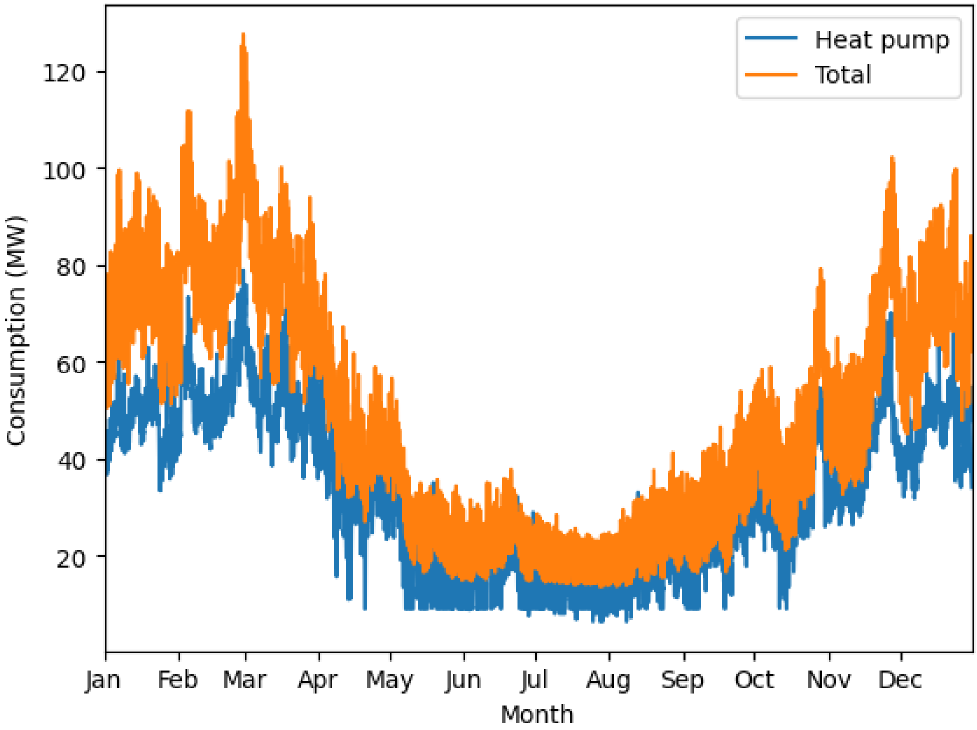

Long term flexibility forecasting for grid planning

Estimation of demand-side flexibility in the residential sector

Master's thesis in Sustainable Electric Power Engineering and Electromobility

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Gothenburg, Sweden 2023
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Master's thesis 2023

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Supervisor: Alexander Kärkkäinen and Simon Siöstedt, Göteborg Energi
Examiner: David Steen, Department of Electrical Engineering at Chalmers University of Technology

Master's Thesis 2023
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Cover: Total consumption of the detached and semi-detached households along with the modelled aggregated heat pump consumption simulated in Python showing the variation in space heating demand throughout the year.

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Abstract

With the expected electrification in Gothenburg, distribution system operators (DSOs) must cope with the increasing peak demand. Traditionally, it is done with grid reinforcements but in recent years, other strategies have emerged. One strategy is demand-side flexibility (DSF), which refers to the change in consumption that consumers may provide to support the grid. For a DSO to plan ahead, long-term forecasts of the available DSF are required in order to assess how its application can be incorporated into the network expansion plans and support the increasing capacity demand.

In this study, a long-term forecast of the available DSF was conducted for the customer base of Göteborg Energi in order to investigate the availability and impact of DSF, both today and for the years 2030 and 2035. A customer segmentation and weighting of the total customer base, showcased the residential segment as most suitable for flexibility applications. The load shifting capability of heat pumps (HPs) and electric vehicles (EVs), as well as peak shaving effect from photovoltaic (PV) solar panels proved to be the most fitting demand side resources (DSRs) to investigate. The results indicated that on the coldest day of the year, the theoretical maximum DSF in 2035 from HPs, PV solar panels and EVs would reach 145 MW during the expected morning peak load hours at 8 a.m. to 11 a.m. and 100 MW during the evening peak load hours at 4 p.m. to 7 p.m. Due to higher HP consumption and solar production during the early hours of the day, more DSF was consequently available in the morning, although there was no contribution from smart home charging of EVs at that time. With an expected 68% increase in power demand from today to 2035, the application of DSF from the residential customer base, could provide a 10% reduction of the expected power demand in Gothenburg during the morning peak load hours and 7% during the evening peak load hours.

Keywords: Demand response, power demand, capacity demand, demand-side flexibility, load management techniques, load shifting, peak shaving, PV solar energy, heat pumps, EV charging.

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Adam Passachin and Hadi Kenaan
Gothenburg, June 2023

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

AC	Alternating current
ASHP	Air-source heat pumps
AWHP	Air-water heat pumps
BC	Balanced charging
BESS	Battery energy storage system
BEV	Battery electric vehicle
COP	Coefficient of performance
DC	Direct current
DHW	Domestic hot water
DR	Demand response
DSF	Demand-side flexibility
DSO	Distribution system operator
DSR	Demand-side resource
EV	Electric vehicle
GSHP	Ground source heat pumps
HP	Heat pump
HVAC	Heating, ventilation, and air conditioning
IEA	International Energy Agency
LDV	Light-duty vehicle
PHAS	Public health agency in Sweden
PHEV	Plug-in electric vehicle
PV	Photovoltaic
SMHI	Swedish Meterorological and Hydrological Institute
SNI-codes	Swedish industry classification codes
ToU	Time-of-use
V2G	Vehicle-to-grid

Nomenclature

Below is the nomenclature of variables and parameters that have been used throughout this thesis.

Variables and parameters

COP	Coefficient of performance
$SCOP$	Seasonal coefficient of performance
τ	Thermal inertia
T_{flex}	Duration time of load shift
P_{shift}	Mean hourly load shift
T_{reg}	Regeneration time after load shift
P_{reg}	Regeneration load increase
$\frac{dQ}{dt}$	Change in heat over time
C	Heat capacity
T	Temperature
U	Thermal transmittance
R_{eq}	Thermal resistance
T_{in}	Indoor temperature
T_{out}	Outdoor temperature
P_{heat}	Power output from heating system
C_{tot}	Total heat capacity of a building envelope
$\frac{dT_{in}}{dt}$	Change in indoor temperature over time
W_{parks}	PV power output from all solar panel parks
W_{total}	Total installed PV capacity
P_x	Total installed PV power of a specific costumer segment
P_{dsdh}	Total installed PV power on detached and semi detached houses in Gothenburg

P_{ab}	Total installed PV power on apartment buildings in Gothenburg
P	Hourly PV power
A_x	Total PV panel area used by a specific costumer segment
A	Average PV panel area needed per 1 W
A_{dsdh}	Total PV panel area used by detached and semi detached houses in Gothenburg
A_{ab}	Total PV panel area used by apartment buildings in Gothenburg
r	Efficiency of PV panels
H	Solar radiation
PR	PV Performance ratio
$A_{maximal}$	Maximum area of a PV panel installation with a specific power capacity
$A_{minimal}$	Minimal area of a PV panel installation with a specific power capacity
P_{gen}	Generated PV power capacity
RP	Total reduced power of PV panels due to aging
TE	Percentage of lost power from the tilt of an installation in reference to the angle and orientation
LE	Percentage of lost power from cables, inverters and other secondary electronics
r_{year}	PV efficiency during a chosen year
r_{year-1}	PV efficiency during one year prior to the chosen year
r_{year-2}	PV efficiency during two years prior to the chosen year

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1

Introduction

1.1 Background

Gothenburg is currently undergoing a transition to employing more sustainable energy sources as a part of Sweden's commitment to 100% renewable energy sources by 2040 [1]. Together with the expected electrification and urbanisation of society, this shift is expected to place additional pressure on the grid's capacity, which is what the grid can handle or is dimensioned for [2]. As a result, there is a need for operators such as Göteborg Energi to use long-term forecasts of capacity demand in order to establish a foundation for decision-making. These forecasts allow operators to plan ahead for future investments in infrastructure and energy production.

Since grid owners typically base their system design on the expected peak power, the grid is continuously reinforced by adding capacity in order to meet the increasing demand. But to only rely on grid reinforcements is costly and expanding the transmission grid takes a long time. The increased demand and complexity of grid development, poses an increased risk of capacity shortages in Gothenburg [3]. Therefore, incentives exist for more effective utilization of the current grid. Demand-side flexibility (DSF) are such solutions that customers may deliver to reduce peaks in periods of high demand [4]. As a result of shifting the demand and reducing the peak power, less grid investments will be needed as the existing grid will be able to manage the demand more effectively.

There are several approaches to achieve DSF, but these often differ depending on the sort of customer segment and the resources available to them. Smaller customer such as residential owners have the ability to allow independent aggregators to control their loads. By pooling the flexibility of many household's appliances, such as heat pumps (HPs) and water heaters, as well as private charging stations for electric vehicles (EVs), it is possible to reduce the peaks during times of high demand by shifting the energy consumption of the aggregated loads [5]. The potential for flexibility in other areas such as the industrial sector, is also considered promising. Heavy and light industries may provide DSF through their industrial processes that require electricity. Such processes could temporary be stopped or shifted to off-peak hours in response to certain signals, provided that their is enough incentives. Commercial buildings such as supermarkets, hotels and restaurants may also contribute with DSF by aggregating demand side resources (DSRs) such as power-to-heat systems, cooling systems and EVs in public car parks [6].

In order for the distribution system operators (DSOs) to effectively plan for grid reinforcements, long-term forecasts of the DSF potential is useful. Previous studies on DSF have mainly been centered around qualitative research. Up until recently, more extensive studies have estimated the DSF potential in Sweden for the coming years. A study conducted by [7], estimated the technical DSF potential of different sectors in Sweden for year 2045. The study identified each load and process eligible for DR (demand response) within each sector and found that households will account for the largest portion DSF during winter peak-hours, contributing with 7 GW whilst EVs would contribute the most during summers of up to between 2 GW during the day and 3 GW during nights. In a similar study [8], the authors identified the residential sector to potentially be the largest contributor in Sweden and found that power-to-heat systems could contribute with 5.5 GW during the winter and 1.5 GW during the summer in 2030. However, as the DSO's are the ones responsible for distributing power to the end-consumers within their operating region, estimates of the DSF potential in urban areas of Sweden is also required.

A previous study conducted by [9], estimated the theoretical flexibility of different sectors in Uppsala municipality and found a potential DSF of 10 MW from HPs in the residential and commercial sector. Another study [10], estimated that HPs in households in the Vallentuna municipality could contribute with 4-13 % peak-reduction in 2021. DSF is however a relatively recent solution that is anticipated to grow in the coming years as a result of more integration of renewable power sources. Loads such as EVs and battery energy storage systems (BESSs) may contribute with a significant DSF in the coming years, hence long-term forecasts of the available DSF potential is important for a DSO's network planning. Hardly any studies has been done on the long-term DSF potential in urban areas within Sweden.

As Göteborg Energi must effectively plan for how much grid reinforcement will be required in the future; long-term forecasts of the available DSF are required to understand how flexibility can contribute to the capacity issue. Since the consumption of different loads varies across the different seasons and the time of the day, it is advantageous to forecast the DSF on a seasonal and hourly basis to better understand when the flexibility is available. These forecasts can be made in several ways, each with its advantages and disadvantages. It is therefore important to use a method that fits the customer segment and loads to be as precise as possible.

1.2 Aim and goals

The aim of this study is to perform a long-term forecast of the available DSF in Gothenburg for both today, year 2030 and 2035. In order to estimate the DSF, the relevant customer segment connected to Göteborg Energi will be identified and chosen, as well as the resources eligible for DR. The forecasts will then serve as a basis to determine the impact of DSF on the increasing capacity demand in Gothenburg.

The following questions will be answered to achieve the objective:

- What types of customers and loads can provide demand-side flexibility?
- How much flexibility is available from the relevant customer segment today and in the long-term?
- How can long term flexibility forecasts be incorporated in the network expansion plan of a DSO?

1.3 Scope and limitation

The study will be geographically limited to Gothenburg and will only consider customers connected to Göteborg Energi. The study will assess the different loads within each customer segment, and only the relevant loads within the chosen customer segment will be studied. Hence, barriers of DSF will be included in the study to choose the customer segment and loads eligible for DSF estimations. Moreover, only existing loads that are in use now or intended to increase in the future will be examined, since emerging technologies and loads are difficult to predict. The forecasts will be made for both the present, year 2030 and 2035 since DSF will be crucial to Sweden's objective of transitioning to 100% renewable energy in the coming years.

The study will not consider the economic aspects of DSF, such as economic barriers and financial incentives to provide flexibility or how these may be formed for the different customer segments. Neither will it consider the organisational realisation of DSF, as these inquiries call for a understanding of human behaviour as well as insight on societal justification and regulation, which are considered to be outside the paper's purview. Similarly, the technical barriers regarding the integration of automation and control systems for the loads will not be covered in this study as technology today is limited but may be mature enough in the future.

2

Theory

2.1 Power demand in Gothenburg

Expected investments in the transportation and maritime industries are anticipated to raise the power demand in the coming years, particularly in the Gothenburg region [11]. The extensive electrification of industries as well as increase of EVs will present a challenge during the winter months, when the demand is at its highest.

Gothenburg's maximum power consumption during a peak hour is today at 850 MW, but the last 100 MW are rarely used and and when they are, they are typically only released 6 times per year, often during the cold winter months [3]. Historically, the annual peak demand occur during the winter, since demand for electricity is higher during this time of the year, see figure 2.1. Contrarily, the summer months often result in a lower demand since heating demand is significantly lower.

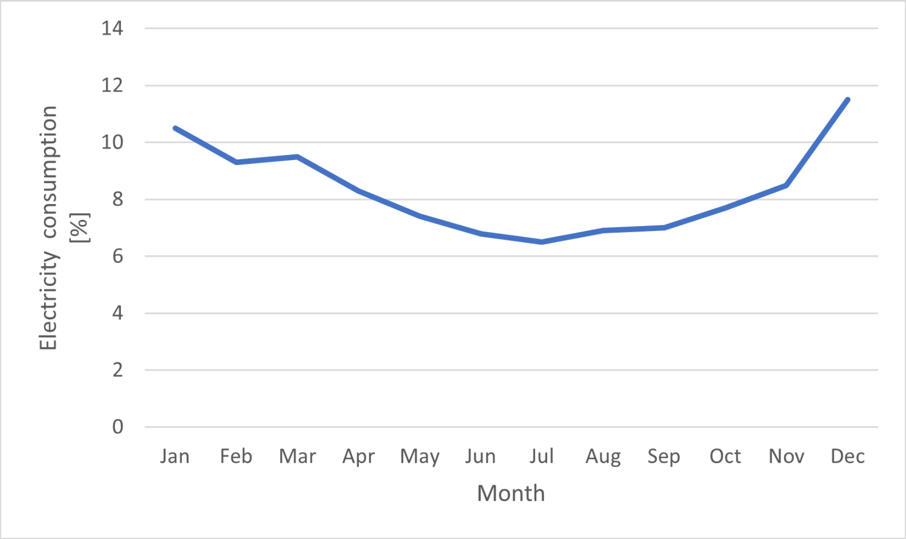


Figure 2.1: Monthly share of total electricity consumption in Gothenburg, 2022.

On a 24-hour basis, the day-ahead prices in the electricity price region SE3 displays the hours with highest demand, see figure 2.2. The peak load hours often occur in the morning, when people get up and use their household appliances at the same time, and the evening, when commuters arrive at home from work or school. Each year the peak load hours often falls within one of the time intervals. The peak load hour between December 1, 2022 and March 31, 2023, were projected to be between 8 a.m. to 11 a.m and 4 p.m. to 7 p.m [12].

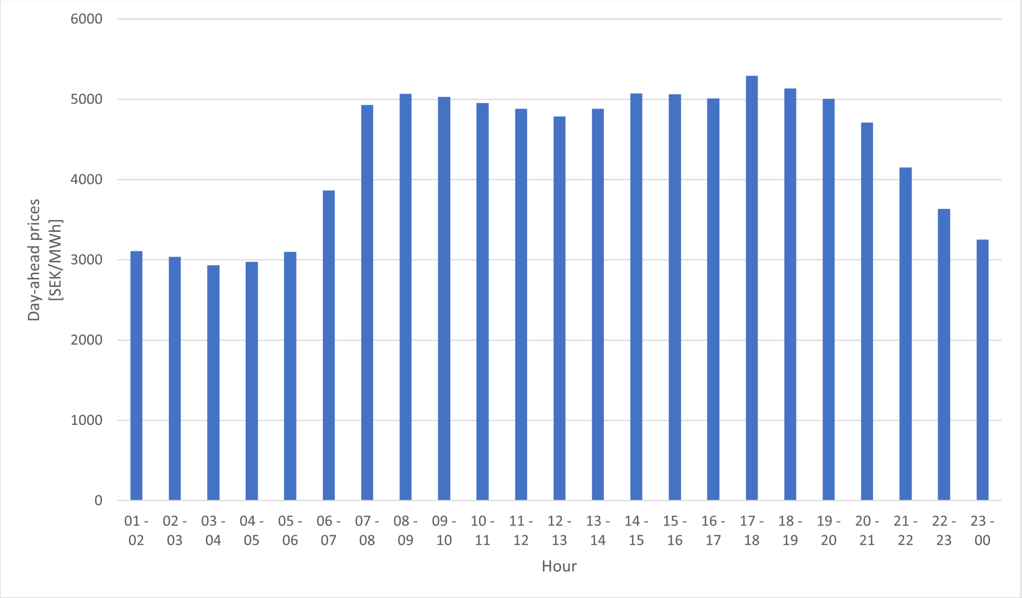


Figure 2.2: Hourly day-ahead prices on Nord Pool during a typical winter day in SE3, retrieved from [13].

2.2 Demand-side flexibility

Demand-side flexibility refers to the portion of demand that can be changed to help balance the grid. The method serves as a technique for DSO's to stabilise the grid by involving different actors in society to adjust their electricity usage. The change in consumption could be done in response to external pricing signals, such as time-of-use (ToU) tariffs or other incentives-based programs [14].

The adjustment of electricity usage is often referred to as DR and can be achieved by either reducing or shifting the consumption, as can be seen in figure 2.3. Load shifting refers to when the electricity consumption during peak-load hours, i.e. when demand and electricity prices are high, are shifted to a time when demand is lower. This results in lower electricity prices for the consumers and reduced grid peak power, but not a reduced consumption, since the consumption is only moved to another time [15].

Peak shaving, on the other hand, relates to a direct peak reduction achieved through the use of DR. The DR could be provided by electricity generating resources such as photovoltaic (PV) solar systems whereby the loads are momentarily powered by the resource during periods of high demand [15].

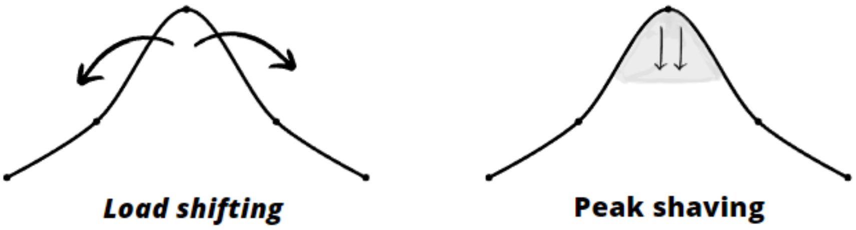


Figure 2.3: Load management techniques, with inspiration from [16].

2.3 Demand-side resources

While DSF is the broad notion that refers to consumers' capacity to modify their electricity use, demand-side resources (DSR) are the specialized technologies and loads that enable customers to actively engage in the management of the energy grid [14]. DSRs are tools and strategies that empower customers to take a direct part in the operation of the electrical grid [17]. This mainly includes conventional loads with integrated control systems. These loads used by the consumers can provide flexibility to the grid and assist in balancing the supply and demand for electricity when needed.

There are several DSRs accessible for various sectors. HPs, regular home appliances, and renewable-energy sources such as PV panels are the most prevalent DSRs in the residential sector [6][18]. EVs are becoming more popular, and this is also seen as a potential resource for flexibility applications in the future [6]. However, some loads might be eligible to offer DR, but due to low flexibility potential they might be too small to be considered or there might not be enough incentives to support its application. Therefore, in order to pinpoint the sector most appropriate for DR and determine which loads that qualify for DR applications, it is necessary to form a comprehensive image of the consumers connected to the DSO.

2.3.1 Heat pumps

Space and water heating systems are essential in maintaining a comfortable living and working environment [19]. Today, around 60 % of all detached and semi-detached households in Sweden have some type of HP installed, while district heating continues to account for nearly 90 % of heating in apartment buildings and commercial buildings [20]. HPs are devices that transfer heat from the ground or air to both space heating and domestic hot water (DHW) using a relative small amount of energy. They are a popular alternative to traditional heating systems since they are more energy-efficient [21].

There are several types of HPs, that uses different sources for heat extraction. The most prevalent types of HPs in Sweden are ground source heat pumps (GSHP) and air-source heat pumps (ASHP) which includes air-water heat pumps (AWHP) and air-air heat pumps [22]. The air-air HP works by extracting heat from the outside air and transferring it to the indoor air. The AWHP works in a similar way but is instead designed to extract heat from the outdoor air to water, which then is used to heat the building using heat exchangers such as waterborne radiators or floor heating. This type of heat pump can be used to provide both space heating and DHW [23]. GSHP is a type of pump that extracts heat from the ground to the indoor air. The heat can be extracted from the soil, bedrock or sea water [22].

The efficiency of a HP, also known as the coefficient of performance (COP) is an important feature. The COP refers to the ratio between the heat or cold produced and the energy consumed. All HPs have a COP greater than 1, since the energy consumed is not directly converted to heat, rather used to extract additional heat from the heat source which requires less work. The HP can therefore produce more kilowatt-hours (kWh) heat than the amount of kWh electricity it consumes. The COP is however temperature-dependent, meaning it decreases when the temperature of the heat source decreases, thus resulting in a higher electricity consumption since the temperature difference between indoor and outdoor becomes larger. Yet, as the temperature varies throughout the year, another metric known as the seasonal coefficient of performance (SCOP) is used. The SCOP considers different outside temperatures during the year, and gives a more accurate measure of the HPs performance. The SCOP values are often presented in different climate zones, since the yearly outside temperature varies depending on where the HP is placed [24].

2.3.1.1 Heat pumps as demand side resources

HPs are considered as a potential resource for DR as they can be turned off during periods of high demand due to the thermal inertia of buildings. The thermal inertia of a building introduces an exponential temperature behaviour, when turning off the heating system, since some of the heat is stored in the building and is slowly released when the HP is turned off. A comfortable indoor temperature for the occupants can therefore still be maintained [25].

The thermal inertia of a building refers to the degree of delay in which the temperature of the envelope reaches the surrounding temperature. The inertia relates to the thermal mass within the buildings envelope, which is the total mass of all components of the building or more specifically, the amount of heat that is stored within the envelope [26]. A higher thermal inertia will allow HPs to be turned off for a longer period of time, since the building will react slower to external temperature changes.

The thermal inertia of a building is often described in terms of a time constant τ, given as [27],

$$\tau = \frac{\text{thermal mass}}{\text{heat losses}} \tag{2.1}$$

where it is determined by the building's thermal mass or heat capacity, and the heat losses which relates to the insulation of the building. The time constant can vary significantly depending on the envelope of the building. A smaller house with high insulation can have a time constant of 2 days, whilst a bigger house with the same insulation can have a time constant up to 8 days [27]. A higher thermal mass and insulation, will therefore result in a larger time constant which allows the HP to be turned off for a longer period of time.

The duration a HP can be turned off is however also determined by the accepted indoor comfort temperature of the occupants in the buildings and recommendations from the public health agency. According to the public health agency in Sweden (PHAS) [28], the indoor temperature should be between 20-23 °C measured with a standard thermometer and should not subceed 18 °C, nor exceed 26 °C during shorter periods.

2.3.1.2 Flexibility metrics for HPs

The duration of load shift and maximum peak reduction during the peak hours is an important measure of flexibility. However, since the heating system must be switched on again in order to restore the desired indoor temperature, the aggregated rebound effect of switching on all HPs at the same time, could create aftermath peaks during the off-peak hours. The off-peak period is therefore also important to assess. The flexibility metrics for HPs can be seen in figure 2.4.

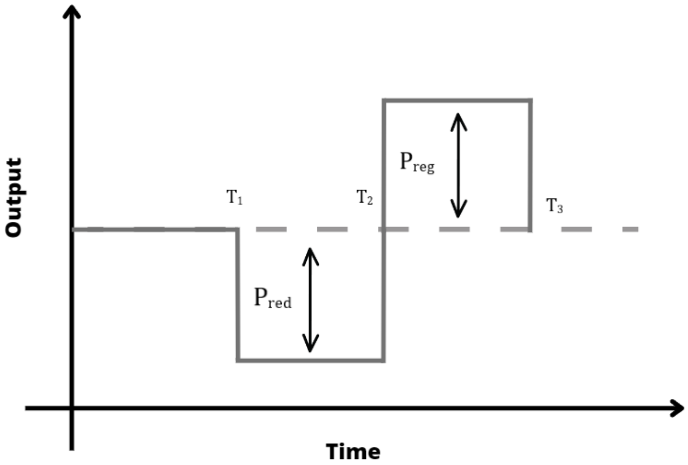


Figure 2.4: Simplified holistic description of flexibility metrics for a HP, with inspiration from [25].

The duration time T_{flex} refers to the period of time, during which the HP is turned off before exceeding the lower boundary temperature and turned back on, thereby representing the time for the total load shift,

$$T_{flex} = T_2 - T_1 \tag{2.2}$$

where T_1 marks the start time in which the HP is turned off and T_2 represents the end of the load shift and start of regeneration period. P_{red} represents the hourly mean peak power reduction achieved during the load shift, as seen in the figure. The regeneration time T_{reg} is the time it takes for the system to reach the desired indoor temperature after the load has been shifted, described as

$$T_{reg} = T_3 - T_2 \tag{2.3}$$

The rebound-effect after turning on the HP again, is represented as a hourly mean load increase P_{reg} after the load shift, as seen in the figure and T_3 is the time in which the regeneration period ends. The increase is simply caused by the regeneration demand of the aggregated HPs when restoring the indoor temperature to the original temperature.

2.3.2 Photovoltaic solar panels

PV solar panels converts solar energy into electrical energy [29], not to be confused with solar collectors which look similar but converts solar energy into heat instead [30]. They are a great green energy option since they do not emit any toxic or greenhouse gas emissions, are reliable and require low maintenance [29]. In other words, PV panels are a renewable and clean source of energy [31]. They convert the solar energy through a made up network of linked PV panels that take in and transform solar energy into direct current (DC) power [29]. After being transported through an inverter, this DC electricity is transformed into alternating current (AC) that may be utilized to power buildings, commercial establishments, and other electrical equipment.

There are different types of PV panels, whereby the most common in Sweden is silicon solar panels, such as monocrystalline and polycrystalline solar panels [32]. This is due to their higher efficiency, longer lifespan and wide commercialization. Despite both being silicon solar panels with a lifespan of approximately 25 years, monocrystalline and polycrystalline panels have their technical differences. The most significant differences are the monocrystalline's higher efficiency and lower temperature coefficient, in comparison to the polycrystalline's lower cost [33].

PV panels can be installed with BESSs which can help utilize the produced energy more efficiently [34]. These batteries can help producers significantly increase both the power generated from the PV panels and sold out to the grid, as well as the power stored. These BESSs would be extra helpful in areas close to the arctic and antarctic with fluctuating solar radiation, such as Gothenburg for example, due to the long nights in the winter and long days in the summer [35]. Despite the economic benefits of using BEES with PV panels, only 1 in 40 PV installations has such batteries included in Sweden, although it exist subsidies to promote BESSs even further. It is also not clear how this number will change in the future [36].

Finally, it is worth to mention that the Swedish government help create incentives for consumers to install PV panels by introducing so-called green deductions for solar cells, charging boxes and batteries [36]. These deductions can reach up to tens of percent, and are extra beneficial for microproducers of electricity, with installations under 43.5 kW, as they are already offered tax reductions, free in- and output meter changes, more favorable electricity trading agreements and no grid feed-in fees [37].

2.3.2.1 Photovoltaic solar panels as demand side resources

PV power generation enables owners to assist the grid with peak shaving, whereby the consumption during peak hours can be reduced by the electricity production from the PV panels. The average PV panel efficiency, taking into account all types of PV panels in Sweden, was estimated to be around 21% [38] with a power output of 1593 MW during the previous years [39]. They produce most their energy during the summer months, due to clear skies and higher solar irradiance [40] [41]. PV solar panels can today be found on detached and semi-detached houses, apartment buildings and in clusters forming solar PV parks.

In 2021, Sweden had 37 solar parks with an individual installed capacity above 1 MW [42]. Two of these parks are situated in Gothenburg, with a combined capacity of 10 MW [43]. The average installed PV panel power on detached and semi-detached houses in Sweden is about 9 kW [44], while the average installed PV panel power on apartment buildings in Sweden varies considerably, it typically is around 22.5 kW [45]. These numbers are larger than ever, and are also estimated to increase heavily in the coming years [46].

2.3.3 Electric vehicles

EVs are becoming a vital part of our society as we strive to reduce our carbon emissions. Today, there exists around 460 000 battery electric vehicles (BEVs) and plug-in electric vehicles (PHEVs) in Sweden [47] and forecasts estimate that half of the vehicle fleet will be fully electric by 2030, corresponding to nearly 2.5 million EVs [48]. In 2022, around 33 % of all the newly registered vehicles were electric and whilst the EV market has witnessed a significant growth, the number of privately owned EVs have also grown. In the same year, 51 % of the newly registered EVs were privately owned [49].

As more and more people switch to EVs, the demand for a reliable charging infrastructure increases. Due to the convenience of overnight charging, more private residences install their own private chargers. In Sweden, most private residences are equipped with three phase systems, yet most EVs' on-board chargers only support single-phase charging. The maximum charging speed is therefore limited by the vehicle but also the main fuse rating of the building. Home charging can typically only deliver a maximum power of 3.7 kW or 7.4 kW depending on if the main fuse rating is 16 A or 32 A [50]. Higher charging powers of up to 150 kW is only available at public charging stations, where fast chargers are accessible. These chargers can typically give up to 150 kW, while even more powerful chargers exist with speeds up to 350 kW[51].

Whilst the increase of EVs supports Sweden's environmental target of reducing greenhouse gases in the transport sector by 70 % until 2030 [52], the increasing demand for electricity could possibly strain the grid. In 2021, roughly 8.5 % of all EVs in the region Västra Götaland existed in Gothenburg municipality, along with only 200 public charging stations [53]. Lack of charging infrastructure causes the demand for charging to be concentrated to a specific time duration, with almost 80-90 % of EV charging currently taking place at home or at work [54].

As seen in figure 2.5, during weekdays the typical EV driver often starts charging right away after arriving from work in the evening and continues until fully charged [55]. Residential charging does therefore tend to cluster in the evening, which coincides with the daily peak load hours. The additional strain the charging demand places on the grid in the evening, will create even larger peaks during the annual peak demand in the winter.

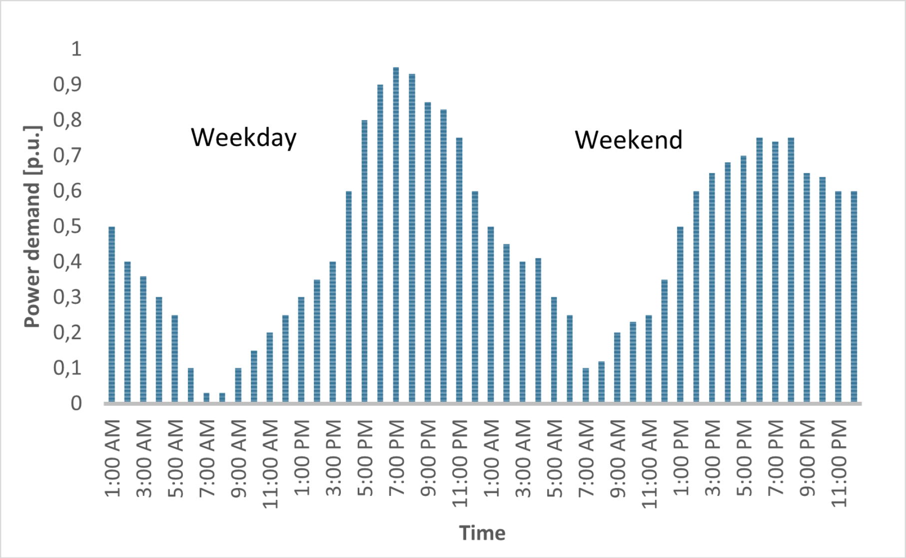


Figure 2.5: Hourly residential EV charging profile during a typical weekday and weekend, with inspiration from [56].

2.3.3.1 EVs as demand side resources

The posed capacity issue caused by the increasing charging demand, can ultimately be mitigated by a more diversified charging behaviour. Privately owned EVs are on average parked 23 hours per day [54] and since most EVs in general are left parked after being fully charged and not used until the next day, a large window is available for the charging to be done instead. By shifting the charging to times of lower demand rather than directly charging the EV when plugged in or alternatively lowering the dispatch power and extending the charging time, peak demand can be reduced. The change in charging behaviour can automatically be achieved using so-called smart chargers. Depending on the desired load management technique, different smart charging technologies can be used to control single EVs or even larger vehicle fleets.

Balanced charging (BC) is a smart charging scheme that controls the dispatch power and causes the EV to charge for a longer period of time with reduced power. As the dwelling time of a EV in general is longer than the charging time, the technique makes use of the entire dwelling time to attain a low constant charging power [57]. Therefore, charging time is longer, but the peak power is reduced, as seen in figure 2.6.

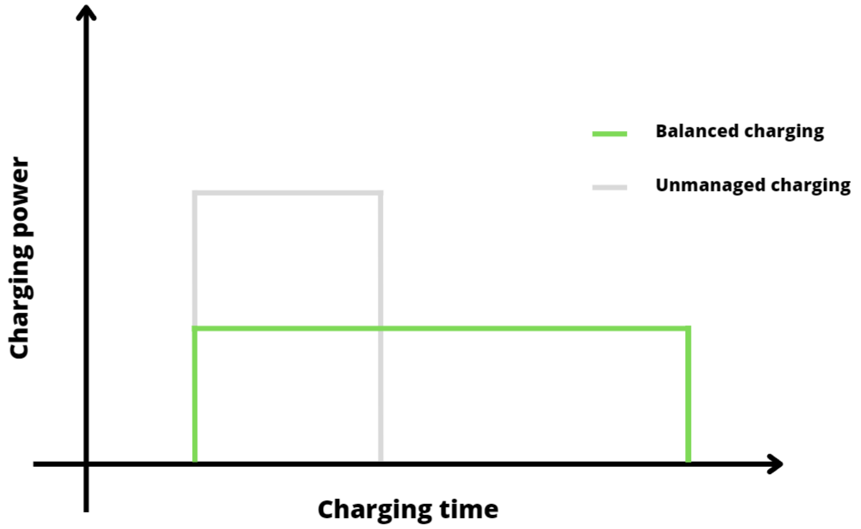


Figure 2.6: Balanced charging strategy with inspiration from [58].

2.4 Barriers for demand-side flexibility

For DR to be implemented; technical, operational and economic aspects must be taken into consideration. The amount and duration of flexibility available is generally limited by the characteristics of the load, hence some loads may not be eligible for flexibility applications. Loads such as lightning and ventilation which are evident in nearly all sectors, are already optimized enough and therefore not feasible. Some industries with high-consumption processes might not be able to provide DR since turning off production is often not economically justifiable.

Electricity consumers are somewhat aware of DSF but are unaware of the available resources and commercial prospects [59]. Flexibility implementation is hampered by organizations' competing agendas, worrying about upsetting their fundamental operations, and financial advantages. However, clear financial advantages, increased benefit awareness, and successful case studies are all necessary for businesses to get beyond these obstacles. The following are the most common barriers for implementing DR:

- Lack of knowledge and awareness.
- Low or limited flexibility potential.
- Reluctance of third party control.
- Acceptance issues.
- Conflicting priorities within the organization.
- Lack of business case.
- Requirements for participation.
- Limitations of different properties.
- Too high costs of lost production and market shares.
- Adjusting production processes not always being possible.
- Complexity.
- Fear of disrupting the core business.

2.5 Models for estimation

In this section, a technical description of the models used for simulating the space heating demand and EV charging demand are presented.

2.5.1 Lumped capacity model for space heating

The lumped capacity model reduces the complexity of heat transfer equations by assuming that an object can be represented by a single node with uniform temperature. Each node has a heat capacity and thermal resistance, whereby it is assumed that the node is in equilibrium with the environment such that the temperature gradient inside the object is negligible. Depending on the number of nodes used, the accuracy of the model increases [60].

Any thermal system that adheres to Newton's law of cooling can be modelled as a lumped capacitance. The principle simply states that the rate of heat loss of an object is proportional to the difference in temperature between the object and its environment, resulting in that the object's temperature ultimately reaches the surrounding temperature in an exponential behaviour. Assuming the object can be approximated as a heat reservoir, Newton's law of cooling can be expressed as [60],

$$\frac{dQ}{dt} = -\frac{T_{in} - T_{out}}{R_{eq}} \tag{2.4}$$

where $\frac{dQ}{dt}$ is the change in heat, corresponding to the total heat capacity C_{tot} and temperature T by $Q = CT$. R_{eq} is the total thermal resistance, T_{in} is the object temperature and T_{out} is the surrounding temperature.

Considering the thermal behaviour of a building, all heat transfer can be assumed to follow a linear relationship [60]. The building envelope will therefore lose or gain heat linearly through conduction to the environment if there exists a difference between the indoor and outdoor temperature. During e.g. winter periods, buildings will lose heat at a higher rate since the difference between indoor and outdoor temperature is higher.

A building can hence be represented as a single node, as seen in figure 2.7, where P_{heat} is the output from the heating system. The total thermal resistance of the building envelope represents its ability to resist heat transfer and the total heat capacity considers the building envelope's ability to store heat and delay temperature variations.

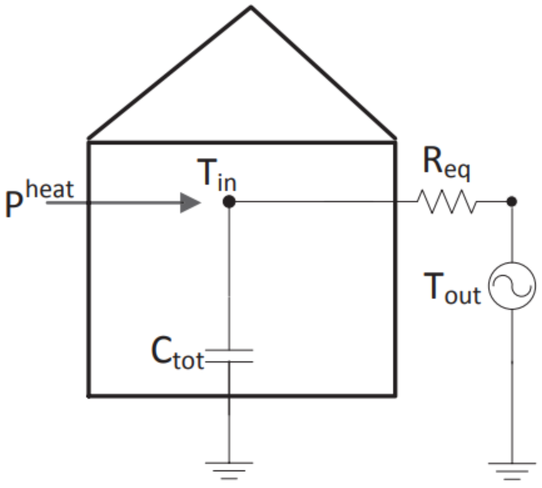


Figure 2.7: Lumped capacity model using one node with permission from [61].

2.5.2 Modeling and management of electric vehicles

Estimating the flexibility from EVs requires realistic load profiles of the charging demand, which can be challenging due to different driving patterns and charging probabilities. The International Energy Agency (IEA) has developed an electric vehicle charging and grid integration tool to enable actors to understand the impact of EV charging on the power system [57]. The tool creates realistic weekly EV charging profiles based on a set of input parameters entered by the user. The tool also support managed charging scenarios to visualise the effect of different smart charging technologies, as well as the impact on battery efficiency caused by ambient temperatures. Other functionalities are available in the tool, but only the used modules are explained in this study. This section gives a brief description of the tool's methodology, input parameters and output data.

2.5.2.1 Input data

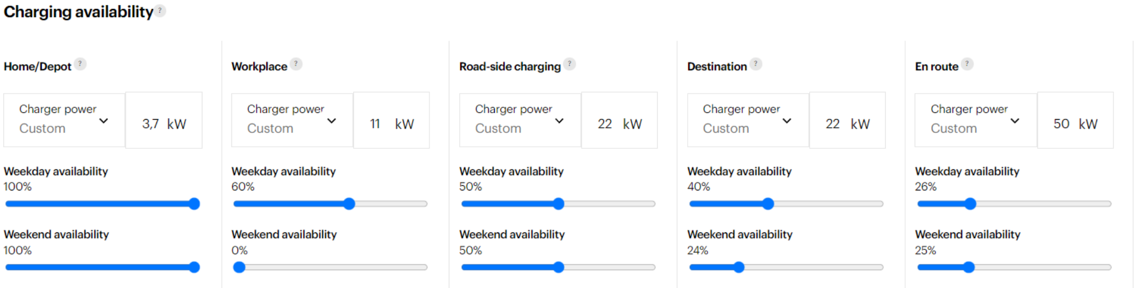
The EV charging load profiles are created using data on the EV fleet, driving and charging behaviours. Following are the input parameters related to the fleet and driving behaviour:

- Vehicle type
- Vehicle stock
- Average daily driving distance during weekdays and weekends

- Average battery capacity
- Energy consumption per kilometre

A snippet of the tool's charging behaviour widget is shown in figure 2.8 and the input parameters for the charging behaviour are as followed:

- Charging location - home/depot, workplace, road-side, destination or en route
- Availability of charging location
- Charging power at charging location
- Arrive time and stay time during weekdays and weekends
- Probability of shifting charging to next day
- Preference of charging location



Charging availability

Home/Depot
Charger power: Custom
3,7 kW
Weekday availability
100%
Weekend availability
100%

Workplace
Charger power: Custom
11 kW
Weekday availability
60%
Weekend availability
0%

Road-side charging
Charger power: Custom
22 kW
Weekday availability
50%
Weekend availability
50%

Destination
Charger power: Custom
22 kW
Weekday availability
40%
Weekend availability
24%

En route
Charger power: Custom
50 kW
Weekday availability
26%
Weekend availability
25%

Figure 2.8: Screenshot of the input parameters related to the charging behaviour.

Currently, only balanced charging is available for the managed charging function. The only input setting related to the managed charging is the participation rate of each charging location. The rate considers the charging location's ability to provide managed charging and the likeliness and tendency of the driver to engage in smart charging schemes. Furthermore, the ambient temperature can manually be set to a value that reflects the average temperature of a place, month or scenario to include the effect from temperatures on the EV efficiency, since it impacts the rate of charging.

2.5.2.2 Modeling steps and output

Using the input parameters, the program models the charging behaviour of the fleet with respect to driving preferences and behaviours as well as charging availability at different locations. The tool sets a time step of five minutes and simulates the charging demand for a week. The modeling of charging load profiles are conducted in four steps. First, the program estimates the available charging windows for the vehicle stock. It then calculates the daily energy consumed as well as the energy needed to charge. Afterward, the calculated energy needed to charge is allotted to the available charging windows. Finally, the charging energy for the charging windows are converted to power to visualise the load profiles. In addition to the simulated load profiles; the max power demand, average power demand, weekly energy and annual energy are determined for the fleet [57].

The addition of managed charging includes a final step, wherein the model first decides which location type is to participate with smart charging and then establishes if it is possible. It then applies the chosen smart charging strategy to generate the desired load profile [57].

3

Method

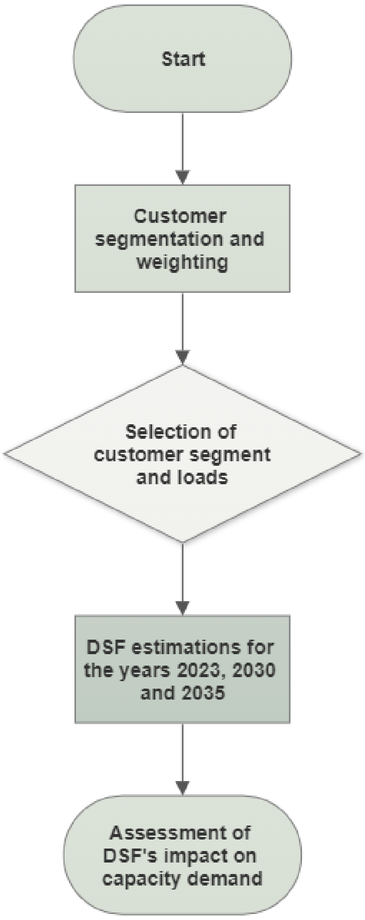


Figure 3.1: Flowchart of methodology.

A flowchart of the methodology can be seen in figure 3.1, which parts aims to answer the research questions and achieve the objective of the study. The initial step involved a customer segmentation and load identification, followed by a weighting, for the customers connected to Göteborg Energi in order to identify the customer segments that can offer DR. The second step comprised of estimations of the potential DSF for the chosen customer segment and its DSRs, both for today, year 2030 and 2035. The estimated DSF from the customer segment was finally incorporated into the capacity demand forecast made by Göteborg Energi, for an assessment of its potential support to the increasing capacity demand.

3.1 Customer segmentation and weighting

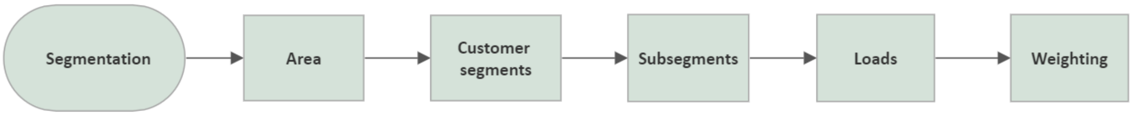


Figure 3.2: Chronological framework for the segmentation and weighting performed.

Above, in figure 3.2, the layout for the segmentation and weighting can be seen in chronological order. To effectively understand the customer base of Göteborg Energi, a comprehensive customer segmentation was carried out through a literature study, corresponding to the current circumstances of their customer base and loads. The segments were first categorized under one of the three main areas; city, transport or industry, wherein their respective segments, under-segments and loads were identified with the aid of Göteborg Energi.

The quantification of each customer segment was done using a data file achieved from Göteborg Energi. The file contained the yearly electricity consumption of different customer segments presented in the Swedish industry classification codes (SNI-codes) measured by installed grid station meters. By mapping the SNI-codes from the file with the identified customer segments, each segment and its under-segments were quantified in terms of their yearly electricity consumption for the previous year 2022. The yearly consumption was then compared to the total electricity consumption of Göteborg Energi's customer base in order to receive the share of total consumption for each segment. The loads eligible for DR were then identified through literature studies and mapped to the relevant customer segment.

Finally, in order to choose the customer segment to investigate, a weighted decision matrix was used, where each segment was graded based on four criteria; the size of the customer segment, amount of resources available for DR, barriers which considers the limitations in actualizing the DR and the possible size of DSF. Depending on its importance, each criterion received a weight and the segments were assigned a score between 1-3 for each criterion.

3.2 Demand-side flexibility estimation

In this section, the procedure of the DSF calculations for HPs, PV solar panels and EVs are presented, as well as the necessary assumptions and data used for the estimations.

3.2.1 Heat pumps

The flexibility estimations for the HPs in the detached and semi-detached houses was determined by the thermal behaviour of the building envelope. A heating demand model was created in Python to simulate the space and water heating demand of the households with a HP, both on a yearly and daily basis. Due to insufficient data, the current year 2023 was represented by parameters from 2018. Given that Göteborg Energi serves a variety of building types, three different building envelopes were considered in order to include the range of diverse buildings within the customer base.

The load shift time and regeneration time were calculated through the model, as well as the load shift and peak load increase after the load shift. The estimations were repeated for the year 2030 and 2035, whereby the potential DSF depended on the increase in newly built houses and share of households with controllable HPs.

3.2.1.1 Modelling of heating demand

The flexibility estimations for the HPs in the detached and semi-detached houses were done through the lumped capacitance model using one node, as described in section 2.5.1. The thermal behaviour of a building considering both heat gain from the HP and heat loss through conduction were derived as [62],

$$\frac{dT_{in}}{dt} = T_{in,t+1} - T_{in} = \frac{P_{heat} \cdot COP}{C_{tot}} - \frac{(T_{in} - T_{out})}{C_{tot} \cdot R_{eq}} \tag{3.1}$$

where $\frac{dT_{in}}{dt}$ is the change in indoor temperature, P_{heat} is the input electricity to the HP, COP is the coefficient of performance, C_{tot} is the total heat capacity in kWh/K, R_{eq} is the total thermal resistance in K/kWh, T_{in} is the indoor temperature in Kelvin and T_{out} is the outdoor temperature in Kelvin.

The indoor temperature was assumed to remain constant at 21 °C throughout the year. The yearly outdoor temperatures during 2018 were extracted from the Swedish Meteorological and Hydrological Institute's (SMHI) station Gothenburg A [63] and used in equation 3.1, to calculate the hourly energy consumption of the HP required to maintain the desired indoor temperature. The SCOP of the HP was retrieved from a measurement study conducted by the Swedish Energy Agency. The SCOP of GSHPs were between 3-5 [64] and for AWHPs 2.6-2.7 [65]. The SCOP was chosen as 3 in this study, since the performance of the HP is likely to be decreased by the cold temperatures during the coldest day.

The total thermal resistance was chosen according to an end-use metering campaign in 400 swedish households conducted by the Swedish Energy Agency [66]. The yearly space heating consumption for two common household types were averaged and adjusted to match the total measured household consumption from the residential customer base connected to Göteborg Energi. The yearly space heating consumption of households with families between the age of 26-64 and households with only couples between the age of 26-64 were extracted and averaged. Since, 62.8 % of the residential sector's consumption in EU was from space heating in 2020 [67], the yearly consumption was adjusted and scaled to receive a load profile, where the space heating accounted for around 60-65 % of the total measured household consumption. A yearly consumption of approximately 6000 kWh/year was chosen and the thermal resistance was adjusted in the model until the value was met. R_{eq} was chosen as 5.52 K/kWh.

During the warmer months where the outdoor temperature exceeds the indoor temperature, there is no need for space heating since the building gains heat from the outside temperature. There would however be a need for cooling, since the indoor temperature would increase above the allowed upper boundary temperature, but in this study it was assumed no occupants were in need of cooling during the hot days, since cooling is quite uncommon in Sweden and because the warmer indoor temperature during the day often is leveled out by the later decrease in temperature during the night. As the building stores the heat during the day, parts of that heat will slowly be released in the night, keeping the indoor temperature within the allowed temperature boundaries.

The DHW system was assumed to be integrated with the space heating system for all residential buildings, hence the energy consumption for the HPs covers both the space heating and hot water usage. The DHW consumption was extracted from the same measurement campaign done by the Swedish energy agency [66]. The average daily water heating profile for houses with families of the age between 26-64 was used, where the average consumption drawn each hour was around 0.3 kW, which totalled a yearly water heating electricity consumption of 2700 kWh/year. The daily water heating profile was assumed to be the same every day and was therefore added onto the space heating profile for each day of the year.

The modelled yearly heating profile was scaled by the share of houses with a HP, which was assumed to be 60 %, the same as the share in all of Sweden [20]. The number of detached and semi-detached households connected to Göteborg Energi in 2023 were 54 000, and thus 32 400 households were assumed to have a HP. The profile was then used to create the daily heating profile for the coldest and warmest day during 2018. The specific days and corresponding outside temperatures were extracted from SMHI's database [63].

3.2.1.2 Simulating load shift time

To maintain a comfortable indoor temperature when shifting the load, the maximum and minimum allowed indoor temperature was set to 21 ± 1.5 °C. As described in section 2.3.1.1, the recommended indoor temperature should remain between 20 and 23 °C, and hence the average temperature of 21 °C was used with an 1.5 °C margin corresponding to the halfway point of the temperatures. The indoor temperature change and load shift time on the coldest day during the peak load hours was simulated using equation 3.1, where the HP was completely turned off until the indoor temperature had reached 19.5 °C from the initial indoor temperature of 21 °C. The HP was simulated to be switched off at the expected initial hours of the daily peak periods; 8 a.m. and 4 p.m., as described in section 2.1. The load shift time was estimated using Eulers's iteration method with a time step Δt of one minute, where the change in outdoor temperature each hour during the load shift was taken into consideration. The simulation was done for the three different building envelopes; light, average and heavy.

Using the relationship 2.1 as described in section 2.3.1.1, the total heat capacity for each building envelope scenario could be simplified by the lumped capacitance method as,

$$\tau = R_{eq} \cdot C_{tot} \tag{3.2}$$

where the previous thermal $R_{eq} = 5.52$ K/kWh was assumed to be the same for the building envelopes and the time constant τ varied for the three different building envelope scenarios. The time constant and corresponding heat capacities are shown in table 3.1.

Table 3.1: Parameters for three different building envelopes. [68].

Envelope	**Time constant τ [days]**	**Heat capacity C_{tot} [kWh/K]**
Light	1	4.3
Average	2.5	10.8
Heavy	4	17.4

The load shift time of the HP did only consider the boundaries of space heating, although these may be different for the DHW system, it requires modelling of the water tank and occupants' hot water usage, which were not considered in this study. The load shift time of DHW was therefore assumed to be the same as the calculated time for space heating, as they were assumed to be integrated. During the warmest day, however, the load shift time was not modelled since there was no space heating demand due to the high outside temperatures. Since only DHW demand existed during the warmest day, the load shift time was assumed to be the same as for the coldest day, in order to compare the seasons.

3.2.1.3 Simulating regeneration time

The same equation 3.1 was used to simulate the regeneration time during the coldest day in order to estimate the peak load increase after the load shift. After the initial temperature drop to 19.5 °C, the HP was simulated to be switched on after the load had been shifted, until the original indoor temperature of 21 °C was reached. The installed HP power for all houses was assumed to be 4.5 kW, since building regulations limits the allowed power to a maximum of 4.5 kW for houses up to 130

m^2 [69]. The average household size in Sweden is 122 m^2 [70], hence the installed HP power was deemed reasonable. The building regulations does however only apply to newly built houses, and not existing houses or older houses in need of a upgraded heating system, but due to the difficulty of knowing the distribution of construction year for the residential customer base, the maximum allowed installed power was used. The regeneration time was simulated for the same three building envelopes, hence the same parameters were used. The simulation was repeated for the warmest day using the same regeneration time, but since only hot water demand existed during this day the power drawn from the HP was assumed to instead be 20 % of the installed power, corresponding to 0.9 kW.

3.2.1.4 Forecasting maximum DSF from HP control

Since the average building envelope was deemed the most representative of the residential customer base, the load shift and regeneration time for that case were used in the modelled daily HP consumption during the coldest and warmest day to achieve the mean hourly load shift during the peak hour periods and mean hourly regeneration increase after the load shift periods. As the daily HP consumption was simulated on a hourly basis, the load shift times and regeneration times were rounded to the nearest hour.

To estimate the DSF for the years 2030 and 2035, the number of newly built houses were forecasted using the increase of newly built houses during the previous years 2020, 2021 and 2022. The newly built houses each year were 351, 262 and 282, respectively [71]. This corresponded to an average of approximately 300 newly built houses each year, where it was assumed that 60 % of these houses installed a HP, the same as the share in Sweden [20], which corresponded to nearly 180 newly built houses each year. The average number of houses with HP was added onto the number of detached and semi-detached households that had a HP in 2023, up until years 2030 and 2035. The forecasted number of households with HPs are shown in table 3.2.

Table 3.2: Forecasted number of households with HP.

Year	2023	2030	2035
Increase of houses	0	1 260	2 160
Number of houses	32 400	33 660	34 560

Given that HPs have a quite long life expectancy of on average, 10-15 years for air-air HPs, 15-20 years for AWHPs and up to 20 years for GSHPs [72], it is difficult to determine the distribution between older and modern HPs in the customer base as well as how many of the newer HPs that support smart-control. Today, the aggregation of residential HPs is quite rare and does not exist on the bigger scale, other than the few independent households that have installed modern HPs with smart-control for personal steering. Due to the difficulty of predicting the number of households with controllable HPs today and in the future, all households with HPs were assumed to provide DR in order to obtain the theoretical maximum DSF for each year.

3.2.2 Photovoltaic solar panels

In this section, the method used to determine the total installed PV power of all detached and semi-detached houses and apartment buildings is described along with the forecasting approach used. The calculations performed for the potential power output and achievable peak shaving reduction on the household consumption during the daily peak load hours is also presented. The calculations and forecasts were performed in Matlab, both for the warmest and coldest day. Due to insufficient data on Sweden's total PV power in 2023, the values for each year instead represented the values for the two subsequent years. Hence, all parameters concerning the total PV power and efficiency in 2023 were represented by values from 2021.

3.2.2.1 Scaling and sizing of parameters

The estimation of PV solar power output from the detached and semi-detached houses and apartment buildings connected to Göteborg Energi were conducted in a top-down approach, wherein the share of the total solar power production from the different PV systems were determined for all of Sweden, to then be reduced to the region of Gothenburg.

The total installed PV capacity in Sweden 2023 was 1593 MW [39] and it could be assumed that 86% of the total installed PV power in Sweden belonged to detached and semi-detached houses [39].

Furthermore, the total output of all ground mounted solar panel parks put into operation before 2022 [42] [73], and all roof mounted solar panel parks having a power output of at least 1 MW and put into operation before 2022 [42], was found to be 130.3 MW. The roof mounted solar parks smaller than 1 MW were regarded as PV panels potentially attached to apartment building, hence not all sizes of roof mounted PV installations were included in the park estimations.

The share of total PV power in Sweden belonging to apartment buildings was estimated by the following equation,

$$\%_{ab} = \frac{W_{total} - W_{parks} - (W_{total} \cdot \%_{dsdh})}{W_{total}} \tag{3.3}$$

where W_{parks} is the total output of all ground mounted solar panel parks put into operation before 2022 and all roof mounted solar panel parks having a power output of at least 1 MW and put into operation before 2022, W_{total} is the total installed PV capacity in Sweden and $\%_{dsdh}$ is the share of installed PV power in Sweden attached to detached and semi-detached houses.

To scale down the estimations from Sweden to Gothenburg, it was assumed that the shares of PV panels attached on detached and semi detached houses and apartment buildings in Gothenburg was the same as for all of Sweden. The shares were therefore multiplied separately with the total installed PV power produced in Gothenburg, i.e. 58.4 MW [74] to obtain the total installed PV power of a specific costumer segment, P_x, for each residential type, where x refers to either detached and semi-detached houses or apartment buildings.

3.2.2.2 Forecasting power and efficiency

To forecast the potential PV power produced in 2030 and 2035, a linear regression was performed using the installed PV capacity in Sweden, achieved from the year 2021 and earlier, with the same assumptions made earlier [39]. After the forecast, the Swedish PV power values achieved for 2030 and 2035 were taken out and divided by the 2023 PV value respectively, in order to attain the PV power increase for these two years compared to the PV power existing today in Sweden. The PV power development was assumed to be the same in Gothenburg as the rest of the country, hence these scalars were finally multiplied to the earlier estimated PV power production from the detached and semi-detached houses and apartment buildings respectively in Gothenburg.

The forecasted PV efficiencies in 2030 and 2035 were estimated using a linear regression based on the PV efficiencies in Sweden for the previous years up to 2023, found in [38]. Similarly, the PV efficiency development for Sweden was assumed to be the same as in Gothenburg.

3.2.2.3 Estimating potential power output

The hourly PV power output profile was achieved for the years 2023, 2030 and 2035 using the determined values. The estimations were made for both the warmest and coldest day of the year, using the year 2018 as a reference year to match the forecasts of the other DSRs in this study. The hourly power output was determined according to [75] as,

$$P = A_x \cdot r \cdot H \cdot PR \tag{3.4}$$

where P $[W]$ is the hourly produced power achieved from PV installations, A_x is the total PV panel area $[m^2]$ installed for a specific customer segment x, r is the efficiency [%] of the panels, H is the solar radiation hitting the installations during each hour of the day $[W/m^2]$ and PR is the performance ratio [%] of the installed system.

As 1 kW solar cells cover an area of approximately 5 m^2 to 8 m^2 [44], the average panel area needed per 1 W was calculated as

$$A = \frac{(A_{maximal} + A_{minimal})}{(2 \cdot P_{gen})} \tag{3.5}$$

where $A_{maximal}$ is the maximum needed PV panel area to generate a specific power output, $A_{minimal}$ is the minimum needed PV panel area to generate a specific power output and P_{gen} is the generated PV power. The value was assumed to be the same for the years 2023, 2030 and 2035.

The total PV panel area for each residential type was determined by multiplying the average panel area needed per 1 W with the total installed PV power for each residential type according to,

$$A_x = A \cdot P_x \tag{3.6}$$

where x refers to either detached and semi-detached houses or apartment buildings as mentioned in 3.2.2.1.

The performance ratio PR was also assumed to be the same for all three years. Although the performance ratio usually is measured yearly [75], as it can vary during days and hours, it was assumed to be constant for all studied time intervals here. Also despite the performance ratio containing more parameters, these three were assumed to be the largest and most important to consider [75] [76] and the following equation was used to estimate PR,

$$PR = RP \cdot TE \cdot LE \tag{3.7}$$

where the total reduced power of PV panels due to aging, RP, was assumed to be 10% [76], the share of lost power from the tilt of a installation in reference to the angle and orientation, TE, was assumed to be 11% and the share of lost power, LE, from cables, inverters and other secondary electronics was assumed to be 11% as well [76].

The assumption of TE was based on the average detached and semi-detached house roof having an angle of between 40^o to 45^o [77], while PV panels on apartment buildings can differ widely in tilt and orientation [78], and to generalise the matter the TE was assumed for both residential types to be the average of the fourteen values achievable for detached and semi-detached houses in Sweden with a tilt angle of between 40^o and 50^o [77].

The average efficiency r was calculated separately for each of the studied years, by taking the average efficiency of the three latest years, for each year. This was to take into account that different solar panels in use were manufactured during different years and has different lifespans, efficiency and degradation. The efficiency was estimated by,

$$r = \frac{(r_{year} + r_{year-1} + r_{year-2})}{3} \tag{3.8}$$

where r_{year} is the PV efficiency during a chosen year, r_{year-1} is the PV efficiency one year prior to the chosen year and r_{year-2} is the PV efficiency two years prior to the chosen year.

The warmest and coldest day in 2018 were extracted from SMHI's measurement station Gothenburg A [63], whereby the hourly solar radiation H was found for the days [79]. The hourly solar radiation during the warmest and the coldest days in 2018, were assumed to be the same for the years 2023, 2030 and 2035.

3.2.2.4 Estimating peak shaving effect

To estimate the peak shaving effect of the produced PV power during the daily peak load hours of the residential consumption, a data file containing the aggregated household consumption of all the detached and semi-detached houses and apartments buildings measured by Göteborg Energi during the coldest and warmest day was used. Since, BESSs are rare today and their increase in the future is difficult to predict, it was assumed that no residential building today or in the future had installed storage systems for their PV panels. Hence, the produced solar power was limited by the installed PV capacity and no solar energy could be stored for later uses. The estimated power production from PVs for the different household types were subtracted from the aggregated household consumption during the peak load hours in order to peak shave. The expected peak load hours were assumed to be between 8 a.m. to 11 a.m. and 4 p.m. to 7 p.m. as mentioned earlier in section 2.3.1. The mean peak shaving power was then calculated for each residential type, days and daily peak load periods, by taking the mean value of the difference achieved in consumption peaks with and without the effect of solar energy.

3.2.3 Electric vehicles

This section provides an overview of the base parameters employed in the electric vehicle charging and grid integration tool to generate the charging demand profiles, along with the two different charging scenarios that were considered in the simulations. The estimation of DSF from the use of balanced charging strategies is also presented, as well as the necessary assumptions made for the forecast of future years.

3.2.3.1 Estimating base parameters

The DSF estimation of EVs did only consider light-duty BEVs, since PHEVs charging pattern is difficult to simulate due to the combined use of internal combustion engines [80]. To simulate the BEVs charging demand in 2023, it was assumed that every privately owned BEV had access to one charging point, and that all home charging points where each constituted by a charging box with a charging power of 3.7 kW [50]. In the case of regular destination- and workplace charging, it was assumed that a maximum charging power of 22 kW dominated [81], while en route charging stations were assumed to have a maximum charging power of 50 kW [82]. Due to the lack of available data on the number of BEVs existing in Gothenburg today, the number of BEVs in 2021 was used instead, corresponding to 7228 BEVs within Gothenburg's municipality [53]. Similarly, no data existed on the share of BEVs that were privately owned, hence the share of privately owned BEVs in Gothenburg was assumed to be the same as in all of Sweden, i.e. 42 % were privately owned [83].

Furthermore, it was assumed that the average battery capacity of the BEVs was 48 kWh [84] and that their average energy consumption was 17 kWh per 100 km [85]. Similarly, the average driving distance in Gothenburg was assumed to be 29 km for both weekdays and weekends with a 1 km standard deviation [86]. The probability of shifting charging to the next day was assumed to be 25%, as it was the recommended default percentage of the IEA tool. The smart charging strategy participation rate was set to 100 % on home/depot locations and 0 % on all other charging locations, as only the DR from the residential charging was of interest. The simulations did only consider the temperatures during the coldest week, to be able to evaluate the impact of DSF on the expected yearly peak load hours occurring in the winter. A summer scenario was therefore not considered in the simulation. The average temperature was assumed to be -10.1^o C for the entire week, which was obtained by taking the average hourly temperature recorded from SMHI's measurement station during the coldest week in 2018 [63].

3.2.3.2 Modelling scenarios and forecast

As the charging behaviour of each driver is diverse and random, two different charging scenarios were considered to observe the effect of different charging locations. In the first scenario, it was assumed that all the privately owned BEVs only charged on their respective residential charging spots and in the second scenario, a more mixed and realistic charging pattern was assumed with charging conducted outside the residence as well.

Both the preference and charging availability at the home/depot location was set to 100 % on weekdays and weekends in the first scenario. The arrival time to the home/depot location was assumed to be 4 p.m. on weekdays with a 2h standard deviation, and 3 p.m. on weekends with a 4h standard deviation [87]. The typical stay time was set as 12h on both weekdays and weekends.

In the case of the second scenario, it was instead assumed that the preference for charging was 50% at home/depot, 30% at the workplace, 10% at destination and 10% en route. The charging availability was assumed to be 100% for all four locations on both weekdays and weekends. Furthermore, the arrival time to the home/depot location was set as 4 p.m. on weekdays with a 2h standard deviation, and 3 p.m. on weekends with a 4h standard deviation, similar to the first scenario. Also, the typical stay time for these locations were set to 12h on both weekdays and weekends. The arrival time at the workplace was assumed to be 8 a.m. on weekdays with a

1h standard deviation, and 6 a.m. on weekends with a 2h standard deviation [87]. The typical stay time at the workplace was assumed to be 9h on weekdays and 5h on weekends. As for the public destination charging, the arrival time was assumed to be 5 p.m. on weekdays with a 2h standard deviation, and 11 a.m. on weekends with a 4h standard deviation [87]. The typical stay time was assumed to be 2h on weekdays and 4h on weekends. Finally, the arrival time en route was assumed to be 6 a.m. on weekdays with a 2h standard deviation, and 10 a.m. on weekends with a 4h standard deviation. The typical stay time for en route locations was assumed to be 1h on both weekdays and weekends [88].

3.2.3.3 Reducing peak power through balanced charging

To derive the available DSF from the BEVs using a balanced charging strategy, the generated charging profile with regular unmanaged charging was compared to the case of balanced charging. The average charging consumption was derived from the peak load hours; 8 a.m. to 11 a.m. and 4 p.m. to 7 p.m. for both the unmanaged and balanced charging cases. The average consumption was also calculated separately from the weekdays and weekends, since the charging behaviour differed between the days. The quantity of DSF was achieved as the difference between the charging consumption using unmanaged charging and balanced charging.

3.2.3.4 Forecasting available DSF from BEVs

To estimate the available DSF from the BEVS in 2030 and 2035, the achieved DSF today was scaled using the expected increase of BEVs in the future. All other parameters regarding the base parameters and scenarios were assumed constant. It is expected that the number of BEVs and PHEVs in all of Sweden increased with around 320 000 vehicles each year [89]. Thus, it was estimated that the accumulated number of BEVs and PHEVs in Sweden would reach 2 700 000 by the year 2030 and 4 300 000 by the year 2035, corresponding to a 587.0% and a 934.8% increase, respectively, when compared to the number of chargeable vehicles today [47]. As the share between the number of BEVs and PHEVs was assumed to remain constant, the percentage increase was used to scale the amount of available DSF today until the years 2030 and 2035. The percentage increases corresponded to 42 429 BEVs by 2030 and 67 568 BEVs by 2035.

3.3 Incorporation of DSF into the capacity demand

In order to assess the impact of available DSF on the expected capacity demand, the estimated DSF from each load was summed depending on the time period of the day, i.e. the morning or evening peak hour interval. Despite PV solars not providing DR, as mentioned in section 2.3, the peak shaving contribution from the PVs was added to the DSF achieved from the HPs and EVs, in order to obtain a total flexibility potential for each peak load hour interval. Since, the peak load hours in Sweden is expected to fall on a winter weekday presumably between these peak periods, only the DSF available during the coldest day was considered as well as the weekday scenario for the EV estimation.

The capacity demand prognosis used was developed by Göteborg Energi, wherein the expected power demand during 2023, 2030 and 2035 were forecasted. The expected power demand was based on that the highest demand of the year would fall on one hour of the year, seemingly a winter weekday either during the morning or evening peak load hour period. The forecast considered the current loads from all sectors of Gothenburg, expected energy-effectivisation of the current loads in the future and the expected addition of loads from all sectors. To determine the attainable reduction in capacity demand, the forecast was compared with the effect of the available DSF during the morning and evening peak time intervals for each year.

4

Results

4.1 Customer segmentation and weighting

In this section, the customer segmentation of Göteborg Energi's customer base is presented as well as the weighting decision matrix performed for a selection of the segment to be investigated.

4.1.1 Customer segmentation

The residential customer segmentation can be seen in figure 4.1 together with the identified loads. Similar mapping was performed for the other customer segments, which can be found in appendix A.1.

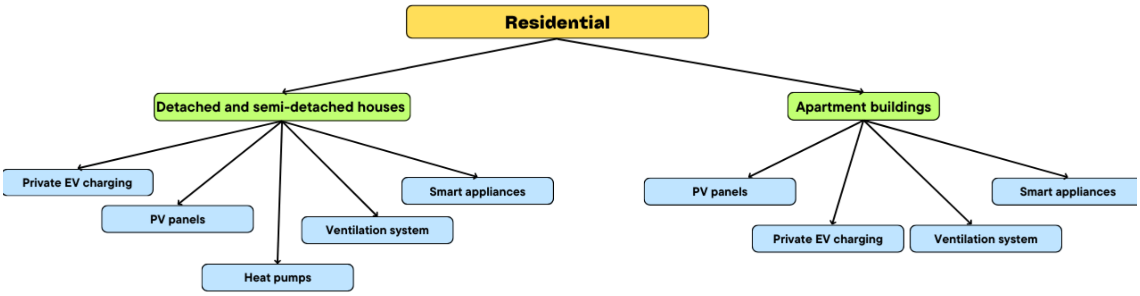


Figure 4.1: Customer segmentation and load identification of the residential customer base.

4.1.2 Weighted decision matrix for customer selection

Table 4.1 reveals the weighting conducted on the customer segmentation. Three of the four criteria were appointed a weight of two, as they were deemed moderately important. However, the criterion concerning the limitations in actualizing the DR was deemed more important and was appointed a weight of three. This was due to the reason that the barrier criterion mainly determines whether the DR has the potential to be achieved by the customer type, while the other criteria rather determines the potential DSF size to be achieved by the customer type.

Table 4.1: Weighted decision matrix for customer selection.

	Criteria 1	Criteria 2	Criteria 3	Criteria 4	
Criteria description	Customer segment size	Available DSR	Barriers	Potential size of DSF	Weighted score
Weight	2 (22 %)	2 (22 %)	3 (33%)	2 (22 %)	9 (100 %)
Customer type	Criteria 1 scores	Criteria 2 scores	Criteria 3 scores	Criteria 4 scores	Scores
Residential	3	3	3	2	3
Commercial	2	3	2	1	2
Transport	1	1	2	1	1
Industry	3	1	1	3	2

Both the residential and industry segments were appointed a score of three concerning the size of the segment in terms of its yearly consumption. It is obvious that the residential segment was designated the highest score, as it accounted for almost 20% of Gothenburg's entire electricity consumption in 2022, as seen in appendix A.2. The industry segment did however only account for about 6% of the total electricity consumption in Gothenburg, but since it only concerned the largest industries in Gothenburg and because the extensive electrification of industries, especially within the Gothenburg region, is expected to increase in the future [11], it was also given the highest score.

The commercial sector received a score of two, although making up over 12% of the total electricity use in 2022. Despite being a significant consumer, the commercial sector is highly diversified, therefore smaller commercial activities make up the overall consumption rather than a single segment like the residential and industrial sector. This complicates a potential forecast of DSF, since only a smaller sub-segment can be investigated. The transport industry was given the lowest score, although making up around 6% of the total yearly consumption. It is still relative small compared to the other segments and there is an uncertainty to which extent the segment will be electrified in the future.

The residential and commercial segment each received the highest score of three for the second criteria pertaining to the availability of DSR evident within the segments. Both segments offer both similar and a wide range of loads that can be utilized as DSRs, as can be seen in figure 4.1. The industry segment was only given a score of one, since it is unclear whether the large variety of industrial process machines are eligible to provide DR. The transport segment was also given a score of one, since currently only public bus charging and power onshore for boats are potential DSRs.

For the barriers criteria, only the residential customer segment was given a score of three, since the limitation in DR is only limited by the willingness of residents in households to contribute or the technical limitations of the DSRs. The commercial segment was appointed a score of 2, since the diversity allows some operations to be flexible, whilst others can not. Medical centers and educational facilities may not be able to change their consumption since many of the activities must be kept on continuously to ensure the comfort of the individuals.

Similar obstacles are also found within the transport segment, mainly due to the scheduling of travels in accordance with the charging of the vehicles. Adjusting the charging demand from public transport or on-shore may therefore not always be possible due to the time limit. Also, coordinating shutdowns of machines that affect hundreds of people, compared to the residential segment where households are affected separately. Contrarily, the industrial segment received a score of one, as the limitations in DR from industrial process machines are often hard to overcome. The complexity of realizing flexibility in industries stems from the fact that most machines are required to be on continuously [6], due to too high costs of lost production and market shares. The aspect of disrupting the core business is also a barrier which obstructs the application of DR [59].

Finally, the industry segment was the only one to receive a score of three for the criteria pertaining to the scale of achievable DSF. Due to the high energy consumption of the industrial machines, one large company from a certain industry could offer as much DSF as hundreds of residential buildings together would offer. Therefore, the realisation of DSF from industries would be more beneficial than other sectors in terms of quantity. The residential segment was appointed a score of two, since only by aggregating households, can the achievable DSF be impactful. The commercial segment received the lowest score, as the majority of commercial buildings uses district heating, which is not eligible for DR. Although, other loads can provide DR, space- and DHW heating accounts for nearly 80% of a households' energy use [67] and without a domestic HP, a high DSF is difficult to achieve. Additionally, since commercial facilities are very diversified, the aggregation of multiple commercial operations will be even harder to realise.

As can be seen in table 4.1, the weighting resulted in a highest score for the residential sector and it was therefore chosen as the segment to be investigated further in this report. The residential customers segment will be divided into detached and semi-detached households and apartment buildings. The DSRs considered in this study are HPs, PV panels and private EVs. Ventilation systems and smart appliances where not included, despite being part of the identified loads within the residential customers base. Ventilation systems have a low DSF potential as they are already optimized by modern technology [59] and smart appliances make up less than around 7% of the total household consumption [67] and estimations of such loads require consumer behaviour knowledge which is difficult to access. Also, since apartment buildings mainly use district heating as their primary heating source, as mentioned earlier in section 2.3.1, the DSF from HPs will only be investigated for the detached and semi-detached household customers.

4.2 Potential demand-side flexibility

This section presents the DSF estimates and results for the HPs, PV solar panels and EVs within the residential customer base.

4.2.1 Heat pumps

The yearly modelled HP consumption for all detached and semi-detached households is presented in this section along with the specific load profile on the coldest and warmest day. The DSF estimation with regards to the potential load shift and regeneration effect is displayed as well for the years 2023, 2030 and 2035.

4.2.1.1 Modelled HP consumption

The aggregated yearly modelled HP consumption is shown in figure 4.2 together with the total measured consumption of all detached and semi-detached houses connected to Göteborg Energi.

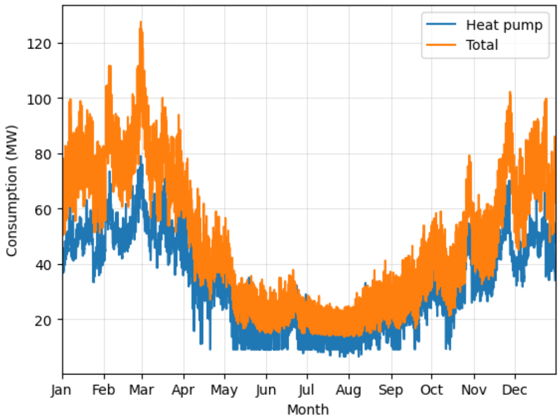
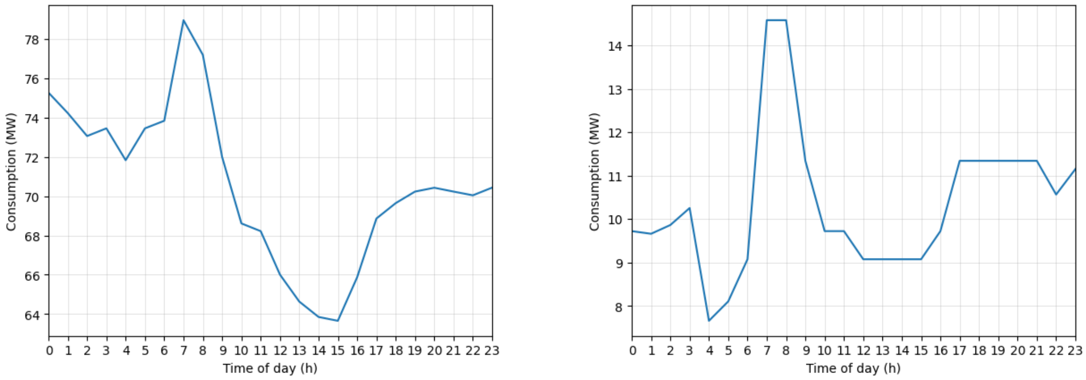


Figure 4.2: Modelled yearly HP consumption and total yearly measured household consumption for all detached and semi-detached houses.

The simulation shows a large difference in HP output between the warmer and colder months. During the winter, the HPs accounts for nearly 60-70 % of the total household consumption, indicating that most of the available DSF exists during this season. The coldest and warmest days of the year can be seen in figure 4.3.



(a) Coldest day

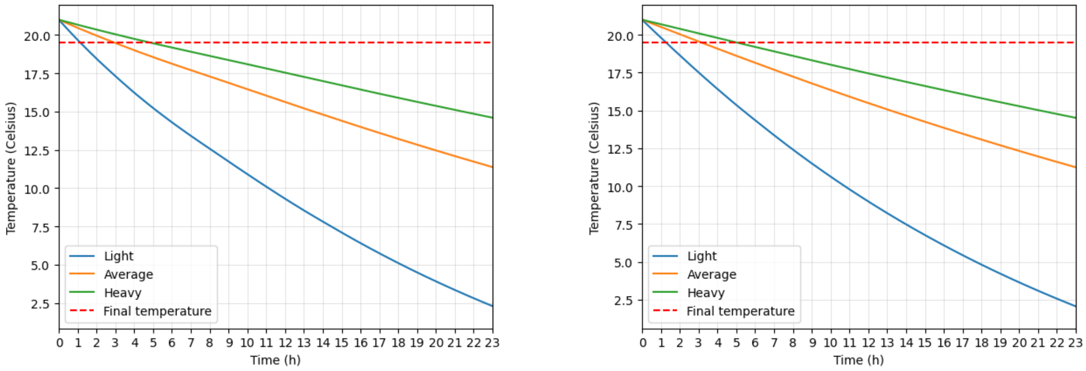
(b) Warmest day

Figure 4.3: Modelled HP consumption during the (a) coldest day and (b) warmest day.

The difference in HP consumption between the days is substantial, with the coldest day's consumption being nearly 7 times greater than the warmest day. The similarity between these days are however the occurrence of the peak load hours. Both days shows two peak load periods, where the morning peaks are larger than the evening peaks.

4.2.1.2 Load shift and regeneration time

The potential load shift times for the coldest day during the initial expected peak load hour occurring at 8 a.m. and 4 p.m. are shown in figure 4.4 for the three different building envelopes.

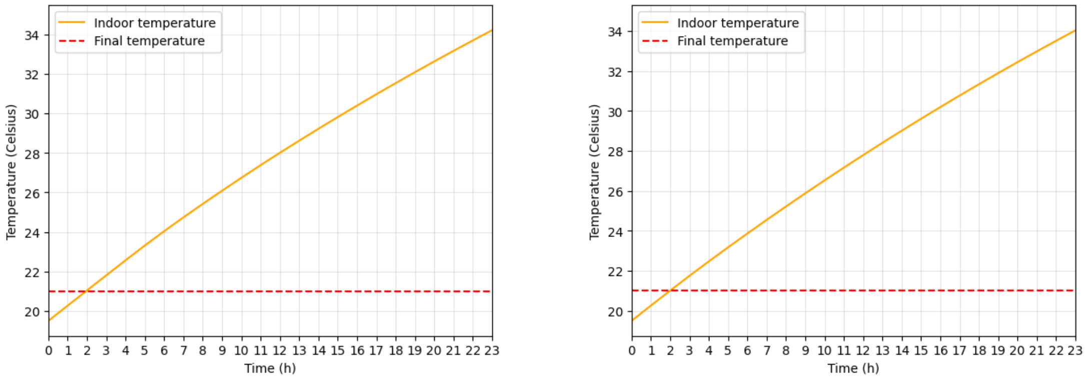


(a) 8 a.m.

(b) 4 p.m.

Figure 4.4: Modelled indoor temperature drop on the coldest day during initial load shift period hours (a) 8 a.m. and (b) 4 p.m. for three different building envelopes.

The figure demonstrates that the duration of load shift for the average building envelope scenario is 178 minutes during the early morning peak and 188 minutes in the evening, hence the load shift is possible from around 8 a.m. to 11 a.m. and 4 p.m. to 7 p.m. The regeneration time for the average building envelope scenario is presented in figure 4.5, where the regeneration starts directly after the load shift, i.e. at 11 a.m. and 7 p.m., and continues until the desired indoor temperature is restored.



(a) 11 a.m.

(b) 7 p.m.

Figure 4.5: Modelled indoor temperature increase on the coldest day during initial regeneration period hours (a) 11 a.m. and (b) 7 p.m. for the average building envelope.

The figures demonstrate that the regeneration time for the average building envelope scenario takes roughly 118 minutes after the morning load shift and 119 minutes after the evening load shift. The regeneration period therefore occurs between 11 a.m. to 1 p.m. and 7 p.m. to 9 p.m. The estimated load shift and regeneration times for the different building envelopes are presented in table 4.2 for comparison.

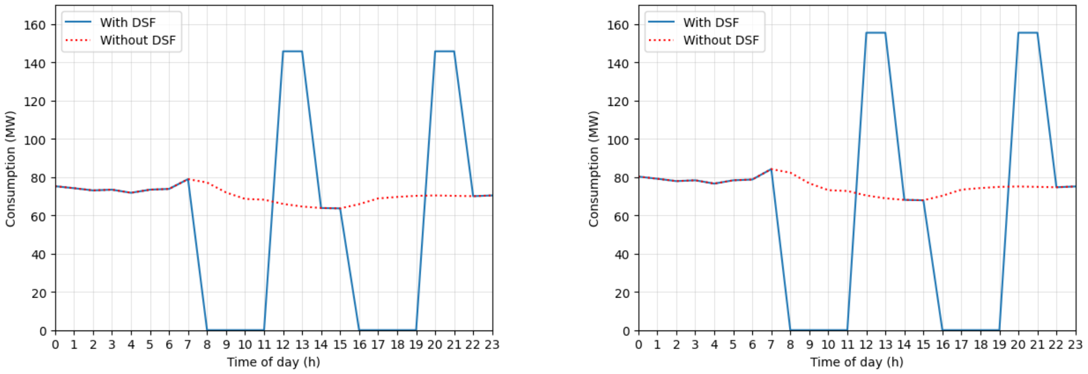
Table 4.2: Load shift time and regeneration time for the three building envelope scenarios during the coldest day.

Scenario	**Load shift time T_{flex} [min]**	**Regeneration time T_{reg} [min]**
Light	69 (morning) 77 (evening)	49 (morning) 47 (evening)
Average	178 (morning) 188 (evening)	118 (morning) 119 (evening)
Heavy	292 (morning) 300 (evening)	184 (morning) 193 (evening)

The heat capacity of the building's envelope heavily impacts the duration of the load shift and regeneration time. The heavier the buildings are, the longer the HP can be turned off, but it also results in a longer time for the HP to restore the indoor temperature. A heavy building envelope has a load shift time, nearly 4 times longer than the one for a light building envelope during the morning peak. But the same applies for the regeneration time. As can be seen from the figures, the duration of the load shift and regeneration time also varies depending on the time of the day. The evening hours allows the HP to be turned off for a longer time, due to the lower outside temperature.

4.2.1.3 Load shift and regeneration power

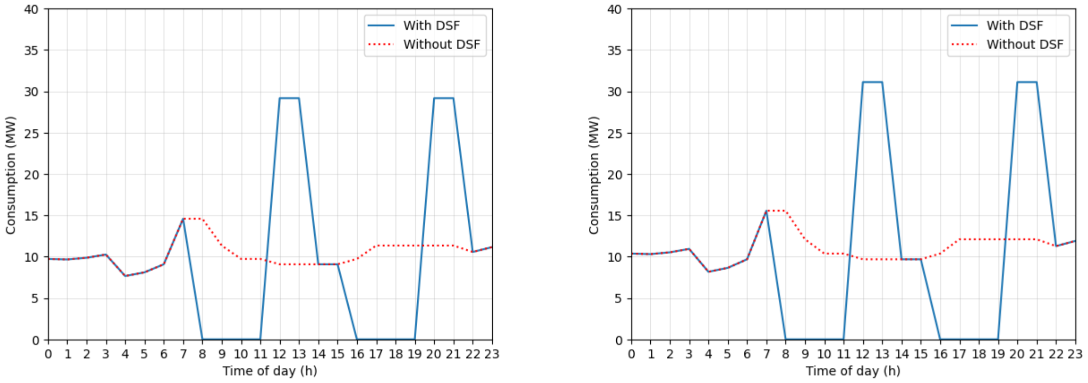
The figures 4.6 and 4.7 depict the HP load control on the coldest and warmest day for the years 2023 and 2035 using the average building envelope scenario. A similar load control for year 2030 can be found in appendix A.3.



(a) Year 2023

(b) Year 2035

Figure 4.6: Load control of aggregated HPs during coldest day for the years 2023 and 2035.



(a) Year 2023

(b) Year 2035

Figure 4.7: Load control of aggregated HPs during warmest day for the years 2023 and 2035.

As can be seen from the figures, the load shift occurs during 8 a.m. to 11 a.m. and 4 p.m. to 7 p.m. and the regeneration period the two subsequent hours after the load shift. The tables 4.3 and 4.4 display the maximum theoretical load shift potential and regeneration power increase for the morning and evening peak load periods, during both the winter and summer for years 2023, 2030 and 2035. The result shows, that the load shift potential is greater in the morning than the evening during both the coldest and warmest day, due to the higher household consumption in the early hours of the day. The load shift potential during the winter is around 6 times greater than the load shift during the summer for all scenarios. The increase in load shift potential throughout the years is also higher during the winter. Contrarily, in the winter the regeneration power is substantially larger than for the summer. As the need to restore the indoor temperature only exists in the winter, the regeneration power increase is lower in the summer.

Table 4.3: Maximum theoretical load shift P_{shift}.

Scenario	**2023** [MW]	**2030** [MW]	**2035** [MW]
Winter morning	71.5	74.3	76.3
Winter evening	68.7	71.3	73.2
Summer morning	11.3	11.8	12.0
Summer evening	10.9	11.4	11.7

Table 4.4: Maximum theoretical regeneration power P_{reg} after load shift.

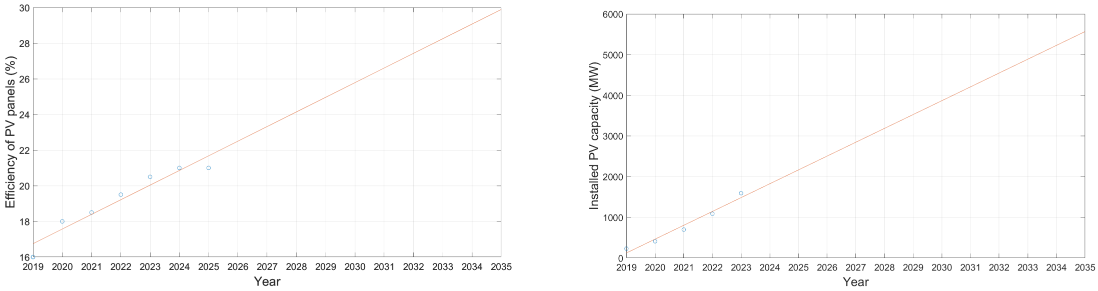
Scenario	**2023** [MW]	**2030** [MW]	**2035** [MW]
Winter morning	145.8	151.5	155.5
Winter evening	145.8	151.5	155.5
Summer morning	29.2	30.3	31.1
Summer evening	29.2	30.3	31.1

4.2.2 Photovoltaic solar energy panels

In this section, the forecasted PV parameters used in the DSF estimations are presented. The estimated potential solar power output during the coldest and warmest day of each year is displayed as well, along with the addition of its peak shaving effect on the household consumption during the peak load hours.

4.2.2.1 Forecast of PV parameters

The result from the forecast of PV efficiency- and power development in Gothenburg can be seen in figure 4.8, while the scaling parameters achieved are visible in table 4.5.



(a) PV efficiency development.

(b) Total installed PV capacity development.

Figure 4.8: Linear regression forecast of installed PV capacity- and efficiency development in Sweden.

Table 4.5: Forecasted and calculated parameters

Parameter	**Value**
Scalar used for the year 2030	2.4
Scalar used for the year 2035	3.5
P_{dsdh}	50.2 MW
P_{ab}	3.4 MW
$\%_{ab}$	5.8 %

It is predicted that Gothenburg's total solar power production will increase by 140% until year 2030 and by 250% until 2035. The table also displays the calculated share of total PV power in Gothenburg belonging to apartment buildings, which is estimated to be roughly 5.8% of the total solar power production. Finally the table reveals the estimated values for total installed PV power on detached and semi detached houses and apartment buildings in Gothenburg, being 50.2 MW and 3.4 MW respectively.

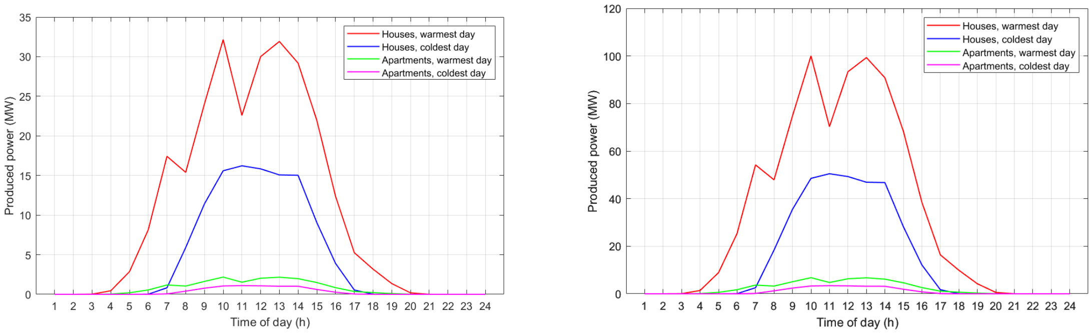
4.2.2.2 Estimation of potential power output

In table 4.6 the parameters used in the estimation of potential PV power output are presented. The average PV panel area needed per 1 W was calculated to be 6.5·10^{-}3 m^2/W. The average efficiency of installed PV panels in Sweden for the year 2023 is estimated to be 19.5%, and is estimated to increase with 28.2% and 49.2% for the years 2030 and 2035 respectively. The assumed performance ratio is 71.3 %, the estimated total PV panel area in Gothenburg is 326 456 m^2 for detached and semi detached houses and 22 016.8 m^2 for apartment buildings.

Table 4.6: Potential power production parameters.

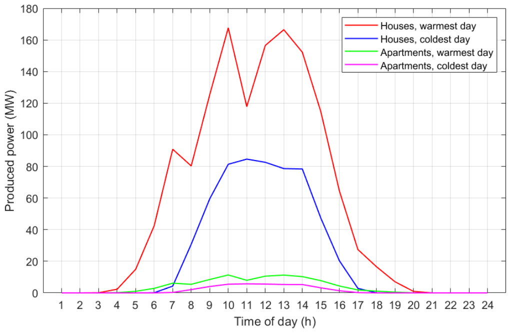
Parameter	Value
A	6.5·10^{-}3 $\frac{m^2}{W}$
PR	71.3 %
r_{2023}	19.5 %
r_{2030}	25.0 %
r_{2035}	29.1 %
A_{dsdh}	326 456 m^2
A_{ab}	22 016.8 m^2

Figure 4.9 displays the modelled potential power output from Gothenburg's solar panels for the different residential types, seasons and years. The prediction shows a very large increase of produced solar energy in the coming years.



(a) Produced PV power over 24 hours for 2023.

(b) Produced PV power over 24 hours for 2030.



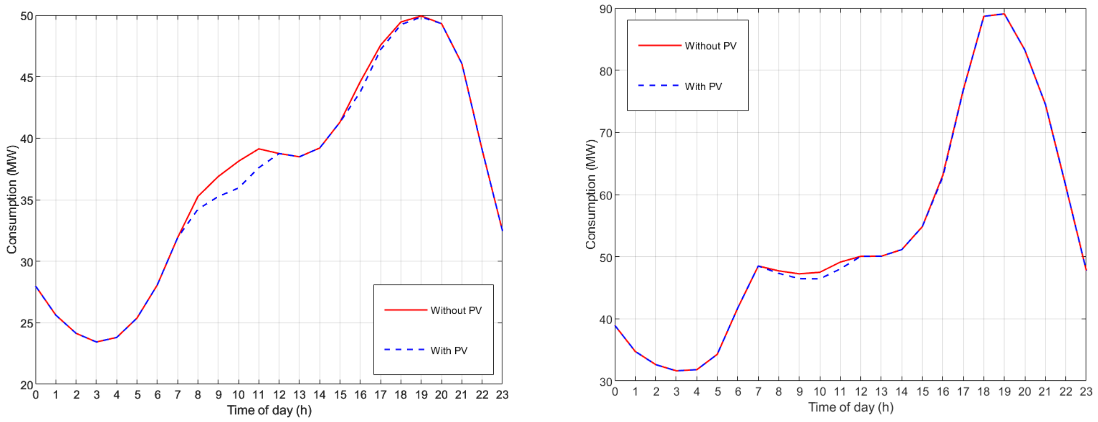
(c) Produced PV power over 24 hours for 2035.

Figure 4.9: Hourly produced PV power by detached and semi-detached houses and apartment buildings during the warmest day and coldest day, for the years 2023, 2030 and 2035.

It can be seen that the warmest day of the year, compared to the coldest day, has approximately 6 more hours of sunlight and 98.1% higher solar radiation. The solar production during the warmest day does however show to be irregular, whilst the coldest day demonstrate a fairly large solar production. The simulation does also show that the PV power output from detached and semi-detached households in general are larger than for apartment buildings.

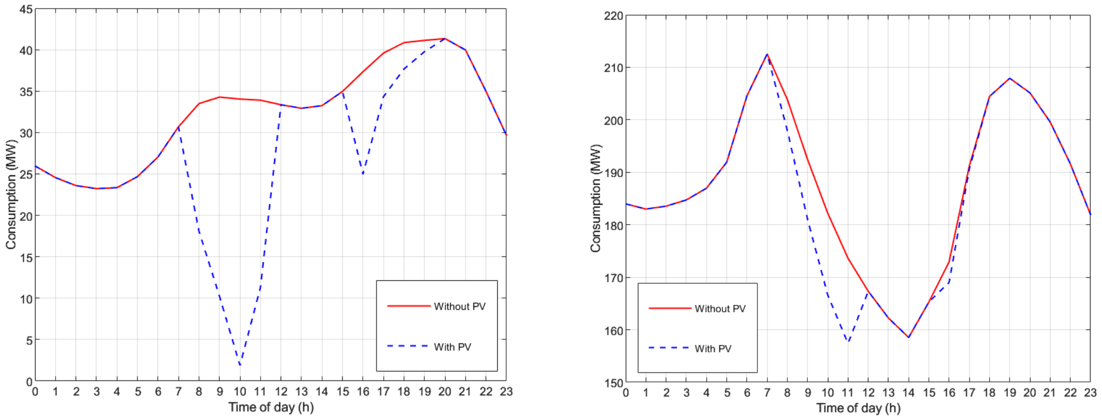
4.2.2.3 Peak shaving effect

In figure 4.10 and 4.11 the peak shaving effect on both residential types' total household consumption for the years 2023 and 2035 are displayed, respectively. A similar figure for the year 2030, can be found in appendix A.4.



(a) Consumption from apartment buildings over 24 hours during warmest day.

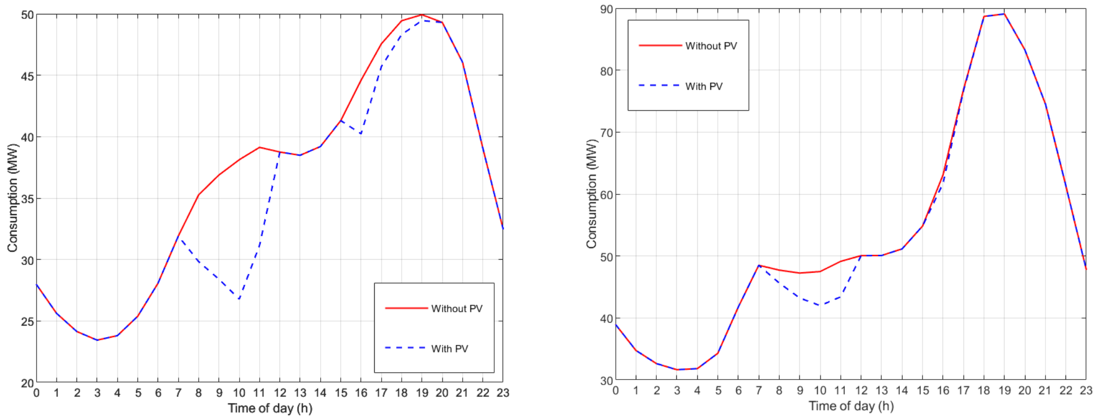
(b) Consumption from apartment buildings over 24 hours during coldest day.



(c) Consumption from detached and semi-detached houses over 24 hours during warmest day.

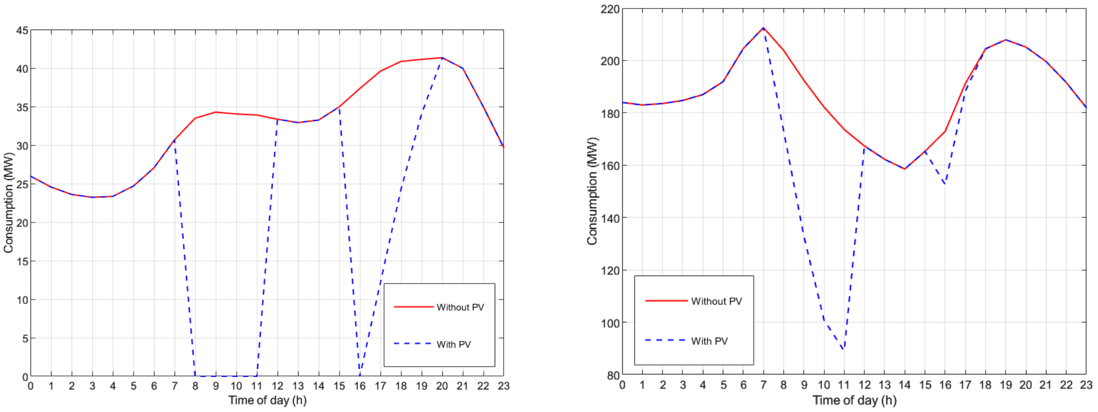
(d) Consumption from detached and semi-detached houses over 24 hours during coldest day.

Figure 4.10: The consumption of detached and semi-detached houses and apartment buildings during warmest day and coldest day, with and without PV solar production, for the year 2023.



(a) Consumption from apartment buildings over 24 hours during warmest day.

(b) Consumption from apartment buildings over 24 hours during coldest day.



(c) Consumption from detached and semi-detached houses over 24 hours during warmest day.

(d) Consumption from detached and semi-detached houses over 24 hours during coldest day.

Figure 4.11: The consumption of detached and semi-detached houses and apartment buildings during warmest day and coldest day, with and without PV solar production, for the year 2035.

The figures shows that the peak shaving effect is larger during the morning peak load hours, as more solar energy is produced at this time of the day. It is also noticeable that the detached and semi-detached houses can achieve around 15 times higher power peak reduction compared to apartment buildings, in both the warmest and coldest day. In figure 4.11c, the increase of solar production predicted in 2035, shows that the solar production from the PV panels for detached and semi-detached houses is large enough to even cover the entire household consumption of these consumers during the morning peak load hours. In table 4.7 the average power peak reduction achieved during the daily peak load hours for each scenario are summarized.

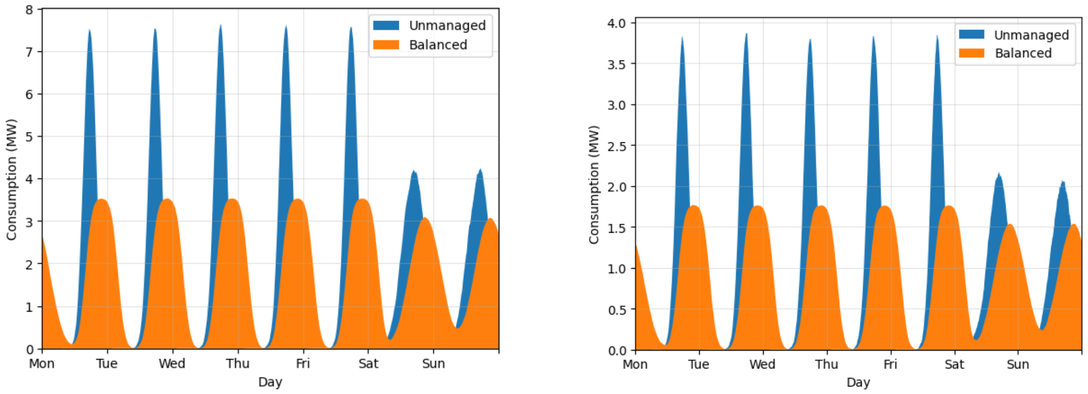
Table 4.7: Average peak reduction achieved for the different scenarios from PV panels.

Scenario	**2023** [MW]	**2030** [MW]	**2035** [MW]
Winter morning, apartment buildings	0.8	2.6	4.3
Winter evening, apartment buildings	0.1	0.2	0.4
Winter morning, detached and semi-detached houses	12.3	38.2	64.1
Winter evening, detached and semi-detached houses	1.1	3.5	5.8
Summer morning, apartment buildings	1.6	5.0	8.3
Summer evening, apartment buildings	0.4	1.2	2.0
Summer morning, detached and semi-detached houses	23.5	33.9	33.9
Summer evening, detached and semi-detached houses	5.5	17.0	22.1

4.2.3 Electric vehicles

The BEV charging profile for the charging scenarios considering only residential charging and mixed charging locations are shown in figure 4.12 for the year 2023. The simulations shows the impact of cluster charging occurring on all weekdays after people arrive home from work at around 4 p.m. The high peaks visible with unmanaged charging is due to the traditional instant charging done with full charging power. For the scenario where only residential charging is conducted, the highest peak demand during the week with unmanaged charging occurs during the weekdays and is around 7.6 MW in 2023. With balanced charging the peak power is almost reduced by 50%.

For the mixed charging scenario, the cluster of residential charging does also occur after work at around 4 p.m. and with unmanaged charging the peak demand falls on the weekdays, reaching a maximum of 3.9 MW in 2023. With balanced charging the maximum peak power can be reduced to 1.8 MW. The peak power is in general much lower in the mixed charging scenario since charging at other locations reduces the need for residential charging. The amount of DSF available during the weekdays for both charging scenarios and all the years are summarized in table 4.8.



(a) Residential charging only

(b) Mixed charging locations

Figure 4.12: EV charging demand profile with unmanaged and balanced charging for the two charging scenarios.

Table 4.8: The potential DSF from balanced charging of BEVs during the weekdays for both scenarios and all the years.

Scenario	**2023** [MW]	**2030** [MW]	**2035** [MW]
Residential charging only	4.3 (evening) 0 (morning)	25.2 (evening) 0 (morning)	40.2 (evening) 0 (morning)
Mixed charging locations	2.2 (evening) 0 (morning)	12.9 (evening) 0 (morning)	20.6 (evening) 0 (morning)

The results shows that the potential DSF is only available during the evening hours of the weekdays. In the morning, most people leave their residence and therefore no charging is generally done at home at this time. Also, due to the assumption that balanced charging only is available from residential home chargers, the DSF potential is approximately twice as large in the scenario where only residential charging is done, compared to the mixed charging scenario. As the typical EV driver charges more at home, more DSF is available since only residential chargers were assumed to provide DR. Therefore depending on where the smart charging technology is available, the amount of flexibility available will vary. Also noticeable is that the increase of DSF in 2030 and 2035 is high due to a large expected increase of EVs in the future.

The potential DSF is in general lower on the weekends, since people are in less need of charging their EVs during the peak load hours. The preference for charging is therefore more distributed and as seen in the figures, the clustering of EV charging is not as large. The variation in charging times on the weekends does also allow some flexibility to be available during the morning hours. The amount of DSF available during the weekends for both charging scenarios and all the years are summarized in table 4.9.

Table 4.9: The potential DSF from balanced charging of BEVs during the weekends for both scenarios and all the years.

Scenario	**2023** [MW]	**2030** [MW]	**2035** [MW]
Residential charging only	1.4 (evening) 0.5 (morning)	8.2 (evening) 2.9 (morning)	13.1 (evening) 4.7 (morning)
Mixed charging locations	0.7 (evening) 0.3 (morning)	4.1 (evening) 1.8 (morning)	6.5 (evening) 2.8 (morning)

4.3 Effect of DSF on capacity demand

The maximum available DSF on the coldest day during the morning peak load hours 8 a.m. to 11 a.m. and evening peak load hours 4 p.m. to 7 p.m. is shown in figure 4.13. The amount of DSF is evidently higher in the morning compared to the evening and the increase of DSF throughout the years is also greater in the morning.

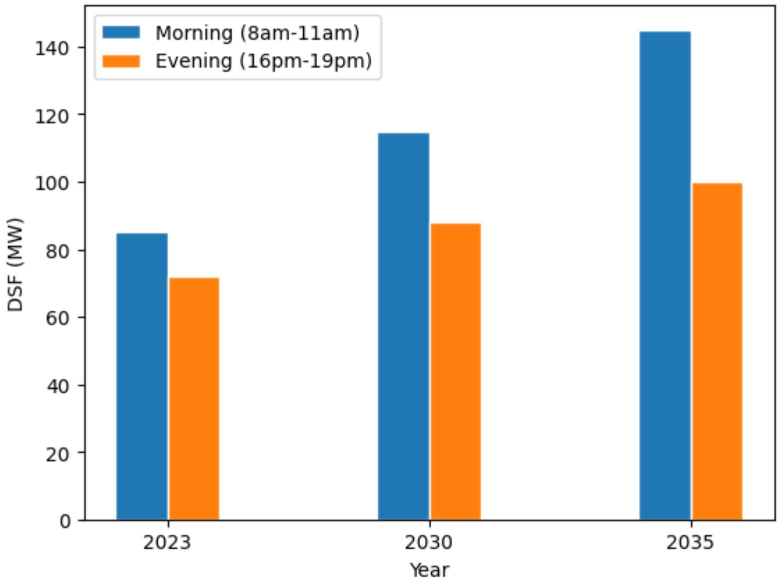


Figure 4.13: Available DSF on the coldest day during the peak load hour periods.

The forecasted power demand with and without the reduction from DSF for the years 2023, 2030 and 2035 are presented in figure 4.14. The expected addition in power demand, during the year 2030 corresponds to nearly a 55 % increase from today, and 68 % in 2035.

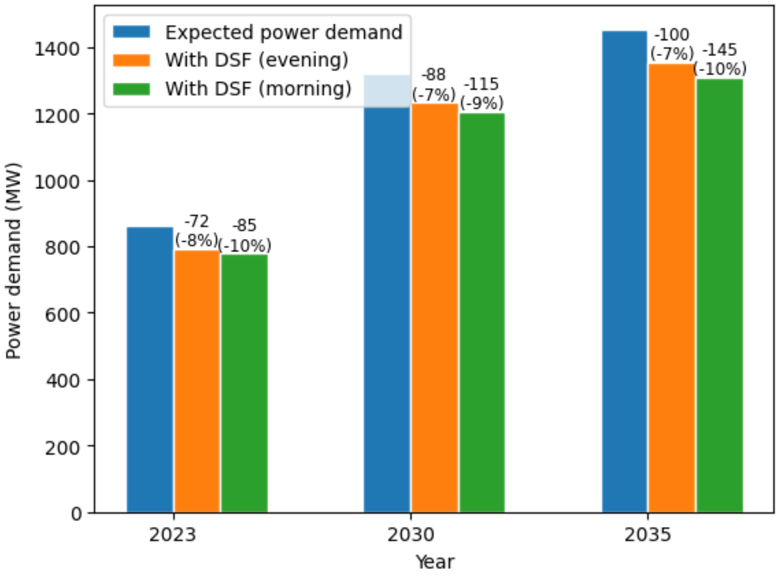


Figure 4.14: Power demand forecast and the impact of available DSF during the morning and evening peak load periods.

The impact of DSF shows a 7-10 % reduction in power demand depending on the year and time of peak demand. The potential reduction in power demand is greater if the peak period falls during the morning hours since more DSF is available. In 2035, it is predicted that a maximum reduction of 145 MW can be achieved in the morning, whilst a 100 MW reduction is obtainable in the evening, corresponding to a 10% and 7% power demand deduction, respectively. The expected power demand with and without the effect of DSF is summarized in table 4.10 for each of the years.

Table 4.10: Current and forecasted power demand with and without the effect of DSF.

Scenario	**2023** [MW]	**2030** [MW]	**2035** [MW]
Expected power demand without DSF	864	1320	1454
With DSF (evening)	792	1232	1354
With DSF (morning)	779	1205	1309

5

Discussion

This chapter discusses the results and methods of this report, before finally forming suggestions for future related work.

5.1 Future outlook on the customer segmentation

The customer segmentation and weighting showcased the residential customer base as most appropriate for DR applications. However, as the segmentation was based on the current situation, the outcome could have altered if one were to perform the segmentation and weighting based on a future scenarios. The extensive electrification in the coming years would prove other sectors to be viable for DR, especially the industry segment. In terms of segment size, the industries are one of the largest consumers in Gothenburg and will continue to increase drastically in the future. With more data on the available DSRs and formed incentive policies, the industry segment could be considered for DR applications due to its potential size of DSF.

The same is true for the transport sector, as the various modes of transport do not currently have the largest electricity consumption, but this may change in the future. Only public buses are charged today and able to provide DR through depot and end-stop charging. All electricity consumption from other public transport types as well as most of the freight traffic is from the supply of continuous electricity through overhead lines, and such is not eligible for DR. However, if other transport types such as trucks, ships and airplanes are electrified in the future, vehicle charging would be eligible for DR applications.

The commercial segment could on the other hand be considered for DR applications today due to its consumption size and number of DSRs. Its deployment is only hampered by the quantity of DSF achievable and, subsequently, if it is financially feasible for the commercial facilities and DSOs. With the expected increase of EVs in the future, workplace and public charging could prove to be a deciding factor.

5.2 Heat pumps

This section discusses the implications of the results obtained from the HP estimations, as well as the space heating and DHW model along with the assumptions made.

5.2.1 Potential demand-side flexibility from HPs

According to the projected load shift times for the scenario with average sized building envelopes, shown in table 4.2, the duration of load shift time on the coldest day, coincided with the duration of peak load hours both in the morning and evening. This is desired for a DSO, since it allows the entire HP consumption during the peak hours to be shifted. The maximum theoretical load shift in table 4.3 does also show that more DSF is accessible in the winter, which is advantageous since it is during the winter the yearly peak load hour is expected.

However, the expected peak load intervals used in this study does not necessarily coincide with the hours of highest HP consumption. For example, as seen in figure 4.6 during the coldest day, the HP consumption in the off-peak hours at night is higher than the peak load hours in the evening. As a result, the potential DSF might be higher in the night, where the HP consumes more due to lower outdoor temperatures. Consequently, the duration of load shift would be shorter since indoor temperature would drop faster as a result of the colder outdoor temperatures.

The peak load hours would also in reality not be the same in the coming years. The study used the same time intervals for all years, which in fact would vary in the future. Similarly, the days and temperatures during the warmest and coldest day would in reality not be the same in the future. It is important to recognize that these assumptions must be made, since it is difficult to predict such conditions. The variation in peak load hours and temperatures in the future could however impact the available DSF forecasted.

The regeneration power shown in table 4.4 displayed a high rebound effect caused by restoring the indoor temperature. Since, the study considered a theoretical scenario wherein all households would load shift and restore at the same time, the power would in reality be much smaller. Similarly to the load shift, the regeneration is also higher in the winter due to higher HP consumption. As seen in figure 4.6, the regeneration period occurs during the off-peak hours, but since these hours may change in the future, the positioning of regeneration during the day will be important in order to avoid rebound peaks.

5.2.2 Space heating model and domestic hot water

The space heating demand in this study used the the one-node lumped capacity model. While the model gives a sufficiently accurate demand profile, more nodes would increase the accuracy of the model. Evidently, there is a difference between the indoor temperature and the temperature of the interior walls, and therefore more nodes would simulate the demand more precisely. The use of a one-node analysis, caused the model to increase the indoor temperature as long as the outdoor temperature is lower than 21 °C. In reality, the heat gain from occupants and sun would result in that the HP would not need to consume as much, especially when the the difference in indoor and outdoor temperature is small. In addition to external heat gains, the model does not consider ventilation or other losses, which would cause the indoor temperature to drop faster.

The parameters used to simulate the demand for space heating were selected based on average values, due to the large diversity of the households. The COP was therefore chosen accordingly. In practice, every home has a different HP where every COP is unique. Depending on the type of HP installed, the COP varies considerably since the operating temperature of the heat source affects the efficiency immensely. The COP is therefore very sensitive in colder climates, especially for HPs extracting heat from the air.

In the simulation, the thermal resistance of the building envelope was also based on the average value of several households. The ability to resist heat transfer does however vary significantly due to the different insulation of the households. As it is difficult to ascertain the characteristics of each building envelope, only an average value can be considered. It is important to understand, nevertheless, that the assumption impacts the amount of flexibility available, since the HP consumption is directly related to the amount of power that can be released when switching off the HP.

Additionally, the DHW used in this study was assumed to be the same each day, although it is clear that the demand usually varies on a daily basis. The DHW system was also assumed to be integrated with the heating system for all households, while in reality this is not the case for every household, since some HPs such as air-air HPs can not provide hot water.

5.2.3 Load shift and regeneration

The amount of DSF is directly related to the load shift time pertaining to the upper and lower boundary of allowed indoor temperatures. Hence, the limitation in achievable flexibility related to the comfort of the occupants. The indoor temperature was set to 21 $\pm 1.5°C$ in this study, which resulted in a lower limit of 19.5 °C. Evidently, reducing the boundary to $\pm 0.5°C$, would reduce the load shift time and hence less power would be shifted. Contrarily, an increase of the boundary would result in a longer duration of load shift and higher average power reduction.

The load shift time as well as regeneration time is also impacted by the building envelope. In the study, three building envelope scenarios were considered where the heat capacity varied. As seen in table 4.2, a larger heat capacity allowed the load shift time to be longer. Heavier buildings are therefore more useful as DR providers if the load shift time is of essence. The downside is however a longer duration of regeneration which may not necessarily be an issue as long as the regeneration period occurs during off-peak hours. For the DSF estimation, we assumed all buildings had a medium-heavy envelope, but in reality, there is a mix of both lighter and heavier envelopes, which would have impacted the DSF potential; including more lighter envelopes would cause a slight reduction in the DSF potential, while the heavier building envelopes would enable a longer duration of load shift.

Similarly, the assumed installed HP power affects the duration and peak of the regeneration period. In the study it was assumed that all HP had the same installed power, due to the difficulty of determining each household's installed HP power. Although the assumed installed HP power for all households were set to 4.5 kW, the actual installed power varies between each household. A smaller power installed, would reduce the size of the regeneration peak, and consequently increase the duration of the regeneration period, while a higher installed HP power would increase the size of the regeneration peak and reduce the duration.

Furthermore, the load shift and regeneration times for the DHW were not modelled; rather, it was assumed that they would coincide with the load shift and regeneration times for space heating. On the warmest day, when there was only demand for hot water the load shift and regeneration times were also assumed to be the same as for the coldest day. The study therefore assumed that hot water production would be switched off as soon as space heating was turned off, which in reality is not the case since hot water production still is possible without space heating. The DSF gained from shifting the hot water production is therefore more of a theoretical indicator of the maximum hot water production that can be shifted during the peak load hours. In reality, DHW flexibility results from postponing the production of hot water until there is demand for it rather than heating it as soon as the temperature in the water tank drops below a certain limit. A model of the water temperature inside the water tank is required to provide a more accurate DSF estimate from DHW.

5.3 Photovoltaic solar energy panels

In this section, the PV estimations are discussed. The discussion lifts forecasts and some unsure parameters, before considering the fortune of weather behaviour during the chosen days. Finally, peak power reduction is discussed along with the impact of future BESSs.

5.3.1 Forecasts and parameters

Future solar energy production entails predicting PV-panel related characteristics, which due to its uncertainty, provides a level of inaccuracy. The PV efficiency forecast performed, as seen in figure 4.8, is likely overestimated due to the choice of taking the average value of only the three latest years as can be seen in equation

3.8. Perhaps taking another approach to include more of the older installed PV panels would have given a more accurate estimation. The efficiency of PV panels has been increasing throughout the years, but the increase rate has started to slow down lately. It is believed that the efficiency increase rate will likely slow down in the coming years. The installed PV power development, on the other hand, is anticipated to continue growing, at least for the next few years, possibly more than originally predicted.

A linear regression method was used for the forecasts due to the simplicity of the method, and less prone to overfitting when dealing with limited data. Also, linear regression assumes a linear relationship between the independent and dependent variables, making it fit better with the linear scaling assumptions used in the method. The efficiency increase of PVs has historically not been completely linear, however if an exponential regression was made instead for example, the efficiency forecast would be over estimated to an even greater extent because of the high slope of such a curve.

Also worth to mention is that a reasonable PR value of 71.3 %, laying between 50 % and 90 %, was achieved. Of course, taking more parameters into consideration when calculating the performance ratio, other than the three mentioned in section 3.2.2.3, would increase the preciseness of the estimations. To however assume that this yearly based parameter will be the same for all installed PV panels and constant for all hours of a day is a very bold and critical assumption. The degradation of PVs varies a lot, depending on circumstances such as operating environment, panel type, panel age, and more. Taking these circumstances and differences into consideration would likely significantly increase the accuracy of the estimations.

5.3.2 Seasons and weather

The results achieved from the produced PV power estimations in figure 4.9, displayed a large difference between the winter and summer days. This is due to Gothenburg being situated near the Scandinavian polar circle, with late sunsets and early sunrises during the summer, compared to the early sunsets and late sunrises during the winter [35]. The result did however demonstrate a larger solar energy production on the coldest day than expected, which likely is due to fortunate weather this specific day. The solar radiation during this day was higher than the general solar radiation during the whole winter season. Similarly, the solar production achieved on the warmest day was lower than anticipated, which likely is due to unfortunate cloud formations during that specific day.

Except for the sunlight being stronger with higher solar radiation [79] during the summer, the clearness of the sky plays a huge role in the solar energy production as mentioned in section 2.3.2.1. Generally, winter days are usually cloudy while summer days have clearer skies [40]. These facts arguably make PV panels less useful as DSRs in Sweden since the yearly peak load hour in Sweden accrues during darker winter hours. However, in this study the specific days showed contrary behaviours, where the summer day had a less continuous and jagged solar production, as seen in figure 4.9. The results would have revealed a far higher disparity in produced solar power if all summer and winter months had been considered. One alternative to deal with this, would be to use two scenarios, one with high solar production and the other with low solar production.

5.3.3 Peak shaving effect and future impact of battery energy storage systems

The results in table 4.7, showed a higher peak shaving effect during the winter day, although solar energy production was higher on the summer day. This is due to the higher electricity consumption during the winter, which allows more of the produced solar energy in the winter day to cover the household consumption. In the summer, the solar energy is higher than the electricity demand. The time of highest solar production and highest electricity demand does not coincide and without the addition of BESSs, most of the surplus solar energy produced in the summer would be sold back to the grid.

As seen in the figure 4.11c, the estimation in 2035, shows that the total household consumption in the morning was covered by the solar energy production but the additional PV power produced could not be saved since no PV installation was assumed to have BESS installed. However, if more PV owners implemented storage systems in the future, solar energy produced during the morning could be saved and used during the night. Similar to this, if it becomes economically feasible in the future, perhaps the battery could be used as a seasonal storage. The addition of BESSs are therefore necessary in Sweden to allow for a higher peak shave effect, especially in the hours of low solar production.

There is also an uncertainty with the estimated peak shaving effect, since the same total household consumption was used for all the years in the estimation. The produced PV power increased each year, but the household consumption remained constant which resulted in a lower achieved peak shave for the future scenarios. In reality, household consumption is likely to increase in the future due to population growth and increase in residential buildings. If that had been taken into account, the peak shaving effect would most likely be higher, especially for the days where there is already a surplus of solar power.

5.4 Electric vehicles

The following section discusses the DSF obtained using a balanced EV charging scheme. The section also analyzes the impact on DSF caused by the assumed charging behaviour used in the simulation, as well as uncertainties with the IEA tool and forecast.

5.4.1 Achieved flexibility potential using balanced charging

The flexibility potential from residential charging is higher during the weekdays, as seen in figure 4.12. For a DSO, this is advantageous, since the yearly peak load hour is expected to fall on a weekday. The DSF is also apparent only in the evening, and this is because commuters usually charge their EV when they arrive home from work or school, hence the cluster of charging.

Both scenarios does also show that no DSF could be achieved from residential charging during the morning peak load hours on the weekdays. Since no residential EV charging is done at the time, this creates strong incentives to implementing smart chargers at other locations, such as the workplace. People usually charges their EVs when arriving to work in the morning, and smart chargers at these locations could potentially allow DSF. The amount of DSF is therefore very dependent on the availability of smart charging stations.

Other smart charging technologies could also provide more or less DSF depending on the scheme used to shift the EVs. Smart chargers with time-of-use tariffs whereby the complete EV charging is moved to another time, would seemingly increase the DSF, in comparison to the balanced charging scheme where only the dispatch power is reduced.

5.4.2 Impact of charging behaviour and vehicle parameters

The DSF achieved from BEVs are highly influenced by the charging behaviour of the BEVs. In the mixed charging scenario, the preference and duration of each charging location were chosen arbitrarily. In reality, these parameters could vary significantly, which would change the amount of flexibility available from residential charging. If the preference for charging outside the home would be higher, less DSF would be available since charging at home would be less likely. This also encourages the expansion of smart charging beyond residential use.

The installed power of residential chargers does also impact the degree of flexibility. In the simulation, it was assumed that all residential chargers had a maximum power of 3.7 kW today and in the future, which in reality would vary. With newer and faster chargers expected to develop in the future, higher residential charging powers would result in a larger potential load shifts. The demand for electricity would however be higher.

5.4.3 Uncertainties with the IEA tool

The IEA tool used for the simulations, included certain constrains which meant that it could not be used for the forecast. The increase of DSF, reduced for each year, although the number of BEVs increased. This characteristic may be due to a mismatch between the increase of BEVs and existing charging infrastructure, as the option to change the number of charging stations was not available in the tool. In reality, the number of charging stations would definitely need to increase in the future to meet the increasing charging demand. To forecast the DSF in 2030 and 2035, the current achieved DSF was instead scaled according to the expected increase of BEVs. The increase assumed in the study proved to be more realistic than using the IEA tool, although it is uncertain how this increase will continue in the future. There may be a even greater growth in BEVs, which would have increased the amount of DSF available.

5.5 Impact on capacity demand

The estimations showcased more available DSF during the morning peak load hours, as well as a higher increase rate in the coming years. This is due to that HP accounts for most of the available DSF, whereas it was larger in the morning. If the yearly peak hour period falls in the morning, a higher power demand reduction would theoretically be available. A power demand reduction of 7-10% would reduce the need for grid reinforcements for a DSO, but since the DSF available from HPs considered a maximum theoretical scenario, the realised DSF would in reality be much lower.

The results does therefore indicate that the increasing capacity demand outpaces the increase in DSF. It becomes clear that more measures needs to be implemented in order to face the increasing capacity demand, and flexibility from other sectors could play important roles.

5.6 Future research

In this thesis, models and methods were used to estimate and forecast the available DSF within Göteborg Energi's residential customer base. There are however other methods available to use depending on the depth of the desired outcome. Since, most of the methodology was based on average scenarios and assumptions, more domain knowledge, would allow a more precise and broader investigation of the DSF available from the different residences. Case studies on specific households would improve the accuracy.

As the project was completed with regards to grid congestion, the estimations only considered the DSF available during the expected peak load hours. However, in future work other hours would be interesting to investigate. The excess of generated solar power caused by too low demand was neglected in this study, hence no negative values were presented in the figures. It would however be useful to investigate this surplus to assess how the large solar production would affect the grid, especially in the summer when the high solar production can cause a reversed power flow. The hours of highest solar production, often in the middle of the day, would therefore be interesting, as it is during these hours the generated solar power would exceed the local demand, causing the power to flow back to the grid due to high voltages.

This project investigated the DSF available from HPs, EVs and PVs, but an assessment of the DSF available from common household appliances could also be interesting as they exist in the majority of households. An extensive modeling of the DHW systems would also be interesting in future studies in order to generate more precise load shift estimates, especially in the summer when only hot water demand exists.

The weighing did also prove the residential sector as most suitable for DR estimations, but other sectors were also eligible for DR applications. Investigating other sectors would also be interesting, whereby the contribution of DSF from different operations could be compared, especially for sectors anticipated to increase in the future.

Future research should also evaluate emerging technologies and loads since they will have a significant impact on the DSF accessible in the years to come. The integration of BESSs for PV panels would therefore be interesting to study, and the inclusion of smart charging technologies for PHEVs could also be of interest, since they make up the majority of the EV fleet in Sweden. Vehicle-to-grid (V2G) could also have more significant impact, if it becomes a reality in the future.

6

Conclusion

The residential customer base of Göteborg Energi proved to be a potential DR contributor due to its large electricity consumption, flexibility potential and amount of DSF available. During the winter months in Gothenburg, load control of residential HPs are utmost effective since HP consumption is at its peak and the thermal inertia of houses allows HPs to be turned off for a period of time, consequently reducing the power demand. The aggregation of HP load control allowed the maximum release of over 70 MW on the coldest day in year 2035.

Along with the integration of residential PV panels a notable peak reduction in 2035 could also be achieved. The highest obtainable peak shaving effect achieved from PV panels installed on detached and semi-detached households, as well as apartment buildings occurred in the early morning hours on the coldest day and resulted in a power reduction of around 60 MW. The solar energy production is significantly higher in the morning, and a higher peak shaving effect was thus achieved at this time. BESSs will therefore be crucial in the future as solar energy could be stored in the morning and used later in the day. However, it is crucial to understand that the DSO would have no control of the solar production during the day when the peak load hour fall, as it rather depends on the day's weather. If it is partly cloudy, there would be almost no solar production.

The use of balanced charging schemes for home EV chargers demonstrated a smaller contribution. With very little EV charging conducted at home in the morning, there are incentives to implement smart chargers at workplaces or other charging stations, in order to minimize the power demand during the morning peak load hours. It did however prove to reduce the power demand during the evening peak load hours with 6 MW in 2035.

The maximum available DSF from the residential sector does prove to be a useful asset for Göteborg Energi, reducing the expected power demand in 2035 by 6-10%. Its application could make an adequate impact on the increasing capacity demand and the grid reinforcements needed. But ultimately, how much of the maximum available DSF can be realized relies on the number of households willing to contribute.

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A

Appendix

A.1 Customer segmentation

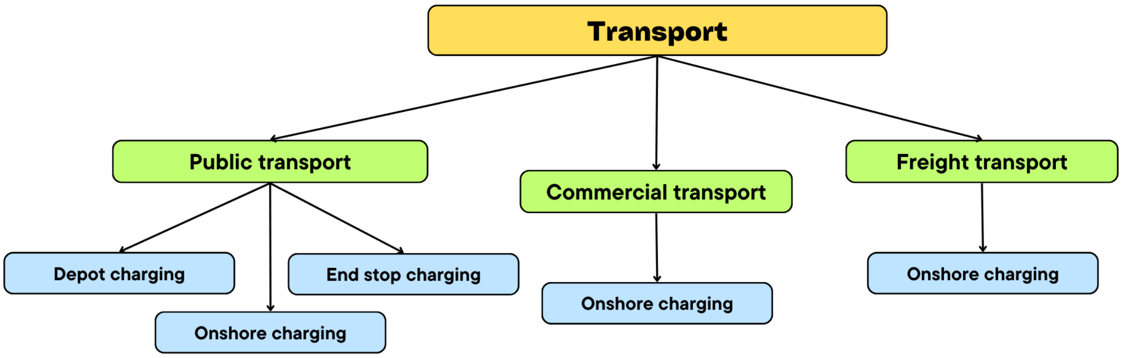


Figure A.1: Customer segmentation and load identification of the transport customer base.

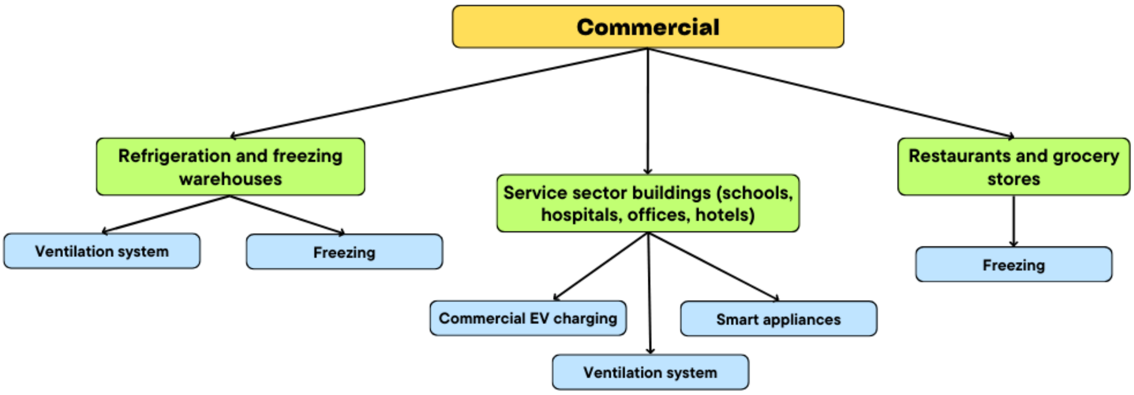


Figure A.2: Customer segmentation and load identification of the commercial customer base.

A.2 Customer segments' yearly consumption

Table A.1: Göteborg Energi's residential customer base, their loads and size.

Customer type	Consumption [GWh]	Percentage [%]	Loads
Detached-and semi detached houses	545	11.9	PV solar cells, private EV charging, smart appliances and HVAC: heat pumps and ventilation
Apartment buildings	349	7.6	PV solar cells, private EV charging, smart appliances and HVAC: ventilation
Total of residential customers	894	19.5	

Table A.2: Göteborg Energi's commercial customer base, their loads and size.

Customer type	Consumption [GWh]	Percentage [%]	Loads
Warehouses and supermarkets	61.1	1.3	Freezing, cooling and HVAC: Ventilation
Educational facilities	82.4	1.8	Smart appliances, commercial EV charging and HVAC: Ventilation
Medical Centers	88.5	1.9	Smart appliances, commercial EV charging and HVAC: Ventilation
Hotels	32.6	0.7	Smart appliances, commercial EV charging and HVAC: Ventilation
Restaurants	83.4	1.8	Freezing, cooling and HVAC: Ventilation
Offices	206	4.5	Smart appliances, commercial EV charging and HVAC: Ventilation
Total of commercial customers	541	11.8	

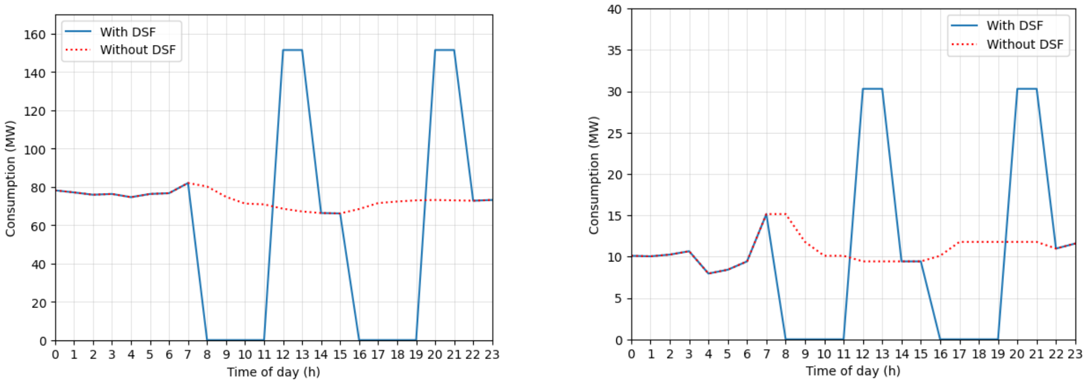
Table A.3: Göteborg Energi's industrial customer base, their loads and size.

Customer type	Consumption [GWh]	Percentage [%]	Loads
Total of the largest industries in Gothenburg	260.3	5.7	Labratories and process machines. Pressing, assembly and other process machines. Pressing, painting, assembly and other process machines. Separators, evaporators and preheaters, condenser and vacuum pump, feeding pump, circulation pump, discharge pump, condensed water pump and system pipe fittings.

Table A.4: Göteborg Energi's transport customer base, their loads and size

Customer type	Consumption [GWh]	Percentage [%]	Loads
Public transport	150.4	3.3	Depot charging, end stop charging and power on shore
Commercial transport	1.9	<1	power on shore
Freight transport	76.0	1.7	power on shore
Total of transport customers	228.3	<6	

A.3 Load control of HP

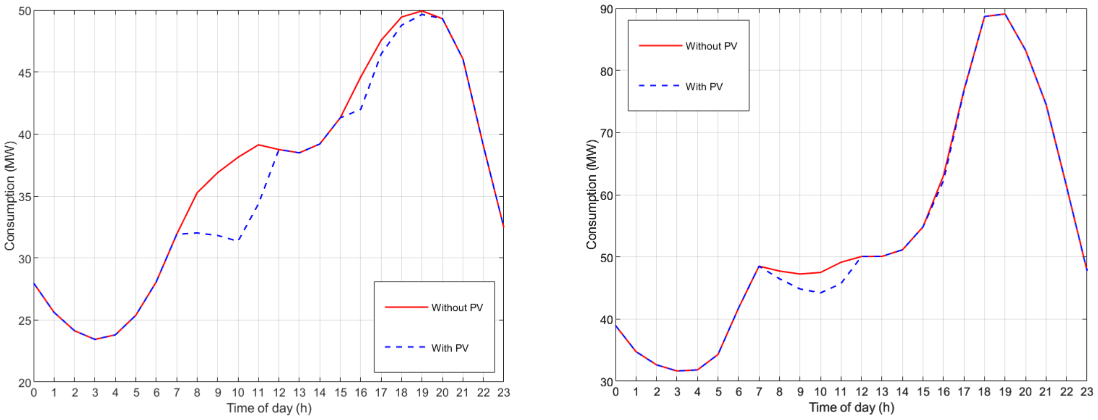


(a) Coldest day

(b) Warmest day

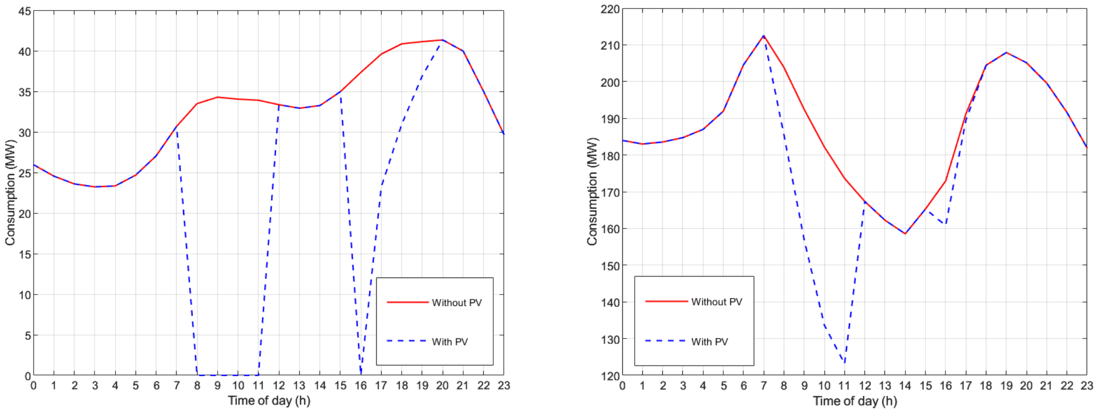
Figure A.3: Load control of aggregated HPs during coldest and warmest day for the year 2030.

A.4 Photovoltaic solar energy panels



(a) Consumption from apartment buildings over 24 hours during warmest day.

(b) Consumption from apartment buildings over 24 hours during coldest day.



(c) Consumption from detached and semi-detached houses over 24 hours during warmest day.

(d) Consumption from detached and semi-detached houses over 24 hours during coldest day.

Figure A.4: The consumption of detached and semi-detached houses and apartment buildings during warmest day and coldest day, with and without PV's contribution, for the year 2030.

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