UPPSALA
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UPTEC ES 21031
Examensarbete 30 hp
Augusti 2021

Determining the Technical Potential of Demand Response on the Åland Islands

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Abstract

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With increasing intermittency from renewable energy production, such as solar and wind power, the need for increased flexibility is quickly arising. The Åland Islands have an ambitious energy transition agenda with the goal of having a 100 % renewable energy system. Since there is no possibility of hydropower acting as regulatory power on Åland, reaching the goal is a challenging task. Increasing flexibility can be achieved by either implementing energy storage in the system or by matching the demand with the production.

The purpose of this study was to estimate and evaluate the technical potential of demand response (DR) on Åland, both in 2019 and for a scenario in 2030 when domestic production of wind and solar have increased. Six areas of interests were identified; electric heating, refrigeration processes, lighting, ventilation and air conditioning, electric vehicles and industries. Electricity import from Sweden to Åland was examined since high import coincides with either low domestic renewable production or high consumption. Import is therefore a good indicator for when flexibility is most required.

The results show that the technical potential of DR on Åland can lower the maximum electricity import from Sweden by 18 % in 2019. 4.3 % of the total import can be moved to times when there is less stress on the grid. Electric heating is the biggest contributor, and can by itself lower the import with three fourths of the total reduction. The domestic renewable production for 2019 is too low for DR to have an effect on the self-sufficiency. In 2030 the self-sufficiency and utilization of domestic renewable production could be increased with 4.2-9.9 % and 5.4-12 % respectively when using DR, depending on if vehicle-to-grid is implemented on a large scale or not. The cost of implementing DR is still uncertain and varies between different resources. Nonetheless, DR in electric heating is presumably a less expensive alternative in comparison to batteries, while providing a similar service.

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ISSN: 1650-8300, UPTEC ES 21031

Preface and acknowledgements

This work was done as a master thesis project for Uppsala university in collaboration with Flexens Oy AB and we want to thank Flexens for the opportunity to write this thesis.

Also, we would like to thank both our supervisor at Flexens, Juhani Riikonen, and our subject reviewer Cecilia Boström, Senior lecturer/Associate Professor at Uppsala university, for the guidance and help during the work. Furthermore we would like to thank Tuukka Vainio at Flexens as well as Johannes Hjalmarsson, PhD student at Uppsala university, for their thoughts and comments during the work process. An additional thank you to everyone that have participated in interviews or in other ways have helped with providing useful information. Lastly we would also like to thank our peer reviewers, Andrea Carlgren and Madeleine Stolpe, for valuable feedback.

The work process has been different due to COVID-19, but has also taught us to cooperate very efficiently and we want to thank each other for the combined efforts and hours put into this thesis.

Best regards,
Emil Lind & Edvard Nordlund

Executive summary

More renewable production means that more flexible consumption could be necessary in the future. One way to achieve this is with demand response (DR). Unlike batteries, which store energy so that it can be used at a different time, DR shifts the time of usage to when either production is high or consumption is low. This means that little or no new infrastructure is needed in order to utilize DR.

This study aims to answer how big the technical potential of DR is on Åland in two cases. One where historic data of production and consumption in 2019 is used, and one for a future scenario in 2030. Furthermore, it aims to investigate how big the possible import reduction could be by using DR and how much more domestic renewable production that could be utilized. Finally, a brief economic analysis is performed.

Six DR resources were analyzed; electric heating, refrigeration processes, lighting, ventilation, industry processes and electric vehicles (EV).

DR has the potential to lower the peak import by 11.4 MW in 2019, while it in 2030 could increase the self-sufficiency with 4.2-9.9 % and the utilization of domestic renewable production with 5.4-12 %. Electric heating is the resource with the most potential on its own in 2019, and could also be economically viable in comparison to an equivalently sized battery storage. EVs have a lot of potential in 2030, especially if faster average charging power as well as vehicle-to-grid is introduced on a large scale.

Populärvetenskaplig sammanfattning

En av de viktigaste uppgifterna för transmissionsnätsoperatören är att se till att generering och konsumtion av elektricitet är lika stora. Om dessa skiljer sig ändras frekvensen på nätet, och det kan uppstå problem för apparater som är inkopplade.

Historiskt sett har oftast styrning skett på produktionssidan då genereringen justeras så att den hela tiden matchar konsumtionen. I Sverige har denna roll framförallt legat på vattenkraften. Med ökad intermittent energiproduktion, så som sol- eller vindkraft, ökar också snabbt behovet av flexibilitet, då det blir svårare att styra när produktionen kommer att ske. Därför blir det allt mer aktuellt att undersöka möjligheten till att styra elbehovet. Ett sätt att göra detta på används redan till viss del vid laddning av elbilar. Om elbilen står inkopplad under en längre tid, och inte har ett laddbehov under hela inkopplingstiden, finns möjligheten att lägga laddningen då antingen produktion av elektricitet är hög eller det övriga behovet är lågt. Det här är ett exempel på efterfrågeflexibilitet (eng. demand response). Efterfrågeflexibilitet kan användas både för att minska behovet under särskilda tider, eller för att flytta användningen från en tidpunkt till en annan.

Åland har som mål att på sikt bli 100 % självförsörjande inom elektricitets-, värme- och transportsektorn. Fram till 2030 finns ett framtaget scenario med 170 MW vindkraft och 15 MW solkraft installerat jämfört med dagens installerade vindkraft på 21 MW. Denna studie syftar till att reda ut huruvida efterfrågeflexibilitet skulle kunna användas som redskap för att minska importtopparna från Sverige samt för att öka självförsörjandegraden, både för det nuvarande energisystemet samt för ett framtidsscenario där ovan nämnd förnybar elproduktion har installerats.

Sex stycken sektorer som skulle kunna använda sig av efterfrågeflexibilitet identifierades; elektrisk uppvärmning av byggnader, kyl- och frysprocesser, belysning, ventilation och luftkonditionering, elbilar och industrier. För både elektrisk uppvärmning samt kylprocesser utnyttjas att en termisk tröghet finns i systemen, det vill säga att värme eller kyla finns lagrad. Fjärrstyrning används för att reglera när uppvärmning och kylning aktiveras, så att hög elnätsbelastning kan undvikas. Mätare ser till att temperaturen inte går utanför tillåtna intervall. Belysningen kan regleras ned om dimmbara lampor finns installerade, och under en kortare tid kan användningen minskas utan att leda till större besvär för användaren. Ventilation är svår att använda som efterfrågeflexibilitetsresurs på grund av de lagar och bestämmelser som finns inom sektorn. Det finns stora möjligheter att styra ventilationen, men detta har större potential som energieffektivisering än som flexibilitetsresurs. Om smart styrning av ventilation redan används, så att den till exempel stängs av under natten, finns det dock potential att ändra tidpunkten för när ventilationen sätts igång igen och nattluften ventileras ut. Industrier kan tillfälligt stänga av delar av sina processer, medan elbilar kan flytta sin laddning. Det finns också teknik som möjliggör att elbilar kan användas som batterilager där de levererar elektricitet tillbaka till nätet. Om denna teknik, som kallas vehicle-to-grid (V2G), introduceras i stor skala ökar elbilarnas potential som flexibilitetsresurs.

Studiens resultat visade på att det är möjligt att sänka den högsta importtoppen med 18 % för 2019 om all den teoretiskt framtagna potentialen för Åland kunde användas som efterfrågeflexibilitet. För hela året flyttades 11,0 GWh till tidpunkter med lägre import, motsvarande 4,3 % av den totala importen. 2019 var den inhemska produktionen av förnybar elektricitet för låg för att efterfrågeflexibilitet skulle kunna påverka självförsörjandegraden, men för 2030 kunde denna ökas med 4,2 % för fallet med enbart efterfrågeflexibilitet och till 9,9 % för fallet med både efterfrågeflexibilitet och V2G.

Elektrisk uppvärmning av hushåll har den största potentialen av de sex enskilda sektorerna för år 2019. Den står för nästan 75 % av den totala importsänkningen räknad till effekt och cirka 70 % räknad till mängd energi som flyttas. Därefter följer kylprocesserna. Belysningens totala potential går inte att fastställa, då det inte är möjligt att flytta den elektriska lasten, utan enbart att minska användningen. Den totala potentialen beror då på hur mycket belysningen tillåts minska. Ventilationen har lägst flexibilitet av de resurser som flyttar lasten, då det bara går att reglera användningen under morgonen.

Industriernas möjlighet att delta med efterfrågeflexibilitet utelämnades i den här studien, då det visade sig att det var svårt att göra en generell uppskattning av potentialen utan att kontakta enskilda industrier. Detta rekommenderas att undersökas vidare.

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Abbreviations

aFRR - Automatic frequency restoration reserve

ASHP - Air source heat pump

BEV - Battery electric vehicle

CAPEX - Capital expenditure

COP - Coefficient of performance

DR - Demand response

DSO - Distribution system operator

ESS - Energy storage system

EV - Electric vehicle

FCR-D - Frequency containment reserve for disturbances

FCR-N - Frequency containment reserve for normal operation

GSHP - Ground/geothermal source heat pump

HP - Heat pump

HVAC - Heating, ventilation and air conditioning

IH - Immersion heater

LFC - Load frequency control

mFRR - Manual frequency restoration reserve

OPEX - Operating expenses

PHEV - Plug-in hybrid electric vehicle

PV - Photovoltaics

SCOP - Seasonal coefficient of performance

SH - Supplementary heater

SoC - State of charge

SVK - Svenska Kraftnät

TSO - Transmission system operator

V1G - Unidirectional controlled charging

V2G - Vehicle-to-Grid

V2H/B - Vehicle-to-home/building

V2X - Vehicle-to-everything

VESS - Virtual energy storage system

VRES - Variable renewable energy system

Glossary

Balance point temperature - The outside temperature where no extra heating is needed to achieve the desired indoor temperature.

Coefficient of performance - The ratio of how much useful heating or cooling a device, for example a heat pump or a refrigerator, will produce given a certain energy input. A higher coefficient of performance indicate a higher efficiency.

Electric heater - The electric heater uses an electric resistance heater, such as a coil or similar, to directly heat the surrounding medium, which can be both air and water.

Heat pump - A heat pump does not use electricity to directly warm the surrounding medium. Instead it uses it to drive a cycle which, through compression and expansion, gathers heat from a source, such as the ground or outside air, and transfers it to the space that are to be heated.

Immersion heater - The immersion heater is an electric heater that is submerged into a water tank, and uses an electric resistance heater to heat the water surrounding it. For simplicity, in this study all electric heaters which uses water as the heat carrier are called immersion heaters.

Ramp up/down - The definition of ramp up/down varies depending on the application. From the grid's perspective, ramp up indicates that the grid frequency is increased meaning that either production is increased or consumption decreased. Ramp down means that the grid frequency is decreased, so either production is decreased or consumption increased. However, when ramp up/down is mention regarding a demand response resource such as heat pumps, ramp up defines how quickly the heat pumps can be turned on which increases consumption and therefore decreases grid frequency. Since these statements regarding ramp up/down are contradictory, the exact meaning is specified whenever the phrase is used in this paper.

Seasonal coefficient of performance - Similar to coefficient of performance, but measured during different circumstances. Since the efficiency varies with temperature, seasonal coefficient of performance is used as a measure to determine the efficiency in a different climate.

Supplementary heater - The supplementary heater is an electric heater that functions as a reserve heater. It is used for example when the heat need exceeds the possible heat production from a installed heat pump. In this paper an assumption was made that all heat pumps have been installed together with a supplementary heater, which handles peak loads.

1. Introduction

With the increasing penetration of variable renewable energy sources (VRES), such as wind and solar power, the electric grid faces a challenge in maintaining equilibrium between the demand and the production of electricity. To keep the grid stable, either the demand needs to be matched with the production, also called demand response (DR), or vice versa. With large shares of wind and solar power present in the energy system, the intermittency of these technologies have to be compensated by DR, regulatory power and energy storages. Utilizing only one of these technologies will not be enough to cover the increased flexibility needs that we are globally facing (Zöphel et al., 2018).

The Åland Islands, located in the Baltic sea between Finland and Sweden, has an ambitious energy transition agenda to reach the goal of a 100 % renewable energy system, heavily reliant on wind power, by 2030. Furthermore, it is a desirable quality for an island society to be self-sufficient on renewables without any import from the mainland, but this is not feasible without a great deal of flexibility present in the energy system (Lindqvist et al., 2019). In general, the Nordic countries have renewable regulatory power available through the utilization of hydro power, but no such opportunities exists on Åland. Therefore, reaching 100 % self-sufficiency is a more challenging task for Åland in comparison to, for example, Sweden.

This thesis is a cooperation between Uppsala University and Flexens Oy Ab. Flexens has identified the opportunity to develop an energy system, based exclusively on renewable energy sources, on Åland that is both technically and economically sustainable. This pilot is called Smart Energy Åland (Flexens Oy Ab, 2019) and will help Flexens gain knowledge and skills essential to achieve their vision: "to become a market leading company for project development in the RES energy system sector" (Flexens Oy Ab, 2020).

1.1. Purpose

The purpose of this thesis is to investigate the potential of DR on the Åland Islands and examine how electricity import can be optimized from a flexibility perspective. Furthermore the goal is to create an extension to an already existing model of the Åland energy system, which showcases the effects of utilizing DR in the current and future energy system of the Åland Islands. Also, technical limitations are examined as well as cost analysis of DR compared to other flexibility resources.

1.2. Problem Statements

- What is the aggregated potential of DR on the Åland Islands?
- How much can the peak electricity import be lowered by using DR?
- How much more of the domestic renewable energy production can be utilized locally, with the help of DR, if increased self-sufficiency is prioritized?
- What is the optimal implementation of DR from an economical viewpoint and how does it compare to other flexibility resources?

1.3. Scope and constraints

The subject of DR can be divided into two parts. The first one is the technical aspects, which defines the use cases for DR on a technical level, and how much regulation that can be achieved by using smart meters and regulators. The second one is the social aspects, how much the population and/or service providers are willing to regulate given certain conditions. This study will mostly focus on the first part: to evaluate the potential of DR, but the second part will also briefly be discussed.

The concept of DR can also be applied both to electricity and heating, where in the latter case it could be used to regulate the amount of district heating that is used among other things. This study will not delve deeper into this, and will only focus on the the usage of electricity. Heating, ventilation and air conditioning (HVAC) units will be examined because, even though they are used to regulate heating and cooling, they use a substantial amount of electricity to do so.

An overview of the electric grid on Åland can be seen in figure 1. However, the transmission limitations within the local grid have not been taken into consideration in the simulations.

1.4. Thesis outline

This part of the thesis explains the structure of the report and can help the reader to navigate through the thesis with a brief overview of each of the upcoming sections.

Section 2 presents the background and theory of the thesis. Focus lies on electricity markets and different DR resources which are broken down individually in upcoming sections as the following:

- Heat pumps (HP) and other electric heaters
- Refrigeration processes
- Lighting
- Ventilation and air conditioning

- Industries
- Electric vehicles (EV)

Section 3 contains the data used in the thesis and explains the methodology and assumptions behind the calculation of the DR potential on Åland.

Section 4 consists of both a summary of the highest theoretical DR potential possible from the all different resources available on Åland and the results from the model optimization. The purpose with the optimization is to showcase a more realistic utilization of DR, with technical constraints, for a full year on Åland for a base case with data from 2019 and a future scenario for 2030. Section 4 answers the problem statements of the thesis. Section 4.9 examines a few parameters that are considered to be of high relevance for the results and how changing them affects the results.

Section 5 discusses the results and further research that could be conducted.

2. Background and Theory

2.1. The energy system of the Åland Islands

This section is intended to give insight into the current energy system on the Åland Islands as well as the future plans of 2030. Currently, as was the case in 2019, the majority of locally produced renewable electricity is supplied by wind power with an installed capacity of 21 MW. This corresponds to approximately 19 % of the yearly electricity demand on Åland. There is a 1.8 MW_e biomass combined heat and power (CHP) plant that is rarely used for electricity production due to low electricity prices at summertime when there is excess heat. During wintertime, when electricity prices usually are higher, it is economically viable for electricity production but then the heat demand is higher and the plant is mostly used for heat production. The remaining electricity is almost exclusively imported from Sweden. The yearly total electricity demand is around 300 GWh with a peak load of 67 MW and a minimum load of 16 MW (Lindqvist et al., 2019).

The transmission grid is owned and operated by the local transmission system operator (TSO), Kraftnät Åland. There is one 80 MW, 110 kV, AC connection to Senneby, Sweden, and one 100 MW, 80 kV, DC-link to Nådendal, Finland. The DC-link was installed in 2015 with the main purpose to serve as a back-up (Kraftnät Åland Ab, 2021). Figure 1 shows the voltage levels of the transmission grid on Åland.

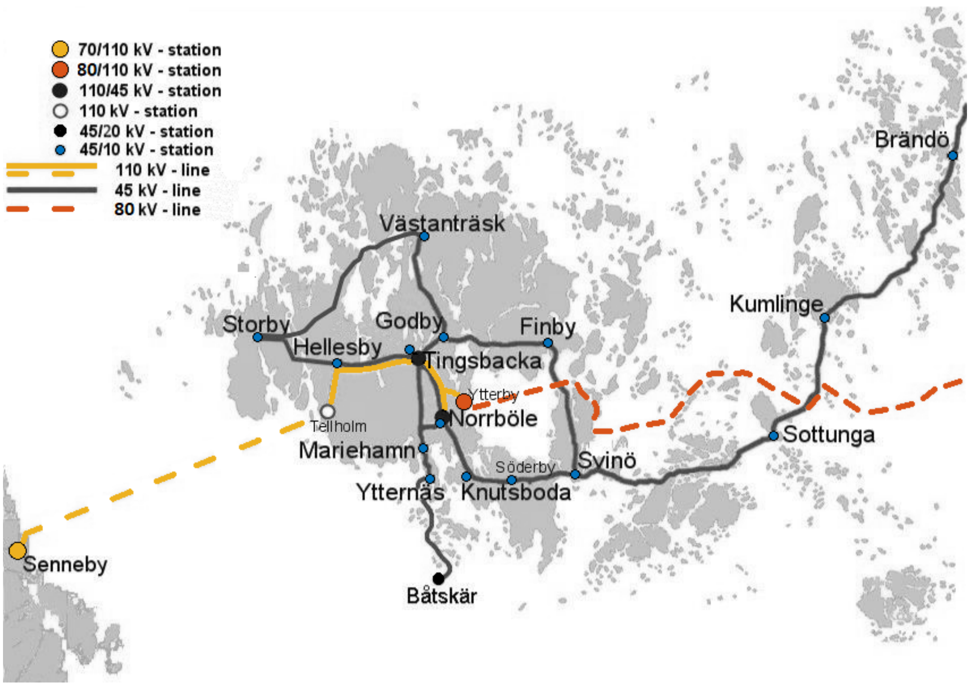


Figure 1: The transmission grid on Åland. Original figure from Kraftnät Åland Ab (2021).

By 2030 the electricity demand is expected to increase to 400 GWh with a peak load of 85 MW while remaining at the same minimum load of 16 MW. Regarding the renewable energy production one of the suggested scenarios for 2030 consist of 170 MW wind power, 15 MW solar power and 0 MWe biomass CHP. In other words, a capacity mix of 90 % wind power, 10 % solar power and 0 % biomass CHP (Lindqvist et al., 2019).

As of the end of 2020 there were 236 EVs on Åland (Fordonsmyndigheten, 2021). The government of Åland has a goal that there should be 4,000 EVs on Åland by the year 2030. The distribution between battery electric vehicles (BEV) and plug-in hybrid vehicles (PHEV) has not been specified. The sale of fossil-powered vehicles on Åland should also not be allowed after 2030 (Ålands lagting, 2020).

2.2. Markets and actors

Before delving deeper into the subject of DR, this part of the report will examine the market structure of trading electricity to and from the grid. This is important to consider when investigating the potential of DR since the economic feasibility will differ depending on whether DR can participate in the reserve markets or are limited to load-shifting and/or peak-shaving towards other incentives.

2.2.1. Current electricity market structure

The electricity market in the Nordic countries, including Finland, Sweden, Norway and eastern Denmark, consist of several marketplaces with different time windows for physical trading of electricity: the day-ahead market, the intra-day market and the reserve markets. The day-ahead market sets the price of electricity for every hour of the upcoming day and the price is determined by the predicted demand and supply of electricity. This is called the spot price and the market is handled by Nordpool. The intra-day market, also handled by Nordpool, give the producers and purchasers of electricity the option to adjust the bought and sold electricity from the day-ahead market until one hour before the operating hour, if it turns out the initial prediction was incorrect. However, the predictions are always subject to an error compared to the real demand and supply even if the intra-day market is considered. Thus, the reserve markets are used to maintain grid stability during the hour of operation. The reserve markets are handled by the TSOs and consist of automatic and manual reserves. The TSO is also responsible for maintaining and developing the transmission grid (Alvehag et al., 2016).

Other actors on the market are the distribution system operators (DSO), who are responsible for the distribution grids, as well as the end-customers. When an end-customer purchases electricity one must choose the corresponding electricity network operator in the area, the local DSO, but is free to choose the electricity supplier, the party which sells the electrical energy to the end-customer. A DSO can be both the electricity network operator and the electricity supplier. The electricity supplier estimates how much electricity that will be consumed by its customers and the electricity producers estimates how much electricity that will be produced, whereas the TSO and DSO is responsible for delivering the electricity in the grid. In the price for the end-consumer fees for the electricity price, grid fees, taxes and and balancing fees are included. The TSO has contracts with balance responsible parties, such as electricity suppliers, who are economically responsible for balancing. This means that if the predicted load is higher than expected and the TSO has to activate reserves the additional cost will be payed by the actor causing the imbalance. An aggregator is an actor who combines several customers' consumption for trading of electricity so that smaller resources also can be used for flexibility (Alvehag et al., 2016).

2.2.2. The availability of reserve markets on the Åland Islands

Åland is a self-governing part of Finland but has its main grid connection to the Swedish SE3 electricity market. Kraftnät Åland, the TSO on Åland, is the system and overall balance responsible actor on Åland and there are currently three balance responsible parties that works towards Kraftnät Åland: energy producer Allwinds Ab and the DSOs Mariehamns Energi Ab and Ålands Elandelslag. The Åland electricity market is deregulated since January 1st 2000, meaning that anyone can trade with electricity on the Åland market. The same companies that are balance responsible parties towards Kraftnät Åland are also the only electricity suppliers on Åland (Kraftnät Åland Ab, 2021).

In general, the load frequency control (LFC) areas are operated by only one TSO but there is one exception in the Nordics. SE3, one of four LFC areas in Sweden in which Åland is included, is operated by both Svenska kraftnät (SVK), the TSO in Sweden, and Kraftnät Åland. Kraftnät Åland only operates on Åland. Consequently, there is a separate agreement between Kraftnät Åland and SVK which is often not included in public documentation (Fingrid et al., 2019).

Production and demand are locally balanced by Kraftnät Åland, and the remainder is either imported or exported via the 80 MW AC connection to Sweden. Currently export to Sweden is seldom required but this will change when wind power is further expanded on Åland. The electricity import contract is currently set to a maximum of 58 MW but has been gradually increased over the years. The annual subscription fee is 10.9 €/kW[1]. If Kraftnät Åland is unable to handle an imbalance they have a contract with

[1] Conny Rosenberg, CEO of Kraftnät Åland, e-mail [10-06-2021]. SEK to EUR conversion via valuta.se [22-06-2021]

SVK to supply regulatory power for the price of the reserve market and the electricity supplier that caused the imbalance will have to reimburse for the increased price. This means that Åland cannot participate in the reserve market, and discussions whether this would be possible to implement is ongoing between SVK and Kraftnät Åland, but it is a technically complicated and time consuming process that requires special solutions due to the conditions on Åland[2]. For more information on the reserve markets, and other flexibility markets, see appendix A.

The 100 MW DC-link to Finland is only meant to be used if there is a disturbance in the Swedish connection. If this happens the market is turned to Finnish prices for both purchasing and selling electricity. For the cold periods at the start of 2021 the cable was used for peak shaving to avoid exceeding the power limit towards Sweden. There is also local reserves in the form of gas turbines. The DC-link is technically impossible to utilize for frequency regulation in SE3 since the Nordic countries are synchronously connected with the same frequency, the only impact would be a slight decrease in frequency from the losses in the line. There is also a special solution in the archipelago. These locations are supplied with Finnish electricity because the connection with the main island, which is supplied with Swedish electricity, is too weak. The current structure has to be overhauled for expanded wind power in the case that export is needed to both Sweden and Finland at the same time since the prices in the two regions differ[2].

2.3. Demand response

Increasing the share of VRES reduces the system inertia in the grid due to a decrease in mass of spinning generators. When a sudden change in supply or demand happens in a power system with low inertia more severe frequency deviations will be encountered, making the grid unstable. To counteract this, energy storage system (ESS) can be used. However, ESS is still expensive as a large-scale investment even though prices have started to decrease in recent years (Cheng, Sami and Jianzhong, 2016). The average cost of a 4-hour li-ion utility-scale battery system was 1252 €/kW[3] and 313 €/kWh in 2019. The forecast in 2030 for the same system is 682 €/kW and 170.5 €/kWh (Cole and Frazier, 2020).

A virtual energy storage system (VESS) is a combination of all different controllable components in the energy system. DR, in aggregated form, can be seen as a VESS with properties similar to charging and discharging by intelligent load-controlling. Using already existing network assets such as fridge-freezers and heating loads with a flexible demand,

[2] Conny Rosenberg and Jan Mörn, CEO and CTO at Kraftnät Åland, online interview [22.2.2021].
[3] USD to EUR conversion via https://www.valuta.se/ [2021-05-18]

DR can be deployed at a large scale to a lower cost than ESS. It is estimated that DR has the potential to reduce the need for ESS with 50 % by 2030. DR relies on information and communication technology. With the help of a controller the power output for aggregated freezers', for example, can be varied in relation to frequency deviations by changing the temperature of the freezers. The purpose of the controller is to contribute with regulatory services without impacting the cooling performance, the original purpose, of the cold storage. However, there are challenges with DR regarding uncertainties in the response of the controllable loads. Therefore, combining DR with ESS could provide a reliable frequency response with lower cost than a traditional ESS (Cheng, Sami and Jianzhong, 2016).

Another main benefit is that DR allows for improved integration of renewable electricity production. The utilization degree of wind power and solar photovoltaics (PV) will increase if customers' electricity loads are shifted to match the production. This will improve the value of produced electricity and help to avoid negative electricity prices and will contribute to a better investing climate for wind power and solar PV (Alvehag et al., 2016).

But not all devices and appliances are suitable for DR usage. Some might also only be suitable to a certain degree; either in order to not affect user comfort or not being able to regulate quickly enough for certain reserve markets.

According to Alvehag et al. (2016) the following areas could be suitable for DR on the residential side:

- EVs
- HPs and resistance heaters
- Freezers and refrigerators
- Lights
- Heating, ventilation and air conditioning (HVAC) units

DR can also be used in industries and commercial buildings. Apart from the residential ones mentioned above, which also could be applicable in the industry and commercial sector, some industries have a greater potential to regulate their processes. Some of these are the forestry, paper and pulp industry and food industry (Alvehag et al., 2016).

2.4. Demand response resources

2.4.1. Electric heating

There are many different kinds of HPs, but in general they all consists of the following four components:

- Evaporator
- Compressor
- Condenser
- Expansion device/valve

Through all these components a refrigerant/cooler fluid is flowing. The system has both a cold and a warm side. Thermal energy is absorbed in the evaporator by the cooler fluid from the cold side energy source, which can be ground/geothermal heat (GH), a lake or the outside air. The fluid, now in gas form, then passes the compressor, where both the temperature and pressure increases due to the decrease in volume. The now hot gas goes through the condenser, where a heat exchanger transfers the heat from the gas to the exchangers medium, either air or water. The transfer of heat makes the gas shift back to a liquid. In the expansion device/valve the pressure is lowered, and the device makes sure that the pressure difference between the cold and hot side is kept equal at all times. The now cool and low pressure fluid then passes the evaporator, where the fluid absorbs the heat from the source, as mentioned before, and is turned into a gas and the cycle repeats (Heat Pumping Technologies, 2021).

An important aspect of the HP is its efficiency, which is known as the coefficient of performance (COP). The COP value shows the ratio of heat compared to used electricity. It changes depending on outside temperature, as well as with the radiator temperature. The manufacturer usually calculates COP at a specified outside- and radiator temperature. The lower the temperature difference is between these two variables the higher the COP. If the radiators are few or small then a higher temperature is needed to get the same indoor temperature, which lowers the efficiency. Therefore floor heating is usually more efficient than normal radiators, since they have a bigger surface area and therefore can have a lower temperature. This also means that the COP lowers with decreasing outside temperature. Therefore it is most usually better to look for a seasonal coefficient of performance (SCOP) value, which uses the yearly mean outside temperature, and gives a more fair estimation of the energy usage. The mean outside temperature differs depending on where the HP is located, and manufacturers therefore often have SCOP values for different "climate zones" (Swedish Energy Agency, 2010c).

In table 1 the energy savings, compared to a system which uses an electric heater option with water as the heat carrier[4], can be seen. The pumps that use geothermal energy, as well as the water source, all have equal energy savings. From now on the term ground source heat pumps (GSHP) will be used for these heat pumps. These alternatives also have the highest savings. The air-water, air-air and exhaust air will collectively be called air source heat pumps (ASHP) in the rest of this report.

Table 1: Energy savings for different types of HPs (Swedish Energy Agency, 2010c).

Type of HP	**Energy savings***
Vertical geothermal	65-75 %
Horizontal geothermal	65-75 %
Air-water	50-70 %
Air-Air	30-60 %
Water source/lake water	65-75 %
Exhaust air	40-60 %

*The energy savings are in relation to a system that uses an electric heater and water as the heat carrier.

HPs with higher COP exists, but as mentioned before it depends on what radiator temperature and outside temperature there are. The COP value also varies with the outside temperature, as can be seen in table 2.

Table 2: COP for ASHP and GSHP for different ambient temperatures (Oehme, 2018).

Ambient air temperature (°C)	-20	-15	-10	-5	0	5	10	15	20
Lower value	1.5	1.9	2.5	2.7	3.6	3.8	4.0	4.5	3.6
Upper value	2.0	3	3	3.5	3.8	3.9	4.5	5.0	4.0
Mean COP	1.75	2.45	2.75	3.1	3.7	3.85	4.25	4.75	3.8

The HPs are usually dimensioned to cover more than 95 % of the total energy need. This often results in that the maximum power of the HP is approximately 65-70 % of the maximum power needed. A supplementary electric heater (SH) is almost always installed in or next to the HP, which turns on when the temperature outside is too cold and the HP cannot deliver enough heat (Swedish Energy Agency, 2010c).

The HPs can be controlled individually, for example by the owner, in which the owner can use different settings to change the usage given certain input signals such as power usage or price. Another way is if an operator has the ability to control a large amount of

[4] A common type of electric heater which is used to heat water is called an immersion heater. To avoid misunderstandings, immersion heaters will from now on be used when electric heaters in water is referred, since electric heaters could mean both the heaters that heat air and those that heat water.

HPs. If enough HPs are controlled by an aggregator then 90 % of the total regulatory capacity can be reached within 15 minutes. The reason for this is that the HP can be damaged if it is interrupted mid-cycle. It is possible to shut down the HPs quicker, but this might decrease the lifetime of the pumps[5].

The amount of energy passing through the building shell is directly related to the temperature difference between indoor and outdoor temperature. Therefore the heat losses decrease with time if no further heat is supplied, and the regulation time increases exponentially with an increase in allowed indoor temperature interval. Aside from temperature there are many other parameters which determine the amount the HP is able to regulate. One of the most important is the permeability of the outer parts of the house. The more easily that air can travel through the walls, floors and roof, the more heat leakage there will be. Another important factor is the thermal inertia. A building made out of stone has a bigger potential for regulation than that made out of wood, since it has a larger thermal inertia. A third factor is the amount of solar radiation through the windows and onto the walls (Persson et al., 2012). With all this considered, a typical normal sized detached family house has a thermal inertia which enables a 10 kWh heat loss before the temperature decreases with 1 °C. This is approximately the same regardless of the outside temperature. But the outside temperature has a big impact on the amount of regulation that is possible. With high outside temperature the power supply is low, and therefore the regulation degree decreases. Although as long as some power is needed, then it is possible to regulate small amounts for a much longer time. When the temperature outside is low the possible regulation is high. When the HP no longer is able to generate enough heat the supplementary heater is turned on, with a COP of 1. This means that more electricity is needed, and the possible power regulation becomes larger[6].

In order to be able to down-regulate, or reduce HP consumption, for a longer time a "pre-heating" of the building is possible, by increasing the amount of heat generated by the HP in advance. But a short time heating has a small effect on the thermal inertia, and the cooling effect is initially higher since much of the heat in the air is lost through ventilation (Persson et al., 2012).

[5] Björn Berg, CEO of Ngenic, online interview [5.2.2021].
[6] Björn Berg, CEO of Ngenic, online interview [5.2.2021].

2.4.2. Refrigeration processes

Refrigeration processes such as freezers and refrigerators is another resource that could be used for DR, both in private households, commercial buildings and in industries.

The refrigeration cycle is similar to the HP cycle mentioned in section 2.4.1 and based on same thermodynamic processes. A refrigeration fluid, refrigerant, flows through the system and is repeatedly converted between liquid and vapor form. The compressor, which is the component using electricity, increases the pressure and the temperature of the fluid from evaporation pressure (low) to condensing pressure (high). At high pressure the compressor pushes the vapor into the condensing coils outside the refrigerator where it is turned into a warm liquid. The condenser works as a heat exchanger rejecting heat to the surroundings with lower temperature which causes the phase shift. The next step in the process is the expansion device where the high pressure, now liquid, refrigerant is expanded. The pressure drops and some refrigerant is turned to vapor which decreases the temperature of the refrigerant. The evaporator coils, inside the refrigerator, also works as a heat exchanger. Here it is removing heat from the warmer surroundings, which is how the refrigerator inside is cooled. Absorbing heat increases the temperature of the refrigerant turning it into a vapor again where it enters the compressor and the cycle repeats. A thermostat controls the temperature by switching on and off the compressor (Ronzoni, 2020).

There are many different factors that determine when a refrigerator can participate in DR, mainly the maximum and minimum temperature allowed but also the ambient temperature and how often the refrigerator door is opened (Lakshmanan et al., 2014). The cooling demand is relatively consistent over the day but slightly increased during opening hours. Over the different seasons the cooling demand is higher during summertime when the outdoor temperature is higher (Grein and Pehnt, 2011). This indicates that there is higher DR potential during summertime. In a report based in the UK a seasonal factor of 0.75 of the average DR potential is used in week 1 and 1.12 during summer at week 29 (Cheng et al., 2015).

To make sure that the cold storage's primary function is not undermined when utilizing refrigeration for DR, a temperature span is allowed for when the cold storage can be turned on or off. In practice, this means that a refrigerator can be turned off for a while if it is cold enough, which corresponds to a discharging storage, or it can be turned on if it is warm enough which corresponds to a charging storage. When it reaches either minimum or maximum temperature the refrigerator has to be turned on or off again no matter what the frequency is if that is the regulation signal used for controlling the refrigerator. The temperature can be compared with the state of charge (SoC) of a battery.

A low temperature indicates a high SoC, because the cold storage can be turned off for a longer period "discharging" more energy and increasing the frequency of the grid. A high temperature therefore indicates a low SoC because there are fewer, or none, possibilities to turn off the cold storage. All cold storages can then be run in aggregated form to participate in regulation markets (Cheng, Sami and Jianzhong, 2016).

One refrigerator has a DR potential of approximately 100 W, simply because when the compressor is turned on the nominal power is 100 W and when it is turned off there is no power usage (Lakshmanan et al., 2014). Cheng et al. (2015) and Design & Engineering Services (2012) also state that the average DR potential of a refrigerator is 100 W, however the operational pattern varies from case to case and cycles can vary between 15 minutes and 1 hour. No major changes in efficiency occur when utilizing load shifting in refrigerators (Design & Engineering Services, 2012) and the recovery period, time turned on to reach minimum temperature, is shorter than time turned off when the refrigerator reaches maximum temperature (Lakshmanan et al., 2014).

A typical domestic freezer has a nominal power consumption of 70 W and a yearly demand of 208 kWh. During regular operation an on cycle lasts for 26 minutes and an off cycle for 40 minutes on average but the compressor could make cycles of five minutes without incurring mechanical damage (Baghina et al., 2012). The majority of load shifts in commercial and domestic refrigeration are 30 minutes (Grein and Pehnt, 2011).

Cooling applications is an important aspect in everyday life and vital for the food industry and the processing and availability of groceries. Cooling processes are also used in industries. To summarize, the main refrigeration systems can be split into the following categories:

- Commercial refrigeration in food-retailing
- Commercial refrigeration in warehouses
- Process cooling in industries
- Domestic refrigeration (Grein and Pehnt, 2011)

2.4.3. Lighting

The average energy usage in a year for lighting for a household in Sweden is 600 kWh and for Finland it is slightly above 700 kWh (Bring, 2018).

Regulation of lighting has existed for some time, and there are a few different ways to control the lighting demand. One of the more usual ones is a timer, which has set levels of light during different times of the day, week or year. One drawback with some timers is that they themselves consume energy. Another way is with motion detectors, which turns the lights on if someone is within the area. There are also sensors, which measures the amount of solar radiation and adjust the amount of light accordingly. The above solutions can be combined, and a dimmer can be used with the different systems to regulate to a specific degree of lighting (Benediktsson, 2009).

In a study called "Demand-responsive lighting: a field study" by Newsham and Birt (2010), they recommended to split lighting DR into two parts, which they called stage 1 and stage 2. The first stage is for when only smaller load reductions are necessary and where the changes should go unnoticed by the majority of people, while the second stage is for bigger reductions and where the noticeability of the changes are not as important. The limits that they recommend can be seen in table 3.

Table 3: Lighting limits for demand response (Newsham and Birt, 2010).

Stage 1			
	No daylight	**Low prevailing daylight**	**High prevailing daylight**
Rapid response	20 %	40 %	60 %
Slow response	30 %		80 %
Stage 2			
	No daylight	**Low prevailing daylight**	**High prevailing daylight**
Rapid response	40 %	40 %	80 %
Slow response	50 %		80 %

The rapid response is a change that happens within 10 seconds and the slow response should happen within 30 minutes or more. They also emphasize that the dimming process should only be temporary, and that it should only be used occasionally for a few hours at a time, and that these levels should not become the new "normal".

The numbers seen in table 3 might not be representative for many of today's systems. If the lighting already has some sort of control system, either based on photoreceptors which measures the amount of light/sunlight, or follows a time-based schedule, the potential might be much lower. Ryan Firestone, Contract Analyst at the Regional Technical Forum (RTF), made an investigation for which the focus was to find what kind of spaces are suitable for lighting DR as well as the possible potential in these spaces. The investigation was based on previously performed studies as well as discussions with different DR implementers, engineers and the RTF DR subcommittee (Firestone, 2021)). Firestone found that most of the previous studies were focused on offices and retail spaces, and that these were the most suitable for DR since they tend to be relatively large and have a homogeneous lighting load, which in turn can be dimmed without too much interference regarding productivity or safety. Most studies were made more than 10 years ago, and no newer studies were found. RTF still reached the conclusion that the findings in these studies would be applicable today in terms of percentages, although due to the development in energy efficiencies the total regulation for a similar building would be smaller in term of absolute numbers. The savings potential was estimated at 25 % for office-like buildings and 35 % for retail-like buildings. The regulation time period was one hour, and no more specifics were supplied. It also turned out that implementers of DR programs saw little participation for lighting, and small interest for it in the future. HVAC systems were perceived to be easier to regulate and cause smaller disturbances to the occupants (Firestone, 2021; 2019a; 2019b).

2.4.4. Ventilation and air conditioning

HVAC is often grouped together, but since HPs and immersion heaters (IH) have already been covered in a separate chapter, this section will focus on ventilation and air conditioning. The difference between ventilation and air conditioning is that the purpose of ventilation is to exchange to indoor air with new outdoor air, while air conditioning is supposed to make the air more comfortable, either by cooling or heating it, or by treating the new or circulating air to improve its purity or humidity. Ventilation can be divided into three different categories:

- Natural ventilation
- Exhaust air
- Exhaust and supply air

Both the exhaust air as well as the exhaust and supply air can be combined with a heat exchanger to reuse some of the heat from the building. The ventilation can also be coupled with a exhaust air HP. For more information on HPs see section 2.4.1.

In bigger buildings, such as apartments or non-residential buildings, two different ventilation systems exist, centralized and decentralized. Decentralized means that each apartment or building part have its own ventilation unit and separate control of the ventilation, while centralized means that all ventilation is aggregated from one point (Thors, 2014).

DR in ventilation is not widely used, but ventilation control is not unusual. Demand controlled ventilation (DCV) changes the rate of ventilation regarding, for example, the degree of particles. By using different sensors it can regulate the ventilation to compensate for increased or decreased occupancy, or other sources of emissions. Most ventilation units already have a lot of the necessary components in order to handle precise regulation, but may need to be complemented with different sensors and a controller that can communicate either with a localized or centralized control system (U.S. Department of energy, 2012).

There are a number of laws regarding the ventilation that must be followed when controlling the air flow, for more information see appendix B.1. If these demands are met then it is possible to regulate the ventilation. One way to do this is to track the occupancy, and in extension to this the amount of unwanted substances in the air. Occupancy in different locations can be measured in a few different ways. One of the most common methods is carbon dioxide (CO_2) sensing. Meters are placed either in the different spaces or in the return air ventilation shafts, and the amount of ventilation is then regulated by measuring the degree of CO_2. Another way to measure is with a more practical solution. In certain locations cameras, ticket sales or other means of counting could be used to estimate the occupancy (U.S. Department of energy, 2012).

2.4.5. Industry processes

According to Shoreh et al. (2016) DR in industrial loads is more complicated to implement in some aspects compared to DR in residential and commercial buildings. This is mostly due to the fact that many manufacturing processes are time-dependent and need scheduling, thus reducing flexibility. For the industry sector the best option for DR might be to use large consumers and utilize non-critical loads such as ventilation, lighting, heating, refrigeration and, if possible, also industrial processes. Suitable industries for DR are listed in table 4.

Table 4: Suitable industry processes for DR (Shoreh et al., 2016).

Industry	**Process**
Metal (Steel/Aluminum)	Smelting/electrolysis
Food	Refrigeration
Chemicals (Chloride)	Chloralkali process
Cement manufacturing	Grinding, crushing
Paper and wood pulp	Mechanical refining
Textile	Wrapping, weaving
Glass manufacturing	Electric furnace
Oil refinery	Catalytic cracking

There are not many energy intense industries on Åland and the total electricity consumption of the industry sector was 62.8 GWh, or 22 % of the total consumption, in 2019 according to ÅSUB (2019b). As a comparison, the electricity usage from the industry sector in Finland reached 40,610 GWh, or 47.2 % of the total consumption (Statistics Finland, 2019). The consumption used in industries in relation to the total consumption is much lower on Åland in comparison to Finland. There are 340 industry buildings of 171,052 m^2 on Åland, or 5.9 % of the total building area, (Statistics Finland's PxWeb databases, 2020) and 227 different industry enterprises (ÅSUB, 2019a).

2.4.6. Electric vehicles

EVs consists of two different types; purely electrical, also known as BEVs and PHEVs. PHEVs have both a battery and an internal combustion engine, and usually have a smaller battery than BEVs.

Instead of charging EVs directly when they plug into the charger, the option exists to move the charging to another time, where either the demand or price of electricity is lower. This is known as load shifting or unidirectional controlled charging (V1G). Many of todays chargers already provide this option. Vehicle-to-grid (V2G) is the next step in the development. It uses the car's battery as a temporary storage and can store and retrieve electricity from it. This further expands the flexibility of EVs as a DR resource. There are a few different concepts of this; V2G, vehicle-to-home/building (V2H/V2B) and vehicle-to-everything (V2X)[7]. In order to make V2G work both the charger and the EV need the correct protocols, and communication between the vehicle and the charger needs to be possible. A technical standard to simplify this communication has been developed, called ISO/IEC 15118. Some of the parts of this protocol have already been completed, while others is still under development. This protocol also enables something called "plug-n-charge", a charging and payment system which automatically handles identification and payment of parking and charging, and takes away the need for RFID-tags, apps or credit cards (Powercircle, 2020). According to Schram et al. (2020) the average round trip efficiency of V2G could be around 80 %.

The traffic patterns for passenger cars and their variations with both hourly, daily and monthly values, as well as particular data for bigger holidays, are described in Trafikvariation över året (eng: Traffic variations throughout the year) written by Björketun and Carlsson (2005). This is known as the annual average daily traffic (AADT). For passenger cars the traffic has been divided into four subgroups; tourist traffic, transit traffic, local traffic and public road average. Public road average is the overall average of the other categories, and is the number which will be used in this report. The variations for passenger cars can be seen in figure 2 and the variations for weekdays and over the year can be seen in figure 3.

[7] This report will use the name V2G from now on for all of these, since it is the most common expression out of the three.

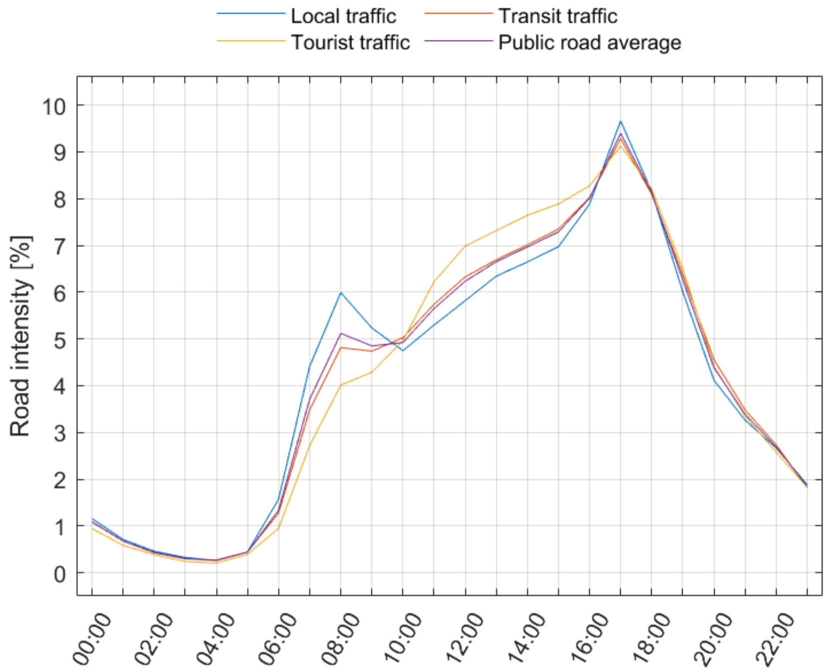


Figure 2: Road intensity for different traffic types throughout the day (Björketun and Carlsson, 2005).

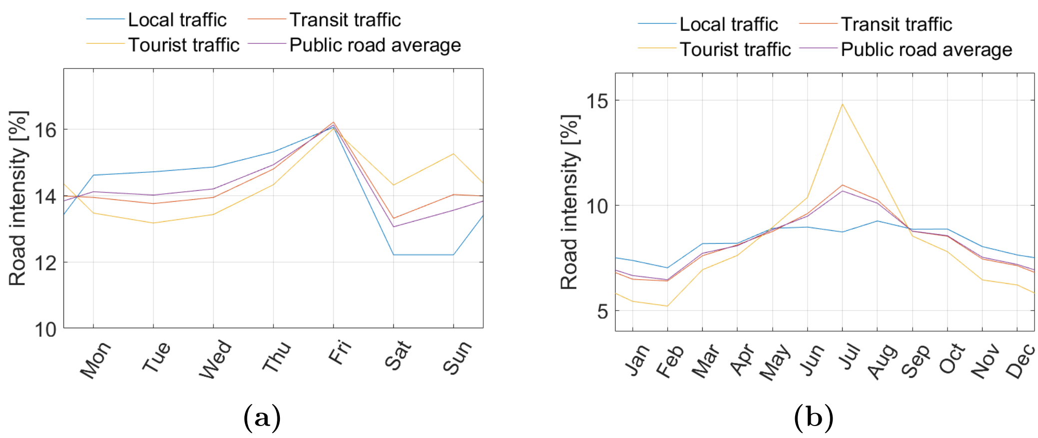


Figure 3: Road intensity weekdays (a) and monthly (b). The figures show how the intensity differs for different traffic types during the week and year (Björketun and Carlsson, 2005).

According to a few different studies, which have been summarized by Barter (2013), private vehicles are parked about 95 % of the time. This means that they are driving approximately 72 minutes each day.

2.5. Different use cases for demand response

Two different use cases for DR exists. These are called emergency-based regulation and economic-based regulation. The first one is used for frequency regulation, and changes the energy of the end-user depending on load signals, whereas the second case changes the energy usage with price signals, such as tariffs for example (Al Essa, 2017)

Regulation with DR can therefore be used with multiple purposes in mind and for Åland the following opportunities were identified:

- Optimization according to daily and nightly electricity tariffs
- Optimization according to SE3 spot prices
- Local flexibility market
- Other flexibility market
- Momentarily reduce the load to avoid exceeding max power limit of aggregated users

The Swedish reserve markets has been left out due to the reasons mentioned in section 2.2.2. Another approach, as previously described in section 2.3, is to utilize DR to facilitate the integration of renewable energy. By matching demand better with local wind and solar production, the investing climate for these technologies are improved.

2.6. PLEXOS Market Simulation Software

The software used to create the model in this work was PLEXOS by Energy Exemplar. It is a simulation-optimization software that, based on user-defined economic and technical parameters, can model, simulate and analyze energy systems and markets. The optimization algorithm will satisfy the specified demands to the lowest available cost. Therefore, the goal is to maximize profit regarding expenses and revenues from sold heat and electricity (Tomsic et al., 2018).

PLEXOS can be used for multi-objective decision optimization which involves maximizing or minimizing several objective function subject to multiple constraints. These problems can be solved with modern commercial solvers. CPLEX is one of the available solvers in PLEXOS and utilizes both blended and lexicographic optimization. Lexicographic optimization, also known as hierarchical optimization, has a priority order given by the different objective functions which allows the user to specify additional objectives compared to the regular cost minimization or profit maximization. A blended optimization is a linear combination of several objectives with specified weights. PLEXOS with the CPLEX solver can combine blended and lexicographic objectives in the same optimization problem where weight and priority are set for each objective. How this is handled in detail is by having the optimizer perform separate optimization steps, and for each step decrease priority. Every step is optimized based on its objectives multiplied by its weight attributes while applying constraints making sure that higher priority steps are not degraded (Papadopoulos, 2020).

3. Method and Data

The method and data section will walk through the same resources as in section 2.4. Each one will explain the methodology, assumptions and data used to reach the results regarding the DR potential on Åland of that specific resource. The goal is to minimize the impact on the users of the different resources. In other words the resources should be controlled in such a way that the primary function or comfort is not decreased.

Acquiring high quality data is vital to make accurate estimations regarding DR. This thesis focuses on a high level concept, aggregating the total potential for all of Åland. Therefore, the main methodology has been to split the buildings into different sectors where one DR-concept can be applied to a sector as a whole. Unfortunately, this detailed data does not exist for Åland in many cases. Data from Statistics and research Åland (ÅSUB) and Statistics Finland have been used. Interviews with the TSO and a DSO on Åland have been conducted, and contact with the government of Åland has been made. Data have also been provided directly from Flexens.

An important aspect is that data collected for different sectors can be outdated. Even if the yearly consumption is updated the customer may no longer be active in the same sector. There is no standard way of reporting data. Inconsistent grouping are therefore used among the different parties, which makes combining different data sets to acquire more detailed data in different sectors a complex matter and does not necessarily provide realistic results. Therefore, this report will be transparent with how data have been used and what assumptions that have been made. Data directly from Åland have been used as much as possible whenever it has been deemed applicable and otherwise mostly Swedish data have been applied to increase the detail and granularity of the data on Åland. The data gathered in section 3 will then either be used as input in the model or directly used as results for the DR potential.

A big source of data for this study was the STIL2 investigation, which included the sub-reports "Energianvändning i hotell, restauranger och samlingslokaler", "Energianvändning i handelslokaler", "Energianvändning i vårdlokaler", "Energianvändning i idrottsanläggningar" and "Energianvändning & innemiljö i skolor och förskolor". These included energy usage for, among other things, heating, refrigeration, ventilation and lighting for different building categories. ÅSUB had total building data for a category called commercial buildings, which included all hotels, restaurants, assembly buildings, retail stores, strip malls and supermarkets, but no specific data on the mentioned sub-categories. Therefore the buildings on Åland belonging to this category was divided based on a Swedish average of the relative area for the Swedish buildings provided by the

STIL2 study. This procedure has been used in the electric heating, refrigeration processes, lighting as well as ventilation and air conditioning sections.

In this study two different cases were examined, one for 2019 and one for 2030. The main factor that will determine the model results for 2019 and 2030 is the optimization goal. As previously mentioned, DR could be utilized for peak shaving, local optimization for renewable energy or price optimization after either reserve markets or the spot price of electricity. It was determined that a combination of peak shaving and local optimization currently is the most relevant scenario to examine for Åland. This is based on the fact that participation in the regulation market will likely not be available for Åland in the near future, which was addressed in section 2.2.2, and optimizing towards the spot price is not as economically attractive.

The import is a good flexibility measure since it is high either if local production is low or consumption is high. If there is local production available, it can be used directly and a peak in the consumption at the same time is not considered as a problem. Also, if there is no local consumption renewable electricity can be used to "charge" the DR resources, instead of exporting it. This will indicate how much more renewable generation that can be integrated when utilizing DR. Therefore, the optimization objective is to peak shave imported electricity and not the consumption. From an economical stand point, reducing peaks in the imported electricity could enable lowered connection fees. Load-shifting towards nighttime consumption is indirectly included. Since consumption peaks normally occur during daytime the model is likely to move daytime consumption to nighttime if it is technically possible for the resource. For the scope of this study, it is assumed that the number of each DR resource, except for EVs, are constant between 2019 and 2030.

3.1. Electric heating

The energy for heating can in theory be estimated by calculating the losses. But due to the lack of detailed building data this method was deemed too unreliable. For more information see appendix C.1.

Instead, the total amount of energy needed for heating was approximated by using an average energy usage per square meter, with statistics from a number of different sites and organizations. Data on electrically heated buildings were collected from Statistics Finland, and can be seen in table 5. These numbers do not include the buildings heated with a GSHP, which instead can be seen in table 6. The data included both the number of buildings for the different categories as well as the total gross area of the buildings in each respective group.

Table 5: Number of buildings for different house categories that uses electricity as main heat source and the respective total gross area [m2] (Statistics Finland's PxWeb databases, 2020).

Building type	**Number of buildings**	**Gross floor area [m2]**
Detached and semi-detached houses	3,234	441,118
Attached houses	128	45,362
Blocks of flats	32	17,995
Commercial buildings	703	55,417
Office buildings	26	5,376
Transport and communications buildings	299	26,750
Buildings for institutional care	11	3,548
Assembly buildings	49	9,390
Educational buildings	8	1,445
Industrial buildings	115	65,623
Warehouses	42	21,268
Other buildings	21	4,181
Total	**4,668**	**697,473**

Table 6: Number of units for different house categories that uses ground heat as main heat source and the respective total gross area [m2] (Statistics Finland's PxWeb databases, 2020).

Building type	**Number of buildings**	**Gross floor area [m2]**
Detached and semi-detached houses	898	171,582
Attached houses	48	19,409
Blocks of flats	20	18,153
Commercial buildings	17	11,240
Office buildings	2	581
Transport and communications buildings	12	979
Buildings for institutional care	8	9,055
Assembly buildings	3	5,069
Educational buildings	2	5,711
Industrial buildings	6	3,844
Warehouses	7	3,403
Other buildings	4	1,210
Total	**1,027**	**250,236**

Since the data in table 5 makes no distinction between the different ways to heat a building with electricity, the distribution between the different heating configurations was made with data from Swedish households, which can be seen in table 7. The distribution is assumed to be the same on Åland as it is in Sweden, and was directly translated to the small households (Detached and semi-detached houses) on Åland.

Table 7: Percentage of different configurations of electricity heated households in Sweden (Nilsson, 2020c).

Heating configuration	Number of households [1000-]	Percentage [%]
Direct heating no HP	82.032	13.796
Direct heating with HP	176.344	29.657
Water carried heat no HP	85.121	14.316
Water carried heat with HP	251.112	42.223

By combining data from table 5, 6 and 7 and data from Swedish Energy Agency (Nilsson, 2020c) the total amount of electricity used for the heating of small households could be calculated. This was done by multiplying the gross area for the small households with the distribution of heating configurations and their corresponding electricity usage. The results can be seen in table 8.

Table 8: Electricity usage for heating for small households on Åland.

Heating configuration	Air carried heat	Water carried heat	Ground heat	Total
Number of buildings in Åland (detached or semi-detached)	1,410	1,824	898	4,132
Gross floor area [m2]	215,749	279,255	171,582	666,586
Electricity usage for heating [kWh/m2]*	78.0	72.4	58.8	70.7[1]
Total electricity use for heating [GWh]	16.8	20.2	10.1	47.1

*Data from Swedish Energy Agency (Nilsson, 2020c)
[1]Mean value

The attached buildings was assumed to have the same electricity usage per square meter as the detached or semi-detached. The electric consumption per square meter for heating for the other buildings can be seen in table 9.

Table 9: Electricity usage for heating and warm water for different building types (Nilsson, 2020a, 2020b).

Heating configuration	**Electricity for heating with ASHP and IH [kWh/m2]**	**Electricity for heating with GSHP [kWh/m2]**
Blocks of flats	104.273	91.117
Hotels, restaurants, dormitories	137.441	125.095
Offices and administration	121.131	93.696
Supermarkets	184.488	140.766*
Other trade	130.304	99.423
All hours healthcare	108.522	95.597
Other healthcare	115.182	105.769
Educational buildings	131.281	101.804
Theaters, concert halls, movie theaters	130.563	96.181
Other buildings	123.967	116.130

*No value was available. This value has instead been calculated by taking the value for supermarkets for IHs and ASHPs, and scaling it with the difference from the category "other trade".

Tables 5 and 6 were then combined with table 9 to calculate the total electricity need for the remaining buildings. Some of the categories do not match exactly. For example, since the split in different buildings for institutional care is not known, all have been assumed to belong to *Other healthcare*. The *Commercial buildings* category has been divided into its sub-parts in the same way as can be seen in section 3. The sub-categories that do not have a directly correlating category, retail stores and strip malls, have been assumed to be *Other trade*. Finally, *Assembly buildings* have been paired with *Theaters, concert halls, movie theaters*.

This total electricity usage is both for heating and warm water. Since no information could be found for the separate usage the warm water usage was approximated to 20 kWh/m^2 (Andréasson et al., 2012). 20 kWh/m^2 is used as a standard for residential buildings, but has in this study been used also for the non-residential buildings. Since HPs need less electric energy compared to a normal electric heater to achieve the same heat the needed total heat was divided by SCOP[8] for the different HPs with a water medium. No information was given on how the directly heated buildings provide warm water, so it was assumed that they used an electric water heater with a SCOP of 1. No data could be found on how the water usage was distributed during the year, so it was approximated to

[8] SCOP is normally given as the COP-value for a lower specified temperature than what the standard COP is given at, but here it is instead used as the value directly corresponding to the energy savings seen in table 1.

be split evenly for each time interval, and thereby constant during the whole year.

The balance point temperature in all of the buildings was assumed to be 17 °C, which is the same balance point temperature used for example by the Swedish Meteorological and Hydrological Institute. Boverket (2010) did a study showing that the average indoor temperature for detached buildings was 21.2 °C, while it for apartment buildings was 22.4 °C, and that a balance point temperature of 17 °C was a good approximation in order to achieve these temperatures indoors. The heating need was assumed to directly follow the outside temperature in relation to the balance point temperature. It was also assumed that no cooling was needed, and therefore that the HPs and heaters were turned off completely when the outside temperature exceeded the balance point temperature. No added heating from solar irradiation was accounted for.

For the attached buildings, apartments and other non-residential properties no local data on what the split between different electric heating alternatives looked like could be retrieved. The attached buildings were assumed to have the same constellation as the detached and semi-detached buildings. According to Nilsson (2020a) there are approximately 20,600 ground heat/lake heat, 17,600 air-water/exhaust air and 2,500 air-air HPs in Sweden used in apartment buildings. There are 65,000 apartments heated by ground heat/lake heat and 55,000 apartments heated by electricity. Since there are approximately the same amount of GSHPs as there are air-water/exhaust air and air-air HPs combined, and the GSHPs are used to heat more apartments than the electrically heated, the assumption was made that all other electrically heated buildings uses a HP. The split was therefore made according to the absolute number of different HPs. This might not be entirely correct, since some of these HPs are not used as a primary source of heat but in combination with other heating methods[9].

A similar assumption has been made for the non-residential buildings. There are 12,495 non-residential buildings where the heat is supplied by electricity, and there are 5,900 air-water/exhaust air and 7,400 air-air HPs in non residential buildings in Sweden, giving a total of 13,300 HPs (Nilsson, 2020b). Given the same premise as with the apartment buildings, that some HPs are not used as the primary heat source, it could still be enough to cover all non-residential buildings. Therefore the assumption has been made that all electrically heated non-residential buildings are getting their heat supplied by a HP, and that the split on Åland is the same as in Sweden.

Since it is harder to regulate air carried heat systems, due to the fact that water has a much greater capacity to retain heat than air, the potential from air heating has been excluded in this thesis.

[9] Lars Nilsson, Swedish Energy Agency, phone interview, 2021.04.12

To calculate the electricity usage for heating in buildings with a HP an assumption was made that all aggregated HPs was dimensioned to cover 65 % of the maximum power need with the HP working at SCOP. This gave a maximum total installed capacity, which was then combined with the varying COP-values given in table 2. In the report by Oehme (2018) a semi-random COP value was used, which depended in part on different temperature spans, but it was also bounded by a lower and upper value for each span. For this study the mean of the lower and upper value for the different ambient temperatures from that study have been used instead. By multiplying the total power with the COP for each interval, a maximum HP heat production for each time interval was achieved. These values were then scaled so that the mean COP value for the different type of HPs for the whole year gave the same energy savings as given by table 7. All extra heat is then assumed to be handled by an immersion heater. By choosing a HP capacity of 65 % of the maximum heat power, with the rest being taken care of by the IHs, while using the SCOP-value derived by the energy savings numbers given in 7, an energy coverage of 95.5 % was achieved for the studied year. This seems to be in line with the statement in Swedish Energy Agency (2010c), which states that a HP is usually dimensioned to cover 65-70 % of the maximum power and more than 95 % of the energy.

All households have been aggregated, and the potential have been examined without direct regard to the perceived temperature in individual buildings. According to Björn Berg[10], an aggregated amount of HPs can regulate down with 90 % in 15 minutes, and if the regulation is assumed to be linear then 60 % of the active HPs can be turned down in 10 minutes. The rate of up-regulation of the HPs has been assumed to be the same. 60 % of the inactive capacity can be turned on in a 10 minute interval.

If 10 kWh of heat is removed from a household during one day the temperature will lower with about 1 °C[10]. The amount of electricity that can be moved depends on what kind of heating solution exists for the different households. A HP with a COP of 3, for the specific time period, can only move a third of the electricity, 3.33 kWh, compared to an electric heater which can move 10 kWh in order for the temperature to not decrease more than one degree. Using the distribution of heating alternatives given in table 7 for the number of households, and combining that with table 1 an estimation of the maximum heat and electricity that can be moved during one day can be calculated. In this study it has been assumed that the temperature is allowed to change by 1 °C both up and down without the inhabitants noticing a difference.

If the temperature is raised above the standard temperature then extra losses are obtained. Since it takes time for the air from the heaters and HPs to heat up the walls

[10] Björn Berg, CEO of Ngenic, online interview [5.2.2021].

and other surfaces, these extra losses has been assumed to be ventilation losses, and this has been included in the model. The ventilation losses can be calculated with equation 1.

$$P_{loss} = N * \rho * c_p * V * \Delta T \tag{1}$$

where N is the number of of times the total air volume in the building is exchanged during an hour, ρ is the density of air [kg/m^3], c_p is the specific heat capacity for air [kJ/(kg·K)], V is the volume [m^3] and ΔT is the temperature difference [K].

Both the specific heat capacity of air and the air density depends on the temperature, but at 20 °C the heat capacity is 1.007 and and the air density is 1.204. The average height in the households is assumed to be 2.8 meters, and the floor area is taken from table 8. The opposite is also true. When the temperature in the buildings is lower than the target temperature, the losses are lower as well. This has not been included in the model.

No normal year correction has been made for any numbers, since this is not possible to do for some of the other data used in PLEXOS. For more information on the software and how it is used see section 3.8 on page 36.

The results, which can be seen figures 6a and 6b in section 4.1, are then used as input files for the optimization in PLEXOS. A small detached household has been assumed to be 122 m^2, since this is the average size in Sweden (Boverket, 2020). The allowed movable energy per square meter and category has been calculated for the Swedish buildings, given the constraint that the temperature is only allowed to change with a maximum of 1 °C. This has then been applied to all building categories on Åland using electric heating.

3.2. Refrigeration processes

To model the DR potential in non-residential refrigeration processes on Åland the electricity consumption from these processes were required. The commercial buildings have been divided using the method described previously in section 3. For supermarkets, retail stores and strip malls there are STIL2 data regarding the electricity consumption per square meter for refrigeration processes exclusively. In hotels, restaurants and assembly buildings the electricity consumption is given for a whole kitchen. 37 % of the energy is used for refrigeration processes, including freezers and refrigerators and the remaining 63 % is used for cooking and dish-washing (Swedish Energy Agency, 2011; Swedish Energy Agency, 2010a).

The total yearly consumption as well as the consumption of refrigeration processes can be seen in table 10.

Table 10: Electricity use for commercial and assembly buildings on Åland.

	Total annual electricity [MWh]	**Electricity for refrigeration [MWh]**	**Category area [m2]**
Supermarkets	16,589	7,458	51,615
Retail stores	11,740	862	102,629
Strip malls	4,332	32.0	29,093
Hotels	3,565	407	30,759
Restaurants	1,793	392	4,999
Assembly buildings	4,212	93.1	71,877
Total	**42,232**	**9,245**	**290,973**

Supermarkets make up 81 % of the electricity demand for refrigeration even though the yearly consumption of super markets is only 39 % of the total consumption of commercial and assembly buildings. In aggregated form, the demand was assumed to be constant over the year for refrigeration processes, meaning that the average DR potential in momentarily reducing consumption was calculated by dividing annual refrigeration consumption with 8,760 hours.

There is data available for the number of buildings and total area of warehouses, but no information regarding if it is for storing wares at refrigerated temperatures or at room temperatures. Warehouses were therefore excluded from the potential of refrigeration processes.

For households a different methodology was used. The number of households were 14,085 at the end of 2019 (Häggblom, 2020) and it is assumed that each home has one refrigerator and one freezer. The same assumptions regarding the ambient temperature and varying daily demand as for commercial buildings were used, meaning that the DR potential is constant over the year.

The cycle pattern for freezers and refrigerators as well as commercial is assumed to be the same for the scope of this study. Even if the length of cycles might differ the slope of the temperature change during an on-cycle and off-cycle are similar. When modelling aggregated households and commercial buildings without data of specific cooling equipment, a more detailed estimate is difficult to acquire.

The combined nominal power in a refrigerator and a freezer is 170 W. This power is drawn 40 % of the time, which in aggregated form corresponds to an average power of 68 W since cycles are assumed to evenly overlap between different units.

To implement commercial refrigeration in the model constraints regarding availability and recovery times have to be included. A maximum cycle length of 30 minutes has been applied. As previously mentioned, the compressor cycle can be shortened to five minutes but due to the model resolution being 10 minutes, the minimum cycle length has also been assumed to be 10 minutes. More information regarding the general model and the modelling resolution can be seen in section 3.8.

The refrigeration processes were modelled in PLEXOS to replicate the behaviour of turning off available refrigeration, equivalent to discharging, or turning on available refrigeration, equivalent to charging, with the relevant constraints mentioned above. Turning on refrigeration can be done with higher power, in comparison to turning off refrigeration, since on average 60 % of the refrigerators are momentarily turned off during normal operation. Load shifts were set to a maximum of 30 minutes and were used in combination with the on/off-rate of 40/60 % to calculate the storage size.

3.3. Lighting

To calculate the possible DR potential for lighting a number of data sources have been combined. First of all, building data from Statistics Finland, have been used (Statistics Finland's PxWeb databases, 2020). Commercial buildings have been divided according to the same procedure as previously described in section 3. By multiplying the energy usage per square meter for lighting, provided by Swedish Energy Agency (2010a) and Swedish Energy Agency (2011) included in the STIL2-study, the total electricity usage for the different subgroups could be calculated. The lighting usage for different sectors on Åland as well as their size can be seen in table 11.

The energy usage of lighting for households have been calculated in a different way. According to Häggblom (2020) the total number of households on Åland is 14,085. The total energy usage from households (detached or semi-detached houses on Åland, attached houses and blocks of flats), was calculated by multiplying the number of households on Åland with the total yearly energy usage for one household, assuming the same usage as in Sweden. For industries, the lighting usage might differ greatly from industry to industry and no approximate value could be found. These buildings have therefore been excluded from the total potential lighting DR.

Lighting schedules for different building types have been used to get an estimation on when and how the lighting in different buildings are used. Since no such data was available for Åland, numbers from the National renewable energy laboratory's (NREL) report "Commercial Reference Building Models of the National Building Stock" have been used (Deru et al., 2011). No schedule could be found on transport and communications buildings and assembly buildings, and these were therefore not included in the calculation of the total potential. Industries have the same problem with the schedule as with the energy usage, it varies greatly regarding operation type and is therefore hard to generalize.

Table 11: Lighting usage for Åland in different buildings.

Sector	**Area m^2**	**Lighting usage (kWh/m^2)**
Commercial buildings (excluding hotels and restaurants)	154,004	71.4[1]
Retail stores	86,169	58.7[1]
Strip malls	23,834	84.4[1]
Supermarkets	44,001	89.5[1]
Hotels	30,759	52.4[2]
Restaurants	49,993	29.3[2]
Office buildings	130,976	21.4[3]
Transport and communications buildings	101,457	N/A
Buildings for institutional care	84,893	22.1[3]
Assembly buildings	71,877	25.8[2]
Educational buildings	104,099	21.4[3]
Industrial buildings	171,052	N/A
Warehouses	89,236	0.0103*[1]
Other buildings	14,297	N/A

*kW/m^2, not kWh/m^2, [1]Swedish Energy Agency (2010a), [2]Swedish Energy Agency (2011), [3]Swedish Energy Agency (2010b)

More in-depth studies on the specific industries on Åland needs to be performed in order to evaluate the DR potential. Buildings for institutional care consists of healthcare buildings, social work activity buildings and prisons. Even though hospitals have a schedule and a lighting usage, this entire sector has been excluded as well, with the motivation that it could be potentially harmful to lower the lighting in certain areas in this sector. Since further knowledge on how the exact split and usage looked could not be required, no reliable estimation could be made. Examples and further description of the lighting schedules for the studied buildings can be seen in appendix D.

The total area, schedule and and energy usage have been combined to create a vector with yearly values for the total energy usage for lighting for different buildings. The vectors have then been multiplied by 0.3, see table 3 in section 2.4.3, in order to get the DR potential for the slow response, which have then been used as input in PLEXOS. The slow response has been used since frequency regulation is not investigated in this study. In the model, it is assumed that lighting can be decreased for a maximum of four hours and then requires the same amount of time to recover. Lighting DR has been set to activate when the import reaches two thirds of the maximum import capacity in order to only participate during the peaks.

3.4. Ventilation and air conditioning

The modelling of air conditioning, or other comfort cooling, will not be included in this thesis due to the fact that there is not enough relevant data available for Åland.

For ventilation, the building data for commercial buildings have been divided according to the same procedure mentioned previously in section 3. The area have then been multiplied by the energy usage for ventilation. Table 12 shows the energy usage per square meter and the calculated total energy usage for ventilation for the different buildings.

Table 12: Energy usage for ventilation for different type of buildings.

Type of building	**Gross floor area [m2]**	**Average usage [kWh/m2]**	**Total energy usage [GWh]**
Retail stores	86,169	19.1[1]	1.65
Strip malls	23,834	23.7[1]	0.56
Supermarkets	44,001	23.9[1]	1.05
Hotels	30,759	27.0[2]	0.83
Restaurants	49,993	59.6[2]	2.98
Office buildings	130,976	18.0[3]	2.36
Buildings for institutional care	84,893	29.3[3]	2.49
Assembly buildings	71,877	15.3[2]	1.10
Educational buildings	104,099	21.0[3]	2.19

[1]Swedish Energy Agency (2010a), [2]Swedish Energy Agency (2011), [3]Swedish Energy Agency (2010b)

In this study it has been assumed that all investigated buildings have some sort of demand controlled ventilation, which turns the ventilation off at night. The operating hours for the different buildings, as well as the calculated average power usage given these operating hours, can be seen in table 13. When the ventilation is turned on it is assumed that it runs continuously, which means that every hour it is turned on it consumes the same amount of energy.

Occupancy schedules from Deru et al. (2011) were used to see when the first persons arrive to the different buildings. The standard case was assumed to be that the ventilation turns on one hour before the first building occupants arrive, and has the energy consumption calculated above. Even if the ventilation, on average, only needs to be on for about half an hour to completely renew the inside air, see appendix B.2 for more information, one hour was used to make sure that all air has been ventilated. In the DR case it was instead assumed that the ventilation could be turned on within a specified number of hours before the first occupants arrive. In the model the number of hours were set to three, meaning that the optimization tool will choose the most favourable intervals

Table 13: Ventilation operating hours for different buildings.

Type of building	Operating hours Sweden	Average power [MW]
Retail stores	4,091[1]	0.402
Strip malls	4,449[1]	0.127
Supermarkets	5,747[1]	0.183
Hotels	6,100[2]	0.136
Restaurants	4,600[2]	0.648
Office buildings	4,100[3]	0.575
Buildings for institutional care	6,670[3]	0.373
Assembly buildings	2,800[2]	0.393
Educational buildings	3,530[3]	0.619

[1]Swedish Energy Agency (2010a), [2]Swedish Energy Agency (2011), [3]Swedish Energy Agency (2010b)

within these three hours, before the first occupant arrive, to turn on the ventilation.

3.5. Industries

To determine the DR potential in industries, each type of industry needs to be analyzed individually due to different industry processes. Calculating the potential in other DR areas, such as heating and cooling, is also challenging to do in aggregated form since all industries are not necessarily aiming towards standard room and/or refrigeration temperatures. Therefore, 12 larger industries within different industry areas on Åland were contacted and asked about an estimation of their DR potential. They were also asked how familiar they were to the concept of DR and if they would be interested to participate in a DR project if the economic compensation was sufficient. The form is included in appendix E. 25 % of the candidates replied to the form and the individual replies have been kept confidential. The number of replies was deemed too low and uncertain to be representative for the industries on Åland, and the potential from industries was therefore omitted in the following calculations and simulations.

3.6. Electric vehicles

To calculate the DR potential of EVs on Åland, an average driven distance per vehicle was needed. The daily driving distance was calculated to 23.9 km which corresponds to an electricity demand of 1.7 MWh per EV annually. The calculations can be found in appendix F.1. There is no data for Åland on how the driving distance is divided throughout the day, week and year. It is possible to use a recurring driving pattern each day, with variations for example weekdays and weekends. But to get a more dynamic model, driving pattern data from Sweden have been used, seen in section 2.4.6. These data have then been combined in order to get a varying driving pattern and charging demand for each hour during the year 2019. It has been assumed that the driving patterns are the same in both Sweden and Åland, that the driving patterns for EVs are the same as for cars in general and that they will be the same in 2030. By using the pattern for driving regarding daily, weekdays and yearly variation, and that cars are parked 95 % of the time, an hourly probability of how many cars are parked during a certain time has been calculated.

At the end of 2020 there was a combined battery storage from electrical vehicles of 4,500 MWh in Sweden (Power Circle, 2021). The same average battery capacity for one EV is assumed for the cars on Åland for the case of 2019, calculated to approximately 24 kWh per vehicle.

The exact number of EVs in Åland in 2030 is hard to estimate. If a similar percentage of EVs compared to the total number of cars is assumed to be the same as in Sweden, then the number of EVs in Åland would be somewhere between 5,200-13,800, see appendix F.2 for more information. Given the broad interval and the uncertainty of the calculations, the number estimated by the Åland government for 2030, mentioned in section 2.1, has been used instead. The distribution between BEVs and PHEVs has not been determined.

By combining the energy use of an average EV with the traffic intensity allowed EVs to be modelled as an aggregated DR resource for the different cases for 2019 and 2030. An average EV profile, with the yearly electricity demand as described above, was used along with an average battery capacity of 24 kWh for 2019 and 48 kWh for 2030. The aggregation takes into account that depending on the current road intensity only a certain percentage of the cars are able to charge. For the standard case it was assumed that cars start to charge directly after they return from a driving session, which were based on hourly intervals. With DR cars are allowed to load shift to a certain extent as long as there is still enough SoC to drive a daily demand without any more charging. For 2019, 236 EVs were modelled with a maximum charging power of 3.7 kW and no discharge, V2G, was allowed. For 2030 both slower and faster charging, 3.7 kW and 22 kW respectively, were tested with 4,000 EVs. V2G was also examined by allowing charging and discharging of 22 kW for all EVs. There are no forecasts for the implementation of V2G on Åland in 2030, therefore a scenario with V2G in all EVs was examined to determine the hypothetical potential if V2G was to become the standard for new EVs. For V2G, a round-trip efficiency of 80 %, see section 2.4.6, was assumed and used in this scenario. The other parameter choices, charging power for 2019 and 2030 and battery capacity for 2030, were uncertain and were based on what could be assumed as a reasonable average.

3.7. Economic analysis

To calculate capital expenditures (CAPEX) for water carried electric heating the number of necessary installations have been assumed to equal the number of buildings with said heating systems. The unit cost, and therefore the cost per building, was set to 493 €[11] and was assumed to be installed by the owner. No commercial alternatives was found for refrigeration, but since the principle for controlling thermal appliances are the same it was assumed that the unit cost was the same for refrigeration as for electric heating. For the domestic refrigeration it was assumed that one controlling unit per household was required. In commercial refrigeration two different cases were examined: one where only one unit per building was required (low) and one where the same price per MW as for domestic refrigeration was used (high). The latter case was investigated to account for several units per building in, for example, a supermarket.

Ventilation has been assumed to have the possibility to turn off during nighttime meaning that there already is some controlling equipment in place and therefore there is zero CAPEX for DR in ventilation. The same has been assumed for EVs since charging stations usually come with some smart charging, like load shifting, directly from the manufacturer. Battery depreciation from increased charging/discharging cycles has been neglected in the scenario with V2G. Economics in industries have not been analyzed at all due to the limitations in estimating the potential and lighting was also excluded since it is unclear what change in lighting infrastructure that would be required to enable DR. Calculating relevant operating expenses (OPEX) has not been considered to be within the scope of the study but will be mentioned in the discussion.

The cost of flexibility, [€/kW], was then acquired by dividing the CAPEX with the corresponding max load reduction [MW] in the simulations. The storage cost is simply the CAPEX divided by the storage size [MWh] for each resource which has been calculated and presented in section 4.1 and 4.2 for heating and refrigeration respectively.

Due to the lack of detailed CAPEX and OPEX estimations two further economic parameters were investigated. Firstly, the cost of a corresponding battery storage to reduce the peak of import in a similar manner to how DR did in the simulations for 2019 and 2030 were examined. Secondly, the savings that would occur from lowering the maximum interconnection to Sweden were calculated using the subscription fee mentioned in section 2.2.2.

[11] Price taken from the commercial solution Ngenic Tune, developed by Ngenic and available at: https://ngenic.se/en/tune/ SEK to EUR conversion via https://www.valuta.se/ [2021-05-17]

3.8. PLEXOS model

At the start of this thesis work there was an existing PLEXOS model for the Åland energy system available, developed by Flexens. This model contains the local generation and demand, integrating both the electricity and the heat sector, as well as the interconnection to Sweden. The model was previously based on historical data with hourly resolution from 2017 but has been updated to more recent numbers from 2019. This data was provided by Flexens' energy portal where local TSOs, DSO and electricity suppliers upload hourly data of production and consumption. The already existing base model was used as starting point but was reworked to suit the purpose of DR. Each resource was modelled with the corresponding input data that have been either directly entered from other sources or simulated through MATLAB.

To model the DR resources in this study with the goal to optimize their consumption regarding import, firstly the data granularity had to be improved since many resources have shorter load shifting spans than one hour. To improve the resolution, hourly data had to be manipulated, see appendix G, since there were no sub-hourly data available.

The 2019 case, as described by Lindqvist et al. (2019) and mentioned in section 2.1, was slightly adjusted to fit the historical data acquired during the thesis work. For 2030 the same prediction was used with the exception of the minimum load which was set to the same value as the for the real data from 2019. The different consumption and production for 2019 and for 2030 can be seen in table 14.

Table 14: System parameters for 2019 and 2030.

Parameters	**2019**	**2030**
Consumption	313 GWh	400 GWh
Wind capacity	20.9 MW	170 MW
Solar capacity	1.2 MW	15 MW
Peak load	64.1 MW	85 MW
Minimum load	18.2 MW	18.2 MW

For the 2030 consumption a built in linear growth algorithm for load forecasting in PLEXOS was used. The algorithm adjusts to the projected annual consumption as well as maximum and minimum consumption peak.

The model was run with a solution step-size of one day plus a one day look-ahead. This indicates that the decisions made in the optimization can only see the forecast for the current and the upcoming day when deciding how to charge/discharge a storage for example. This setting was used to replicate a day ahead market where the approximate consumption and generation is known in advance. Using a look-ahead is important for the optimization since this means that there will never be a decision taken without any information regarding the next day.

3.9. Sensitivity analysis

There are many assumptions made in this thesis, and making a comprehensive sensitivity analysis of all parameters that might change the results would not be feasible. Instead a few key parameters have been examined and adjusted to see how they affect the results. The different investigated parameters were temperature span allowed in electrically heated buildings, oil and gas heated buildings being converted to electrically heated in 2030, lower wind capacity projection in the 2030 scenario and model optimization steps with 1 week + 1 day look-ahead instead of 1 day + 1 day look-ahead steps.

In the standard model a maximum temperature shift of 1 °C up and down from preferred room temperature was allowed in buildings. The temperature shift is a key parameter since the indoor temperature is the main factor that could decrease resident comfort, but increasing the temperature span also increases the storage and therefore the DR potential. It is also a parameter that can be freely chosen by the user. Therefore, two different cases have been examined. First, when the temperature change was allowed to be only 0.5 °C up and down from preferred room temperature and second, when the change was allowed to be 2 °C up and down.

As of the end of 2019 there were 3,693 residential buildings[12] that used oil or gas as main fuel. Therefore a scenario for 2030 where all of these buildings change to electric heating, with HPs using a water carried heat system, has been examined. Since this is a theoretical scenario there is no information on how the split between GSHP and ASHP might look, and an equal split between the two has been assumed.

Currently a 40 MW wind farm, called project Långnabba[13], is being constructed on Åland which is planned to be up and running by 2022. This will bring the installed wind capacity up to approximately 60 MW instead of the 170 MW otherwise used in the 2030 scenario. At the moment, it is unsure if all of the planned wind turbines for 2030, reaching a total capacity of 170 MW, will be installed. Due to these insecurities, a case was examined where the total installed wind capacity was 60 MW instead of 170 MW.

Finally, the step size of the model optimization was examined. The default step size described in section 3.8 is relevant regarding electricity markets. However, regarding temperatures which determines the heat demand a longer solution step could perhaps also

[12] 3,442 detached/semi-detached houses, 61 attached houses and 192 blocks of flats, with a combined area of 627,547 m^2 (Statistics Finland's PxWeb databases, 2020)

[13] https://vind.ax/

be used, especially since electric heating is the major DR resource on Åland. A longer solution step of 1 week plus a 1 day look-ahead was therefore examined in the sensitivity analysis.

4. Results and Analysis

The results have been divided into subsections for each DR resource so that the individual potential of each resource in 2019 can be visualized. The reason for this is that an individual resource might have a larger potential on its own. When combining several resources in the optimization, they will work together and an individual resource might not necessary utilize its full DR potential. The total combined potential of all resources for 2019 and the possible potential 2030 will then be presented.

The 10 minute profile for 2019 is visualized in figure 4. The annually produced wind and solar power for 2019 was 57.7 GWh and 1.4 GWh respectively and the consumption was 313 GWh.

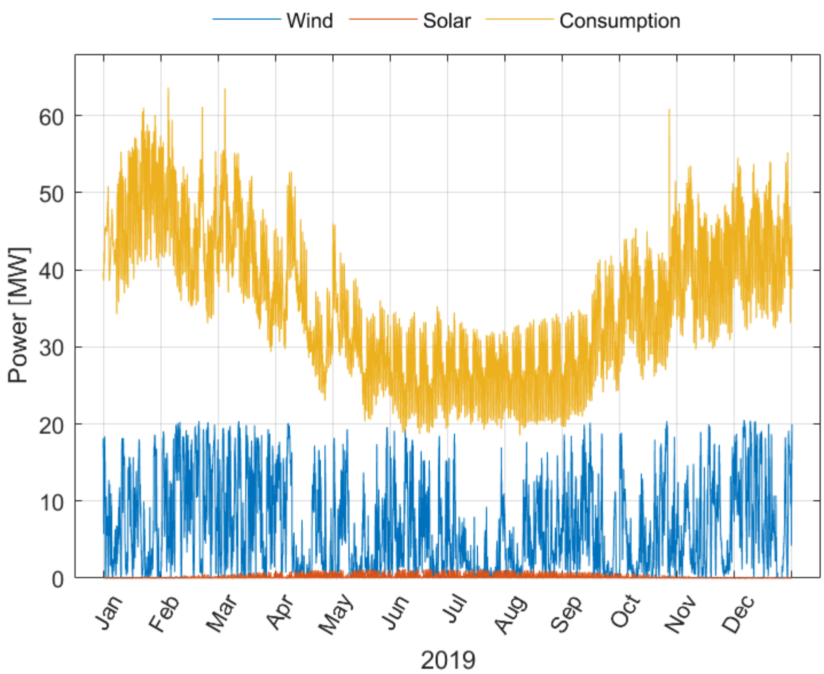


Figure 4: Wind and solar production as well as electricity consumption, for the year 2019.

A flow chart of the estimated energy production and consumption, in 2019, from the different sectors can be seen in figure 5. The energy consumption is the total estimated consumption of each resource and does not indicate the DR potential. Table 15 is a summary of individual model runs where one DR-resource at the time has been activated to analyse the maximum potential of each resource. HPs are the largest contributor of flexibility followed by IHs. The maximum load reduction of HPs is larger than the maximum load reduction of all other resources combined. It should also be noted that

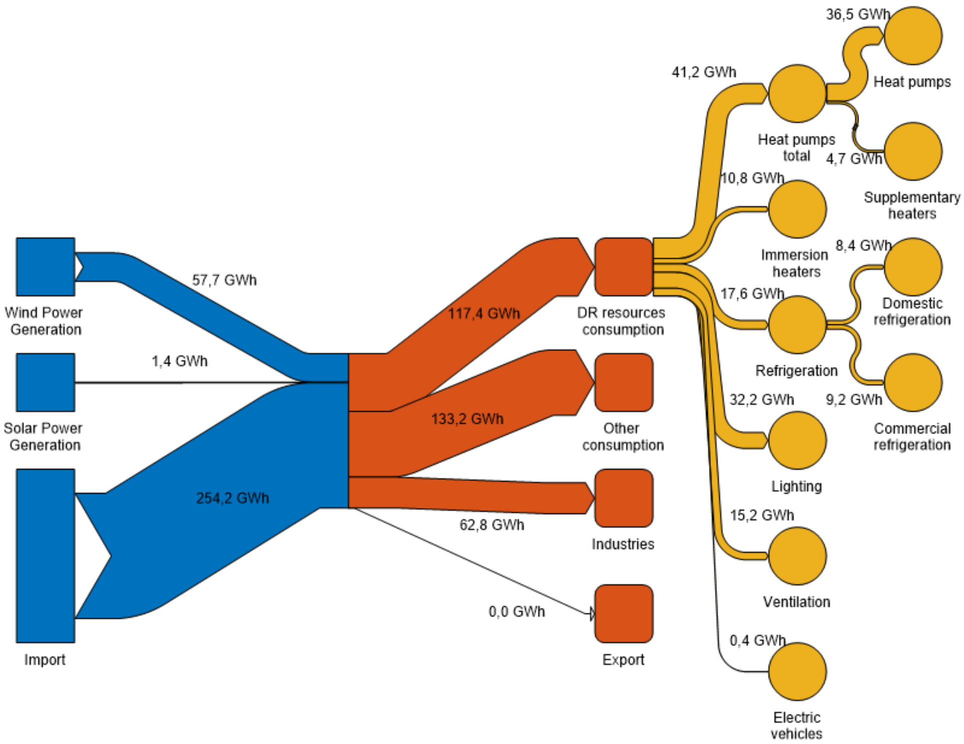


Figure 5: Energy balance for Åland in 2019.

Table 15: Total load shift in different DR resources for 2019, average and peak reduction as well as hours load shifting has occurred.

DR Resource	**Load shifted [MWh/year]**	**Load reduction [h/year]**	**Average load reduction [MW]**	**Max load reduction [MW]**
HPs	7,774	4,564	1.70	13.3
IHs	3,767	4,749	0.79	3.26
Commercial refrigeration	1,664	2,592	0.64	1.06
Domestic refrigeration	1,531	2,772	0.55	0.96
Lighting	N/A	73	1.22	2.02
Ventilation	431	1,103	0.39	0.76
Industries	N/A	N/A	N/A	N/A
Electric vehicles	388	7,995	0.05	0.15

the values regarding load shift and maximum reduction in this table cannot be added together, since they might not occur at the same time for different resources. Furthermore, the maximum load reduction does not necessary happen at the highest import peak since the availability of the resource might not be at it's highest. The load reduction column indicates how many hours during the year that the overall load has been decreased, which corresponds to decreased import since that is the optimization goal. The remaining hours of the year the consumption is either increased or is at its default level, since resources need to recover or, for example, houses can be pre-heated to decrease consumption at a peak that is expected.

4.1. Electric heating

The number of residential buildings that uses water carried electric heating can be seen in table 16, together with the calculated electricity usage and heat production from electric heating. The electricity usage from these is almost four times the amount of electricity usage in the remaining buildings on Åland, seen in table 17, and therefore make up around 4/5 of the potential. Since all remaining buildings with water carried heating are assumed to either use a ASHP or a GSHP all of the potential from IHs comes from households.

Table 16: Total electricity usage for heating for households.

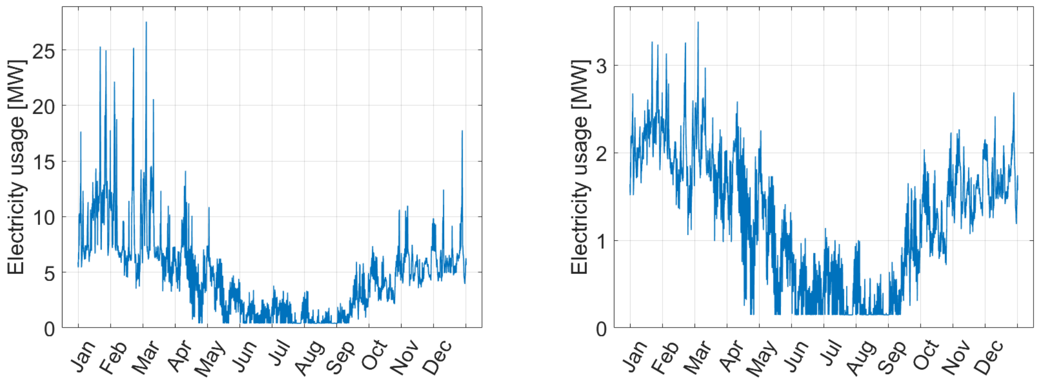
Heating configuration	ASHP	IH	GSHP	Total
Number of buildings:	1,448	481	966	2,889
Gross floor area [m2]	221,726	72,218	209,144	499,347
Total electricity use for heating [GWh]	17.3	11.4	12.9	41.6

Table 17: Total electricity usage for heating for remaining buildings, excluding industries.

Heating configuration	ASHP	IH	GSHP	Total
Number of buildings:	565	0	61	627
Gross floor area [m2]	56,505	0	37,248	126,708
Total electricity use for heating [GWh]	6.54	0	3.95	10.5

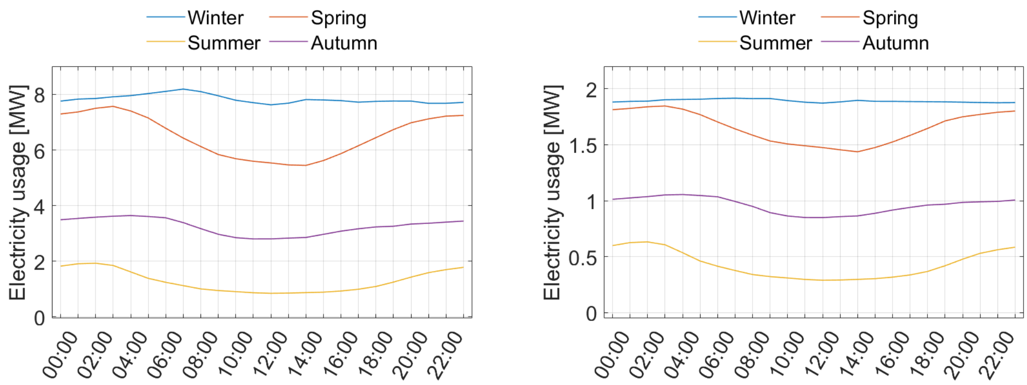
The estimated electricity usage for all buildings on Åland with water carried heat can be seen in figure 6a and 6b. HPs have a maximum capacity of 7.76 MW. The high peaks in the electricity usage for HPs come from cold periods when the supplementary heaters with lower efficiency are needed. These peaks are not noticeable in buildings without HPs since the COP is always 1.

The seasonal mean usage for the two water carried heat systems, HPs and IHs, can be seen in figure 7a and 7b. This gives an indication on how much the average usage during each hour of the day varies for the four different seasons, and gives an approximation on the mean regulatory potential for electric heating. All seasons except winter have a lower usage during the day. Lower usage means that the potential for regulation is lower during those hours.



(a) (b)

Figure 6: Electricity for heating and warm water in all buildings with HPs (a) and in buildings with IHs (b) for 2019.



(a) (b)

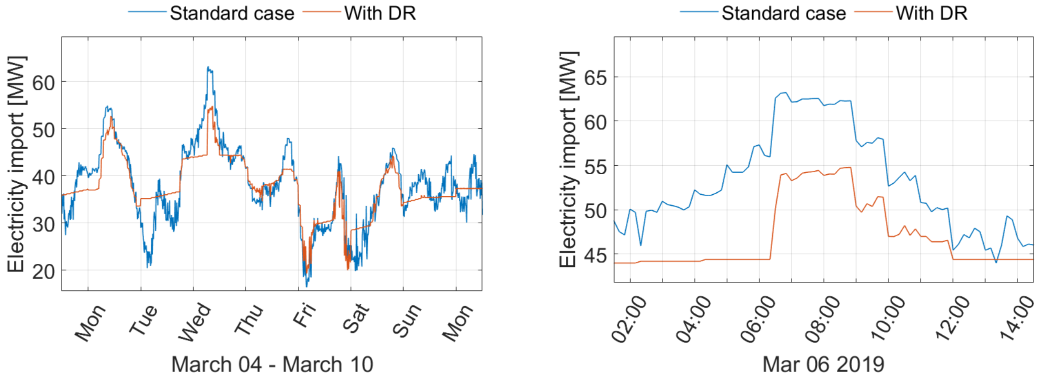
Figure 7: Daily mean usage of electricity for heating and warm water in all buildings with HPs (a) and in buildings with IHs (b) for 2019, divided into the four seasons.

The maximum available heat that can be moved, which can be seen as a kind of virtual storage, for water carried heat systems is 48.6 MWh[14]. If the average SCOP for the different HPs is used, then the buildings with HPs have the capacity to store 15.1 MWh of electricity and buildings with IHs can store 5.33 MWh.

Figure 8 shows how the import has changed when electric heating in buildings are used as a DR resource. During the hours with the highest import the peak has been reduced with 8.5 MW, from 63.2 MW to 54.7 MW. The reduction has been sustained for over 10 hours with an average import reduction of about 7.4 MW between 02:00 and 12:00, as seen in figure 8b.

How the temperature in the buildings varies for the same week can be seen in figure

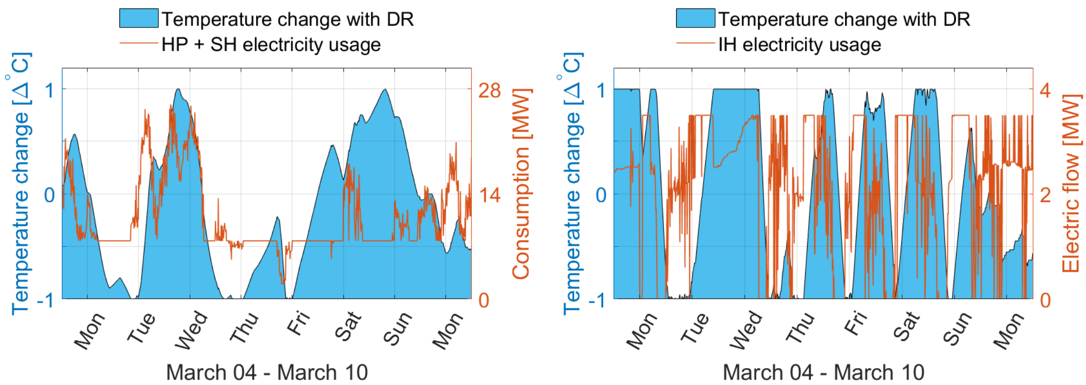
[14] For example when the temperature is allowed to be decreased from one degree above to one degree below reference temperature.



(a) (b)

Figure 8: Comparison between the standard case and when using all electric heating as a DR resources on Åland for the week (a) and hours (b) where the highest import for 2019 occurred.

9. The flow is increased during Tuesday while heat is stored in the building before the highest import peak, and the temperature reaches 1 °C above reference temperature for both the buildings with HP (9a) and those with only an IH (9b). The temperature is then allowed to lower and the flow can be minimized during the peak.



(a) (b)

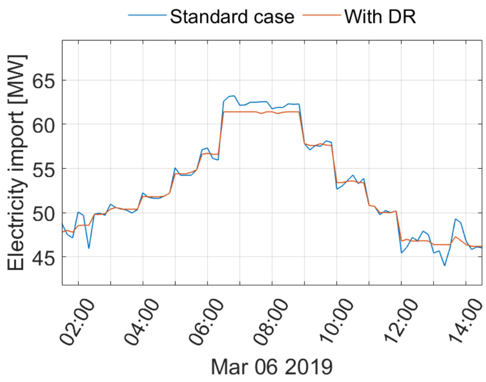
Figure 9: Change in indoor temperature when using HPs and SHs (a) and IHs (b) as a DR resource for the week where the time of highest import occurred. The figure also shows the correlating electricity usage for the two heating configurations.

4.2. Refrigeration processes

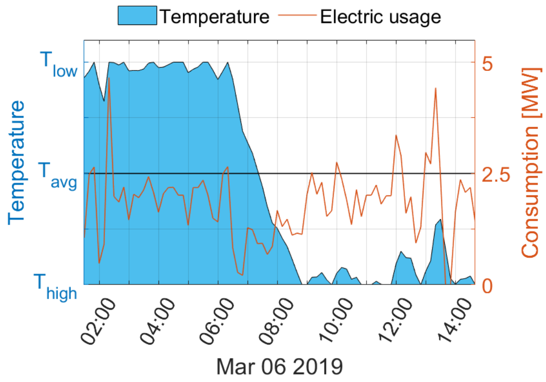
The DR potential for refrigeration processes in commercial buildings was calculated to 1.06 MW when reducing the load and 1.59 MW when increasing the load. The corresponding electrical storage was calculated to 1.32 MWh. Commercial buildings consist of supermarkets, retail stores, strip malls, hotels, restaurants and assembly buildings. Supermarkets make up 81 % of the DR potential of commercial buildings.

For domestic refrigeration, the DR potential was calculated to 0.96 MW when reducing the load and 1.44 MW when increasing the load based on the number of households which is 14,085. The storage was calculated to 1.20 MWh.

Figure 10a shows how much the import has been lowered when using refrigeration processes on Åland as a DR resource. The import peak has been lowered with 1.8 MW, and for the time period with the high peak occurs, between 06:30 and 08:50, the average reduction was 1.0 MW.



(a)



(b)

Figure 10: Comparison between the standard case and when using refrigeration processes in both commercial and residential buildings as a DR resource for the hours around where the yearly highest import occurred (a) and how the temperature in the refrigerators and freezers change for the respective intervals (b) for 2019 and their respective electricity usage for heating.

Figure 10b shows how the temperature changes during this peak within the accepted levels. The electric usage of the refrigeration processes lowers while the temperature increases during peak import hours. It can be seen that the aggregated refrigeration is pre-cooled to the lowest temperature allowed to prepare for the peak and only make small adjustments to the temperature between 02:00 and 06:00. Since the standard consumption to maintain average temperature is approximately 2.0 MW the temperature will decrease with higher consumption and increase with lower consumption which can be seen after 06:00 when the temperature starts to increase and the consumption decreases. When the temperature has reached minimum or maximum limits, there is no more availability to further increase or decrease the consumption. At maximum temperature the corresponding max up-regulation, increasing the load, is available. At minimum temperature the corresponding max down-regulation, decreasing the load, is available.

4.3. Lighting

The average weekday DR potential for the different sectors, given a slow response, can be seen in figures 11a and 11b.

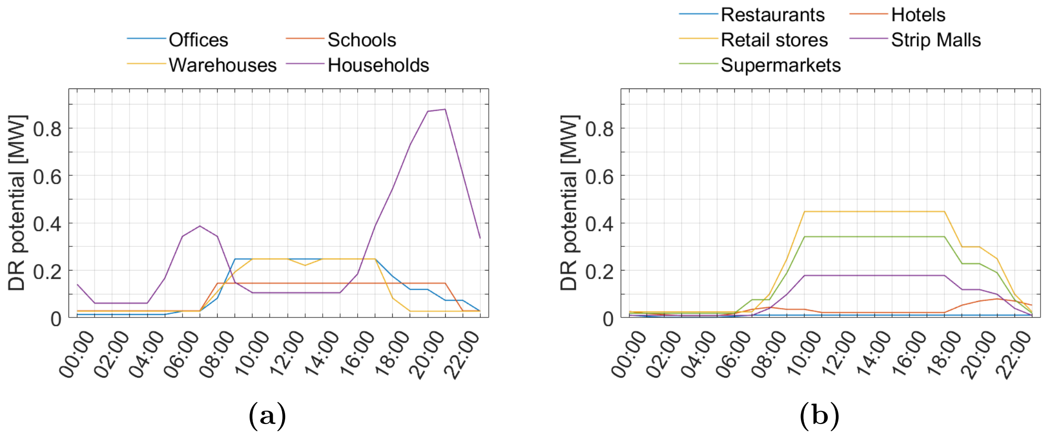


Figure 11: DR potential for weekdays for different buildings types. The left figure shows the schedules for offices, school buildings warehouses and households (a) and the right shows the schedules for restaurants, hotels, retail stores, strip malls and supermarkets (b).

Households have the biggest potential of DR overall, but this potential mainly consists of two peaks. One smaller peak occurring around 07:00 and one bigger around 20:00-21:00. Apart from households, the biggest potential lies with the retail stores and the supermarkets, followed by offices and warehouses. All the previously mentioned also share a similar schedule, with a high steady lighting usage from around 10:00 in the morning to 18:00 in the evening.

The total potential from lighting, for weekdays, weekends and other days/holidays can be seen in figure 12. The maximum DR potential during weekdays is slightly above 2 MW, and occurs at 17:00, and the lowest is around 0.2 MW between 01:00 and 04:00 in the morning. The results seen in figure 12 are all for the slow response. For a fast response the values are lowered by a third all over the year.

Figure 13 shows the import reduction from lighting DR resources. The highest import peak occurs at 06:50, and the lighting lowers the import by 0.50 MW. The average reduction between 06:30 and 08:50 is 0.74 MW. In the simulations, for the case of 2019, lighting DR was activated 26 times in total.

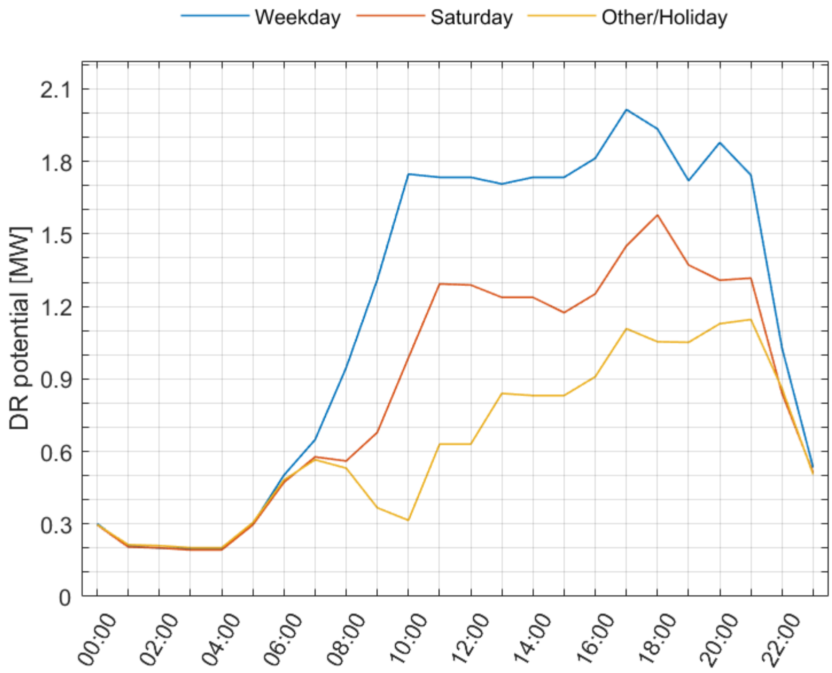


Figure 12: Total potential for lighting DR.

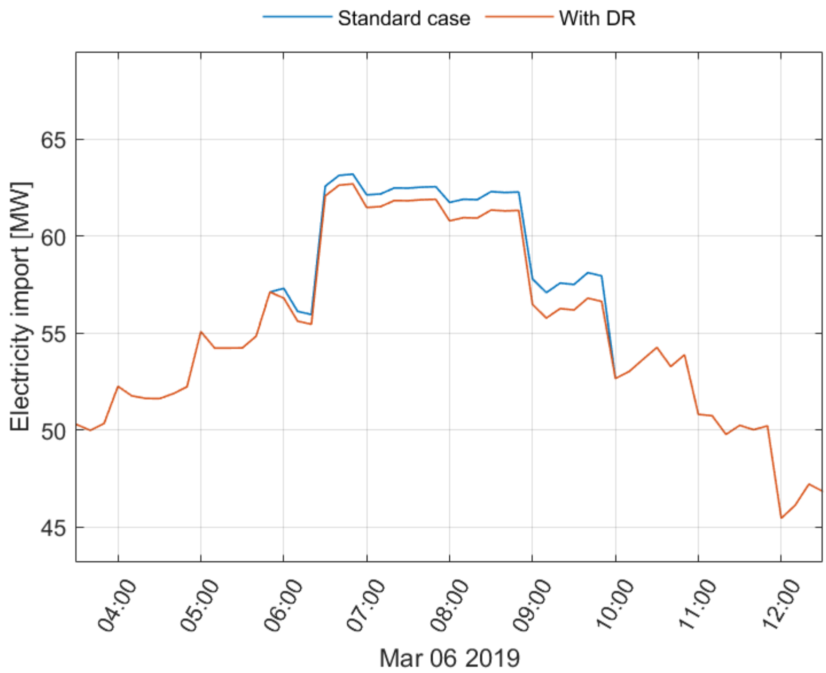


Figure 13: Comparison between the standard case and when using lighting as a DR resource for the for the hours around where the yearly highest import occurred in 2019.

4.4. Ventilation

Figure 14 shows how the total load has been moved both one and two hours ahead of standard usage. The two hour shift is the maximum the usage can be shifted. The individual resources can be moved separately, but with a maximum of two hours from their respective standard usage.

Figure 15 shows the import reduction from ventilation DR resources during the period with maximum import. The ventilation lowers the import peak with 0.76 MW. The average peak reduction between 06:30 and 08:50 is 0.49 MW.

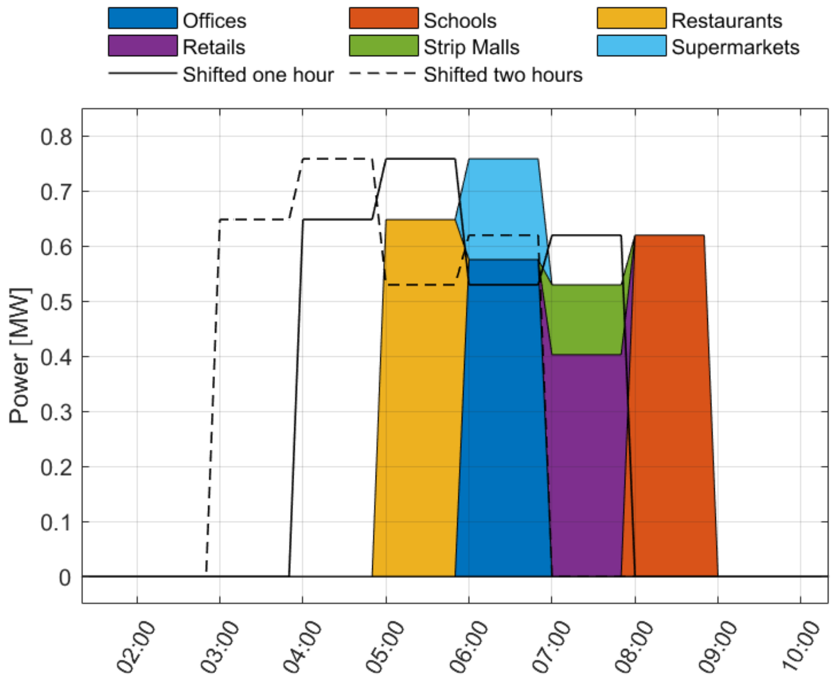


Figure 14: Standard power usage during business days for ventilation for the different sectors, and illustrations on how the resources can be moved to earlier in the morning.

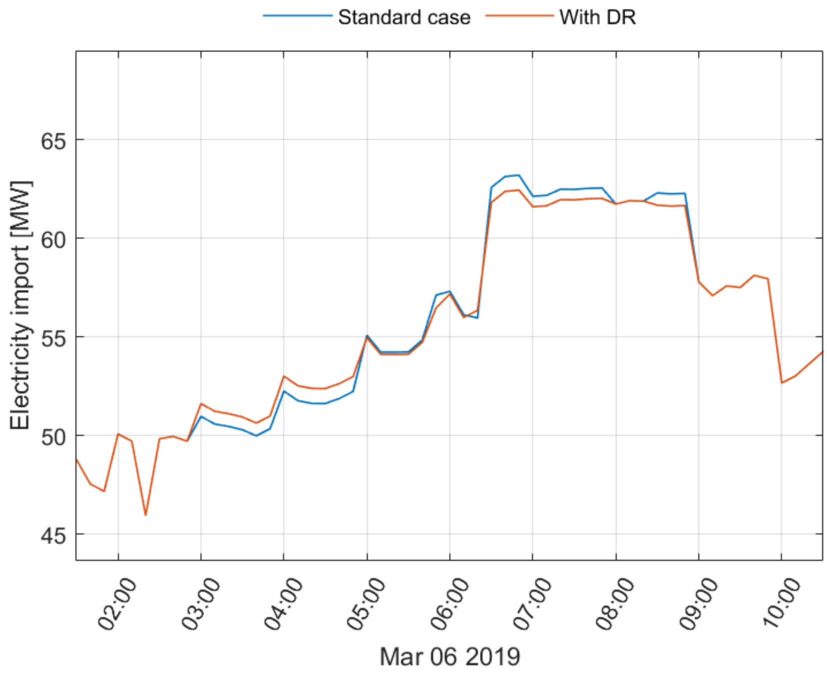


Figure 15: Comparison between the standard case and when using ventilation as a DR resource for the for the hours around where the yearly highest import occurred in 2019.

4.5. Electric vehicles

As of the end of 2020 there were 236 EVs on Åland. 144 of these were BEVs and 92 PHEVs. In 2030 the total number of EVs is estimated to reach 4,000. The estimated total battery capacity of all EVs was calculated to 5.9 MWh in 2020 and 192 MWh in 2030.

Figure 16 shows the charging patterns for EVs when they charge directly after plugging in to the charger, standard case, and when they are controlled. The charging power is higher for the case with DR compared to the standard case, but the charging peaks occur when the overall import is low. In the standard case a few EVs will charge a small amount as soon as they are plugged in. With DR more EVs will wait until the import is lower which usually occurs during nighttime. The charging power is higher since more EVs are charged at the same time. However, the peak is different from day to day depending on how many EVs that are parked and available for charging which in turn depends on the traffic intensity. For the standard case it can be seen that the charging follows the road intensity, visualized in figure 2, but shifted one hour from when the actual driving occurs, causing smaller peaks at 9:00 and 18:00 when the overall consumption usually is high.

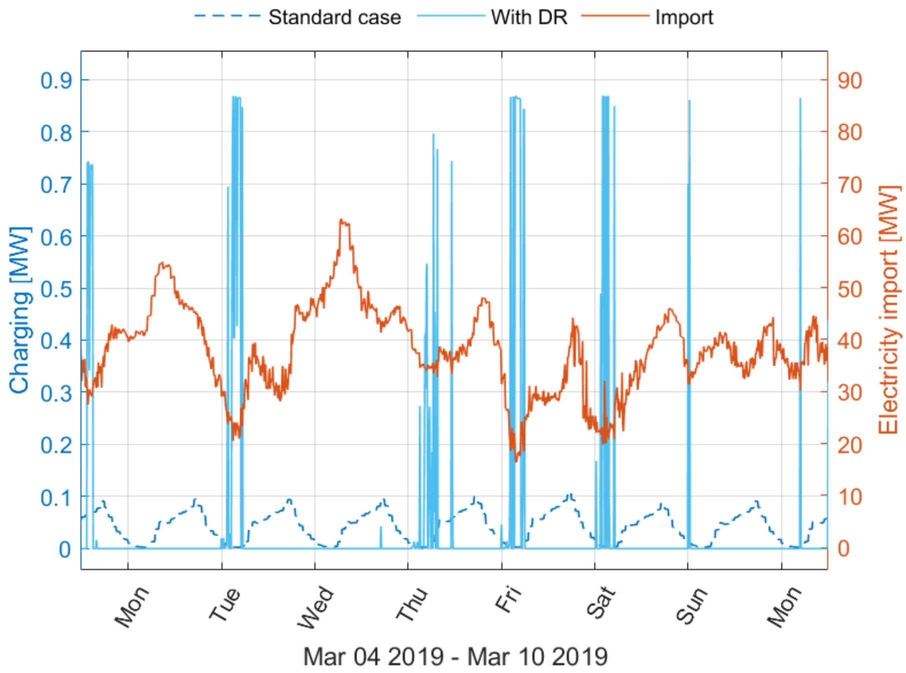


Figure 16: Charging patterns for 2019 for electric vehicles with and without DR, in comparison to the electricity import without DR.

4.6. Combined potential 2019

Figure 17 shows a duration chart of the standard electricity import and the import when all potential DR resources are used. The import peak have been lowered from 63.2 MW to 51.8 MW, a reduction of 11.4 MW. It can also be seen that the import is more equalized during the year in the case with DR, with high import being decreased and the low import increased. During the whole year the amount of down-regulation, decreased consumption, reached 10,990 MWh during 4,871 hours with an average down-regulation of 2.26 MW during the active hours. The remaining hours of the year the consumption was increased. The average up-regulation, increased consumption, was 2.65 MW and a total energy increase of 10,249 MWh. The total energy that was reduced is higher than the energy increased because the HPs are being utilized more efficiently with DR. This is possible when storing heat before a cold period when the IHs otherwise would kick in, reducing efficiency, and therefore the overall consumption decreases slightly even though there are some losses that occur when exceeding the average temperature in households.

Figure 18 shows the import for the standard case and when all DR resources are used. In 18a the difference in import, for the week where the highest import occurred, can be seen. DR lowers the highest peak, but also manages to lower the peaks occurring the remaining days. Figure 18b shows the interval where the highest import occurred and the

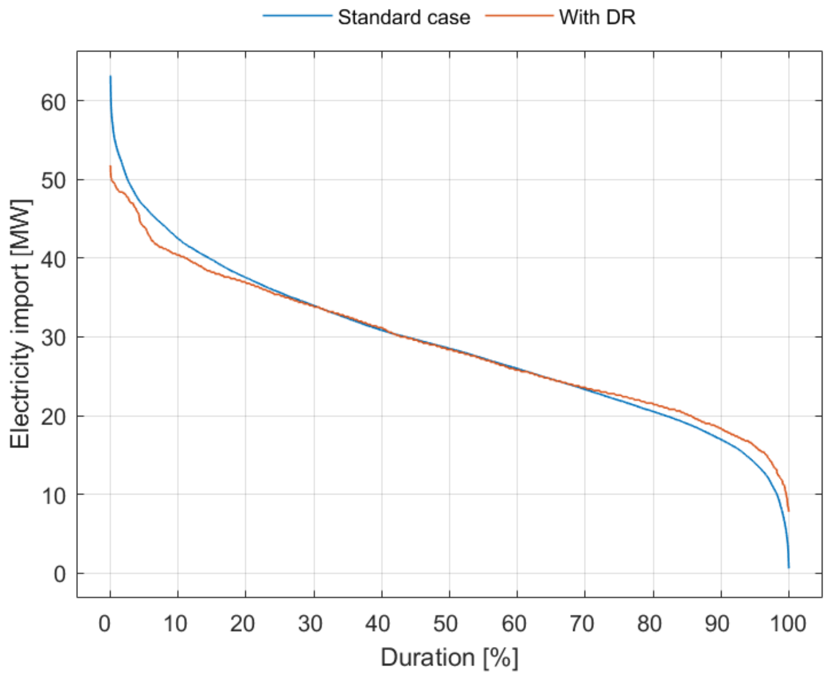
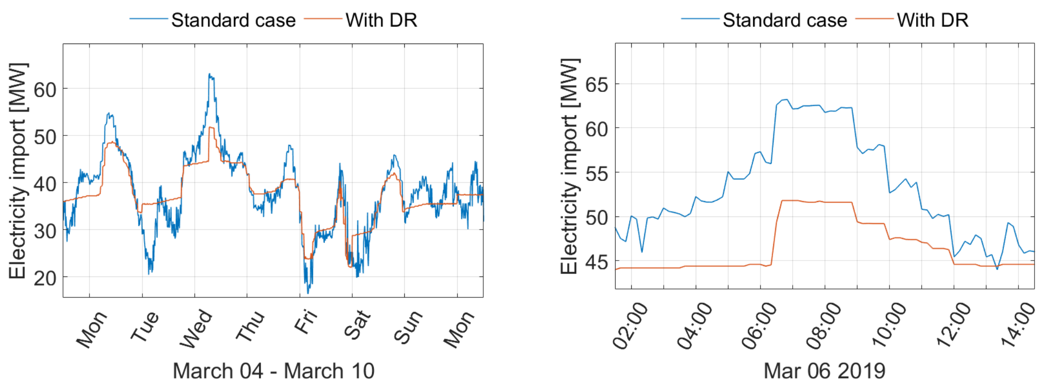


Figure 17: Duration chart of the difference in import of electricity when using all potential DR resources on Åland for 2019.



(a) **(b)**

Figure 18: Comparison between the standard case and when using all potential DR resources on Åland for the week (a) and hours (b) where the highest import for 2019 occurred.

surrounding hours in more detail. The peak lowers from 63.2 to 51.8, and during the 10 hour time period, between 02:00 and 12:00, the average peak reduction is 8.0 MW.

Figure 19 shows how the average import during the different seasons changes between the standard case and the case with DR. The peaks during the day is lowered for all the seasons with DR, and during time periods with a low demand, especially between 01:00

and 05:00, import is increased. The import for the case with DR is more even overall which also was the purpose of the optimization, to reduce peaks and stabilize the grid.

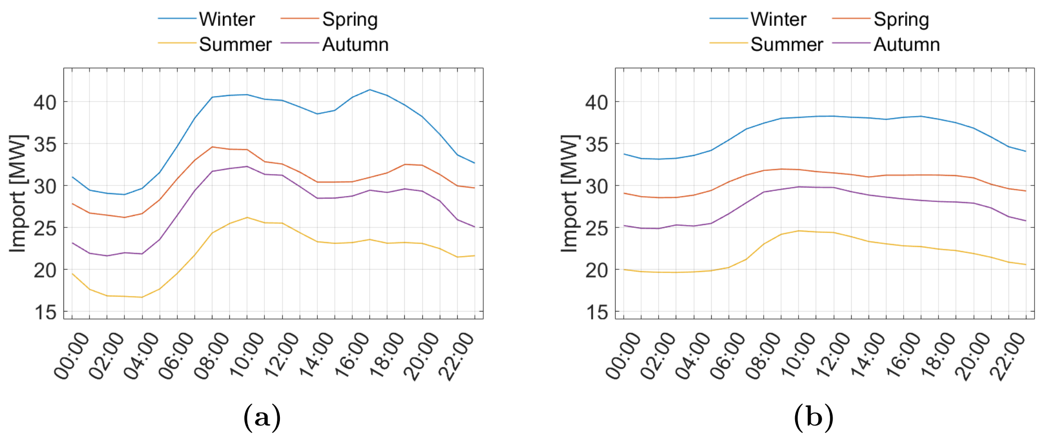


Figure 19: Electricity import an average day for the four seasons without DR (a) and with DR (b) for 2019.

4.7. Possible potential 2030

The annually produced wind and solar power for 2030 were 469.9 GWh and 18.5 GWh with a corresponding consumption of 400 GWh, and is visualized in figure 20. A flow

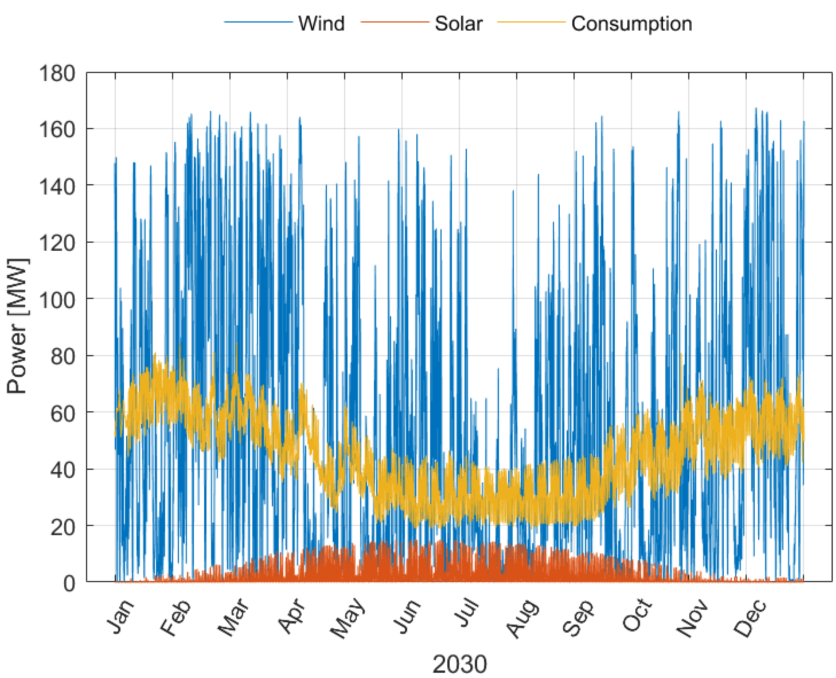


Figure 20: Wind and solar production as well as electricity consumption, for the year 2030.

chart of the estimated energy production and consumption of different DR resources and other sectors in 2030 can be seen in figure 21. The DR resources consumption is the total estimated consumption of each resource and does not indicate the DR potential. The only DR resource that has been changed from 2019 to 2030 is EVs which have increased from 0.4 GWh to 6.8 GWh.

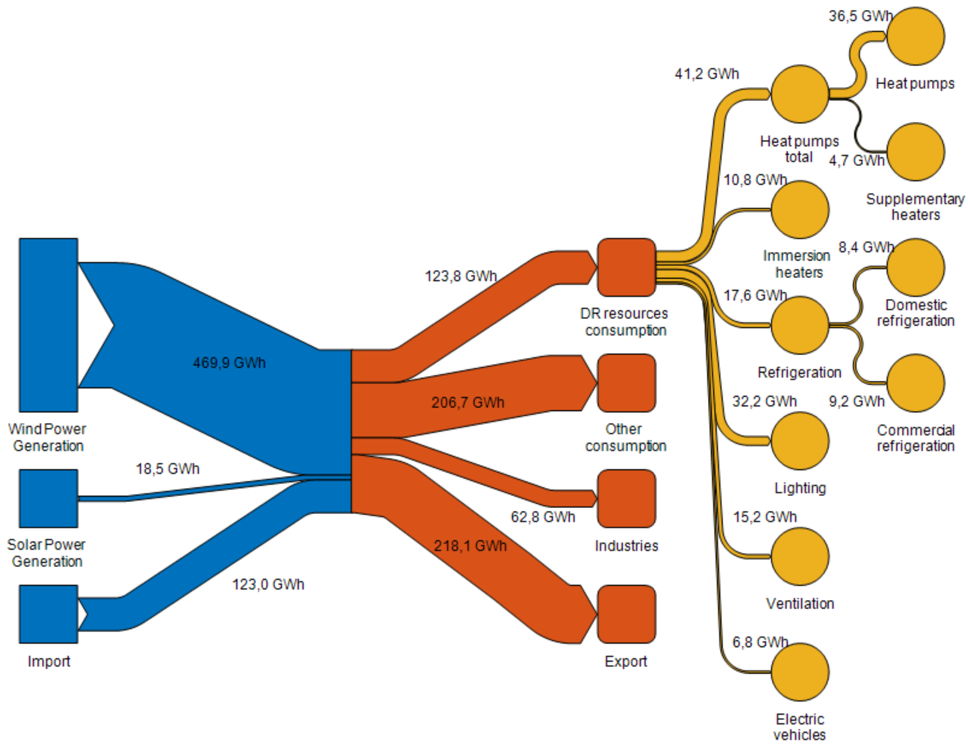


Figure 21: Energy balance for Åland in 2030.

Figure 22 shows how the charging patterns look for the week where the highest import peak occurs. When the charging is negative it is indicated that batteries are discharging to the grid in the V2G case. This happens during import peaks to even out the consumption. The charging peaks are higher, firstly, because of the increased charging power of 22 kW instead of 3.7 kW. Secondly, when there is excess wind power the EVs are more likely to charge close to full capacity since they have use of the discharge when an import peak occurs. In the case without V2G less charging is required, and wanted, since it only is used for the daily driving distance in EVs.

If all cars were parked at the same time and charging with 22 kW, EVs would consume 88 MW. This is higher than the maximum total forecasted load on Åland in 2030. In figure 22 it can be seen that the charging power are approaching those levels when the road intensity is low. However, this charging occurs at times with high wind power production and no need for import. In an optimized system like this, EVs will not affect grid stability but is rather an asset for evening out consumption, especially with V2G. Without V2G

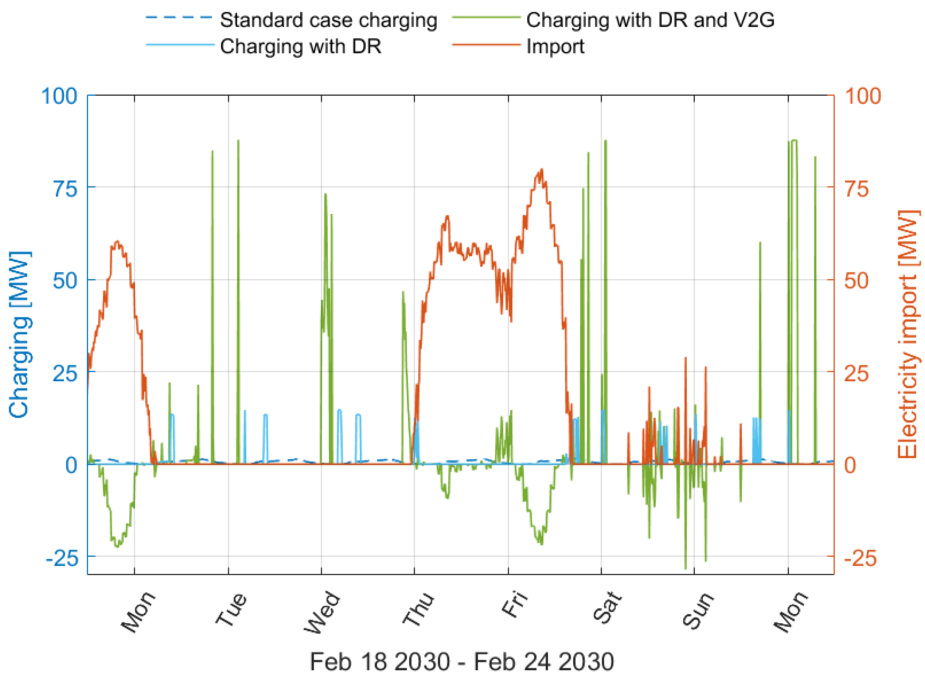


Figure 22: Charging patterns for 2030 for electric vehicles with and without DR, and with both DR and V2G, in comparison to the electricity import without DR. The maximum charging power for the standard case and with only DR is 3.7 kW, while it is 22 kW in the case with DR and V2G

and at a slower charge of 3.7 kW the maximum load for 4,000 EVs would be 14.8 MW and since, on average, approximately 95 % of cars parked and available for charging similar numbers can be seen for charging with DR in figure 22. If EVs are not controlled in any way the maximum charging is 2.5 MW since less EVs are charging at the same time but the charging often occurs at times with already high import.

Figure 23 shows a duration chart of how the import changes for the three different cases in 2030. The overall import is lower for both cases with DR, but especially when the vehicles have V2G-capabilities. The maximum import has lowered from 80 MW to 67.7 MW with DR and 58.2 MW with DR and V2G. There is only a need for import during about half of the year, for all of the cases in 2030, mostly due to the increased wind power capacity compared to 2019 when there was a constant need to import electricity. DR moved 14,298 MWh from times with higher import to lower with an average of 4.29 MW during the hours of load shifting which reached 3,333 h. For the case with DR and V2G 31,822 MWh was moved with an average of 9.25 MW during 3,439 h. The total amount of import and export for the three cases can be seen in table 18. The table also shows the self-sufficiency, how much of the energy consumption that is domestically produced, and the utilization, how much of the production that is used on Åland. What the export

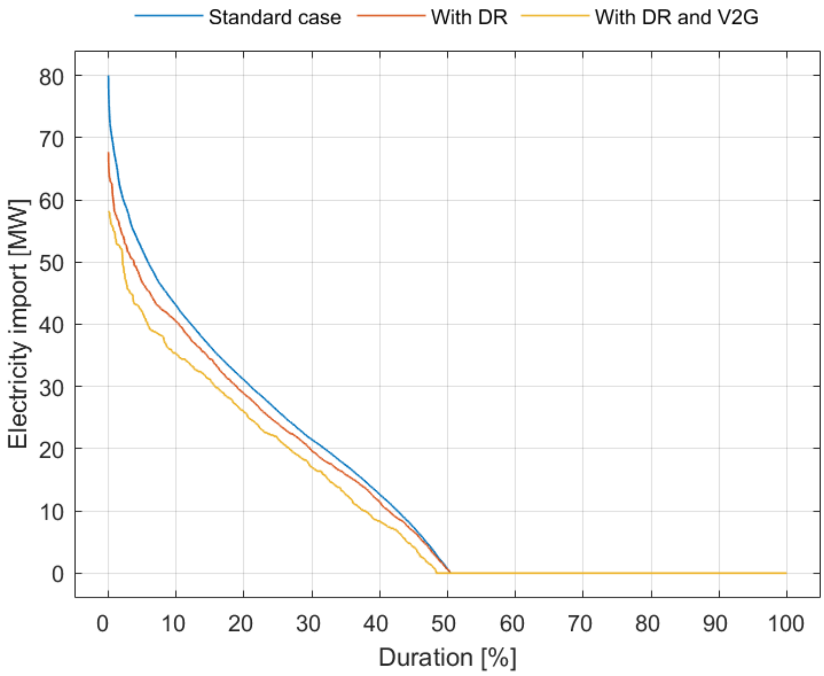


Figure 23: Duration chart of the difference in import of electricity on Åland for the standard case, when using all potential DR resources with and without V2G for 2030.

looks like for the different scenarios for 2030 can also be seen in figure 24. The current export limit is approximately 80 MW and as seen in figure 24 all energy above the shown limit could not be exported with the projected renewable capacity and consumption with the current exporting lines.

Table 18: Import and export, as well as self-sufficency and utilization for the three scenarios for 2030.

Scenario	**Standard case**	**Only DR**	**DR and V2G**
Import [GWh]	126	116	101
Self-sufficiency [GWh]	273	288	307
Self-sufficiency [%]	68.4	71.3	75.2
Export [GWh]	196	192	179
Utilization [%]	56.0	59.0	62.8

In the standard case 19.2 GWh, or 3.9 %, of the total dispatchable renewable production could not be exported. For the case with DR the corresponding numbers were 8.3 GWh, or 1.7 %, and for DR with V2G the numbers were 3.0 GWh, or 0.6 %.

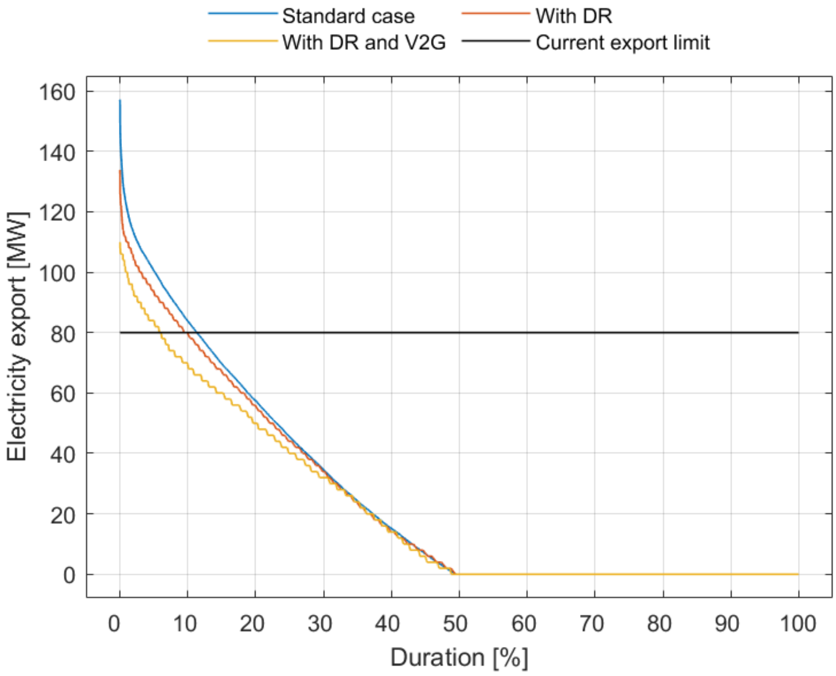


Figure 24: Duration chart of the difference in export of electricity on Åland for the standard case and when using all potential DR resources with and without V2G for 2030.

Figure 25 shows the import reduction when the highest import of electricity occurred in the uncontrolled case. The visualized week only contains one bigger peak, but the peak is partially sustained during two days, with its maximum occurring at 08:00 on February 22. The overall peak is lowered from 80 MW to 66.6 MW for the case with DR and without V2G, and to 53 MW when V2G also is enabled. This means a reduction of 13.6 MW and 27 MW respectively. During the 10 hour period between 02:00 and 12:00 the average import reduction is 10.7 MW and 16.6 MW respectively.

Figure 26 shows how the average import during the different seasons changes between the standard case, the case with DR and the case with both DR and V2G. The peaks during the day is lowered for all the seasons with DR and with DR and V2G, while the usage during the night is similar for all the cases. It should be noted that the average day import is much lower in comparison to 2019. This is due to the fact that there is no need for import at all around 50 % the time, especially during windy days in 2030 compared to 2019, which lowers the average. If compared to the import in 2019, as seen in figure 19, it can be seen that the import for 2030 is overall more uneven and that DR does not manage to even out the import to the same extent.

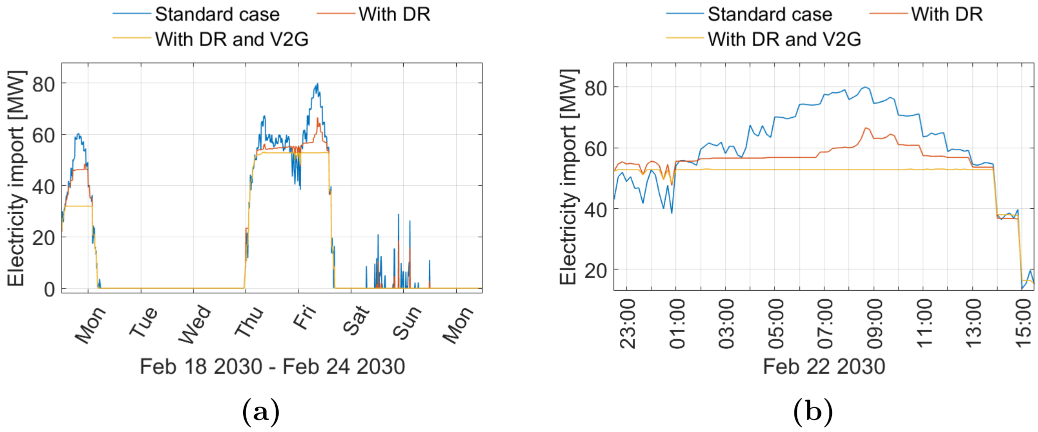


Figure 25: Comparison between the standard case and when using all potential DR resources on Åland with and without V2G for the week (a) and hours (b) where the highest import for 2030 occurred.

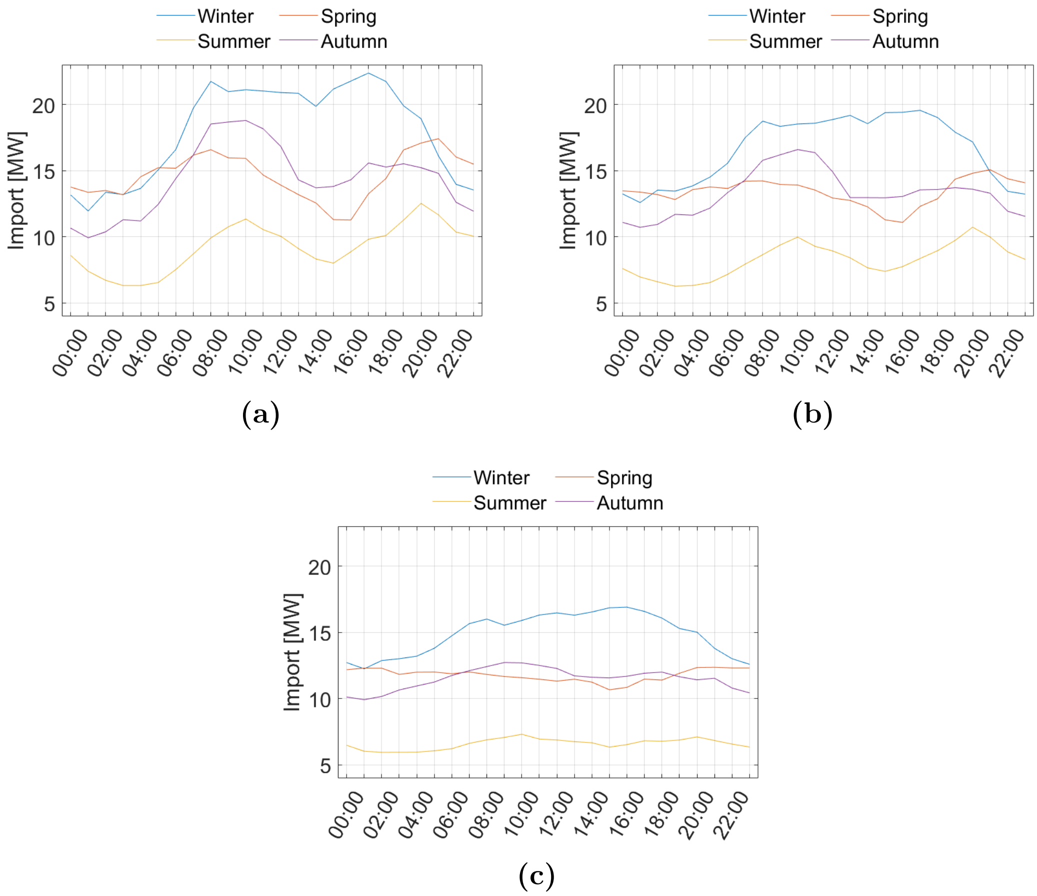


Figure 26: Electricity import an average day for the four seasons without DR (a), with DR (b) and with both DR and V2G (c) for 2030.

4.8. Economic analysis

The results from applying the methodology described in section 3.7 can be seen in table 19.

Table 19: Calculated CAPEX, flexibility cost and storage cost for different DR resources

DR Resource	**Nr of buildings**	**CAPEX [M€]**	**Flex cost [€/kW]**	**Storage cost [€/kWh]**
HPs	3,067	1.51	114	100
IHs	449	0.22	68.0	42.0
Commercial refrigeration (low)	1,255	0.62	584	469
Commercial refrigeration (high)	1,255	7.67	7,230	5,810
Domestic refrigeration	14,085	6.94	7,230	5,790
Lighting	N/A[1]	N/A	N/A	N/A
Ventilation	N/A	0	0	0
Industries	N/A	N/A	N/A	N/A
Electric vehicles	N/A	0[2]	0	0

[1]N/A (not available) is used wherever it is determined that no proper CAPEX can be estimated.

[2]Zero CAPEX is used on resources that likely has some DR possibilities without an additional investment cost. For EVs this is the case of load shifting through a regular charging station, the true cost of V2G is not examined.

The different costs for DR resources and a battery comparison are visualized in figure 27. The prices for batteries are 1252 €/kW and 313 €/kWh for 2019 and 682 €/kW and 170.5 €/kWh for 2030, as mentioned in section 2.3. It can be seen that both types of electric heating seems to be more competitive than batteries for both 2019 and 2030. For refrigeration it is harder to draw conclusions since the price variation is large depending on the type of estimation.

The cost of a corresponding battery storage to reduce the peak of import in a similar manner to how DR did in the simulations for 2019 and 2030 was calculated to 25 M€ and 14 M€ respectively. The lower cost in 2030 originates from declining battery prices. If a DR project is planned and the CAPEX is below these numbers it is an indication of a competitive investment in comparison to flexibility via batteries. Lastly, the savings that could be made from lowering the maximum interconnection to Sweden with 11.4 MW in 2019, from 63.2 MW to 51.8 MW, were calculated to 124 k€ annually.

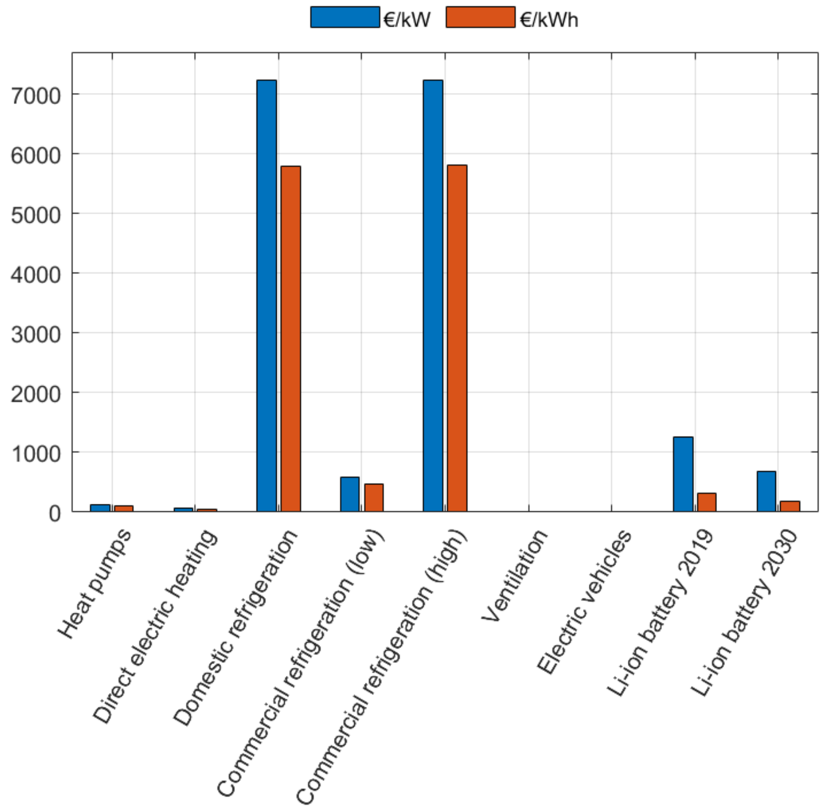


Figure 27: Cost per utilized maximum power reduction and energy storage.

4.9. Sensitivity analysis

In figure 28 the total electricity usage for electric heating when all buildings using oil or gas as their main heat source in 2019 have been converted to using HPs instead. The figure also shows the daily mean electricity usage for the four different seasons. The usage reaches a maximum peak of over 65 MW and during the winter the buildings have an average usage of about 20 MW throughout the day.

In table 20 the change of DR potential from increasing the amount of electrically heated buildings can be seen. For the case with more HPs the load shifted increases with 55.0 % and average load reduction with 47.7 %. The hours of down regulation, decreased consumption, increases by 5.0 % and the peak load reduction increases with 80.9 %.

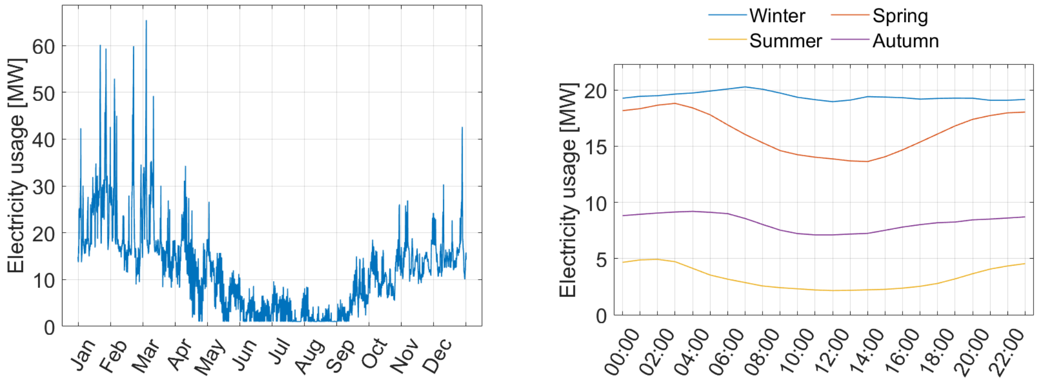


Figure 28: Electricity for heating and warm water in all buildings with HPs (a) and daily seasonal mean electricity usage (b) for 2030 when all oil and gas heated residential buildings have been converted to using HPs.

Table 20: Effects on DR potential from replacing heating systems in buildings with oil or gas to HPs in 2030.

	Oil and gas heated buildings	**HPs instead of oil and gas**
Load shifted [MWh/year]	14,300	22,200
Down regulation [h/year]	3,333	3,499
Average load reduction [MW]	4.29	6,33
Peak load reduction [MW]	21.4	38.7

Table 21 presents the total DR regulation from all combined sources in 2019 when allowing either a maximum of 0.5 °C or 2 °C up and down from preferred room temperature. From increasing the span to ±2.0 °C the load shifted increases with 14.6 % and average

Table 21: Effects on DR potential from allowing different temperature spans in buildings.

	± 0.5 °C	**± 1.0 °C**	**± 2.0 °C**
Load shifted [MWh/year]	9,120	11,000	12,600
Down regulation [h/year]	4,856	4,871	4,884
Average load reduction [MW]	1.88	2.26	2.56
Max load reduction [MW]	12.2	13.4	16.5

load reduction with 14.6 %. The hours of down regulation, decreased consumption, increases by 0.3 % and the peak load reduction increases by 23.6 %. Increasing the temperature span does not proportionally increase the DR potential. For the ±0.5 °C span the load shifted decreases with 17.0 % and the average load reduction with 16.7 % in comparison to the default ±1.0 °C. The hours of down regulation decreases by 0.3 %

and the peak load reduction with 8.8 %.

How the DR potential adjusts to a different amount of installed wind power can be seen in table 22. With an installed wind capacity of 60 MW instead of 170 MW the load shifted increases with 23.4 % and the hours of down regulation with 45.9 %. However, the average load reduction decreases with 15.4 % and the peak load reduction decreases by 6.1 %. With lower wind capacity import is required more often which is why the the DR regulation increases, but due to it being active more often the average regulation decreases.

Table 22: Combined DR potential for all resources in 2030 with different installed wind capacity.

	60 MW wind	**170 MW wind**
Load shifted [MWh/year]	17,600	14,300
Down regulation [h/year]	4,863	3,333
Average load reduction [MW]	3.63	4.29
Peak load reduction [MW]	20,1	21.4

Finally, the effect on DR potential from a longer solution step is visualized in table 23. It shows that there are hardly any differences between the solution step of 1 day

Table 23: Combined DR potential for all resources in 2019 with different solution step sizes for the model optimization.

	1 day + 1 day look-ahead	**1 week + 1 day look-ahead**
Load shifted [MWh/year]	11,000	11,000
Down regulation [h/year]	4,871	4,882
Average load reduction [MW]	2.26	2.24
Peak load reduction [MW]	13.4	13.4

plus 1 day look-ahead and the solution with steps of 1 week + 1 day look-ahead. All examined parameters are within a 1 % increase or decrease between the two cases. Over the year it can be seen that looking at larger periods of time for each solution step does not necessarily improve the optimization in this model. However, looking specifically at the time with the highest import in 2019, the peak could be reduced with 11.6 MW instead of 11.4 MW in the case with the longer solution step size which corresponds to an improvement of 3.6 %.

5. Discussion

This study has relied heavily on previously performed investigations, some of which have been older. The STIL2-studies for example were done between 2005-2011. From these studies the energy usage for refrigeration, lighting and ventilation were collected, as well as the distribution within the commercial buildings category. For heat pumps a study made by Swedish Energy Agency (2010c) called "Välj rätt värmepump" (eng. "Choose the right heat pump") has been used both for the dimensioning of the heat pumps and their respective COP value. The technology has developed within all of these areas, with more energy efficient products as the result. Increased energy efficiency means that the electricity usage for the average appliances used today are probably lower than the values used in these studies. However, it is important to remember that the energy efficiency is not the only factor which determines the change of energy usage. If the overall usage within these areas have or will be increased, then this could compensate to some degree for the increased energy efficiency. The results in this study might not be directly representative for the standard usage today, and even less for the scenario for 2030, but they were deemed reliable enough for the scope of this thesis. Specific information on how the efficiency and usage for a few of the investigated areas have changed are discussed in the separate subsections below.

This thesis work focused on the technical aspects of DR, but as mentioned in section 1.3, the social aspects will also be briefly discussed. Electric appliances that have a clear impact on user comfort if they are being used for DR, such as washers, driers, dishwashers and stoves, have not been considered in this study to minimize the impact on user comfort. Smaller temperature spans were examined in the sensitivity analysis, in section 4.9. Even if a temperature 0.5 °C either above or below preferred room perhaps is not noticeable, it cannot be assumed that all users would agree to having their heating controlled due to other social aspects. Regarding heat pumps, around 70-80 % user participation degree could be assumed[15], which would lower the theoretical potential with a corresponding 20-30 %. For the industries, if it is assumed that the ones who did not reply to the form, which was sent, were not interested in participation, then 25% participation could be achieved but only if there is sufficient economic compensation. It should be noted that only 12 industries were contacted and the numbers might not be significant to represent the participation in a wider context.

Figures 4 and 20 show wind and solar production as well as the consumption for the two cases for all of Åland. Renewable generation never exceeds the minimum consumption in

[15] Björn Berg, CEO of Ngenic, online interview [5.2.2021]

2019, meaning that no export is required and therefore 100 % of the renewable generation can be consumed locally. For 2030, on the other hand, there is significant overproduction the majority of the year, with a maximum overproduction interval of 156.9 MW, so both the current exporting AC cable to Sweden of 80 MW and the backup DC cable of 100 MW to Finland would have to be used. Another option would be to use the overproduction to, for example, produce hydrogen to increase flexibility and/or use it to decarbonize the marine traffic. As mentioned in section 2.2.2 the legislation regarding electricity transfer between Sweden, Åland and Finland would need to be updated to enable these amounts of wind power in the Åland energy system. The legislation aspect should be further investigated.

The reason behind the more uneven import in 2030 compared to 2019 seen in figures 19 and 26 is the increased amount of renewable intermittent energy production. This further highlights the future need of flexibility and is one of the main reasons to why DR and other types of flexibility will be more important in the future.

Regarding the sensitivity analysis, looking at table 22 it might seem that it would be better for the DR potential if only 60 MW of wind power was installed, since more load is shifted. However, for the case with 170 MW the variations in import from day to day varies greatly, since the renewable production is intermittent. If the goal is to equalize the import, and not have big differences throughout the day and week, DR might still be more important for this case even if the regulation time and the shifted load are lower. The results in table 23 indicate that the solution step of 1 day + 1 day look-ahead is sufficient for the optimization of this model and that larger steps, in this case, did not improve the DR potential to any noticeable degree.

5.1. Electric heating

Of the total 11.4 MW peak reduction from DR, 8.42 MW was contributed from electric heating. This makes up 74 % of the total reduction. Electric heating is also the resource which can sustain the peak reduction for the longest time. Lighting can temporary reduce the peak for four hours, and ventilation can move the load a maximum of a couple of hours. Refrigeration processes could potentially move the peak load in the same time frame, since the base principle for the two cases are the same. However, the overall potential for refrigeration processes is lower and therefore it cannot sustain the reduction for the same period of time. Since DR in electric heating makes up the majority of the total potential, this should probably be the the main focus if DR is implemented on Åland.

Regarding the sensitivity analysis, it can be seen in table 21 that allowing allowing a narrower span of ±0.5 °C still enables a good amount of DR potential. This is an important factor when considering comfort, since such small temperature differences should not be noticeable by the user. Another important aspect of electric heating is how it will change in the future. In this study it is assumed that the same amount of houses are heated with electricity in 2030. This is likely not true. If the amount of houses that have electric heating increases then the overall potential will also increase. But it is not only the potential that will change if the number of HPs change. Figure 28 in the sensitivity analysis shows how the electricity usage will increase if all residential buildings using oil or gas as of 2019 switched to HPs. The highest usage peak for electric heating only reaches over 65 MW, and if this peak occurs during a time when there is limited or no domestic production, all of this must be imported. If the current limitation of 80 MW import still exists, this might be hard to accomplish. In this case, DR or other flexibility might be essential. Looking at the DR potential with increased electric heating in table 20, it can be seen that a substantial increase in DR potential will be available in the future if all oil and gas heated buildings currently on Åland are converted to HPs.

If more IHs are converted to HPs the average electricity consumption for heating will decrease, but the difference between the high peaks, when SHs are needed, and the remaining usage will be even more prominent. For this reason, DR in heating might be necessary only to spread out the future heating peaks. Another thing that makes the results uncertain are the COP-values for the HPs. The report from which the data are collected from, Swedish Energy Agency (2010c), are from 2010, and the COP-values for all kind of HPs have increased since then. However, the overall electricity usage for this study would not have changed with a different COP. This is because the total electricity usage is calculated separately, and is then adjusted to fit to the HP pattern. However, if the COP-value would have been higher for all HPs the electricity usage would have been more even, with lower peaks and higher valleys, as compared to the potential seen in figure 6a.

One parameter that could have a big impact is the warm water heating, and how it is distributed during the year. Some IHs, if a large enough accumulator tank is connected to the water system, have the possibility to heat the water during the night. The stored heat in the tank is then enough for the whole day. This shifts some of the electricity usage towards night time, and lowers the potential for regulation during the day. Even if the water usage is a small part of the total heating need, further studies on the exact distribution of water heating could give more detailed results.

Since Åland is such a small community the distribution of heating alternatives could look completely different from that of Sweden, even if the societies are similar. Further studies are needed to get a complete distribution.

5.2. Refrigeration processes

As mentioned in the general discussion previously the reports "Energianvändning i hotell, restauranger och samlingslokaler" and "Energianvändning i handelslokaler" were written in 2011 and 2010 respectively. Therefore, the age and accuracy of the numbers today regarding electricity usage per square meter should be acknowledged. According to N. Lantz (2020) cooling in supermarkets has had an efficiency increase of 2.5 % every year between 1997-2013 but the general cooling demand has also increased due to the fact that we in general consume more frozen and refrigerated products. Also, lower temperatures for refrigerated groceries, as a consequence of higher cooling standards of food products, require more electricity. N. Lantz (2020) also discuss how relevant the numbers are in 2020. In general, it is concluded that for older buildings the numbers can be relevant, but for newer buildings a similar study to STIL2, in which the reports "Energianvändning i hotell, restauranger och samlingslokaler" and "Energianvändning i handelslokaler" were produced, would be required to see how the numbers for electricity usage may have changed. Therefore, for the scope of this study, the numbers already existing from 2010 and 2011 was used.

Refrigeration is the second largest DR resource on Åland for 2019 and could possibly be increased further if industries were to be included as well as warehouses, and this could be a subject of further investigation.

The following paragraph evaluates the assumption regarding constant refrigeration demand. Since the indoor temperature is relatively constant due to heating and, in this study, electrically heated buildings will have controllable temperature as part of the optimization, it is hard to estimate the effect from ambient temperature on refrigeration. Ambient temperature and an increased demand during the day are neglected in this study, since an aggregated approach is applied, and specific details for different supermarkets would be required to make proper estimates for these factors.

The energy consumption of refrigeration processes was simplified in comparison to heating in this study, where outdoor temperature can be utilized to calculate a varying demand. Refrigeration should be examined further with a small scale case study with real measurements so that the aggregated methodology could be validated and the accuracy of it analyzed.

5.3. Lighting

Lighting has the potential to move a lot more of the energy than it does during the highest import peak. During the peak import, happening between 06:00-07:00, seen in figure 13, lighting only has the capacity to reduce the import with a maximum of 0.5 MW, seen in figure 12. If the peak instead had happened around 17:00, the reduction contribution would have been about four times bigger. But lighting DR is limited by a few factors. It can only reduce the consumption when the lighting is already on, see figure 13, and cannot move the load to other parts of the day. Even though it has a maximum potential of almost 2 MW during weekdays, it has almost no potential during night-time and the potential lowers during the weekend. The peak cannot be sustained for more than a few hours, and it is also possible that this reduction comes with some other drawbacks such as reduced work efficiencies and an increase in injuries. In the study performed by Newsham and Birt (2010) they pressed the issue that this power reduction should not be used more than four hours in a row, and not unless completely necessary. Some locations might be better suited for lighting DR than others. Some potential, such as hospitals, have been completely left out in this study, since it might be directly harmful to lower the lighting in certain areas. Others, such as retail stores and supermarkets, might not be affected to the same degree.

Since the buildings for institutional care, assembly buildings, buildings for transport and communications, industries and other/unknown buildings have been left out of the model, due to different reasons, the potential for lighting DR might be higher than is shown. If the total potential is scaled by area to also include the missing buildings then the average DR potential would increase by approximately 18 %.

As can be seen in figure 11, households are the sector with the most potential for lighting DR, especially during the evening. Although it might also be the sector where it is the most expensive and problematic to introduce. Compared to for example office buildings, supermarkets or strip malls, where there might be a centralized control unit and equipment that is controllable from a distance already, households mostly consists of individually controlled lights. Equipment to regulate and aggregate needs to be installed in households, and since the potential per building is much lower than for the other sectors it could be more expensive. Apart from households both retail stores, supermarkets, offices and warehouses have at least 0.2 MW of potential each during mid-day, and this potential might be easier to achieve, especially in places which already use some sort of controlled lighting.

If the lighting would be aggregated in smaller groups, for example into the different sectors already seen in figure 11, instead of one big group as has been the case in this study, the reduction could be spread for a longer time during the day, although to a possible decrease in maximum load reduction.

It is important to reflect over the age of the numbers used. The sources used for lighting energy usage is approximately 10 years old, and might not be representative for today's values due to improved energy efficiencies. The schedules might also be incorrect, mostly due to the fact that some kind of control and regulation already exists. It is therefore possible that the overall regulatory potential of lighting is much lower than the results in this study show. Energy efficient lights lower the usage for the whole year, while daylight adjusted lights mainly lowers usage during the summer and in the daytime, when the amount of sunlight is higher.

It has also been assumed in this study that all lights are controllable. This is not the real case, but is done to estimate the total potential of lighting DR. In a future scenario for 2030 most of the lighting could be controllable, but there is also a possibility that the average light source is much more energy efficient, which in turn lowers the DR potential. Further studies might also be necessary to verify how much of the light that can be dimmed or switched off, based on different locations. If the changes are noticeable, or not, could greatly depend on the location and building type, as well as the type of operation that is performed inside.

5.4. Ventilation and air conditioning

Ventilation has a similar size in potential as lighting, but the way it is modelled here makes it even more limited. Since there are strict regulations on how ventilation and the air flow can be controlled the potential of DR for ventilation is limited. It is not possible to shift the usage in the same way as for example a water carried heat system.

There are some applications where, on a short time basis, the ventilation could be made to oscillate around its mean flow while still maintaining a sufficient air circulation, and adapt to short term grid changes. It could therefore be possible to use ventilation as a short time DR resource throughout the day, but since there are strict regulations on air quality and minimum ventilation, measuring equipment will be needed. The time frame for these changes is too small for the current model to handle, and this type of DR have therefore not been included in this study. However, short time regulation could in theory be utilized for the reserve markets.

If ventilation is turned off during the night, the stale air needs to be exchanged before people arrive. In this study it has been assumed that the ventilation can be moved a maximum of two hours to give an estimation on the potential, but the exact time the load can be shifted might vary greatly depending on which use is intended with the building. The numbers in table 13 show that most buildings have their ventilation turned off about half the time during the year, which could indicate that it is turned off during the night, and makes the assumption made in the method about all building turning off their ventilation during the night more plausible.

Some non-residential facilities, especially those which have a tendency to have high humidity and/or overall bad air quality, might also need to keep the ventilation on for a time after the point that normal operations have ended, to make sure that no damages on the buildings from for example high humidity occurs. It might be possible to schedule this to a somewhat later time, and in i similar way as with the morning usage avoid high grid loads. Although, this needs further study and has not been included in the model.

Demand controlled ventilation, which adjusts the ventilation to fit with the need, also greatly lowers the potential to use ventilation for down-regulation in any longer time perspective. The laws for ventilation demands a certain minimum flow depending on the operation and the ventilation is probably adjusted to that already. If facilities do not turn off their ventilation during off-hours this is most probably due to the fact that they do not have the required equipment or expertise to do so, and therefore DR is not applicable there. If necessary equipment is installed then the facilities is probably likely to lower their usage to the lowest values possible, and therefore the potential of DR is still low, However, turning off or lowering the ventilation during off hours means that the potential for up-regulation of DR rises during these hours, since it is possible to quickly turn on these units in the cases of high grid frequencies.

Regarding air conditioning and other comfort cooling on Åland, most of the cooling usage likely occurs during summertime when the electricity demand is lower and the outdoor temperatures are higher. Since the overall peak loads occur at wintertime, when flexibility is as most required, it is less interesting to examine a resource that is almost exclusively accessible during summertime. Another aspect is that solar generation is likely to occur at the same time as the air conditioning electricity demand. Therefore, a relatively matched production and demand should exist even without utilizing DR, further decreasing the use of DR for air conditioning in energy systems with large shares of solar power. However, in the future air conditioning is likely to play a larger role also in the Nordic countries and should therefore be investigated once proper data starts to become accessible. Furthermore, in warm locations electric cooling could have the corresponding DR potential as electric heating has in a cold location.

5.5. Electric vehicles

The traffic in Åland might be different than that in Sweden. Figure 2 shows the traffic intensity in Sweden, and there it can be seen that the tourist traffic for example does not have a morning peak at all. Instead the intensity is slightly higher overall after 10 and until 16. It is possible that the intensity on Åland will have a pattern more similar to this, especially during the summer, since tourism plays a bigger role there. On Åland, 18.4 % of the BNP is provided by tourism (Visit Åland r.f., 2019), while the corresponding number in Sweden is 2.5 % (Tillväxtverket, 2020). The difference in traffic intensity for different seasons due to tourism should be further investigated.

EVs in 2019 only have a small effect on the electric grid, and is therefore not a major DR resource. In 2030, this is no longer true with the projected amount of EVs. With the increase in EVs, large peaks arise when optimizing vehicle charging in the simulations. However, higher peaks are still preferable from a grid perspective, if they happen when there is an excess of renewable production and if there are no problems with local grid congestion.

It should also be considered that the projected amount might turn out either lower or higher than what is being used in this study. It is not certain what the averages regarding battery size and charging power in 2030 will be and this is the reason to why both slower charging and faster charging are examined. Battery size is only an important parameter for the model if V2G is enabled since the average driven distance on Åland is so short that the required charging per day will never be close to even a smaller battery capacity.

5.6. Industries

According to Lee, Baek and Kim (2020) a load reduction of more than 50 % of the usual load is possible in cement industry cases, which is an industry with suitable processes for DR. As mentioned this is not necessarily the case for all industries but if this was applied to Åland with the assumption that a 50 % reduction was possible and that the yearly electricity consumption of 62.8 GWh was evenly distributed that would correspond to a constant demand of 7.2 MW and furthermore a possible load reduction, or DR potential, of 3.6 MW. If instead the yearly consumption is assumed to be distributed over 52 weeks of 40 working hours, or 2,080 hours in total, the demand would be 30.2 MW during those hours and correspond to a DR potential of 15.1 MW. This indicates a possible DR span of 3.6-15.1 MW and the real potential likely somewhere in between. Further investigations and individual analyses should be considered to make a proper estimate of the DR potential in industries.

5.7. Economics

The economical aspects of DR can be divided into several parts. DR is most suitable if there are big variations in price during the day. But one of the problems with economically based DR is DR itself. If more people uses DR then the variations in usage during the day will even out, and this could also even out the electricity prices. Therefore tariffs or other subsidiaries might be necessary in order to make DR profitable.

Studies made by the Alvehag et al. (2016) shows that the electricity prices will be higher in 2030, but that the variations during the day will be about the same. This is mostly due to an increased cooperation between countries. For DR to be profitable the intraday-differences should be high.

However, DR could make it easier to integrate renewable production. For now Åland has the ability to export the overproduction to either Sweden or Finland, even if export to Finland comes with certain difficulties for now, as mentioned in section 2.2.2. But for countries that do not have that possibility, or in the future if the domestic overproduction in Åland is larger than the possible export, DR could make sure that a larger amount of domestically produced energy is utilized and bought locally. This can in turn make renewable energy production more profitable and create a bigger incentive for investors.

Utilizing DR for the reserve markets and/or flexibility markets, as described in appendix A, is perhaps the most economic use case for DR. A solution to enable participation on Åland should therefore be prioritized in the future to improve the investing climate for all flexibility resources. The possibility to reduce the subscription towards Sweden has been examined in this study but could also be applied on a smaller scale, via a DSO in apartment complexes for example. DR could also reduce the need for grid renovation and the investment cost for grid expansion by lowering peak consumption in areas that are approaching the limits for what the grid can handle. It should be noted that this need is not pressing on Åland currently, as was discussed with DSO Ålands Elandelslag. Another aspect regarding the opportunities of DR, on Åland specifically, is that there already is a significant amount of reserve power available through the DC cable to Finland and through local fossil reserves. The available reserves decreases the value of DR, in comparison to places that might require a completely new cable for reserve power which then perhaps could be completely avoided by utilizing DR.

The economic analysis is simplified to provide an overview of the CAPEX and it should be considered that the real cost of resources set to zero CAPEX in reality would come with some cost. However, for the purpose of this thesis the real cost is not the goal but rather to give an indication of the economics of the resource. OPEX is hard to estimate, but since the measuring equipment is installed on already existing assets in most cases, it should be relatively low. In comparison to a battery, where all maintenance costs are related to the battery itself, regular maintenance that would be required anyways on a HP is not related to DR and the metering equipment should not require any costly maintenance. Since HPs and refrigeration processes are modelled in a way that allows the previous cycle to complete, the lifetime of the resources should not be drastically decreased and measuring equipment should not have a high OPEX as well. It should also be noted that one of the main purposes, and advantages, with DR is that already existing assets can be used to decrease material and investment cost.

Electric heating is the most interesting candidate since it is the resource with the best potential and can be applied to already installed hardware. The same can be said for refrigeration and ventilation, but the potential is much smaller. Lighting, especially in households, would require a bigger change in lighting infrastructure. Industries have a high opportunity cost if production is decreased to participate in DR, and for Åland that currently cannot participate in the reserve markets it is likely not interesting to utilize DR in industries. In the future, if the goal for Åland is to be self-sufficient every hour of the year, this might come to change but as long as import and export are available other resources for DR should be used in the first place. EVs are different compared to the other resources, and will have the possibility of utilizing DR without an additional installation cost, as mentioned in 3.7. They should be used as a DR resource as the traffic sector is electrified, but the true OPEX of V2G should be further examined since it decreases battery lifetime.

6. Conclusion

Demand response (DR) could be used for increased flexibility in the electric grid on the Åland Islands. In this study, the potential of the following DR resources were investigated:

- Heat pumps and other electric heaters
- Refrigeration processes
- Lighting
- Ventilation and air conditioning
- Industries
- Electric vehicles

The potential of DR on Åland could be considered substantial and possible to obtain without decreasing function or comfort. If all technical potential was utilized in 2019 then the peak import of electricity from Sweden could be reduced by 18 %, or 11.4 MW. The resources also moved 11.0 GWh of electricity from times with high import to times with lower import, corresponding to 4.3 % of the total import. The average reduction was 2.26 MW during 4,871 hours. For 2030 the maximum import was lowered with 15 %, or 12.3 MW, without vehicle-to-grid (V2G) and 27 %, 21.8 MW, with V2G. Furthermore, the degree of self-sufficiency in 2030 could be increased with 4.2-9.9 % depending on if V2G has been implemented on a larger scale or not. The utilization degree, which indicates how much of the domestically generated electricity that is consumed on Åland, increased with 5.4-12 %. In 2030, for the case without V2G, 14.3 GWh of electricity was moved with an average of 4.29 MW during 3,334 hours. With V2G, the moved electricity increased to 31.8 GWh with an average of 9.25 MW during 3,439 hours.

Electric heating was established as the resource with the highest potential for 2019, and contributed approximately 3/4 of the total potential. Refrigeration was the second largest resource in 2019. Ventilation and lighting were found to have a relatively small contribution to the overall DR potential. However, if equipment for advanced regulation is already installed due to a previous need or want for controlling, the aggregation of these resources could have a high usage and potential in relation to the costs. No relevant data could be found regarding air conditioning on Åland. Industries were left out of the simulations due to the the difficulty with generalizing different industry sectors and the need for individual analyses.

The economics of DR was hard to determine, and the results varied substantially between the resources. Electric heating seems to be the only resource which is utilized for DR in any larger scale, and therefore it is the only resource where the economics could be determined by any measure of security. Compared to existing flexibility resources such as batteries, electric heating was determined to be a less costly alternative.

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Appendices

A. Reserve markets

A.1. Balancing and frequency regulation

If the generation and consumption of electricity is not equal at a certain time then the frequency will change. If generation is greater than consumption than the frequency will increase, and if the opposite is true then the frequency will decrease. The electric system has an inherent resistance to changes in frequency. This comes from something known as inertia. Large synchronous machines, such as nuclear power plant generators, have a large mass that rotates. When the frequency changes these large generators will oppose this change. If the frequency lowers due to lower production, then the generators will slow down. But the decrease in rotational speed releases energy, that was previously stored as rotational energy, into the grid. So systems with a high inertia, many large rotating machines, have a better buffer towards momentary changes in frequency, and gives the system operator time to adjust the production or consumption on the grid. With the increase of VRES this inherent resistance, or the inertia of the system, is decreased. Lowered inertia also means that the speed of regulation need to be increased. Therefore extended means for complementing the regulation of the frequency is needed. Frequency regulation in the Swedish grid is handled by SVK. In the short term they are responsible for handling disturbances that arise in the grid. This responsibility also includes making sure that a big enough power reserve is available at all times. In the Nordic grid the frequency should remain within a span of 49.9-50.1 Hz. This counts as normal operation. There are different levels of frequency regulation in order to keep the frequency as close to 50.0 Hz as possible. Smaller disturbances are handled automatically, by beforehand purchased reserves, but SVK also has the ability to manually shut down plants and facilities. The handling of the small variations in frequency that arises due to the constant changes in usage is called Frequency Containment Reserve - Normal (FCR-N) and is used when the frequency varies between 49.9-50.1 Hz. If the frequency drops below 49.9 Hz, for example if a big generation unit is disconnected for some reason, then the Frequency Containment Reserve - Disturbance (FCR-D) is used, down to a frequency of 49.5 Hz (Karlsson, Power and Nordling, 2016). FCR is used to stabilize the frequency. To then restore the frequency to 50.0 hz the automatic Frequency Restoration Reserve (aFRR) and manual Frequency Restoration Reserve (mFRR) are used (Svenska kraftnät, 2020).

In May 2020 a new reserve was introduced in the nordic countries, called Fast Frequency Reserve (FFR), with activation times much shorter than the above mentioned alternatives.

FFR is activated automatically and is used to handle the initial and deep transients that occur due to low rotational energy, low inertia, in the system. Since the level of inertia in the system changes, both the volume of FFR and the time periods it is procured might vary. FFR have three levels, seen in table 24, with different maximum times of activation, depending on the drop in frequency. If the deactivation rate is 20 % of the capacity of FFR per second, or lower, then the minimum duration of activation is 5 seconds. Otherwise the minimum duration is increased to 30 seconds. The units available for FFR must also be ready to reactivate within 15 minutes from the previous activation (Modig et al., 2020).

Table 24: Activation frequency and maximum time until full activation must be reached, for the fast frequency reserve (Modig et al., 2020).

Activation frequency [Hz]	Max. activation time [s]
49.7	1.3
49.6	1.0
49.5	0.7

If the frequency starts to deviate due to unmatching production and consumption, generators that for technical reasons are limited to a frequency range will start to disconnect and in worst case this will lead to a blackout. This is why balancing is necessary for a reliable grid (Fingrid et al., 2019).

A.2. Future Nordic market structure

The regulation market will change in the coming years. The development of common European platforms is underway. The nordic TSOs will be connected to the platform Picasso for aFRR and Mari for mFRR. This is planned for 2024. These platforms will be used so that more countries can share their balancing resources. Another big change is that the imbalance settlement period (ISP), which is the time for which the imbalance of the balance responsible parties is calculated, will be shortened from 60 minutes to 15 minutes in 2023. The same shift will happen for the market time unit (MTU) as well, both for the intra-day and balancing markets (Nordic Balancing Model, 2020).

In August 2019, with entry into force in October the same year, a Nordic System Operation Agreement was signed by all the Nordic TSOs. In one of the annexes, Load-Frequency Control & Reserves, several important factors are discussed regarding the future regulation of electricity. Furthermore the agreement is anticipated to require continuous updates to stay relevant to the increasing speed of the transition to more intermittent energy production (Fingrid et al., 2019).

Each nordic country have their own TSO. In Sweden the TSO is Svenska Kraftnät, in Norway it is Statnett, in Finland it is Fingrid and in Denmark it is Energinet. The Nordic countries are all connected synchronously meaning that the frequency is equal everywhere and is balanced for all countries. Balance regulation shall be conducted so that transmission capacities are not exceeded. Sweden and Norway consume approximately 75 % of the annual electricity in the synchronous area. It is therefore agreed by the Nordic TSOs that SVK and Statnett will have the responsibility of maintaining the frequency within specified limits for the Nordic synchronous area. Fingrid and Energinet will normally only balance the grid after contacting SVK or Statnett (Fingrid et al., 2019).

The Nordic TSOs have agreed that the bidding zones will be equal to the monitoring areas and therefore the corresponding TSO will have the balance responsibility. SE3 is an exception since both Kraftnät Åland and SVK operates in this area. Balancing shall take place in a way that ensures the lowest cost considering congestion, legislation and secure operation and consequently the lowest bids will be accepted firstly. It is in general agreed that a more interconnected market for regulation is required to handle the energy transition to VRES and that different Nordic countries should be able to combine reserves for participating in the frequency regulation market (Fingrid et al., 2019).

A.3. Flexibility markets

The reserve market in Sweden was designed for hydro power which made it hard for other flexibility resources to competitively enter the market (Alvehag et al., 2016). However, in the last years flexibility markets like EU-funded Horizon 2020 project CoordiNet, and even more recent SthlmFlex, have started to emerge. These markets are more suited for flexibility resources such as DR where smaller resources can be aggregated without complying with all the restrictions that the frequency market currently has. Flexibility markets aim to be complementary to already existing markets such as spot and balance markets (Svenska Kraftnät, 2020).

SthmlFlex is a project run by SVK, Ellevio and Vattenfall with a test period from December 1st 2020 to March 31st 2021 with the aim to reduce the capacity shortage in the Stockholm region. Entelios is the market aggregator, where customers can participate with available flexibility to momentarily reduce consumption at set times without decreased comfort. As an aggregator, smaller resources can combined to reach the minimum bid size of 100 kW. The market aggregator enter bids on the market available for purchase when flexibility is needed (Ellevio, 2021). An independent market operator, NODES, enable the TSO SVK and the Stockholm DSOs Ellevio and Vattenfall Eldistrubition to buy flexibility (NODES, 2020). This is the first time a flexibility market has been tested in a region with two DSOs where flexibility can be exchanged between the two (Svenska Kraftnät, 2020).

A local flexibility market, or another market such as SthlmFlex, would be technically feasible for Åland to utilize the flexibility resources currently available on Åland.

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B. Ventilation

B.1. Laws and regulations

The supply of air should be minimum 0.35 liters per second per square meter, which is approximately half of a households total air volume during one hour. This is the minimum amount of ventilation needed, regardless if the building is using DCV or natural ventilation (Ministry of the Environment, 2017). But ventilation also have a lot of other regulations. In 2017 the Ministry of the Environment in Finland released a new constitution regarding the demands for, among other things, air circulation and ventilation. The following demands are only necessary for newly constructed buildings or buildings which have their area expanded, but older buildings are still subject to older regulations. Chapter 3, 9 § and 10 § in "1009/2017 Miljöministeriets förordning om inomhusklimat och ventilation i nya byggnader" says that the air flow must be able to be regulated according to the usage of the building. During times when the household is empty it is possible to lower the ventilation by 60 %. The system must also be able to increase its performance by at least 30 % above the normal levels if needed. For non-residential buildings the air flow can only be limited to a minimum of 0.15 $dm^3/s/m^2$ floor area during off-hours, and the air needs to be exchanged in every room.

Apart from the above it is not specified exactly what else is required, but according to chapter 3, 8 § in "1009/2017 Miljöministeriets förordning om inomhusklimat och ventilation i nya byggnader" the ventilation system must make sure that the indoor air is healthy, safe and has a comfortable quality in the rooms that are occupied. The system should also supply a sufficient air flow so that substances that are harmful for people are removed, as well as remove high humidity, unpleasant smells and other pollution caused by humans, building materials or activities.

In chapter 2, 5 § and 6 § in "1009/2017 Miljöministeriets förordning om inomhusklimat och ventilation i nya byggnader", it also says that the momentary amount of carbon dioxide must never exceed levels that are 1450 mg/m^3 (800 ppm) higher than the outside levels, and that the inside humidity should remain within levels so that damages from moisture and microbial growth caused by high humidity can be avoided.

B.2. Air exchange in different buildings

The total air circulation, which is measured as how many times the total air in a building or room has been exchanged in an hour, is in average 1.8 for offices, 1.6 for buildings for institutional care and 2.3 for school buildings (Swedish Energy Agency, 2010). No values could be found for this parameter for the other buildings, so an average of the three previously mentioned buildings was used, which have a calculated mean value of 1.9. If this mean value is used then the buildings need to have their ventilation turned on for approximately half an hour (31.579 minutes) before the first people arrive to the location.

A study made by Engman et al. (2011) on school buildings showed that it is possible to turn off the ventilation, or run the ventilation more intermittently. In the study a comparison between continuous running and semi-continuous running of the ventilation system, as well as turning off the ventilation system during the night is performed. In the last case the ventilation is turned on at least one hour before the first people arrive. The study shows that the energy usage can be lowered, with only minor differences in for example moisture and carbon dioxide levels. It also shows that the amount of particles and moisture can be kept at allowed levels no matter which solution is used.

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C. Electric heating

C.1. Transmission losses

The amount of energy that is needed for heating in a building can be calculated by estimating the losses. Heat losses consist of several parts, but a major contributor in most cases are the transmission losses, which is the amount of energy passing trough the house exterior. The total heat losses per square meter through the building shell for a number of different generalized buildings can be seen in table 25. The heat losses through the shell vary greatly both depending on when the building was constructed, but it is also significantly lower if renovations have been made to the house.

Table 25: Estimated transmission losses for buildings with different construction year and renovation degree (Mälardalens universitet, 2009)

Year of construction	Exterior shell*	Transmission losses (kWh/m2) 125 m2 house	Transmission losses (kWh/m2) 160 m2 house
Before 1961	Original	214	204
	Improved	139	132
	Low-energy	104	99
1961-1975	Original	187	182
	Improved	131	125.5
	Low-energy	100	95.5
1976-1985	Original	137	134
	Improved	106	103
	Low-energy	84.5	81
1986-1995	Original	126.5	124.5
	Improved	101	98
	Low-energy	64	62
1996-2005	Original	119	115.5
	Improved	98.5	95
	Low-energy	41.5	39.5

*More information on the exact values used for the area and U-values in the transmission losses calculations for the three categories can be found in Byggnadstopologier Sverige (Mälardalens universitet, 2009)

The losses, per square meter, are smaller for the bigger house for the same construction year independent of what year the house was built, but not by much. The numbers varies greatly, with more than a five time increase from the building with lowest losses to the one with the greatest losses. Building year data could be retrieved from ÅSUBs yearly statistical summary (ÅSUB, 2020), but not if the buildings had been renovated or not, and therefore this way to estimate the losses proved too unreliable.

C.2. Perceived temperature and indoor climate

DR with HVAC units does not only have mechanical limitations. It is also important that for example the house occupants are not subject to a decrease in living standards. If the decrease or increase in temperature is perceived by the occupants depend on a lot of different factors. The thermal climate is decided by, aside from air temperature, the operative temperature as well as the level of humidity and movement of the air. The operative temperature depends both on the air temperature and the mean temperature from irradiation.

One common way to express how the thermal climate is felt is with perceived temperature. A study was made in the 1960s by professor Fanger, where he studied the perceived temperature not only from the previously mentioned factors but also with respect to metabolism, clothes and the temperature of the clothes (Abel and Elmroth, 2012). It is a complex subject, and the parameters will vary from household to household. Therefore a simplification has been made and individual buildings have not been taken into consideration.

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D. Lighting

The lighting schedules during weekdays for the studied buildings can be seen in figures 29a and 29b. Part load is defined as the average power usage during that hour divided by the total installed capacity, and where 1 represents that all available power is used.

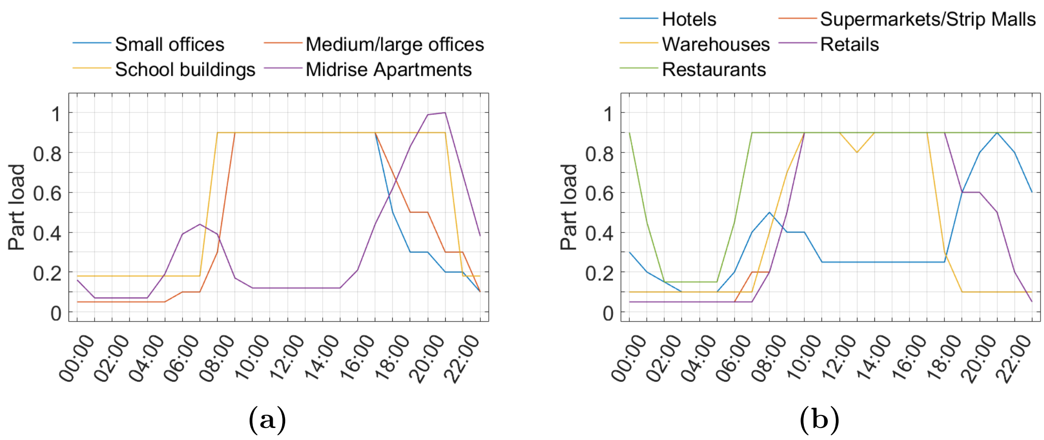

Figure 29: Lighting schedules during weekdays for different buildings types (Deru et al., 2011). The left figure shows the schedules for hotels, offices and school buildings (a) and the right shows the schedules for supermarkets/strip malls, warehouses, retails and midrise apartments (b).

The schedules in figure 29 show how much of the installed lighting capacity that is used in the different buildings for certain hours during the weekdays. Hotels and midrise apartments have two peaks, one for the morning och one for the evening, while the other buildings see a maximum usage for a prolonged time from late morning until evening, with some smaller differences between the different categories. The schedules are different for Saturdays and holidays/other days, and an example of this can be seen in figure 30, which shows the different schedules for medium sized offices. In this figure the office lighting are on a constant level of 5 % of maximum load during the whole day for holidays. This might not be true for all offices, but is used as an approximation for the aggregated group consisting of medium and large sized offices.

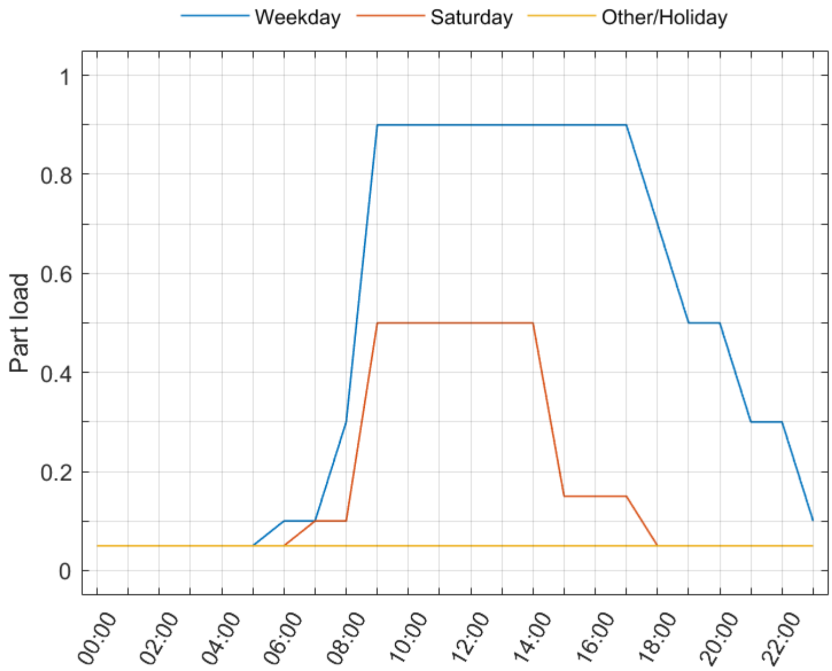

Figure 30: Lighting schedule for medium and large sized offices (Deru et al., 2011).

References

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E. Form sent to industries

The form sent to different industries was originally in Swedish and both the original as well as an English translation are included below:

1. Finns det några processer inom er verksamhet som skulle vara lämpliga att tillfälligt stänga av ifall man får ekonomisk kompensation för detta? Vad för processer är dessa? *(Are there any processes in your business that would be suitable to momentarily turn off if economic compensation is received for this? Which processes are these?)*

2. Om så är fallet, har ni en grov uppskattning på hur många kilowatt (kW) ni kan minska er användning med och under hur lång tid (kan vara allt från minuter till flera timmar)? *(If that is the case, do you have a rough estimation of how many kW the consumption can be decreased with and for how long (could be everything from minutes to several hours)?)*

3. Vad har ni för ungefärlig elanvändning på ett år (för att kunna jämföra med den totala användningen i sektorn och bedöma den totala potentialen, inga individuella siffror kommer att publiceras)? *(What is you approximate electricity consumption during one year (for a comparison with the total consumption in the sector to estimate the total potential, no individual numbers will be published)?)*

4. Har ni stora områden i er verksamhet med antingen eluppvärmning eller kyla? *(Do you have large areas within your business with either electric heating or cooling?)*

5. Har ni hört om demand response sedan tidigare, och tror ni att er verksamhet skulle vara intresserade av att testa detta koncept? *(Have you heard about demand response previously, and do you think that your business could be interested to test this concept?)*

F. Electric vehicles

F.1. EV driving distances on Åland

To calculate the DR potential of EVs on Åland, an average driven distance per vehicle was needed. There is no such data available for Åland and it was therefore estimated through the following methodology. Flexens has provided data of approximately 132,000 MWh of annual consumption from gasoline cars. As a comparison, the number of gasoline cars in 2019 were 21,624 (Fordonsmyndigheten, 2021b) and the amount of sold gasoline was 13,907 m^3 (ÅSUB, 2020). With an assumed energy density of 8.76 MWh/m^3 (Gulnic, 2003) this corresponds to a total yearly consumption of approximately 122,000 MWh for gasoline cars. All sold gasoline is not necessarily used in cars, but cars can also be refilled outside of Åland. By using the annual total consumption of 132,000 MWh, each gasoline car was calculated to consume 6.1 MWh. The average efficiency of a gasoline vehicle was assumed to be 0.08 l/km, or 0.0007 MWh/km (IEA, 2020). This implies a travel distance of 8,718 km per year as the average for each car, or 23.9 km per day. The daily driving distance in Sweden was 32.9 km in 2018 (Trafikanalys, 2019) and as Åland is a small island, shorter daily distances were expected and could be validated through this comparison. To apply the driving distances to EVs an average efficiency of 196 Wh/km was used (Electric Vehicle Database, 2021) corresponding to a yearly electricity consumption of 1.7 MWh per EV.

F.2. Number of charging EVs

As can be seen in table 26, at the end of 2020 the amount of EVs on Åland was 144 BEVs and 92 PHEVs. Compared to Sweden and Finland, Åland has a larger amount of BEVs than PHEVs, but a smaller percentage of EVs in general.

Table 26: Number of vehicles for different regions for 2020 (Fordonsmyndigheten, 2021b; Fordonsmyndigheten, 2021a; Trafikanalys, 2021; Traficom, 2021).

Region	BEVs	PHEVs	All passenger cars
Åland	144	92	25,320
Sweden	56,058	122,977	4,936,954
Finland	9,697	45,632	2,748,448

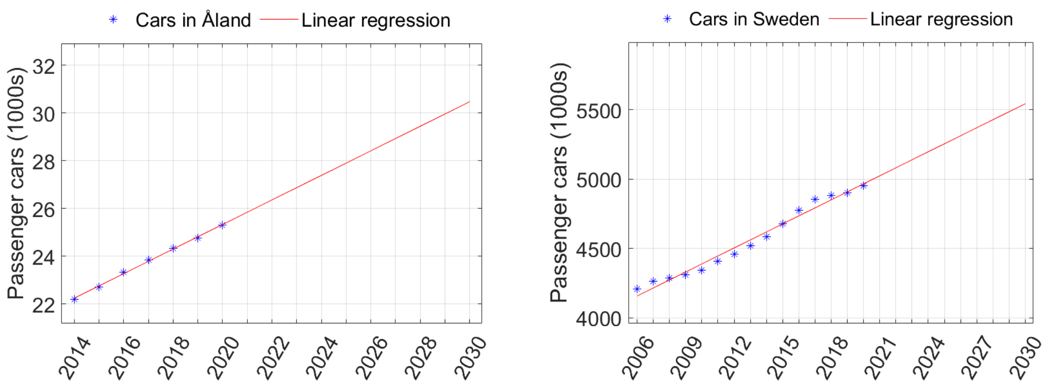
The amount of PHEVs in Sweden compared to BEVs is estimated to decrease in 2030 compared to now. An analysis made by Powercircle shows that two thirds of all EVs in Sweden in 2030 will be BEVs, and that the percentage of PHEVs sold will be

6%, compared to BEVs which will have 89 % of all sales (Kulin and Andersson, 2019). Prognoses on the amount of EVs in the year 2030 from Trafikanalys, Powercircle and 2030-sekretariatet can be seen in table 27.

Table 27: Prognoses of the number of chargeable vehicles 2030. (Trafikanalys, 2020; Kulin and Andersson, 2019; 2030-sekretariatet, 2020)

Organization	Number of chargeable vehicles
Trafikanalys	950,000-1,500,000
Powercircle	2,500,000
2030-sekretariatet	1,710,000

If the number of passenger cars on Åland increases linearly in the same pace it has since 2014, then the total number of cars will be about 30,500 in 2030, see figure 31a. If there is 4,000 EVs on Åland, this means that about 13 % of the passenger cars on Åland will be electric. By using the same linear approximation for Sweden, as seen in figure 31b, the total number of vehicles would be 5.543 million. Depending on what prognosis will come true the percentage of electric vehicles in Sweden will be 17.1-45.1 %. Even with the lowest estimate the percentage is still higher than it is on Åland. If the percentage prognoses for Sweden is assumed on Åland then the number of EVs would be somewhere between 5,200-13,800.



(a) **(b)**

Figure 31: Number of passenger cars on Åland (a) and in Sweden (b) in 2019 and their possible linear fit growth curve (Fordonsmyndigheten, 2021a; Trafikanalys, 2021).

Since the distribution of cars differs greatly for the different locations the development in Sweden or Finland might not be the same as that of Åland, even if the percentage of total EVs would be the same. Åland already have more BEVs than PHEVs, and if they follow the same development as Powercircle (Kulin and Andersson, 2019) think Sweden will, then more than two thirds of all EVs on Åland will be BEVs by 2030, but the exact number is not possible to estimate without more studies.

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G. Data granularity

Wind speed data, solar radiation and temperature data for different stations throughout Finland is published in 10 minute interval on the Finnish Meteorological Institute[16].

For solar radiation data the station on Utö is the closest one to Åland which measures radiation data and was therefore used. For wind and temperature data the western harbour station in Mariehamn was used. The hourly wind power production and solar power production was divided into shorter intervals by using the data with 10 minute interval for solar irradiation and wind speed respectively. The amount of energy produced during one hour was split directly related to wind speeds and solar irradiation. This sometimes caused the power production during certain intervals to exceed the maximum possible production for the plants. In these cases the exceeding energy was split among the other intervals for that hour.

The consumption data was divided into 10 minute intervals by using a linear interpolation. Figure 32 shows that there is a clear correlation between consumption and outside temperature, but that the linear correlation changes around 15-17 °C. Therefore linear regression was used for two different temperature spans, above and below 17 °C, seen in figure 32. The split was made at 17 °C since that is the temperature that is used as a balance point temperature for the heating. These regression plots were then used together with temperature data with a resolution of 10 minutes to attain the consumption values in between the already existing hourly values. In the beginning of 2019 a storm named Alfrida passed over Åland, with both losses in electricity and changes in consumer patterns as a result. These values can be seen in figure 32, where some values between -5 and 0 °C have a comparably low consumption. To avoid irregularities all values during the period from January 1^{st} to January 7^{th} have been replaced with consumption values given by the linear regression (below 17 °C), corresponding to the measured temperatures for the separate intervals.

The 10 minute production pattern of solar and wind was scaled from the 2019 data to the scenario of 2030 so that the maximum capacity matched the forecast. This assumes a scaled annual production based on the installed power which is not necessarily true. For example is the capacity factor, or efficiency, of modern large scale wind turbines higher than for old turbines. These would therefore produce more electricity annually compared to the same peak power of older turbines. However, for this comparison where the objective is to examine the effect on DR resources, it was concluded that proportional up-scaling was sufficient.

[16] Finnish Meteorological Institute. Available at: https://en.ilmatieteenlaitos.fi/download-observations [2021-03-03]

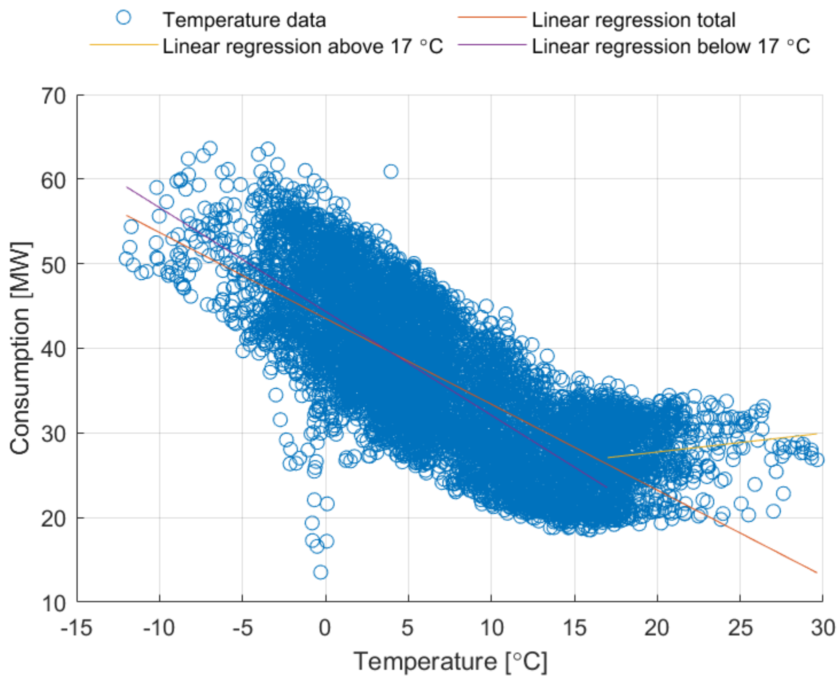

Figure 32: Consumption data plotted versus the corresponding temperature, and the linear regression plots for three different temperature spans.