceptability of ventilation and comfort cooling

The acceptability of ventilation and comfort cooling was evaluated using previously conducted experiments by Siemens. The tests were conducted in building L, which is supplied by HVAC units FTX-39, FTX-40, FTX-41 and FTX-42. For four days, 20th – 22nd of November and 24th of November 2017, the ventilation units were operated with the intake valves on the roof closed for the HVAC units in question. This means that only exhaust air was circulated, and no free cooling from outdoor air or comfort cooling was used. The ambient temperature varied during the four days and was around 0 °C during the 20th, 21st and 25th and 8 °C during the 22nd. The occupancy varied during the four days but was significantly highest on Saturday the 24th of November. The experiments aimed to evaluate the increase in temperature and CO_2 concentrations that followed an exclusion of comfort cooling.

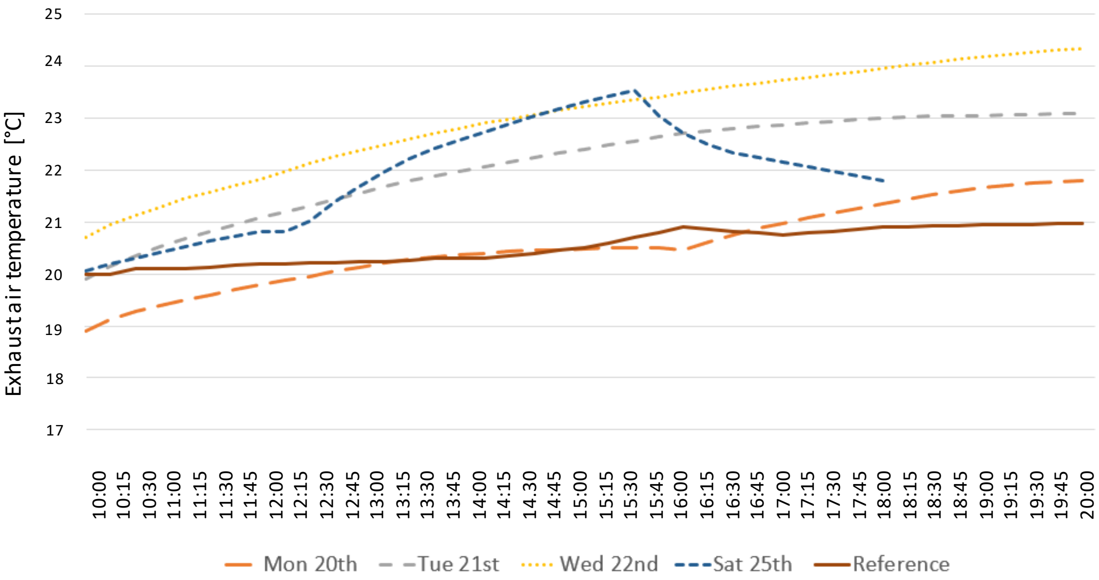


Figure 27. Resulting increase of temperature in the exhaust air of ventilation units FTX39-FTX42 when they were operated in 100 % exhaust air mode.

The resulting temperature rise in the exhaust air from the four days are presented in *Figure 27*. A reference day is also presented, indicating what the temperature increase normally would have been.

In *Figure 27* it can be seen that for all days when the experiments were conducted, the temperature increase is greater than for the reference day, which has an average temperature increase of 0.10 °C/hour. The average temperature increases during Monday the 20th and Tuesday the 21st were 0.30 °C/hour and during Wednesday the 22nd, 0.36 °C/hour. During Saturday the 25th the experiment had to be aborted due to complaints from the occupants in building L. During the 5,5 hours of which the experiment was conducted, the average temperature increase was 0.62 °C/hour. The number of occupants varied during the four test days but were significantly higher during Saturday the 25th. During the four test days CO_2-concentrations also increased more rapidly than those of a reference day.

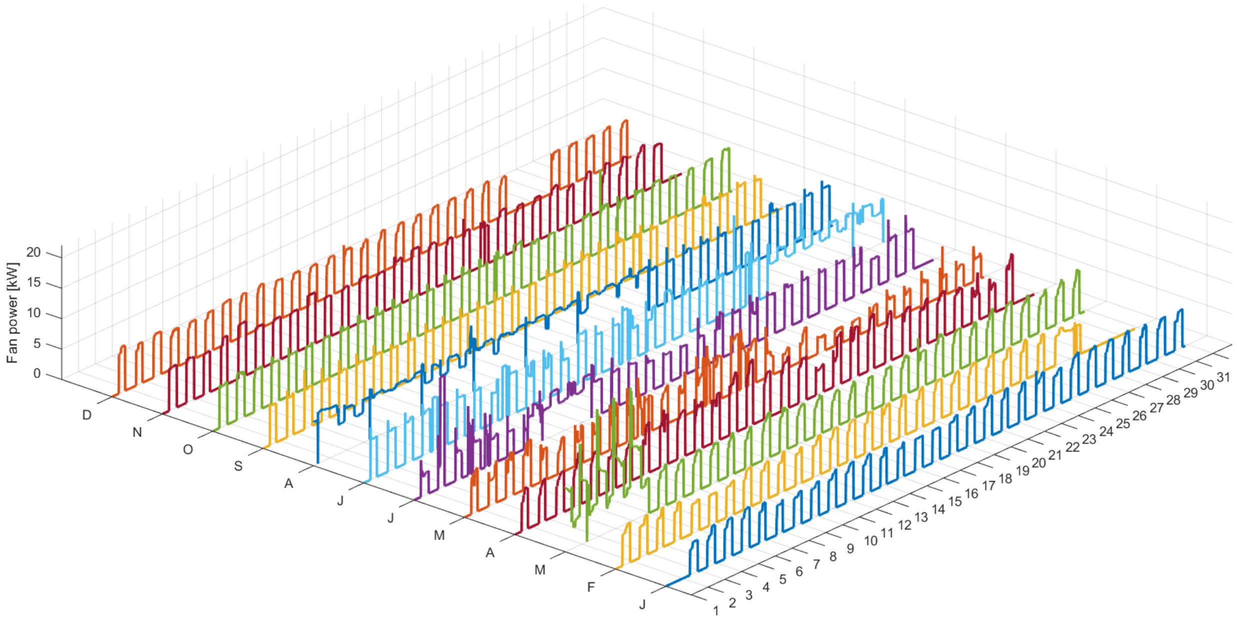
8.7 Availability of ventilation

Except for HVAC unit TA-09, which service premises that are occupied during nighttime, all ventilation fans have limited operating schedules. Operating hours are programmed individually for each ventilation fan into Desigo CC and are presented in *Figure 28*.

As seen in *Figure A* (see *Appendix A)*, most ventilation fans have an availability of between eleven and thirteen hours per day. No seasonal variations in terms of operating hours were found and most ventilation units therefore can be estimated to have an availability period between 46 % to 54 % per year.

With respect to availability in terms of operating power, none of the ventilation fans operate at their rated power. This could be seen from the signal data for the supply and exhaust fan, where few fans were found to operate close to a 100 % signal. As described in *subchapter 7.3.4*, it is not possible to translate the signal data to active power for all of the ventilation fans since measurements of corresponding power were not available. To illustrate both daily and seasonal variations of active power, the availability with respect to operating power for the supply fan of ventilation unit FTX-40 during 2018 is presented in *Figure 28*. When a ventilation fan starts, signal values can initially reach 100 % for a few minutes. These values do not reflect the larger trends of how the active power varies and is therefore filtered away in *Figure 28*.

Figure 28. Daily and monthly variations in active power of the supply fan of ventilation unit FTX-40 during 2018. Months are indicated with their first letter and days are numbered from 1 to 31



From *Figure 28* it is seen that the largest fan power variations are found within single days. These are a consequence of the availability with respect to operating times presented in *Table D* (see *Appendix D*). Public holidays, such as Christmas can also be seen, generating values of zero kW for those days since Väla is closed. Monthly variations seem to be less distinguishable. The patterns for September to December and January to April appear to be very similar. For the first half of August the supply fan seems to have been running all the time. A few days in March, May and June have daily trends which are very different to those of September to December and January to April. Overall, it seems that seasonal fluctuations are small, and that the supply fan usually consumes between 5 kW to 10 kW during operating times. These power levels correspond to 17 % and 33 % with respect to the rated power of the supply fan of FTX-40.

8.8 Availability of comfort cooling

One parameter that determine whether the chillers are powered up at all is the time of the day. During weekdays, the chillers are allowed to operate between 07:00-20:00 and during weekends 07:00-18:00.

Figure 29 shows the relative power of the five chillers at Väla. Relative power refers to hourly ratios of active power measured from the two transformers to which the chillers are connected, and the rated power of the chillers. Included in the active power are all compressors, circulation pumps and coolant coolers, since these all are connected to the two transformers. From *Figure 29,* it is seen that there is a distinct seasonal variation in the availability of comfort cooling. Between the middle of October until the beginning of April, the chillers are practically not running at all. Even though the general trend is that the power ratio is the highest during late spring to early fall, there is a clear decrease of the power demand during June, and the power demand seems to be fluctuating substantially from day to day.

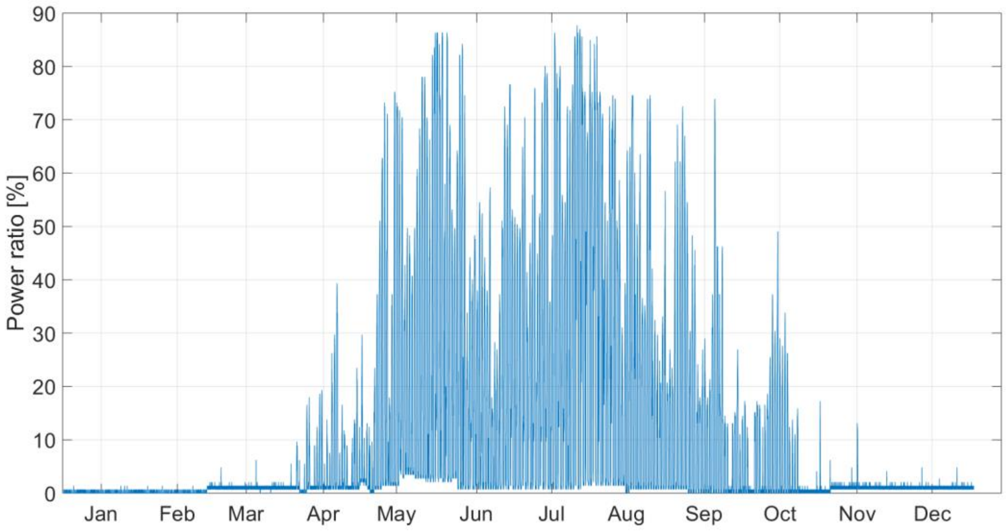


Figure 29. Seasonal variations in the power ratio for the chillers during 2018.

In *Figure 30*, the power ratios are presented as an accumulated sum of their relative frequency to better reflect the distribution during hours when there is a demand for comfort cooling. As an example, it can be seen in *Figure 30* that the power ratio was lower than 50% for 75% of all the hours during 2018 when there was a demand for comfort cooling.

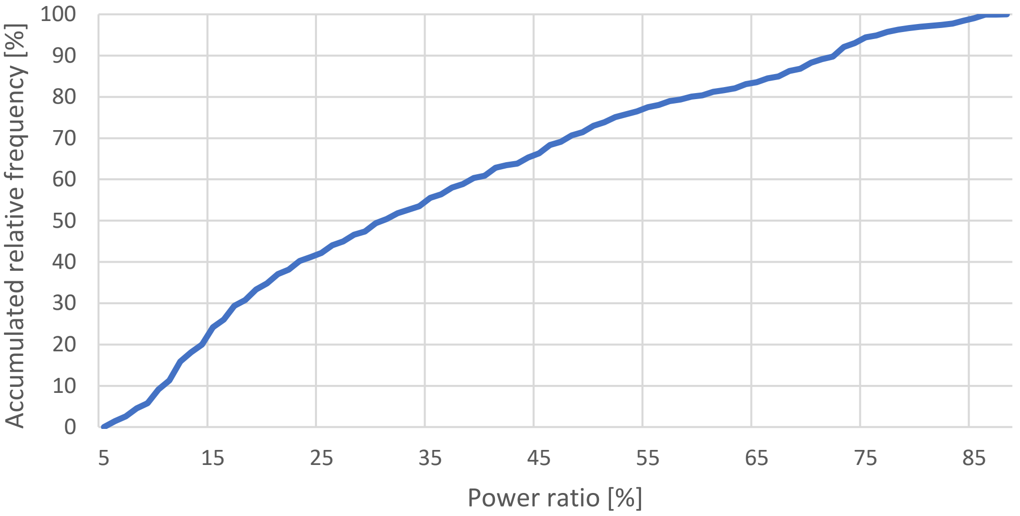


Figure 30. Relative power ratios during 2018 presented as an accumulated sum. A majority of the time (75 % of operating hours) when the comfort cooling is needed, the power ratio is below 50 %.

Apart from occupancy levels and other internal heat gains, the ambient temperature intuitively influences the need for cooling comfort, and thus also the power ratio levels. In *Figure 31*, ambient temperatures and their corresponding power ratios during 2018 is presented. Also, the correlation coefficient R between the ambient temperature and power ratios assuming a linear relationship between the two parameters are also presented. Only hourly values during 2018 that fulfilled both the opening hours criteria and ambient temperature criteria (>17°C) are included in *Figure 31*.

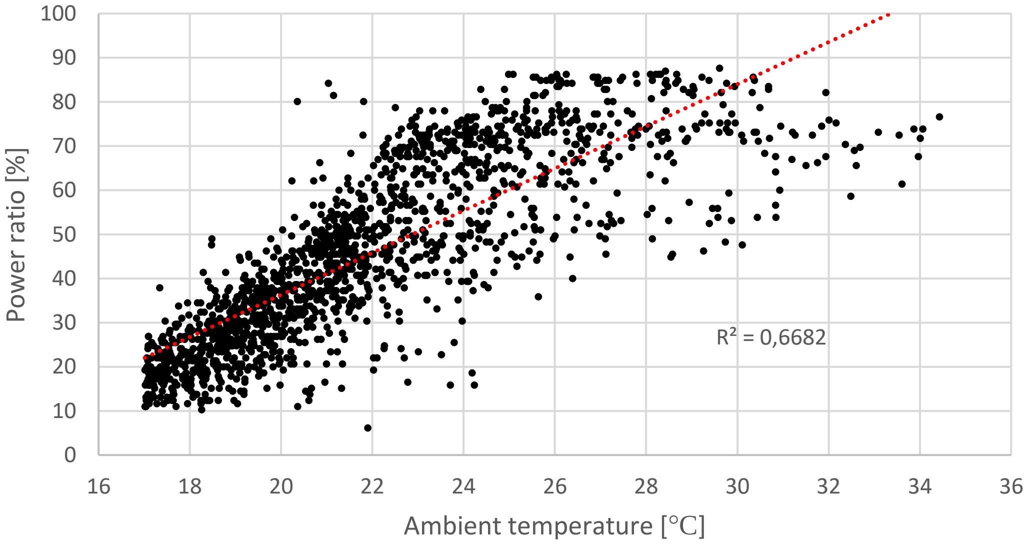


Figure 31: Ambient temperatures and corresponding power ratios for hours during 2018 when Väla was open and the ambient temperature was above 17 °C. R is the correlation coefficient.

From *Figure 31* it can be seen that the correlation coefficient between ambient temperatures and power ratios were 0.812 in 2018.

8.9 Indoor lighting

The indoor lighting at Väla is coupled to controllers that use time channels which determine whether the lighting should be on or off. Daylight sensors are used to some extent depending on where the light source is located. Thus, the solar irradiation is one parameter that influences some of the power needs of the indoor lighting. The lighting is not demand controlled and thus independent of occupancy.

The availability of lighting is primarily determined by time channels. The time channel to which most of the hallway lighting is connected are switched on at 07:00 all days and shut down at 20:30 during weekdays and 18:30 during weekends.

The acceptability has not been evaluated for indoor lighting.

9. Analysis of loads

In this chapter, the results from the load assessment are analyzed. The flexibility parameters chosen to be included in the flexibility analysis process will be discussed from characteristics that are important to consider when loads are to be used as flexibility resources.

9.1 Sheddability

From a sheddability perspective, comfort cooling is fulfilling most characteristics. Even though the sheddability parameter says little about the final flexibility of a load, it is desirable for a load to have several dimensions of sheddability. It can be argued that a load that is both curtailable and shiftable has better prerequisites for being utilized as a DSF asset than if only one of the characteristics are fulfilled.

However, it should be noted that the results and reasonings from the sheddability evaluation will differ depending on if a load is interpreted as one unity, or the actual number of units that together make up the load end-use. The sheddability was evaluated considering that each unit was an integrated part of that end-use. Due to the legal demands of minimum supply air flow, one ventilation unit should not be considered disconnectable if that unit is the only unit supplying an area. Ventilation should only be considered curtailable since ventilation being disconnectable would equal all ventilation units being turned off simultaneously, thus not fulfilling minimum supply air flow requirements.

The comfort cooling was classified as both shiftable and curtailable. However, the curtailability and shiftability of comfort cooling will likely differ during the year due to different ambient conditions.

9.2 Controllability

Independent of what markets to which the flexibility of loads will be offered, there are some key aspect that relate to the controllability of loads that should be fulfilled and therefore are interesting to analyze. Firstly, it is interesting to evaluate the identified parameters that are used to control the loads today at Väla, with respect to how well suited these are if one wants to achieve a certain power output. Secondly, to discuss how accurately the loads can be controlled with respect to power output. For some applications, such as frequency regulation, the response time of the load is important, why this also is interesting to discuss. Further, interactions between loads are factors that determine what flexibility that can be offered, why this also is important to include in the analysis.

9.2.1 Parameters

It can be concluded that the parameters that are used to control the loads at Väla are not the desirable ones if one primarily would like to control the power demand of the different loads. This was however expected, since the primary function of ventilation, comfort cooling and lighting systems are to keep a desired indoor climate with respect to air, thermal and lighting comfort.

For ventilation, the primary control parameter is the fan pressure. Since one pressure in Pa corresponds to one fan signal, which in turn corresponds to one power, it seems that this could be a parameter well suited to control the power need of a ventilation fan. However, from the experiment it was seen that the setpoint pressure was not always the same as the actual pressure. Also, the actual pressure fluctuated, likely due to turbulence in the ventilation duct. Instead, the fan signal should likely be the desired parameter if one would like to control the power need of a ventilation fan during a flexibility event.

For comfort cooling, there is a number of parameters relating both to central and local control that determine the final power needs of the chillers. Firstly, ambient temperature and time of the day determine whether the compressors are even powered on at all. Secondly, the load of the chillers, when they are powered up, mainly depends on the return temperature of the coolant. This in turn is dependent on how much the valves at the cooling batteries are opened and the temperature of the supply air. Thus, the dependencies are complex in the sense that there are several parameters deciding the power demand of the different chiller components.

It also has to be considered that there are 33 individual cooling batteries that are all connected to the same piping system. The inferred change on central control parameters from changes in local control parameters will therefore likely differ depending on what cooling battery the changes are occurring at.

Control strategies must include or bypass the above described complexity. Without experimental investigation it is difficult to assess what strategy that would be the best, but central control is likely preferable due to the complexity of the comfort cooling. Nevertheless, local control options, such as valve control are still interesting to discuss, since these are possible to accomplish with today’s hardware and control parameters. For valve control to have a predictable response, such a strategy should include coordination of all the cooling batteries so that potential interactions between loads are avoided. Closing valves at the cooling batteries would achieve a power reduction of the chillers since cooling of the supply air would stop due to a decrease in circulation of the coolant.

Another control strategy that could be achieved with today’s control parameters is to change the setpoint temperature for the supply coolant for the chillers and coolant coolers. From a controllability perspective, this should be a more preferable parameter to control since it directly correlates to the compressor and coolant cooler power demand compared to the valve position of the coolant batteries. However, such a strategy would need to be tested to evaluate what correlation there is between a change in setpoint temperatures, and power demand of the chiller components.

Both chiller strategies could be viable options. However, the most preferable option would be if the compressors had VFD’s and that the power then could be controlled directly through an input signal. The downsides with such a solution is that the downstream impacts, such as indoor temperature, would be more difficult to control.

Regarding the indoor lighting, the main parameter that is used to control whether the lighting is on, is the time of the day. Further, since daylight control was utilized for some lighting sources, solar irradiation also influences the power demand to a certain extent. Using daylight control is suitable from an energy savings perspective, but likely not from a DSF perspective.

9.2.2 Accuracy

Empirical data of how accurate the loads at Väla can be controlled was only obtained for the ventilation by conducting the experiments on ventilation unit TAFA-06. However, it is still possible to qualitatively analyze this characteristic for the other loads.

For lighting, the precision of control with respect to power output can both be deemed to be good and bad. The lighting can only contribute with flexibility using step changes, equivalent to lighting being switched on or off. This could be achieved by changing operating times of the time channels in the different controllers to which the lighting is connected. In this regard the lighting can be considered to be very exact. However, the size of these step changes is dependent on how many lighting sources that are coupled to each controller. Changing the operating times of one controller, and thereby shedding the lighting connected to this controller may therefore have a different response with respect to power output than for a similar change of operating times for another controller.

No experiment could be conducted for the comfort cooling since this was not available during the data collection phase of the thesis. However, the accuracy can only be discussed with the assumption that the chillers are powered up, since the ambient temperature is not a controllable parameter. The power demand when the chillers are powered up can today be done theoretically in a couple of ways, either by using central or local control parameters. For example, one could raise or lower the setpoint temperatures of the compressors or the coolant coolers. A local control option is to close the valves in the cooling batteries. This would decrease the heat transfer from the air to the coolant in the cooling batteries, making the forward temperature closer to the return temperature. Since the power demand of both the compressors and the coolant coolers are related to what the return temperature is, this would have an effect on the power demand.

It is questionable if either of these two control options can have a high expected accuracy. The central control options where setpoint temperatures are changed should be a more reliable option, since these temperatures have a more direct correlation to the power needs of the compressors and the coolant coolers. The best available control option today, with respect to accuracy, is limited to the coolant coolers since these are equipped with VFD’s.

For ventilation, the experiment showed that when the setpoint pressures were changed, the power output of the fans fluctuated hundreds of watts. This was probably due to the problems the system had in achieving the new pressure setpoints. This could in turn be a consequence of turbulence in the ventilation shaft which infer fluctuating pressures to the pressure sensor. However, for the maximum signal test it was seen that the power output remained constant at rated power. Thus, it would be interesting to conduct further tests were only the fan signal was used to control the fan to test the accuracy of the current setup.

9.2.3 Response time

Depending on the market, response time can be more or less important. For frequency regulation services such as FCR-N or FCR-D, the response time must be in the time span of seconds to minutes. The response time depends on two factors; how fast the grid needs can be communicated to the BEMS and how fast the different loads can be adjusted to achieve the desired power output. Since the signal from the grid to the BEMS should be independent of which loads that are activated for DSF, it is primarily interesting to discuss the response time of each individual load characteristic. Of the three loads, lighting can by intuition be argued to have the fastest response time until full load shed.

If local control measures, such as closing the valves at the cooling batteries, would be used to infer a change in the power needs of the chillers, the response time would be determined by the time it takes for the coolant to be circulated back from the HVAC units to the chillers. The response time of the central control option would likely be fast since this would change the operating mode of the compressors and coolant coolers directly.

For the ventilation it is seen from the experiments in *Figure 26* (*see subchapter 8.5.6*) that there was initially a very fast response both for pressure and fan signal changes. However, as also can be seen in *Figure 26*, it took minutes until the new setpoint was achieved for fan pressure changes. Also, during test four, the supply fan signal was higher than that of test of one. This is contradicting since setpoint pressures during test four became lower than those of test one. The reason for this is likely that during test four, the supply fan never reached the applied setpoint pressure, and thus the test period should have chosen to be longer.

9.2.4 Interactions between loads

For the three loads, interactions should mainly arise between the ventilation and comfort cooling due to their physical interconnection. Supposing that a ventilation fan is used as a flexibility resource and temporarily decreases its power output, the supply air flow will decrease as well. This in turn decreases the total cooling energy that is transferred from the coolant in the cooling battery to the supply air, which is the final coolant. This situation is equivalent to curtailing the comfort cooling and will therefore result in an increase in room temperature.

Even though the ventilation system uses zone control, in which different HVAC units serve their respective area, (see *Figure C* in *Appendix C)*, these zones are not physically compartmentalized. Thus, if the room temperature increases above the allowed value in one zone because the power need of one fan is temporarily reduced, this air will eventually be exchanged and cooled down by air from another zone. As a response to this, another HVAC unit may try to compensate for this temperature increase and increase its coolant flow. Individual HVAC units should be tested together with other units to evaluate the interactions and aggregated effects on the thermal comfort.

Also, as can be seen in *Table 4 (see subchapter 8.4)*, comfort cooling is a curtailable load. However, curtailing or disconnecting the comfort cooling may come at the cost of a worsened comfort. Rebound effects after a flexibility event, in which the system tries to compensate for a worsened comfort during a flexibility event, cannot therefore be excluded.

9.3 Availability

The availability of the three load types was found to primarily be determined by the day of the year and the hour of the day. Time channels programmed into the controllers were used to turn off loads at times the building was unoccupied. This is primarily a measure used to save energy. Extending the operating times could easily be done if one would like to increase the availability but this would result in an increase in energy use.

The ambient temperature was found to be a decisive parameter for the availability of the comfort cooling load. The downsides of this parameter are that it is dynamic and cannot be controlled. Thus, it has to be forecasted, which can likely only be done a few days in advance. However, for all days with temperatures above 17 °C there will be power demand from the chillers. The question is only how large this will be. Further, the availability with respect to operating power was also found to be dependent on what operating mode the chillers were in when they were powered up. This is both dependent on the ambient temperature and the internal heat gains, such as lighting and occupancy. If one would like to be able to forecast the availability of the comfort cooling, one would have to investigate how each one of these factors play in determining the cooling need with respect to power needs.

It should be noted that 2018 had an unusually warm summer, and that this likely will cause power ratios to be higher due to the correlation with the ambient temperature. Preferably, data from several years should be included but this was not available. Also, the power ratio refers to the electric load of the chiller components. Since the coefficient of performance for the compressors varies with operating modes, one kWh of electric energy will not always translate to a constant amount of kWh in cooling energy. Even though high correlation coefficients were found, this likely cannot be used as a viable forecasting method of the power ratio of the chillers since the data points are highly scattered.

Regarding the ventilation, the analysis with respect to how the fan power varied over a year was restricted to one ventilation fan due to lack of data. The analysis of the supply fan of FTX-40 indicated that there is more flexibility up than down. For applications such as frequency regulation on the FCR-markets, submitting a bid with a specified capacity means that this capacity has to be available both for up and down regulation. Thus, to achieve the maximum possible capacity for a ventilation fan it should be running at a setting where there is an equal amount of flexibility up and down, also considering the lower boundary of the VFD’s. For a complete understanding of what the ventilation system can offer on an aggregated level, individual assessment would be needed as the one that was conducted for the supply fan of FTX-40. One argument for this is that the fans operate at different signal values. For example, as can be seen in *Figure 26 (see subchapter 8.5.6)*, the exhaust fan of TAFA-06 was operating at 88 % fan signal, while the supply fan was operating at 58 %. Thus, the operating patterns for the supply fan of FTX-40 cannot be generalized to other ventilation fans.

9.4 Acceptability

The effects on building performance parameters will vary depending on what load that is used as a flexibility resource. The acceptability will also likely be influenced by parameters such as; number of occupants in the building, ambient temperature and current indoor temperature since this influences the power needs of the ventilation and comfort cooling. In order to understand what acceptance there is towards using different loads as a flexibility resource, one must relate these parameters to different levels of flexibility for each load. This could either be done by modelling or conducting empirical experiments.

Even though the acceptability for indoor lighting was not tested, there is probably little acceptance towards switching off the lighting. This is due to the fact that all indoor lighting is coupled to a single time channel. Thus, the option that one should regard from an acceptability point is shutting off most of the indoor lighting at the same time, which at most times should not be deemed a suitable alternative.

The space heating was not included in the scope of the thesis since this was not an electric load. However, it should be noted that comfort heating demand likely will influence the acceptability of controlling the ventilation during those periods of the year when comfort heating is needed.

9.4.1 Previously conducted experiments at Väla

The experiments conducted by Siemens at Väla, used in this thesis to evaluate the acceptability parameter of ventilation and comfort cooling, can both be interpreted as a worst-case and a best-case scenario. It is a worst-case scenario because no comfort cooling was used at all, why this scenario should be equal to a total load shedding of the chillers. However, it is complicated by the fact that there probably was air exchange between building L, were the experiments were conducted, and other buildings connected to building L. Also, the ambient temperature varied as well as occupant levels.

The experiments are a best-case scenario with respect to the month they were conducted. It can be seen in *Figure 29* that there are no comfort cooling needs in November due to the low ambient temperature. If these experiments would have been conducted in summer, the temperature increase would probably have been a lot faster due to the higher ambient temperature. Using the total estimated supply air flow at Väla of 260 m^3/s together with an estimated volume of 550,000 m^3, this means that the air at Väla will be exchanged within 35 minutes. Thus, it can be reasoned that the ambient temperature would be achieved indoors at

Väla within this time if no comfort cooling was used. This hypothetical scenario does not include other indoor heat gains such as occupants or indoor lighting, why the air exchange time should be even shorter. Thus, a total shedding of comfort cooling must carefully regard ambient temperature. Further tests with partial shedding of the comfort cooling as well as total shedding tests should be conducted to evaluate the impact on thermal comfort at different ambient conditions and occupancy levels.

9.5 Summary analysis of loads

From the analysis described in *subchapter 9.1-9.4* it seems that every load both have advantages and disadvantages when it comes to their DSF suitability. The ventilation system has the advantage of having a large installed capacity, have predictable consumption patterns and have VFD which enable direct control of the fan power consumption. However, a disadvantage is that live power consumption is not measured. Further, the large nominal capacity is spread out between 68 separate fans. These all have different operating modes and thus also different room for flexibility up and down. Also, the ventilation system provides air which is the final coolant for the comfort cooling. Thus, the delivery of comfort cooling is dependent on the ventilation system. Further, the complexity of the physical setup of the ventilation ducts, where one ventilation unit provides air to several stores, indicates that the impact of using one ventilation unit as a flexibility resource will probably differ between stores.

For the comfort cooling, the availability was found to vary over the year. Also, the power demand is not easily predicted since it depends on several variables, both relating to ambient and indoor conditions. The fact that the chillers are composed of several components that interact further brings complexity. However, the thermal inertia of the building is an advantage if the comfort cooling is to be controlled within smaller time periods. An advantage for the comfort cooling is that there is 90 m^3 of coolant in the piping system connecting the chillers and the cooling batteries. By only using the circulation pumps, this could probably be used as a thermal battery during short time periods.

It seems that the least suitable load of those investigated were the indoor lighting. With the only option of complete shedding of all lighting, the control options are poor. There is also likely little acceptability towards shedding all the lighting. If the indoor lighting would be used as a flexibility resource, this would probably require rewiring for the lighting to have the option of partial shedding as well as changing light sources to dimmable. The daylight control of the indoor lighting further make indoor lighting complex from the perspective of flexibility since solar irradiation is a parameter that determines the power demand to some extent.

From the analysis, it can be concluded that the already existing hardware at Väla play a large role in deciding the prerequisites for DSF applications. The high degree of building automation, where loads can be controlled and optimized, both have advantages and disadvantages. The systems are optimized with respect to indoor climate and not power flexibility. However, the presence of a BEMS is a prerequisite for controlling loads which makes retrofit solutions easier to implement.

10. BESS simulations and Economical assessment

In the following chapter, the control strategy, results from simulations and the economical assessment are presented. The results presented in this section will constitute the basis for the analysis part presented in chapter 11.

As described in previous chapters, there are many possible control strategies when operating a BESS. However, the purpose of the simulations was solely to evaluate the capability for a BESS to reduce the peak power demand from Väla.

Due to the structure of Öresundskraft's grid fee, it is not economically motivated to reduce the peak power demand during all months, which was considered in the control strategy of the BESS in the simulations. The economic value comes from reducing highest power outtake of the calendar year and the power outtake during the winter months. Thus, operating the BESS for reducing peak power during every day of the year would not be a viable business strategy.

In order to adjust the operation of the BESS according to the price components in the grid fee, it was necessary to take basis in the day with the highest power demand of the year. The potential to reduce the peak power during this day was then evaluated through simulation using the entire capacity of the BESS. The reduced level of power withdrawal accomplished during this day then became the reference for the necessary power reduction every other day.

Simulations were then systematically conducted in order to investigate whether the BESS would manage to keep this reduced level during the months April to October. If the simulations showed that there was one day when BESS did not manage to keep the reduced level, then that day became the new benchmark level for peak power reduction. By using this systematic approach, it was possible to identify the maximum level of power reduction that could be maintained during the period. For the period November to March the economic value comes from reducing the peak power every month, which implicated that dimensioning day had to be identified for each month. Lastly, in order to make the economic comparison using E.ON's grid fee, the potential for reducing the peak power during every month of the year was investigated.

10.1 Simulations of peak power reduction

The results from the simulations indicate that it is possible to reduce the peak power demand at Väla with both investigated BESS dimensions. In *Table 8*, monthly peak power reductions in percentage are presented. The notations LB stands for *Larger BESS* (1600 kW/ 2000 kWh) and SB stands for S*maller BESS* (1200 kW/1500 kWh) and is the notation that will be used in the coming figures and tables.

Table 8. Simulated monthly peak power reduction (%) with Öresundskraft's grid fee.

	2018-LB	2017-LB	2018-SB	2017-SB
January	9.54	9.85	8.02	8.24
February	10.8	8.95	9.19	7.42
March	9.93	9.81	8.43	8.16
April	*0.00*	*0.00*	*0.00*	*0.00*
May	9.32	10.5	8.02	9.03
June	6.11	10.6	4.70	9.08
July	9.98	**14.4**	8.57	**12.9**
August	**12.0**	9.51	**10.6**	8.09
September	*0.00*	*0.00*	*0.00*	*0.00*
October	*0.00*	*0.00*	*0.00*	*0.00*
November	8.58	8.89	7.10	7.24
December	8.85	10.1	7.38	8.50

The largest relative peak power reductions obtained with the load profile from 2018 (green) occurred in August and corresponds to 12.0 % for the larger BESS and 12.9 % for the smaller. Correspondingly, 14.4 % and 12.9 % was achieved in July for the load profile from 2017. It can also be seen that the relative peak power reduction was lower with the smaller BESS dimension for all months and that there were three months where peak power demand was unchanged (orange/italic).

In *Table 9*, the yearly reduced peak power and percental reduction is shown. It can be seen that the yearly peak during 2018 could be lowered from 3610 kWh/h to 3176 kWh/h with the larger BESS dimension, and 3227 kWh/h with the smaller. For 2017, the yearly peak power was lowered from 3366 kWh/h to 2887 kWh/h and 2934 kWh/h for the larger and smaller BESS dimensions respectively. Thus, the results show that both relative and absolute yearly peak power reduction was larger with the load profile from 2017 than what was achieved with the load profile from 2018.

Table 9. Yearly reduced peak power at Väla with reductions in percentage for each year and BESS dimension.

	Peak load (kWh/h)	Large BESS	Small BESS
2018	3610	3176 *(12.0%)*	3227 ***(10.6%)***
2017	3366	2887 **(14.4%)**	2934 *(12.9%)*

Further, in *Table 10*, the results from the simulations conducted with E.ON's grid fee are shown. The outcome from these simulations only differs in the period April to October. With E.ON's grid fee, the largest relative peak power reduction was obtained during April for the load profile from 2018 and corresponds to 16.5% and 13.6% respectively. For the load profile from 2017, the largest peak power reduction was obtained in July, but was increased from 14.4% to 15.2% with the larger BESS and from 12.9% to 13.3% with the smaller BESS. It can also be observed that the peak power was reduced during every month, which was not the case with Öresundskraft's grid fee.

Further, the lowest relative peak power reduction, marked with red in *Table 10*, was achieved in November for both investigated years with both BESS dimensions. Notable is also that the relative peak power reduction was the same with both Öresundskraft's and E.ON's grid fee during August 2018 and May 2017.

Table 10. Simulated monthly peak power reduction (%) with E.ON's grid fee.

	2018-LB	**2017-LB**	**2018-SB**	**2017-SB**
January	9.54	9.85	8.02	8.24
February	10.8	8.95	9.19	7.42
March	9.93	9.81	8.43	8.16
April	**16.5**	14.4	**13.6**	12.4
May	14.8	10.5	12.6	9.03
June	12.5	14.7	10.5	12.9
July	11.5	**15.2**	10.1	**13.3**
August	12.0	9.79	10.6	8.34
September	9.84	10.3	9.84	8.51
October	14.5	10.4	12.2	8.16
November	***8.58***	***8.89***	***7.10***	***7.24***
December	8.85	10.1	7.38	8.50

10.2 Reduced load profiles

The simulated BESS operation differed depending on the daily load profile. Consequently, the discharge pattern varied from short hourly efforts to longer periods of discharge. In *Figure 32* the load profile from 2018-01-03 is shown. The blue curve shows the original load curve and the orange dashed curve shows how the load profile would appear from the grid when the BESS reduces the peak power demand. As can be seen in the figure, the BESS operated continuously for several hours during this day and used a significant share of stored energy, but only a small share of the power capacity. The orange dashed curve is found to rise above the blue load curve for a couple of hours, which indicates that the BESS recharged during this period.

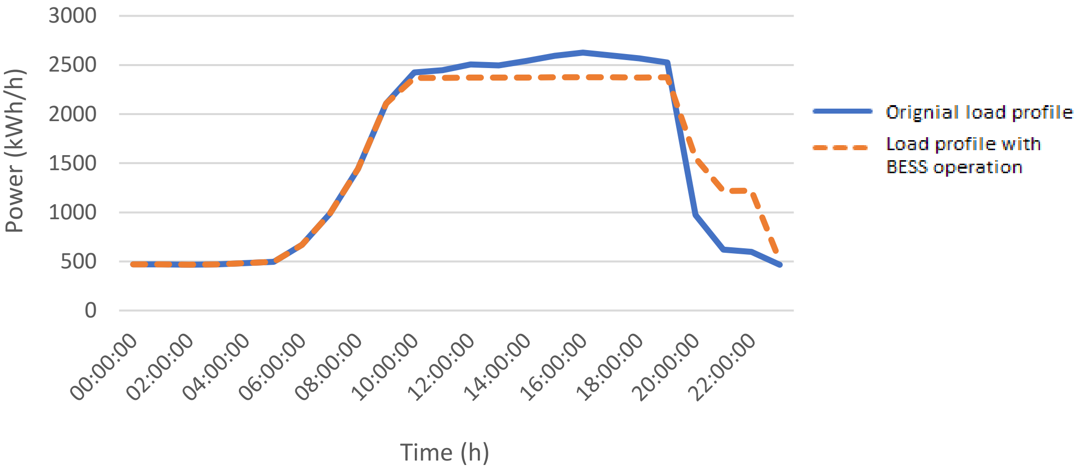


Figure 32. The load profile from 2018-01-03. The blue curve shows the original load curve and the orange dashed curve shows how the load profile would appear from the grid when the BESS reduces the peak power.

In *Figure 33*, the load profile from 2018-08-01 is shown. As can be seen, the BESS operated for three hours during this day, but only used a small share of available energy and power capacity. Similarly, as in *Figure 32*, the BESS recharged as soon as the load decreased, but was completely recharged in less than two hours.

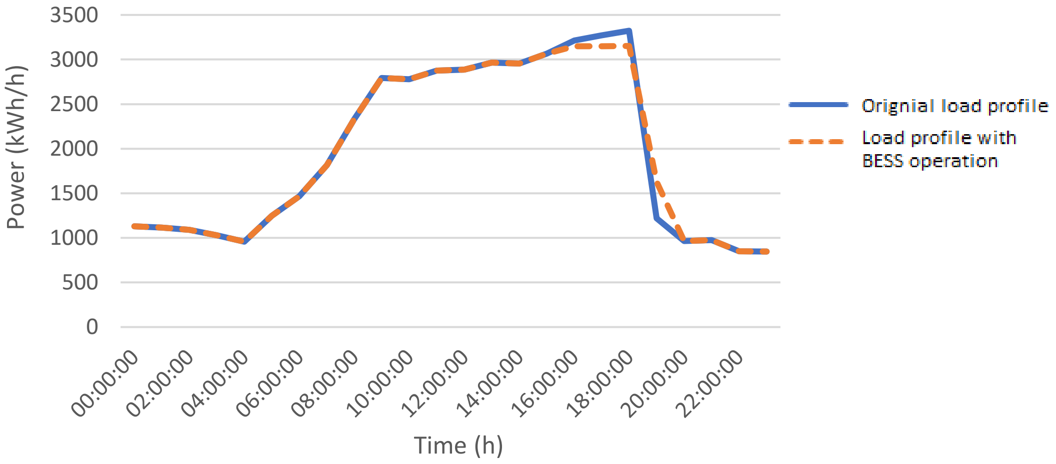


Figure 33. The load profile from 2018-08-01. The BESS operated for three hours during this day and only used a small share of available energy and power capacity.

The previously demonstrated examples have in common that the BESS either was unused or discharged during daytime, but during some days the BESS was recharged in the middle of the day in order reduce the smaller power peak in the evening. In *Figure 34*, one such day is illustrated. During this day (2018-08-03), the BESS operated for four hours to reduce the peak power and then slowly recharged in order to manage the smaller peak in the evening. It can be observed that the recharging from 12:00 to 16:00 was made with very low power in order not to cause a power peak due to the charging of the BESS.

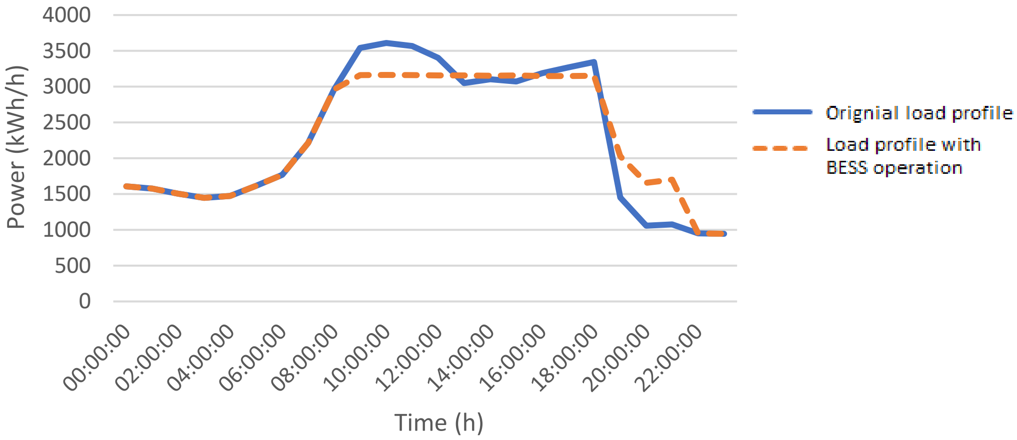


Figure 34. The load profile from 2018-08-03. The larger BESS is operated for four hours to reduce the peak power and then slowly recharged in order to reduce the smaller peak in the evening.

Data from the same day, with the smaller BESS dimension is shown in *Figure 35*. The smaller BESS operated strategically identical but did not manage to keep the power level as low as the larger BESS. It could also be seen that the smaller BESS recharged with higher power during the hours of lower load. This is indicated by the larger area between the orange dashed curve and the blue curve in *Figure 34*, in comparison to the corresponding area in *Figure 35*.

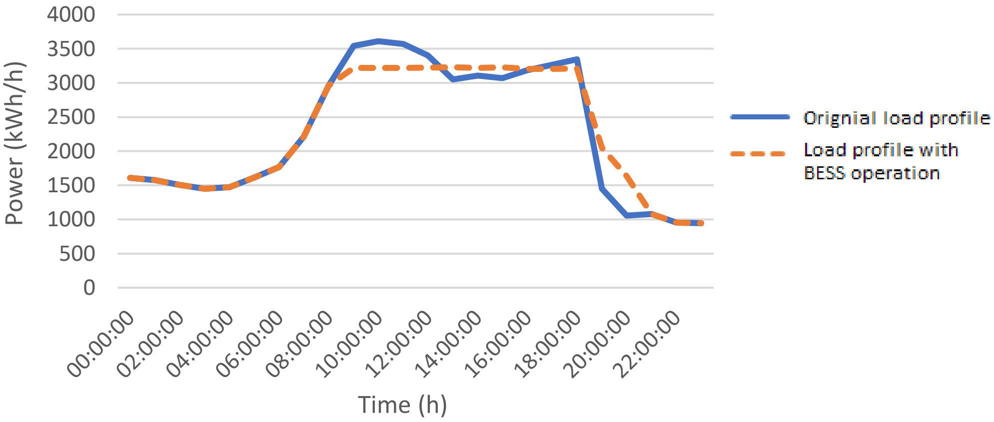


Figure 35. The load profile from 2018-08-03. The smaller BESS is operated for four hours to reduce the peak power and then slowly recharged in order to reduce the smaller peak in the evening.

10.3 Yearly average SoC and operational utilization

Figure 34 and *Figure 35* in the previous subchapter, are examples of days when the entire storage capacity was used to lower the peak power demand. However, when the operational performance is viewed from a yearly perspective, it becomes clear that the BESS was completely charged during the majority of the year. In *Table 11*, the yearly average SoC is shown with both Öresundskraft's and E.ON's grid fee. It can be observed that the average SoC is close to 95% in all simulations, however the yearly average SoC with E.ON's grid fee was slightly lower. In *Table 12*, the yearly average SoC for hours that Väla was open is shown. It can be seen that the average SoC was generally lower during these hours, but still close to 90% on a yearly basis.

Table 11. The yearly average SoC (%) of the BESS with both Öresundskraft's and E.ON's grid fee

	2018–LB	**2017–LB**	**2018–SB**	**2017–SB**
Öresundskraft	92.3	91.9	92.9	***92.8***
E.ON	91.7	**91.1**	92.4	92.1

Table 12. The yearly average SoC (%) of the BESS with both Öresundskraft's and E.ON's grid fee during hours when Väla was open.

	2018-LB	**2017–LB**	**2018–SB**	**2017–SB**
Öresundskraft	89.0	88.3	***90.2***	89.9
E.ON	87.7	**86.3**	89.1	88.4

From observing the results in *Table 11* and *Table 12*, it appears as the BESS was not operated frequently during the year, but that was not the case. In *Table 13*, the number of activation days and hours that the BESS was discharged is shown.

Table 13. Number of activation days and hours that the BESS was operated in the simulations.

	2018-LB	**2017–LB**	**2018–SB**	**2017–SB**
Öresundskraft				
Days	173	192	***156***	170
Hours	1056	1229	***876***	935
E.ON				
Days	229	**280**	198	170
Hours	1298	**1599**	1028	935

Most activation days (280) and hours (1599) was obtained for the 2017 load profile with the large BESS and E.ON's grid fee. Correspondingly, the least activation days (156) and operating hours (876) was obtained with the load profile from 2018 with the smaller BESS.

With Öresundskraft's grid fee, the BESS operated on average 47.3% of all days and 9.02% of all hours in a year. This corresponds to that the larger BESS operated, on average, for 6.25 hours each day it was activated, and the smaller BESS operated on average 5.30 hours. With E.ON's grid fee the BESS operated on average 64.7% of all days and 14.6% of all hours in a year.

10.4 Energy and power capacity utilization

Interesting performance indicators are also how frequently the BESS was deeply discharged and how large share of power capacity that was needed to reduce peak power demand. In *Figure 36*, the number of times the BESS went below 75%, 50% and 20% SoC in the simulations with Öresundskraft's grid fee, is shown.

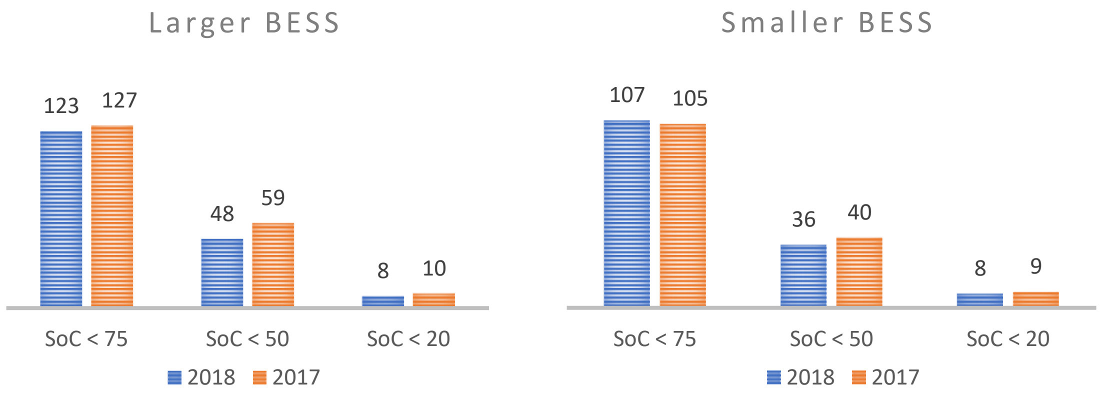


Figure 36. The number of times the BESS was operated below 70%, 50% and 20% SoC in the simulations with Öresundskraft's grid fee.

As can be seen in the figures, the BESS was not deeply discharged regularly and only went below 20% SoC 8-10 times. However, the SoC relatively often went below 75%, but stayed above 50% SoC the majority of times. The larger BESS was more frequently discharged below both 75% and 50% than the smaller BESS. Nonetheless, it could be observed that the dimensioning of the BESS did not affect how often the BESS was deeply discharged (< 20%) in the simulations.

Regarding degree of power capacity utilization, this proved to be rather low in all conducted simulations. The highest discharge powers obtained corresponds to 489 kWh/h for the larger BESS and 409 kWh/h for the smaller. This means that maximally 30% and 34% of power capacity was utilized by the larger BESS respectively smaller BESS for one consecutive hour.

10.5 Average power demand and the cost determinative power level

The difference between the monthly highest power demand and average hourly power demand varied naturally hour by hour, but also over seasons. In *Figure 37*, the monthly power demand determining the price paid towards the grid operator (blue) is presented together with the average monthly outtake of power during open hours (orange) and average outtake of power during hours when Väla is closed (yellow). The values presented in *Figure 37* originates from the simulations with the larger BESS and with the load profile from 2018.

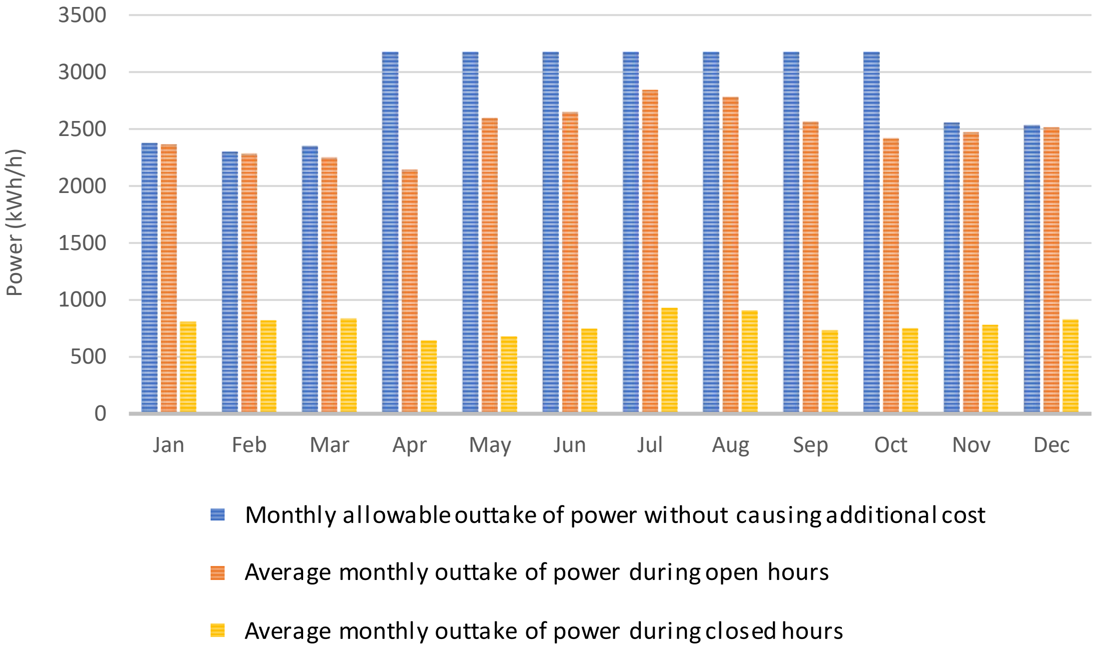


Figure 37. The figure illustrates monthly power level determining the price paid towards the grid operator (blue), the average monthly outtake of power during open hours (orange) and average outtake of power during closed hours (yellow) for the larger BESS dimension with the load profile from 2018.

What can be observed is that the difference between the average power demand and the cost determinative power level varies considerably over the year. During the winter months January, February, November and December the average margin is very small; 33.0 kWh/h, while it in April, September and October, is significantly larger; 801 kWh/h. During the months May, June, July and August, the average margin is 459 kWh/h. It can also be seen that the difference between the cost determinative power level and the average power demand, during closed hours, is large throughout all months of the year for both BESS dimensions.

10.6 Economical assessment

In the following subchapters the results of the economical assessment are presented. Firstly, calculations of yearly saving with both Öresundskraft's and E.ON's grid fee is presented. Secondly, four sensitivity cases are described and applied in the calculations of PBT and NPV for both BESS dimensions and grid fees.

10.6.1 Yearly savings from lowering peak power

The economical assessment indicates that savings could be accomplished by operating a BESS for peak power reductions at Väla. In *Figure 38*, the average yearly savings for Öresundskraft's and E.ON's grid fee agreements are shown. It can be observed that, the average yearly savings would be larger with E.ON's grid fee than with Öresundskraft's. With Öresundskraft's grid fee and the larger BESS, the average yearly saving from lowering the subscription fee would be 128 TSEK and correspondingly 70.3 TSEK for lowering the power fee, giving a total average yearly saving of 198 TSEK. For the smaller BESS, the saving from lowering the subscription fee would be 112 TSEK and 58.8 TSEK for lowering the power fee giving a total average yearly saving of 171 TSEK. The average yearly savings for the larger BESS with E.ON's grid fee corresponds to 333 TSEK and correspondingly 284 TSEK for the smaller.

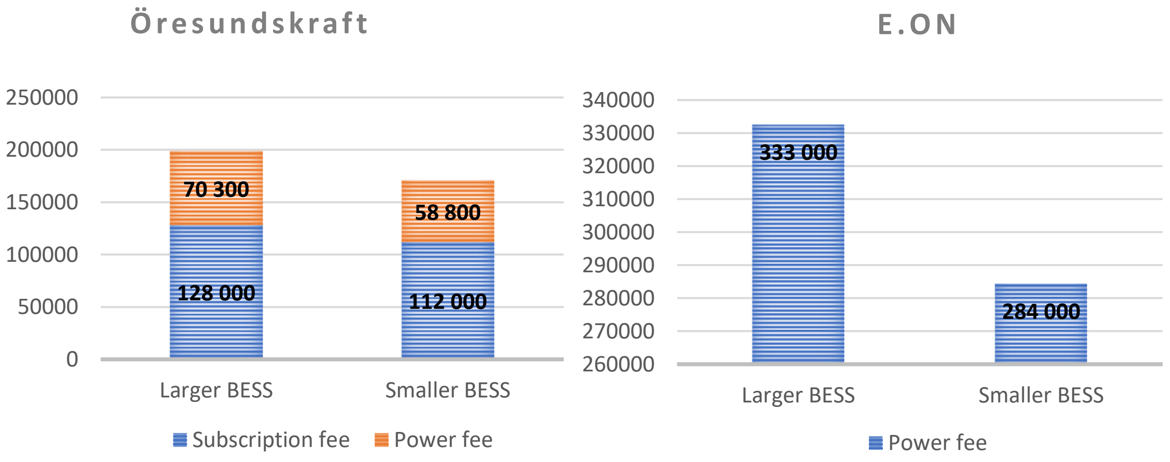


Figure 38. Average yearly saving with E.ON's and Öresundskraft's grid fee.

These savings should also be compared to the total yearly costs of the different grid fees. With Öresundskraft's grid fee, the total cost for the subscription fee, power fee and electricity transfer correspond to 2.25 MSEK. While with E.ONs grid fee, including power fee and electricity transfer, the average yearly cost would be 3.41 MSEK. Consequently, this results in that the percental yearly saving with the larger BESS corresponds to 8.8% with Öresundskraft's grid fee and 9.8% with E.ON's grid fee.

10.6.2 Sensitivity cases

In the calculations of PBT and NPV, different cases have been formulated and applied in order to reflect different scenarios of grid fee component price development. Also, a future BESS installation cost was considered.

For calculations with Öresundskraft’s grid fee, four different cases were formulated.

- *Case 1* - Subscription fee and Power fee are unchanged.
- *Case 2* - Subscription fee increases with *5%* / year and Power fee with *3%* / year.
- *Case 3* - Subscription fee increases with *17%* / year and Power fee with *4.5%* / year.
- *Case 4* - Subscription fee increases with *17%* per year, Power fee with *4.5%* per year and a future BESS price of *285 €/kWh*.

In *Case 2* it was assumed that grid fee prices will increase continuously, but that the increase will be lower than observed the latest years. In *Case 3,* it was assumed that the actual price development in Öresundskraft’s grid fee the last five years would continue in the same pace the coming years (*see subchapter 7.4.3*). Furthermore, in *Case 4* an estimative future BESS price based on the results gathered in Tsiropoulos, Tarvydas & Lebedeva (2018) was also assumed.

For the investment calculations with E.ON’s grid fee, four cases were used.

- *Case 1* - Power fee is unchanged.
- *Case 2* - Power fee increases with *5%* / year.
- *Case 3* - Power fee increases with *10%* / year.
- *Case 4* - Power fee increases with *10%* per year and a future BESS price of *285 €/kWh.*

No historical data was available for grid fee prices, which means that all cases had to be arbitrarily formulated. The cases were formulated to match the corresponding case for Öresundskraft’s grid fee in order to enable a justifying comparison.

10.6.3 Pay-back time and Net present value

When the savings from reducing peak power are compared with the costs of installing a BESS, it becomes clear that these savings solely would be too small to make it a profitable investment. In *Table 14*, the pay-back time at the four different sensitivity cases is presented. The PBT at four different sensitivity cases for E.ON's grid fee is presented in *Table 15*.

Table 14. PBT for the four sensitivity cases with Öresundskraft's grid fee.

Öresundskraft *(Years)*	***Case 1***	***Case 2***	***Case 3***	***Case 4***
Larger BESS	***63.0***	29.9	17.3	**12.7**
Smaller BESS	***55.0***	28.6	16.4	**11.9**

Table 15. PBT for the four sensitivity cases with.E.ON's grid fee.

E.ON *(Years)*	***Case 1***	***Case 2***	***Case 3***	***Case 4***
Larger BESS	***37.6***	21.4	16.6	**10.3**
Smaller BESS	***33.0***	20.0	15.3	**9.9**

The PBT in *Case 1* corresponds to 63 years for the larger BESS and 55 years for the smaller BESS with Öresundskraft's grid fee. Similarly, the PBT in *Case 1* with E.ON's grid fee corresponds to 37.6 years for the larger BESS and 33.0 years for the smaller BESS. In *Case 2* and *Case 3*, the PBT is lowered significantly with both Öresundskraft's and E.ON's grid fee but is still higher than the estimative technical lifetime of ten years. In *Case 4*, which is a purely hypothetical scenario, it could be observed that the PBT is lower than in *Case 2* and *Case 3*, but still higher than ten years with exception for the smaller BESS with E.ON's grid fee.

In summary, the calculations of PBT indicate that installing a BESS for peak power reductions solely would give very long pay-back times. The calculations also show that even with significant price development and a future potentially lower BESS price, it would be very unlikely that the investment could be refunded within the technical lifetime of the BESS. This observation is confirmed in the calculations of NPV.

In *Table 16*, the NPV for *Case 1*, *Case 2* and *Case 3* with 5% and 10% discount rate is presented for Öresundskraft's grid fee. Correspondingly, in *Table 17*, the NPV for *Case 1*, *Case 2* and *Case 3* for E.ON's grid fee is shown.

Table 16. NPV for both BESS dimensions with sensitivity case 1-3 of Öresundskraft's grid fee.

Öresundskraft	***Case 1***		***Case 2***		***Case 3***	
(TSEK)	**5%**	**10%**	**5%**	**10%**	**5%**	**10%**
Larger BESS	-10 980	*-11 290*	-10 680	-11 070	-9 772	-10 440
Smaller BESS	-8 065	-8 334	-7 803	-8 146	-7 015	-7 590

Table 17. NPV for both BESS dimensions with sensitivity case 1-3 of E.ON's grid fee.

E.ON	***Case 1***		***Case 2***		***Case 3***	
(TSEK)	**5%**	**10%**	**5%**	**10%**	**5%**	**10%**
Larger BESS	-9 943	*-10 470*	-9 344	-10 040	-8 571	-9 488
Smaller BESS	-7 186	-7 636	-6 675	-7 268	-6 015	-6 798

As can be observed in *Table 17*, the lowest NPV with Öresundskraft's grid fee corresponds to -11 290 TSEK (red/italic), while the least negative corresponds to -7 015 TSEK (green). With E.ON's grid fee the lowest NPV corresponds to -10 470 TSEK (red/italic) and the least negative -6 015 TSEK (green). The calculations also show that a higher discount rate gives a lower NPV in all cases and that *Case 2* and *Case 3* generally gives a higher NPV than *Case 1*.

All calculations indicate that NPV for a BESS investment would be negative, which means that additional yearly income would be necessary to make it a profitable investment. In *Figure 39*, the yearly revenue to make NPV equal to zero is presented. The yearly income is calculated for the smaller BESS, Öresundskraft's grid fee, *Case 2* price development and 5% discount rate.

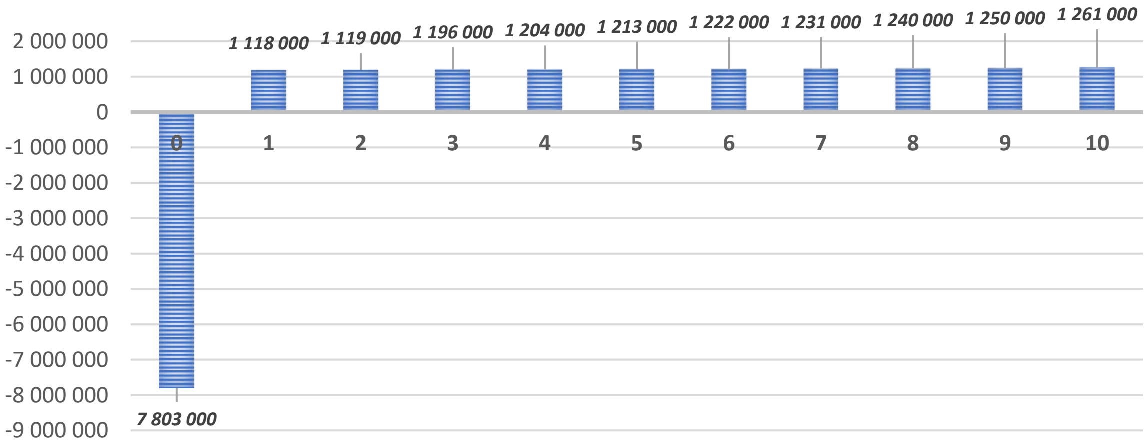


Figure 39. Necessary yearly income to make NPV equal to zero. The yearly income is valid for the smaller BESS, Öresundskraft's grid fee, Case 2 *and 5% discount rate.*

Each calculated yearly income presented in *Figure 39* corresponds to the savings from peak power reduction added with an additional income of 1 010 TSEK. Thus, the yearly income from other value sources must be over 1 010 TSEK in order to make the investment profitable within the technical lifetime. The same case, but with the larger BESS would need an additional yearly income of 1 380 TSEK to make NPV equal to zero.

11. Analysis of BESS

The analysis presented in this chapter is divided into two parts where the first part focuses on outcomes from the simulations and the economical assessment. In the second part, the outcomes are put into context with the participation requirements of the reserve markets, in order to evaluate the prerequisites for accomplishing both peak power reductions and frequency control with a BESS at Väla.

11.1 Technical potential for reducing peak power demand

The simulations indicate that peak power demand can be reduced by operating a BESS in connection to Väla. The results show that the larger BESS could reduce the peak power more than the smaller, which was expected. However, when the ratio of BESS dimensions is compared with the achieved relative peak power reduction, it can be concluded that the storage capacity of the smaller BESS was more efficiently utilized than the storage capacity of the larger BESS. As an example, with the load profile from 2018, the larger BESS managed to reduce peak power by 12.0%, while the smaller BESS managed to achieve 10.6%. This means that the reduction achieved with the smaller BESS is approximately 12% less than with the larger BESS, yet obtained with 25% less power and storage capacity.

This could be explained by analysing the profile of the aggregated load. As shown in *Figure 21* (see *subchapter 7.4.2*), the profile of the aggregated load at Väla has a very consistent pattern throughout the year. There are no recurring distinct periods of peak power where the power demand is significantly higher than during other hours of the day. This means that a small reduction of peak power results in larger portions of energy that must be supplied from the BESS.

Consequently, this resulted in that both BESS dimensions managed the small variations in power demand during the day, but the larger BESS then utilized larger portions of energy to lower the basic level of consumption, which then only lowered the peak power demand marginally. Thus, this explains why a greater relative peak power reduction in relation to storage dimension could be achieved by the smaller BESS.

11.2 BESS control strategy with respect to grid fees

In the simulations, the BESS was periodically operated differently due to the structure of the price components in the grid fees. As can be seen in *Table 8* (see *subchapter 10.1*), the BESS was not operated during April, September and October with Öresundskraft’s grid fee. This was, however, the case with E.ON’s grid fee which can be seen in *Table 10*.

The reason for this is that the subscription fee from Öresundskraft solely depends on the highest outtake of power during the calendar year. Consequently, since the peak power demand of April, September and October were lower than the reduced peak power level during the summer months, it was not economically motivated to operate the BESS during these months. However, with E.ON’s grid fee it was economically motivated to reduce the peak power demand throughout each month of the year, which then also reflected in how the BESS was operated.

Further, during the period from May to August, the BESS was operated with both grid fees, but performed differently. With E.ON’s grid fee, the BESS was operated to the reduce peak power on a monthly basis, while with Öresundskraft’s grid fee, the BESS was operated to lower the peak power on a calendar year basis. This makes a significant difference in the operation strategy since maximum storage capacity only would be used during one day during the period from May to August with Öresundskraft’s grid fee. With E.ON’s grid fee, the BESS would be operated using maximum storage capacity at least one day every month throughout the year.

When comparing the results in *Table 8* and *Table 10*, it can be seen that the relative peak power reduction during August with the load profile from 2018 was the same for both Öresundskraft’s and E.ON’s grid fee. The same applies for May with the load profile from 2017. The reason for this is that the day of the year when the BESS was the least successful in reducing the peak power demand occurred during these months. The peak power demand of these months determines the subscripted power level, which means that it on any other day of the year would be economically unjustified to reduce peak power demand more.

Consequently, the BESS was operated to achieve the same peak power value during the other days as what could be potentially achieved in the day where the potential for peak power reduction was the lowest. Consequently, this then explains why the peak power reduction became lower during some months with Öresundskraft’s grid fee than with E.ON’s grid fee.

During November to March, the BESS performed technically identical with both grid fees. This outcome was however expected since it could be economically justified to reduce peak power as much as possible during this period. Thus, the BESS was operated utilizing full capacity throughout these months and naturally obtained the same results with both grid fees.

Summarized outcomes of the simulations

- The peak power demand at Väla could be reduced by strategic operation of a grid connected BESS.
- The capability for reducing peak power with a BESS does not increase proportionally with storage capacity for the investigated dimensions.
- The structure of the price components in the grid fee impacts how the BESS should be operated for power demand reductions throughout the year.
- The potential for peak power reduction has a seasonal pattern, but still varies stochastically on a daily basis, which means that the technical potential likely will be different every year.

11.3 Yearly average SoC and operational utilization

The results from the calculations of average SoC shows that the BESS was completely charged the majority of the hours throughout the year. Even when only considering open hours, during which the BESS typically was operated, the average SoC only decreased marginally.

The reason for the high average SoC is partly because the BESS never was operated during hours when Väla typically is closed, which implies that the BESS would be completely charged during all those hours. However, this factor was removed in the calculations of average SoC during hours when Väla was open and still indicated a high average SoC in all cases. The reason for this is that the BESS was not operated at all during several days of the year (*see Table 13 subchapter 10.3)*. Since the yearly peak power demand is the reference level for the power reduction level in the BESS control strategy, it naturally occurs several days when operation of the BESS is unnecessary.

11.4 Energy and capacity utilization

In *Table 13* (see *subchapter 10.3*), it can be seen that the number of activation days and operating hours was higher with the larger BESS. The reason for this is that the larger BESS achieves a lower yearly peak power reference, which means that it must be operated during more days in order to maintain the reduced power level throughout the entire year.

The results in *Table 13* also show that the BESS was operated more frequently with E.ON's grid fee than with Öresundskraft's. The reason for this lies in the BESS operation strategy, which is based on that it is economically motivated to reduce the peak power every month of the year. Consequently, this resulted in that the BESS was operated more regularly.

Further, the power capacity utilization was rather low in all simulations, which indicates that the chosen configuration of the BESS is not optimal. This is however not surprising considering the even profile of the aggregated load and that no optimisation was conducted when choosing the dimensions and configuration of the BESS. The results indicate that a smaller BESS generates better cost efficiency. Thus, in order to optimise cost efficiency for a BESS, which is operated solely for reducing peak power demand, smaller BESS dimensions should be further investigated. Also, the results indicate that the BESS was typically operated for several consecutive hours, which according to theory, neither is ideal from a techno-functional perspective nor from a degradation perspective.

11.5 Average power demand and the cost determinative power level

The difference between average monthly power demand during open hours and the power level that determines the yearly costs varied considerably throughout the year, which is illustrated by *Figure 37*. The reason for this outcome lies in the BESS operation strategy and the profile of the aggregated load.

During November to March, the BESS was operated to reduce the monthly peak power as much as possible. Since the daily load profiles at Väla are very consistent during the winter period, this resulted in that the BESS had to be operated regularly to maintain the reduced monthly peak power level. Consequently, this results in that the difference between average hourly power demand and the peak power demand becomes very small.

The difference between average monthly power demand and the subscripted power level proved to be rather large for the months April, September and October. The reason for this lies in the average hourly power demand during these months is significantly lower than the highest power demand of the calendar year, which typically occurs some day in the summer when the comfort cooling load is large.

The difference between average monthly power demand during hours when Väla was closed and the power demand that determines the yearly costs varied slightly over the year. Although, they were still significantly larger than during open hours for all months.

Summarized outcomes operational performance analysis

- A BESS that is operated for peak power reduction at Väla would be completely charged during the majority of hours throughout the year.
- A grid fee, that is based on the monthly highest power demand, requires that the BESS is operated more regularly than if the grid fee is based on the highest power demand of the calendar year.
- A BESS that is operated for peak power reduction at Väla could be dimensioned with a power capacity significantly lower than 1.2 MW, without lowering the capability to reduce the peak power demand.
- The difference between monthly average power demand during hours when Väla is open and the power demand that determines the power fee is small during the winter period.
- The difference between monthly average power demand during open hours and the power demand that determines the subscription fee is largest during April, September and October for the investigated years.

11.6 Yearly savings from reducing peak power

The economical assessment shows that savings can be accomplished with a BESS that is operated to reduce the peak power demand at Väla. With Öresundskraft’s grid fee, the savings originate from lowering both the subscription fee and the power fee. With E.ON’s grid fee, the total saving originates from lowering the monthly power fee.

The calculations indicate that both the absolute and relative yearly saving would be larger with E.ON’s grid fee than with Öresundskraft’s grid fee. This implicates that operating a BESS for peak power reduction would be more economically beneficial if Väla would have had E.ON’s grid fee. However, the total grid fee cost would at the same time become significantly higher, which means that even if a BESS would generate larger monetary value, it would not be economically beneficial or hypothetically possible to change to E.ON’s grid fee agreement.

The reason why the savings with E.ON’s grid fee becomes larger probably lies in the utilization of BESS capacity throughout the year. The structure of E.ON’s grid fee allows the BESS to be more regularly utilized, which also the operational performance analysis indicated. Thus, this results in that the monthly savings aggregates to a higher value than what can be achieved with Öresundskraft’s grid fee.

11.7 Pay-back time and Net present value

Even though the savings from reducing peak power are substantial, the calculation of PBT and NPV clearly shows that an investment in neither of the investigated BESS dimensions would be profitable. However, both the PBT and NPV calculations still indicated that the smaller BESS financially would be the better investment. This is in line with the technical analysis, which indicated that the capacity utilization of the smaller BESS was better than for the larger BESS.

Furthermore, the sensitivity case analysis indicates that even if the development of the price components follows the trend, which have been observed the last years, it would not be profitable to invest in a BESS for reducing the peak power. Investing in a BESS for peak power reductions does not become a profitable investment, even if a future BESS price is assumed.

It should not be forgotten that these results only show that a Li-Ion BESS, which is operated solely for reducing peak power demand, is likely to never become profitable. However, this does not prove that a BESS investment never can be profitable. The calculations do not take into account what revenues that can be obtained from other revenue sources such as the reserve markets. If these revenues would have been included in the calculations, this naturally would make the investment financially more feasible.

Summarized outcomes of the Economical assessment.

- It is possible to accomplish savings by operating a BESS for reducing peak power demand at Väla.

- E.ON’s grid fee would enable larger potential savings from operating a BESS for peak power reductions than Öresundskraft’s, but would also entail a higher total grid fee cost.

- Both PBT and NPV shows that investing in a BESS for reducing peak power at Väla would not be profitable even when assuming substantial increases of grid fee prices and a future lower BESS price.

- In order for a BESS installation at Väla to become profitable, it would be necessary to enable additional income sources to complement the savings from reducing peak power demand.

11.8 Frequency regulation with BESS at Väla

The economical assessment clearly indicates that additional incomes will be needed to make a BESS investment financially attractive at Väla. This could be accomplished by offering regulation capacity on the reserve markets. As described in *subchapter 5.4.4*, the technical characteristics of BESS well suits the technical challenging requirements for participating on these markets.

In the following analysis, the focus lies on the operation of the BESS and the boundaries that exist from general requirements defined by Svenska kraftnät and prerequisites at Väla. However, the analysis does not include how this practically would be pursued concerning balance responsibility and the formulation of necessary agreements between relevant actors.

11.8.1 Framework of operational criteria

Until 2019, it has not been allowed to offer capacity from a BESS on the reserve markets, but due to the coming legislative changes this barrier will partly be erased (*see subchapter 5.4.4*). The coming changes includes allowance of consumption resources to take part on the reserve markets but does not include energy storages. However, this only means that it will not be allowed to offer regulation capacity from pure energy storage solutions, but that a BESS still could be prequalified as a part of a consumption resource. Still, there are several boundaries and requirements that must be considered if this is to be implemented at Väla.

Firstly, the new rules state that there needs to be a net consumption in the grid connection point during the entire regulation hour. This means that the BESS could be charged from the grid for down-regulation but must be discharged to cover a power demand behind the electricity meter to correctly perform an up-regulation. This requirement implicates that the aggregated power demand from loads must be equal to or larger than the offered power capacity during the entire regulation hour.

Secondly, the same capacity for both up- and down regulation must be available, which means that a BESS logically should be at around 50% SoC for it to be possible to maximize the offered capacity. Though, it would not be necessary to reach 50% SoC at all times to participate on the market, but a lower or higher initial SoC would limit the capacity that could be offered. This requirement has also the consequence that maximum capacity from the BESS with a c-ratio around one cannot be offered for several consecutive hours, since it never could be guaranteed that 50% SoC can be obtained before the start of the next regulation hour.

Thirdly, assuming that peak power reductions would be the prioritized operative application of the BESS, it would be necessary to make sure that the BESS is charged in time to manage forecasted power demand reductions.

Fourthly, consideration must be taken to the price components in Öresundskraft's grid fee agreement since it would not be desirable to increase the cost towards the network operator. If the cost determinative power level for the subscription fee would be exceeded during a down-regulation this would affect the yearly costs towards the network operator. As an example, if the subscripted power level would be exceeded by 0.1 MW, this solely would increase the yearly cost by 66.4 TSEK.

Lastly, since the balance settlement is determined by the consumption in the grid connection point, it must be considered that the production from the PV-plant might be affected by rapidly changing weather conditions. Thus, the BESS must have capacity enough to also handle PV production volatility in combination with frequency variations in order to comply with the defined requirements by Svenska kraftnät.

Summarized criteria's for offering regulation capacity with a BESS at Väla

- The aggregated power demand must be equal to or larger than the offered power capacity during the entire regulation hour.

- The BESS must be available for operation and have a SoC before the start of the regulation hour which at least matches the regulation capacity of the placed bid.

- The BESS must be able to recharge in time in order to handle forecasted power demand reductions.

- The momentary power demand from the building must be considered since there otherwise is a risk of increasing the yearly costs towards the network operator.

11.8.2 Matching of operational criteria with prerequisites at Väla

By matching the framework of operational criteria with the previously conducted operational performance analysis, it is possible to evaluate during what periods it is reasonable to operate the BESS for frequency regulation.

The operational performance analysis showed that a BESS would be completely charged during the majority of the year and that it would be activated some time during the day approximately 170-190 days of during the year. The analysis also showed that the BESS very rarely would be deeply discharged, which means that there often would be spare capacity even during those days when the BESS would be operated for peak power reductions.

However, for this to be possible, it would be necessary that the need for power reductions could be forecasted with very good accuracy to avoid interference between the applications. Yet, there are several days throughout the year when it would not be economically reasonable to operate the BESS for peak power reduction, which means that the capacity instead could be used for frequency regulation. Conclusively, there are good opportunities to operate the BESS for both peak power reduction and frequency regulation with regards to the interference of operational applications.

Further, the aggregated load profiles at Väla shows that there is energy consumption during all hours of the year. This means that there always would be a power demand, which the BESS could cover during an up-regulation. However, the power demand during periods when Väla is closed is lower than during open hours. The power demand during hours when Väla is closed lies around 500 kWh/h throughout the year, which then limits how much regulation capacity that could be offered on the reserve market. Consequently, this also limits the potential income from the reserve markets, but also allow for less economically risky operational control. The reason for this is that the difference between average power demand from building and the cost determinative power level is very large during hours when Väla is closed. Thus, this means that there would be no risk to increase the yearly costs towards the network operator due to a down-regulation from the BESS.

During hours when Väla is open, the difference between average power demand and the cost determinative power level varies. During April, September and October, there is generally a good margin towards the cost determinative power level. The average margin during these months is around 800 kWh/h for both BESS dimensions (*see subchapter 10.5*). This means that reasonably 500-600 kW could be offered as regulation capacity without being at significant risk of causing additional yearly costs towards the network operator.

During the period from May to August, the average margin is smaller, around 480 kWh/h, which means that there is higher risk of causing a grid fee cost increase. This implies that approximately 150-250 kW regulation capacity would be reasonable to offer during this period. However, the lower margin towards the cost determinative level indicates that the BESS would have to be operated regularly for peak power reduction, which then limits how available the BESS would be for providing frequency regulation.

For the period from November to March, the prerequisites to offer regulation capacity is limited. The margin between average power demand and the cost determinative level is around 45 kWh/h during hours when Väla is open, which means that the risk of causing additional costs due to a down-regulation is very high. Consequently, it would not be economically reasonable to operate the BESS for frequency regulation while Väla is open during these months.

Summarized prerequisites for providing frequency regulation with BESS

- The BESS would technically be available for providing frequency regulation during hours when Väla is open approximately half of the number of days in a year and all hours of the year when Väla is closed.

- Frequency regulation could preferably be offered during hours when Väla is closed or during open hours in the months April, September or October. A reasonable regulation capacity that could be offered is 400 kW during hours when Väla is closed and 500-600 kW during open hours in April, September and October.

- If regulation capacity is to be offered from a BESS during the period from May to August, it must be carefully considered due to the risk of increasing costs towards the network operator. Still, 150-250 kW could be offered without being at significant risk of exceeding the subscripted power level in the grid fee.

- Offering regulation capacity from a BESS while Väla is open during the period from November to March is not reasonable considering that this most likely would increase the cost from the power fee component in the grid fee agreement.

12. Method discussion

In this chapter, methods used in both the analysis of loads and BESS assessment will be critically discussed with regards to validity. The purpose is to give the reader an explanation of how the scope of the thesis was formulate, to motivate assumptions and reason about defined delimitations.

12.1 Technical load assessment

A disadvantage with conducting a technical case study on Väla, was that the data collection phase became dependent on a few number of people. Both people's knowledge about Väla and their availability to contribute to the thesis has sometimes proven to be a limiting factor in retrieving the results. The indoor lighting has been a load where this has been a challenge.

An alternative that would have partly resolved this problem would have been to only focus on one load category, such as ventilation. The advantage of this approach would have been that more ventilation units could have been researched and quantifying the flexibility for the ventilation system could perhaps also have been included.

12.1.1 Flexibility parameters

As was concluded from the literature survey there are no standard flexibility parameters to include in a flexibility evaluation, no standard methodologies to evaluate these or a consensus on how the parameters should be fractioned into sub-areas that together can provide a complete and representative understanding of the flexibility parameter in question. Thus, the selection of sub-areas will differ depending on what the author aims to accomplish with the flexibility analysis, and what DSF applications that are in question.

Several interesting flexibility parameters, such as recovery time and rebound effects during a flexibility event, have been excluded. Thus, there are dimensions of flexibility that have not been included in the scope of this thesis. If excluded parameters, such as recovery time, would have been evaluated, this could potentially have shown that there are long recovery times from using the HVAC system as a flexibility resource, which then is a clear disadvantage. To increase the reliability of the flexibility evaluation, more flexibility parameters should be included.

Also, the flexibility parameters are discussed from today's perspective. Thus, software or hardware changes or upgrades may change the prerequisites for DSF applications for the different loads. The results can in this sense be seen as somewhat misleading. The thesis does not incorporate the perspectives of retrofitting the current systems with the purpose of changing the prerequisites for DSF applications. As an example, installing VFD's to the compressors would enhance the controllability of the compressors substantially, since this would enable direct control of the power output.

From the literature survey it was concluded that for the scope of this thesis, a goal of quantifying flexibility for all loads and each parameter would be too extensive. Therefore, focus was put on qualitative description for selected loads and the respective chosen sub-areas of interest. Thus, if loads were to be prepared for DSF applications, further technical analysis would be required, since the flexibility analysis in the thesis do not aim to qualify loads for different DSF applications.

12.2 Techno-Economic assessment of BESS

Formulating the scope of the BESS assessment was not straightforward since there are many possible control strategies and potential revenue streams. An alternative, which was contemplated in the initial phase of the working process, was to include peak power reduction, energy arbitrage and the frequency regulation in both the technical and economic assessment.

However, the combination of these possibilities naturally becomes a complicated optimization problem, since it requires that the savings from reducing peak power demand continuously could be weighed against the potential revenue from the physical markets and the reserve markets. Additionally, in order to establish the full picture, it would also be necessary to evaluate what would be technically feasible and how different control strategies would affect the operational performance of the BESS.

Consequently, in order to formulate a reasonably extensive and complex scope, it was determined that only a couple of parameters and applications could be included in the BESS assessment. This framing process resulted in that energy arbitrage was excluded from the scope and that the potential revenue from the reserve markets was not to be quantified. The reasons for these delimitations was that:

- Energy arbitrage through strategic BESS operation not is economically viable with the current price volatility in the Nordic area. (*see subchapter 5.4.4*)

- The electricity supply contract for Väla makes it impossible to lower the costs from the physical markets by shifting the load in time.

- The compensation for provided energy from participation on the FCR-N market would be hard to estimate, since it depends on how the frequency varies in real time.

- The reserve market is a closed bidding market, which means that it would be necessary to continuously consider what would be a reasonable bid at the specific time without knowing what other resources would have bid at the same occasion. This adds a significant uncertainty to any calculations, since there would always be a risk that the bid would not be accepted if the need for balancing power already would be covered by lower bids from other resources.

Even though the choice to exclude these parts could be motivated, it can be argued that other approaches could have been used. One alternative would be to focus entirely on a single application and conduct a more comprehensive analysis including degradation of the battery module. Another alternative would be to make estimative calculations for all possible revenue streams and then evaluate what would be the most valuable application at Väla.

12.2.1 Assumptions and delimitations in BESS assessment

The choice to conduct simulations in the BESS assessment entailed that some assumptions and delimitations had to be defined. In order to perform simulations of peak power reduction historical data was used. This enabled the usage of a theoretical model and optimization of the BESS performance, without having to consider the stochasticity of both momentary load and PV production. The accomplished theoretical results would, however, be challenging to achieve practically since it would require an accurate forecasting model of both PV and load profile. Still, since a well-established simulation tool (SAM) was used to achieve the results, this strengthens the validity of the theoretical results.

It was decided to use similar configuration of the BESS as in the reference case in Finland, which naturally affects the financial outcome. It is likely that better profitability could have been accomplished if configuration and dimensioning of the BESS had been optimized with regards to the technical requirements for reducing the peak power at Väla.

Further, it was decided to exclude degradation of the BESS in the analysis. It was not possible to combine the technical performance aggravation with the financial calculations for several consecutive years in the utilized software (*see subchapter 7.4.6*). Degradation of the BESS would affect both the technical performance and consequently the economic outcome, but exactly how much is difficult to predict.

Furthermore, it was decided to exclude operation and maintenance costs in the economical assessment. This decision was partly motivated by the fact that this cost is related to the degradation of the BESS, which was excluded in the analysis, but also that previous studies indicated that it is hard to estimate this fairly. Nonetheless, adding operation and maintenance costs to the economical calculations would have negatively affected the financial outcome.

Conclusively, the results from simulations and economical assessment should only be interpreted as a theoretical reference. The results, nonetheless, gives an indication of the technical potential for reducing peak power at Väla and how it would perform from a financial point of view given the current circumstances.

13. Discussion and conclusions

This chapter aims to summarize the outcomes of this study and discuss them from a generalized perspective. Observations from the study concerning DSF of loads and BESS will be compared and discussed with regards to their advantages and disadvantages. Finally, both general and case-study specific conclusions will be presented.

13.1 DSF at a power system level

As described in *chapter 3*, there are several impending challenges in the future power system. Problems will arise both at local and national level, which creates the need for a versatile portfolio of solutions. DSF could be part of the solution if it is realised in practice. However, from the review of previous studies concerning energy arbitrage, it can be concluded the price volatility in the physical markets currently is not large enough to make implicit DSF economically motivated. Thus, it will probably be necessary to establish economic beneficial prerequisites for explicit DSF in order to potentially incentivise large-scale implementation of DSF solutions. Whether DSF will play an important role in the future power system is yet to be determined by the politicians in Sweden and in the European Union.

13.2 DSF at Väla

From the literature review it was concluded that flexibility evaluations are strongly case dependent. Buildings differ in their functions, the end-uses of their electricity consumption, their electricity contracts and what hardware that is installed in the building. These have all been shown in this thesis, to be parameters that will influence the prerequisites for DSF applications for both loads and BESS.

Realising DSF at Väla is a challenge with both load control and BESS operation. It requires further work and creative engineering to make it realistically feasible. However, load control and BESS operation have some advantages and disadvantages, which should be considered before either of them is implemented.

A BESS installation at Väla would conceptually enable a variety of DSF applications, including energy arbitrage, peak power reductions and frequency regulation, without causing discomfort in the building. It would always be available and can be optimized for the desirable application. However, the prerequisites for participating on these markets have both proven to be limited by the design of the electricity supply and grid fee agreement contracts.

DSF with loads, on the other hand, constitutes a complex technical challenge since existing control chains and management systems would have to be retrofitted to serve new purposes. This would have to be accomplished while original functionalities are maintained and without causing discomfort in the building. Furthermore, it requires extensive knowledge about the specific loads in the building, the BEMS and energy management strategies. It would also be necessary to negotiate and define agreements between the property owner and the tenants regarding climate in the building.

Still, there are several studies that have showed that DSF applications technically could be accomplished with a variety of load characteristics, but that more research is needed to make it practicable. Summarized, from a pure technical perspective, a BESS installation likely constitutes an easier solution than load control when DSF applications is to be implemented.

In order for DSF applications to be practically realistic, it would be necessary to accomplish long term profitability. It is the thesis authors' perception that it is still unclear if load control or BESS operation have the most favourable economic prerequisites. A BESS installation entails a large investment cost, which naturally constitute a significant financial risk. On the other hand, it is also easier to accomplish a larger revenue since it could be operated without taking the activities in the building into consideration. From the results in this study it could not be concluded that a BESS investment at Väla necessarily would be unprofitable, but it clearly indicates that it would be difficult to accomplish profitability with the current BESS price and market conditions. This conclusion is supported by results presented in Zakeri & Syri (2016) (see *Figure 18 subchapter 5.4.4),* which showed that even if the potential revenue from all available markets in the Nordic area are summed up, a BESS would still not be a profitable investment.

Regarding the economic prerequisites of DSF with load control, this was not included in the technical assessment of loads, but some observations can still be discussed. It is clear that investments would be needed to accomplish DSF with load control at Väla, but it is not likely that these would reach the same level as the costs of a BESS installation. The main cost would likely be labour costs of engineers and consultants to develop a technically functional and acceptable solution.

It is the thesis authors' perception that the prerequisites for a technically functional DSF are met at Väla. However, the cost for realising a functional solution must be weighed against the potential revenue and savings that could be accomplished. Here, the upcoming introduction of consumption resources on the reserve markets constitutes a promising opportunity. It may enable a substantial revenue stream by periodically offering regulation capacity from strategic load control. However, the first consumption resource is yet to be prequalified and accepted on the reserve market in Sweden, which makes it difficult to make any quantitative economical prediction.

Further, it should be mentioned that DSF have benefits other from those included in the scope of this thesis. One of the most important is environmental benefits. Reducing the peak power needs of consumption resources reduce the need for peaking plants, often powered by fossil fuels. Also, if consumption resources are more flexible in their electricity demand, this can facilitate integration of more intermittent electricity production resources, helping to reduce CO_2- emissions.

13.2.1 Conclusions of the analysis of loads

Even though many of the results that relates to the loads might not directly be applicable to the same load type in other buildings, many key areas have been identified that would have to be considered if loads in a building are to be used for DSF applications. As an example, the current hardware at Väla have been proven to influence the prerequisites for DSF applications. The most important conclusions of the technical load analysis are:

- The parameters and control schemes used to control the investigated loads today are not designed with the purpose of controlling the power demand of the loads. For the ventilation it is already possible to directly control the power demand of the fan. For the compressors, which are responsible for the largest portion of the power demand of the comfort cooling, it is necessary to evaluate how different control options influence the power demand.

- The availability differed for the three loads but was primarily determined by the usage pattern of season and of the hour of the day. It was found that it is crucial to include availability also with respect to operating power, and not only operating times. For ventilation, the availability is rather predictive. However, the ventilation units did not operate at their rated power and more room for flexibility was found upwards compared to downwards.

  For applications such as frequency regulation, it is desired that there is an equal amount of flexibility upwards and downwards. For cooling, it seems that the power demand must be forecasted to determine what flexibility that is available. The cooling was mainly available from late spring to early autumn. For some days during summer months the power ratio reached 90 %. Large variations in the power ratio between two consecutive days could be seen. For indoor lighting, it is mainly the hour of the day that determine when the lighting is available.

- From the previously conducted tests by Siemens it was found that acceptability for controlling ventilation and comfort cooling differ depending on the number of occupant's present. For all test days the thermal comfort was affected, and such effects should be further evaluated from the perspective of the building owner or operator since it seems that thermal comfort strains must be relaxed if the comfort cooling are to be controlled.

- One of the prerequisites for choosing a case study building was that it must have a lot of available data on load characteristic, facilitating the data collection process. Without the extensiveness of measurements as well as the availability of historic data, retrieving the results for the load assessment would have been very difficult. Additionally, people with site specific knowledge of Väla have been proven to be a key in assessing the prerequisites for DSF applications. *Figure 9* in *chapter 4.1* introduced the difference between flexibility resources and reserves. Even though no quantification of the flexibility of the loads were conducted, enough have been concluded to validate the conceptual meaning of *Figure 9*. Determining the DSF potential require an extensive assessment of the case study building and there are many additional factors to the rated power of loads that in the end will determine the overall flexibility potential.

- Finally, it is the authors' opinion that ventilation is best suited for DSF applications of the three investigated loads. The reasons for this are the presence of the VFD's, the predictable availability pattern with respect to operating power and the large installed capacity.

13.2.2 Conclusions of BESS assessment

The most important conclusions from the BESS assessment are the following:

- It is possible to both reduce peak power demand and provide frequency control with strategic operation of a BESS at Väla.

- The structure of the electricity supply contract and grid fee agreement is decisive for what revenue that could be accomplished from both peak power reduction and frequency regulation with a BESS. A grid fee, which is based on the monthly highest power demand, gives larger economic incentives to lower power demand than a grid fee where the price of power depends on the highest outtake of power of the calendar year.

- Accomplishing profitability by solely reducing peak power demand through strategic operation of a BESS at Väla is not possible even when considering significant price increase and a future lower BESS price.

13.3 Conclusions of the study

The purpose of this thesis was to identify the prerequisites for Väla to offer DSF with focus on technical aspects. The goal was to establish a framework of important technical aspects that should be regarded when initially assessing the potential for a building to offer DSF through load control and to investigate if an onsite energy storage solution at Väla would be beneficial both from technical and economical perspectives. The research questions have been answered within the scope of the thesis. However, there are still several aspects left to investigate further.

It is the thesis author’s opinion that Väla from a technical point of view, is an interesting pioneer for DSF applications through strategic load control, but that the high standards of indoor climate could make it practically challenging. The alternative is to install a BESS, which can accomplish functional and acceptable DSF with less complications, but where obtaining profitability is challenging given the high investment costs of a BESS. The thesis authors therefore encourage that further studies of DSF with both loads and BESS is conducted with either Väla as case study object or suggestively other similar commercial buildings. The ideas presented in *chapter 14* could be used as an inspiration source for such studies.

14. Future studies

The purpose of this chapter is to present topics for further work identified during the working process of this study. Some topics relate specifically to Väla but can preferably also be generalized to match the prerequisites of other building objects.

The topic of DSF could be analyzed from several perspectives. This was a challenge in the initial parts of this master thesis since the scope had to be defined with regards to available resources. A number of further research topics have been identified during the working process. These are interesting and important to study, if DSF applications are to be both technically and economically viable at Väla, or at other building.

- *Strategic control of loads and BESS for frequency regulation* – It would be interesting to investigate if loads and a BESS at Väla could be controlled in symbiosis to accomplish greater technical functionality and cost efficiency than what they can individually.

- *Revenue optimization for BESS* – It would be interesting to theoretically optimize how a BESS at Väla should be operated with respect to the potential revenue from peak power reductions and reserve markets. This would be a challenging scope, but (Shi et al. 2018) presents some interesting results and concepts that could be used as basis for such a study.

- *BESS optimal dimensioning and configuration* – In order to accomplish optimal cost efficiency of a BESS installation at Väla, the dimension and configuration needs to be optimized with regards to available revenue streams and/or potential savings.

- *Interactions between ventilation and comfort cooling system* – This study identified that the ventilation and comfort cooling systems were strongly interconnected. To further study interactions between these systems, would be interesting since these two load characteristics typically accounts for the highest electricity power needs of a commercial building. Including interactions with the comfort heating should also be investigated, since these might influence the availability of the ventilation fans.

- *DSF versus Energy savings* – It should be evaluated if using loads as a flexibility resources will contribute to a higher energy use, or if the two can be achieved simultaneously. This will likely differ both depending on what load that is used as a flexibility resource and on what market the load participates on.

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List of appendices

Appendix A – Summary of frequency regulation markets

Table A. Summary of frequency regulation markets in Sweden: (SEDC 2015), (Svenska kraftnät 2018c), (Svenska kraftnät 2016b)

	Primary regulation		**Secondary regulation**	**Tertiary regulation**		
Service	FCR-N	FCR-D	aFRR	mFRR	Fast active disturbance reserve	Power reserve
Quantity	230 MW	394 MW	1.6 TWh	No requirement	1360 MW	Maximum 750 MW
Minimum volume for participation (MW)	0.1	0.1	5	10 (SE1-SE3), 5 (SE4)	No defined limit	5
Function	Stabilize frequency	Stabilize frequency	Restore frequency	Restore frequency	Restore frequency	Ensure power sufficiency
Notification time	63 % in 60 s 100 % in 3 min	50 % in 5 s 100 % in 5 min	2 min	15 min	Max 15 min	Max 14 hours
Compensation	Power and energy	Power	Power and energy	Energy	Defined in contract	Power and energy
Activation	Automatic, 49,9-50,1 Hz	Automatic, below 49,9 Hz	Automatic	Market based	Manual	Manual

Appendix B – Rated power for the ventilation fans

Table B. Rated power for supply and exhaust fans for the ventilation units at Väla.

	Rated power				**Rated power**	
Ventilation unit	**Supply fan (kW)**	**Exhaust fan (kW)**		**Ventilation unit**	**Supply fan (kW)**	**Exhaust fan (kW)**
TA-01	7.5	3		**TA-13**	-	-
TA-02	11	7.5		**FTX-14**	2.82	2.82
TA-03	11	7.5		**FTX-25**	1.85	1.85
TA-04	11	4.6		**TA-31**	75	75
TA-05	11	7.5		**TA-29**	-	-
TA-06	11	7.5		**TA-17**	18.5	11
TA-08	11	7.5		**FTX-39**	30	22
TA-09	11	7.5		**FTX-40**	30	22
FTX15	-	-		**FTX-41**	30	22
TA-26	7.5	3		**FTX-42**	30	22
TA-28	37	30		**FTX-44**	0.75	0.75
FTX-10	18.5	15		**FTX-32**	18	15
TA-11	18.5	11		**FTX-33**	18	15
FTX-12	15	11		**FTX-34**	18	15
FTX-36	18	15		**FTX-35**	18	15
FTX-38	18	15		**FTX-37**	18	15
FTX-43	1.1	1.1				
				Total:	**527**	**408**

Appendix C – Overview of building

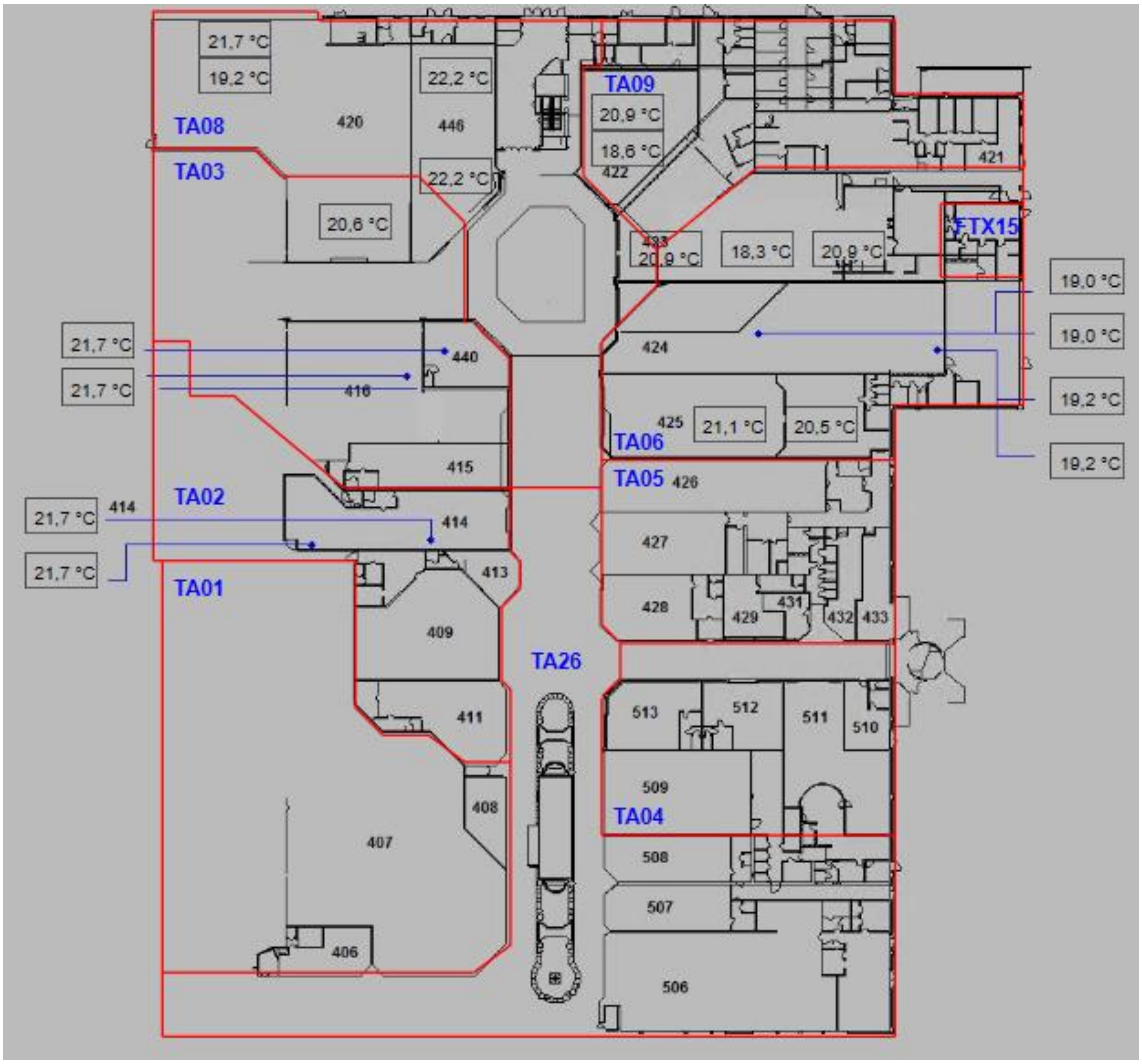


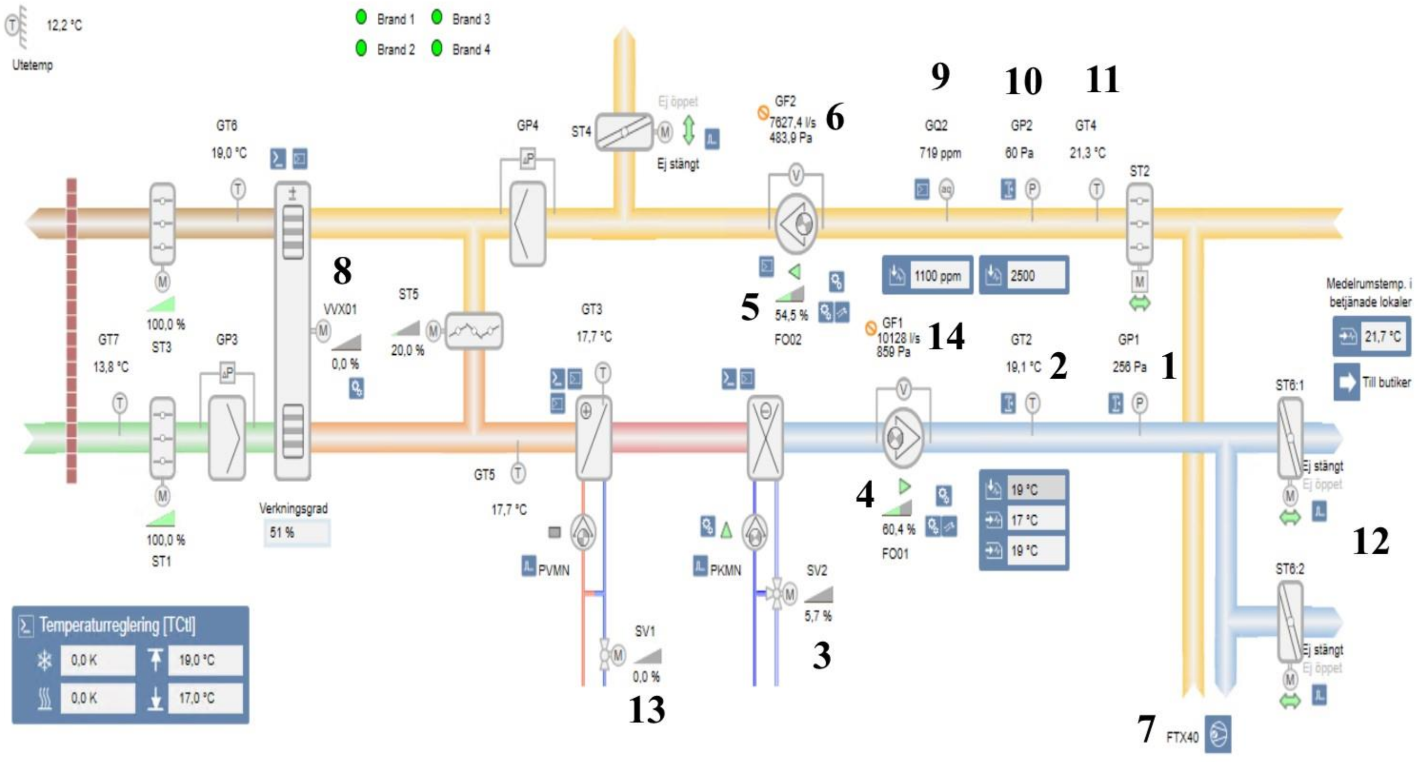
Figure C. A map of building C together with the ventilation units that serve the different parts of the building. Operating areas for each ventilation unit are defined by the red lines. For those areas that have temperature sensors, the actual temperature can also be seen.

Appendix D – Availability of the ventilation fans

Table D. Scheduled operating hours for the ventilation fans.

Ventilation unit	Weekday schedule	Weekend schedule	Ventilation unit	Weekday schedule	Weekend schedule
TA-01	09:00 - 20:00	09:00 - 18:00	**FTX - 12**	09:15 - 20:00	09:15 - 18:00
TA-02	09:15 - 20:00	09:15 - 18:00	**FTX - 14**	07:00 - 17:00	Off
TA-03	09:15 - 20:00	09:15 - 18:00	**FTX-15**	00:00 - 23:59	00:00 - 23:59
TA-04	08:15 - 20:00	10:00 - 18:00	**FTX-25**	05:30 - 20:00	05:30 - 18:00
TA-05	09:15 - 20:00	09:15 - 18:00	**FTX-32**	08:30 - 20:00	08:30 - 18:00
TA-06	09:15 - 20:00	09:15 - 18:00	**FTX-33**	09:00 - 20:00	09:00 - 18:00
TA-08	09:30 - 20:00	09:30 - 18:00	**FTX-34**	09:00 - 20:00	09:00 - 18:00
TA-09	00:00 - 23:59	00:00 - 23:59	**FTX-35**	09:00 - 20:00	09:00 - 18:00
TA-11	09:15 - 20:00	09:15 - 18:00	**FTX-36**	08:30 - 20:00	08:30 - 18:00
TA-13	09:15 - 20:00	09:15 - 18:00	**FTX-37**	08:30 - 20:00	08:30 - 18:00
TA-17	07:00 - 20:00	07:00 - 18:00	**FTX-38**	08:30 - 20:00	08:30 - 18:00
TA-26	09:00 - 20:00	09:45 - 20:00	**FTX-39**	09:15 - 20:00	09:15 - 18:00
TA-28	09:00 - 20:00	09:00 - 18:00	**FTX-40**	09:15 - 20:00	09:15 - 18:00
TA-29	09:30 - 20:00	09:30 - 18:00	**FTX-41**	08:30 - 20:00	08:30 - 18:00
TA-31	07:00 - 20:00	07:00 - 18:00	**FTX-42**	08:30 - 20:00	08:30 - 18:00
FTX-10	09:00 - 20:00	09:00 - 18:00	**FTX-44**	10:00 - 20:00	10:00 - 18:00
			FTX-43	09:30 - 20:00	09:30 - 18:00

Appendix E – Measured and controllable parameters for ventilation



1. **Pressure supply fan**
2. **Supply air temperature**
3. **Valve position cooling battery**
4. **Supply fan signal**
5. **Exhaust fan signal**
6. **Exhaust air flow**
7. **Duct to FTX-40**
8. **Heat exchanger signal**
9. **CO_2-value**
10. **Exhaust fan pressure**
11. **Exhaust air temperature**
12. **Valves to stores**
13. **Valve position heating battery**
14. **Supply air flow**

Figure E. Ventilation unit FTX-39 as seen from the software Desigo CC.

Appendix F – Simulations in SAM

To conduct simulations of the described BESS operations, the software System Advisor model (SAM) was used. The software enables different dispatch possibilities for the operation of the BESS. The first approach that was considered was to manually input an operation scheme, which then would allow control of charge and discharge of the battery during every hour of the entire year. This proved to be a very time-consuming approach. Instead it was determined to use the automated grid dispatch. The BESS was allowed to operate between 15% and 95% in SoC since the BESS otherwise could be damaged and lower the technical lifetime. These values were predetermined in the software in accordance with the choice of BESS technology.

Automated grid dispatch

The automated grid dispatch gives the possibility to set monthly values of allowed peak power demand from the grid. The optimization algorithm then systematically attempts to accomplish these grid power targets by strategic operation of the BESS (Nelson et al. 2015). However, the software considers both the load profile and the capacity of the BESS, which means that desired setpoint cannot be guaranteed. Consequently, an iterative approach had to be applied in order to identify the grid power target, which the BESS managed during the entire month.

The algorithm is composed of several iteration steps but is always initiated by looking forward a 24-hour period and hourly load values are sorted by magnitude forming a load duration curve (*Figure F1*).

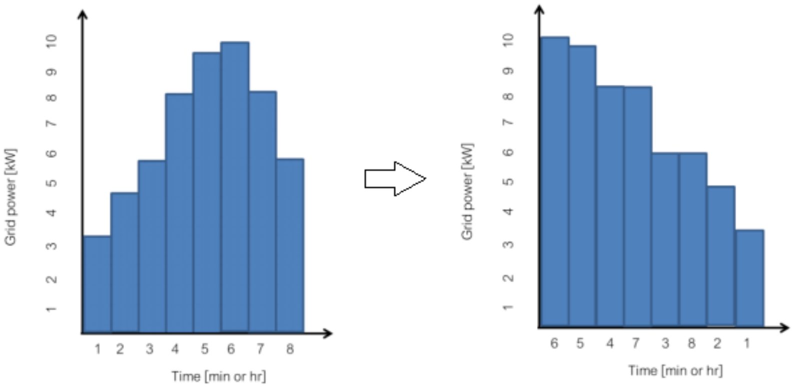


Figure F1. Hourly load values sorted into a duration curve. (DiOrio 2017)

The algorithm then tries to reach the desired grid power target by iterating discharge and recharge of the BESS within the limitations of the BESS capacity. If the grid power target could be reached successfully the BESS will discharge during hours when grid demand is higher than the target and charge during hours when load is lower than the target. An example of a result is shown in *Figure F2*.

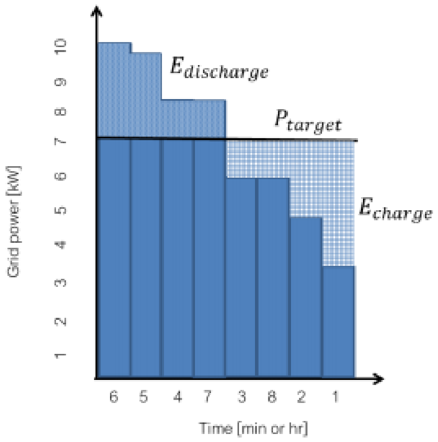


Figure F2. BESS operational strategy for reducing peak power demand from the grid (DiOrio 2017)

Exactly how the BESS is modelled within the software is described by Nelson et at (2015), where also the models of input components are validated through performance comparison with similar available software's'. This validation indicates that the SAM software is able to accurately predict the main important BESS parameters. Thus, this motivates the usage of SAM as modelling tool for this purpose. Further, a more thorough explanation of how the automated grid dispatch algorithm works can be found in (DiOrio 2017). The systematic review presented in the paper gives a good understanding of the algorithm behaviour.