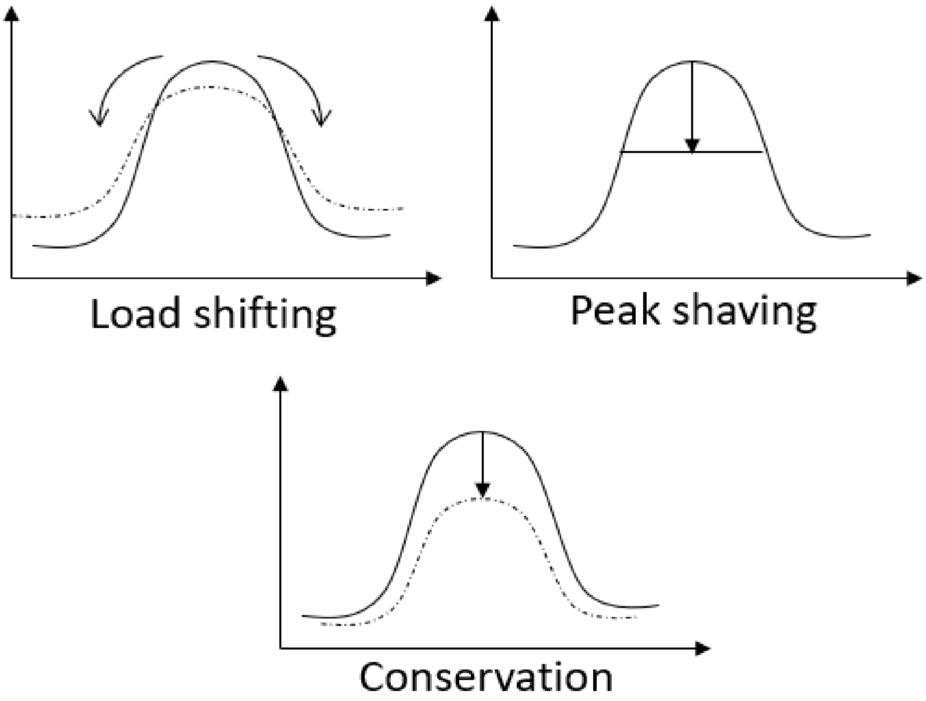
CHALMERS
UNIVERSITY OF TECHNOLOGY




# Energy use in office buildings and their impact on Gothenburg’s energy system

## Assessment of load management measures

Master’s thesis in Sustainable Energy Systems

Johan Kinell
Jonas Larsson

DEPARTMENT OF ARCHITECTURE AND CIVIL ENGINEERING

CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2022
www.chalmers.se

MASTER’S THESIS ACEX30

# Energy use in office buildings and their impact on Gothenburg’s energy system

## Assessment of load management measures

*Master’s Thesis in Sustainable Energy Systems*

Johan Kinell
Jonas Larsson

Department of Architecture and Civil Engineering
*Building Technology*
*Building Physics Modelling*
CHALMERS UNIVERSITY OF TECHNOLOGY

Göteborg, Sweden 2022

Energy use in office buildings and their impact on Gothenburg's energy system:
Assessment of load management measures

*Master's Thesis in Sustainable Energy Systems*

Johan Kinell

Jonas Larsson



Examensarbete ACEX30
Institutionen för arkitektur och samhällsbyggnadsteknik
Chalmers Tekniska Högskola, 2022

Department of Architecture and Civil Engineering
Building Technology
Building Physics Modelling
Chalmers University of Technology
SE-412 96 Göteborg
Sweden
Telephone: + 46 (0)31-772 1000

Cover:
Visualisation of load management strategies, further described in Section 2.7.

Name of the publisher or Department of Architecture and Civil Engineering
Göteborg, Sweden, 2022

Energy use in office buildings and their impact on Gothenburg's energy system: Assessment of load management measures

*Master's thesis in Sustainable Energy Systems*

Johan Kinell

Jonas Larsson

Department of Architecture and Civil Engineering
Building Technology
Building Physics Modelling
Chalmers University of Technology

ABSTRACT

The electrification of society in unison with the transition toward a fossil free energy system create the urge for increased flexibility and energy efficiency measures. Commercial buildings stand for a large portion of energy consumed today and can play a significant role to reach the overarching goal of a sustainable energy system. In this thesis technical actions applicable for property owners were evaluated in their effectiveness to create economic incentive in combination with system benefits. Assessments of load management measures and technical actions were conducted by using building performance modelling in IDA ICE, mixed integer linear programming in MATLAB, and literature reviews.

The technical actions investigated in this report include building envelope improvement, external blind utilisation, global temperature adjustment, local electricity production, and li-ion battery storage. The investigation was conducted as a parameter study in relation to a Reference Case model built with input data from Swedish building industry standards and recommendations aimed for office operation. The system of district heating, district cooling, and electricity are analysed separately within the building boundary and on system level.

Enhanced performance in the form of decreased thermal transmittance reduced the need for heating but also increased the need for cooling. Battery implementation and solar PVs presented opportunities as demand side management strategies to adapt building electricity consumption to allow variable renewable energy technology penetration in the energy system. The results and discussion indicate the importance of cooperation between supply and demand stakeholders to create economic feasibility in energy load management measures.

Key words: District heating, District cooling, Electricity system, Building envelope performance, Solar PVs, Battery storage

Energianvändning i kontorsbyggnader och deras påverkan på Göteborgs energisystem: Utvärdering av lasthanteringsåtgärder

Examensarbete inom Hållbara Energisystem

Johan Kinell

Jonas Larsson

Institutionen för arkitektur och samhällsbyggnadsteknik
Byggnadsteknologi
Byggnadsfysikalisk modellering
Chalmers tekniska högskola

SAMMANFATTNING

En samtida utveckling av fossilfria energisystem och elektrifieringen av samhället skapar ett behov av flexibilitet och energibesparande åtgärder. Kommersiella byggnader utgör en stor del av energikonsumtionen och har en viktig roll för att åstadkomma ett övergripande hållbart energisystem. I detta mastersarbete är tekniska åtgärder tillgängliga för fastighetsägare utvärderade genom deras förmåga att skapa fördelar för både investeraren och energisystemet. En utvärdering av dessa görs med hjälp av byggnadsprestanda genom IDA ICE, linjär programmering i MATLAB och aktuell litteratur.

De prövade åtgärderna behandlade i denna rapport innefattar klimatskalförbättringar, solavskärmning, rumstemperaturjusteringar, lokal elproduktion och batterilagring. Undersökningen är gjord som en parameterstudie i relation till ett referensfall. De indata som används är baserade på svensk byggnadsstandard och rekommenderade schablonvärden gällande kontorsverksamhet. Byggnadens värme/kyl- och elsystem är analyserade separat med de tillhörande tekniska åtgärderna.

Ett förbättrat klimatskal i byggnader leder till stora besparingar i värmebehov, men samtidigt ökar behovet för kyla. Batterilagring och solpaneler påvisar en stor potential till ökad flexibilitet, vilket leder till möjligheter för fortsatt genomslag utav varierande förnyelsebara energikällor i energisystemet. Resultatet av studien påvisar vikten av samarbete mellan energiproducent och energikonsument för att skapa ett tillräckligt ekonomiskt incitament för energibesparande åtgärder.

Nyckelord: Fjärrvärme, Fjärrkyla, Elsystemet, Klimatskalsprestanda, Batterilagring, Solarpaneler.

# Contents

# Preface

The work in this thesis has been carried out in collaboration with GICON installationsledning AB and Chalmers University of Technology. A special thanks to Göran Andersson at GICON for giving us the opportunity to carry out this project with a teaching spirit. Further, we would like to express gratitude to Henric Erntoft for his great insight and guidance.

The interviewees provided great expertise and knowledge in the supply and demand landscape which made the work significantly more interesting. Thank you for contributing to our learning and work on this thesis.

We want to thank EQUA Simulation which has provided us with student licenses for the software IDA ICE 4.8 which has helped us in carrying out the modelling that constitutes a large portion of the methodology. Nord Pool kindly let us use their data on day-ahead markets and the intraday market as a basis for operating cost calculations conducted in this thesis, which we are grateful for.

Göteborg, June 2022
Johan Kinell & Jonas Larsson

# Notations

$A$ – Area [m$^2$]

$A_{Envelope}$ – Area connected to ambient [m$^2$]

$A_{Temp}$ – Floor area that is heated to at least 10°C inside the building [m$^2$]

$c$ – Specific heat capacity of air [Wh/kg K]

$E_{cooling}$ – Annual Energy demand for cooling [Wh]

$E_{el}$ – Annual Energy demand for property electricity [Wh]

$E_{heat}$ – Annual Energy demand for heating [Wh]

$E_{hot\ water}$ – Annual Energy demand for hot water usage [Wh]

$E_{tot}$ – Total energy supplied [Wh]

$EP$ – Primary energy number [kWh/m$^2$ $A_{temp}$]

$F_{geo}$ – Geographical location factor for heat usage

$G_a$ – Annual relative daily heat load variation [%]

$P_a$ – Annual average heat load [Wh/h]

$P_d$ – Daily average heat load [Wh/h]

$P_h$ – Hourly average heat load [Wh/h]

$PE$ – Energy type weight factor used for Primary energy number

$Q_{cool}$ – Energy needed for cooling [Wh]

$Q_{gain}$ - Heat from internal heat gains [Wh]

$Q_{hw}$ – Heat needed for tap water [Wh]

$Q_{hwc,loss}$- Heat losses in the hot water distribution system [Wh]

$Q_{solar}$ – Solar heat gain [Wh]

$q_{t,loss}$– Transmission heat losses through building envelope [W]

$Q_{vent}$ – Heat removed by ventilation [Wh]

$Q_{v,loss}$ – Heat losses through air leakage [Wh]

$R_{Tot}$ – Total thermal resistance of a building part [m$^2$K/W]

$T_i$ – Indoor temperature [K]

$T_o$ – Outdoor temperature [K]

$U$ – Overall heat transfer coefficient [W/m$^2$K]

$U_{average}$ – Average overall heat transfer coefficient [W/m$^2$K]

$\dot{V}$ – Air volume flow [m$^3$/h]

$W_{b,el}$ – Business electricity [Wh]

$W_{p,el}$ – Property electricity [Wh]

$\eta_{PV}$ – Efficiency Solar PV

$\eta_T$ – Efficiency heat exchanger

$\theta$ – Angle between the ground and the panel surface [°]

$\rho$ – Density of air [kg/m$^3$]

*Notations for Linear Programming equations and constraints:*

| ***Indexes*** | ***Parameters*** | ***Variables*** |
|---|---|---|
| t = time [hour] | $D_t$ – Building electricity demand at hour t [kWh/h] | TC – Total Electricity Cost [SEK/year] |
| m = month [1, 12] | $P_{el,t}$ – Electricity price at hour t [kWh/h] | $Netload_t$ – Building net electricity demand |
| | $SOC_{max}$ – Maximum battery storage capacity [kWh] | $Ch_t$ – Battery charging at hour t [kWh/h] |
| | $PVgen_t$ – PV generated electricity at hour t [kWh/h] | $Dch_t$ – Battery discharging at hour t [kWh/h] |
| | $E_c$ – Battery charging efficiency | $SOC_t$ – Battery state of charge [kWh] |
| | $E_d$ – Battery discharging efficiency | $Shave_m$ – Monthly building load shaving factor |
| | $O\&M_{bat}$ – Variable cost for battery [SEK/kWh] | PeakLoad – Sum of monthly load shaving factors |

# Nomenclature

*BBR*:  Boverket's building regulations BFS 2011:6 with changes to BFS 2020:4 (BBR29).

*BEN2*:  Boverket's regulations and guidelines (2016:12) for property energy usage for a normal year and normal use.

*DC*: District Cooling

*DH*: District Heating

*DSM*: Demand Side Management

*g-value*: Solar heat transmission value

*g-value factor*: Window system multiplier of solar heat transmission value

*GTA*: Global Temperature Adjustment

*HRV*: Exhaust and supply air ventilation with heat recovery

*IDA ICE*: IDA Indoor Climate and Energy, building simulation tool designed by EQUA Simulation AB.

*MILP*: Multiple integer linear programming

*Netload*:  Electricity from the local electricity grid for each time step.

*SOC*: Battery state of charge.

*Sveby*: Industry standard data of energy usage for buildings in Sweden.

*TDPA*: Three diurnal peak averages for district heating, used in heating power tariff.

*TPA*: Three peak average on an hourly resolution, used in electricity power tariff.

*VAV*: Variable Air Volume

# List of Tables

# List of Figures

# List of Appendices

# 1 Introduction

Variations in energy production and demand are becoming more important to consider when developing a fossil-free energy system. Intermittent and renewable power sources provide great opportunities in an overarching goal toward a sustainable energy future but also reveal challenges in energy flexibility for multiple sectors of society.

The building sector constitutes a large portion of the current societal energy demand and is therefore of high interest regarding energy optimisation measures. Allowing further involvement of property owners can play a deciding role in the development of smart energy systems with energy trade, local energy generation, energy storage capabilities, and flexibility in energy demand (Bulut et al., 2015).

Energy optimisation and flexibility measures in commercial buildings support the integration of renewable energy generation technologies. This is naturally followed by increased system efficiency and improved utilisation strategies of existing energy infrastructure (Göteborg Energi, n.d).

Incentives toward sustainable buildings often include economic value to motivate wide-scale change. Therefore, before expanding the scope toward a system perspective it is important to understand the direct actions in the building that can enhance the effectiveness of future changes.

In this thesis, an investigation of the roles a commercial office building in Gothenburg can take in the local energy system in terms of energy reduction and as a load controlling utility is made. Technical actions meant to improve building performance are evaluated relative to a described building Reference Case model created in IDA Indoor Climate Energy (IDA ICE). The results are discussed from two different stakeholder perspectives, local energy distributors and property owners, to provide an analysis of technical action effectiveness. The thesis is made in collaboration with GICON Installationsledning AB.

### 1.1.1 Background

The Swedish transmission operator states in their future scenario analysis of the Swedish power system that the electricity consumption will likely increase (Svenska Kraftnät, 2021). Electrification of society will also present larger and more frequent peaks in electricity demand. Accurate future energy demand figures are still difficult to predict because of the large increase during the last years (Teran Öman et al., 2020).
Increased penetration of wind power in Sweden has proven to have a significant effect on the electricity price. The pricing patterns are harder to predict and more volatile. Large energy consumers are therefore urged to become more flexible in energy demand (Svenska Kraftnät, 2021). The transition toward a fossil-free energy system with variable renewable energy sources will expand possibilities and incentives toward flexibility measures in the energy sector.

Several Swedish local grid owners base their pricing models on energy consumed and peak power. There are thus financial incentives for buildings to not only optimise total energy consumption but also reduce power peaks, and simultaneously provide a well-needed service towards the energy system in reducing the need for peak generation technologies. Reducing the amount of energy and power needed in a building will decrease the environmental footprint, and raise the value of the property (Energiforsk, 2016).

The contemporary setup of the district heating network of Gothenburg, owned by Gothenburg Energy, is supplier controlled to always satisfy heat demand. This strategy requires peak heat generation technologies to cover for variations in demand. The purpose of these is to quickly start up and regulate the heat output but generally have a higher operating cost. Often the peak generation units are fossil-based, and therefore large variations in load demand indicate more emissions. With extensive use of peak heat units, the total cost of the district heating system increase (Romanchenko, 2018).

A strong focus on energy-saving measures in the building sector has led to that design and construction is highly focused on reducing heat losses (Werner, 2017). The result of this focus has increased the demand for cooling in newly produced buildings. To handle the increased need for cooling in the city centre of Gothenburg, Gothenburg Energy is expanding its district cooling network to supply more customers in their plans “Vision Fjärrkyla 2030” (Gothenburg Energy, n.d.).

Demand side management is an established concept which mitigates the imbalance between energy demand and supply. This enables more efficient use of existing generation capacity and simplifies the phase-out of non-renewable energy sources (Darwazeh et al., 2022). There is a need for evaluation of actions applicable to manage variable energy production for already existing buildings as well as new ones. There is no real consensus on profitability regarding improving energy efficiency in commercial buildings in Sweden. Mainly due to the different economic conditions of property owners (Ministry of Infrastructure, 2021).

## 1.2 Purpose

The purpose of this study is to provide an evaluation of technical actions as load management measures for an office building. Including load effects, the potential to increase property value, and compatibility with further integration of renewable energy technologies in the energy system. Also, investigate the interaction between the building sector and the energy sector.

### 1.2.1 Scope of investigation

The load management measures, described in Section 1.2.2, are analysed through operating cost calculations by modelling the energy consumption pattern impacts. Feasibility in implementing technical actions in larger scale are investigated through literature review and energy load simulation analysis. The purpose is fulfilled by answering the following questions.

- How do the specific technical actions influence the office building energy demand?
    - Regarding peak load average
    - Regarding maximum peak load
    - Regarding total energy used
- How is the technical action expected to influence the building operating cost?
- What is the energy system impact if the technical actions are utilised in a wider scale?

- How do the technical actions align with the development of the energy system?

### 1.2.2 Load management measures evaluated

The load management measures covered in this thesis and listed below are a mix of building performance improvements together with demand response strategies. The technical maturity and condition are also considered in the scope of investigation.

- Improved building envelope insulation
- Window exchange
- Use of external blinds
- Global temperature adjustment
- Solar PVs
- Battery storage utilisation

## 1.3 Demarcations

The project is limited to the Swedish energy system configuration and Gothenburg's district heating and district cooling network.

The heating/cooling system is decoupled from the electricity system of the model building during the analysis of technical action impacts.

The validation of building is limited to the Swedish building regulations and building standards, to what extent the technical actions show similar results internationally is not treated in this thesis.

Only the current configuration of energy production alternatives with their growth trajectories are considered.

Current pricing models in electricity, district heating, and district cooling are used to estimate operating costs. Long term development of energy markets will not be investigated.

The building is modelled with simplifications to simplify the analysis of the results. The simplifications are described throughout the report.

The modelled building is not compared to other buildings in detail, which exclude the role of building differences, such as thermal bridges, orientation, or glass fraction.

This thesis is not expected to provide investment suggestions.

The return temperature from the building to the district heating and cooling network is assumed to be equal to the system average return temperature.

## 1.4 Methodology

The initial phase of the study consisted of a literature review, interviews as qualitative research, and learning of software tools for computing energy performance. The theory study is divided into two different areas, the energy systems and office building and covers relevant concepts used within this thesis.

Conducted interviews were formed as qualitative research, where the stakeholder's role was to provide insight regarding the chosen subject from different perspectives. The interview subjects were property owners and the local grid owner. The interviews were of semi-structured character, where the interviewees are allowed to fully express themselves (Trost, 2010).

The location of the energy systems and building model was in Gothenburg. Due to large differences in energy consumption of operational activities in commercial buildings, the analysis of this study was only aimed toward office operation. Standardised values and templates regarding energy and occupancy follow Sveby's (2013) office input recommendations. Complementing data and building regulations have followed the National Board of Housing, Building and Planning (Boverket) guidelines (BBR). All simplifications due to demarcations were discussed with experts in the subject at GICON and documented in this thesis at a suitable location.

IDA ICE v4.8 was used as a modelling software tool to describe the characteristics and energy demands of a generalised office building. The building's structural layout was based on floor plan drawings provided by GICON.

The technical actions were evaluated in relation to an office building model created in IDA ICE referred to as the Reference Case. Technical actions investigated as a part of the building's electricity system, battery storage and PV panels, were analysed through multiple integer linear programming (MILP) in MATLAB. The remaining actions are implemented as parameter studies in IDA ICE for the investigation of heating and cooling. Current energy price models from Gothenburg Energy and electricity spot market price from Nord Pool were used together with the building's consumption patterns to evaluate the operating cost. Additional result analysis of the technical actions in form of graphical illustrations and calculations was performed in Microsoft Excel. Further result analysis and discussion to sufficiently answer the research questions were conducted through a literature review and interviews as a framework when evaluating technical action results.

How the results differed depending upon occupancy, electricity price variations, and design of the electricity grid price model was investigated in a sensitivity analysis. The purpose of the sensitivity analysis was to evaluate the robustness of the results.

## 1.5 Outline of report

The report is aimed to provide a view on how changes within a building energy consumption affect property owners as well as the energy system. This section explains the chapter outline for navigation through the report. In Figure 1 a flow chart is presented to demonstrate the overarching report structure.

To give the reader an understanding of how these areas interact, a theory and literature review section in Chapter 2 is written to describe important aspects of the energy supply and demand landscape, as well as the building energy balance.

Chapter 3 presents the overarching method and the strategy for simulating technical actions as load management measures in modelling scenarios. The investigation of technical actions is conducted with a decoupled view of the building energy system, where heating/cooling and electricity are analysed separately. The Reference Case in IDA ICE is thoroughly described in a separate method chapter, Chapter 4. The conducted interviews are summarised in Chapter 5 and is used for method development, result analysis, and discussion support.

Chapter 6 displays the results of the simulation and optimisations. Note that all the results are evaluated from the same research questions, and the decoupled view between heating/cooling and electricity is still present. The result chapter ends with a sensitivity analysis, with three different parameter alterations.

Chapter 7 is used to discuss the simulation outcome. It also presents a discussion of the input data and assumptions made. Chapter 8 concludes the thesis outcome and presents recommendation for future work.

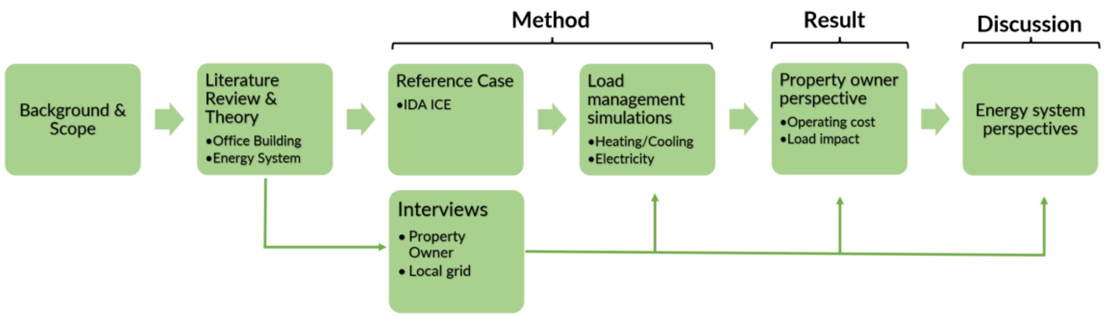



*Figure 1. An overview of the report structure with indicators of how chapters are connected.*

# 2 Theory & Literature Review

This second chapter is formed to cover essential knowledge used to validate the project results and the method used. Here an introduction to concepts frequently used when evaluating building performance and the energy system configuration is described. Also, the literature review supports the reasoning in the Result Analysis & Discussion, Chapter 7.

## 2.1 District heating network in Gothenburg

The district heating network in Gothenburg consists of several different types of generation units, such as heat-only boilers (HOB), heat pumps, and cogeneration of heat and power plants (CHP). The different technologies are used in different scenarios of energy demand and the infrastructure is managed by Gothenburg Energy (Romanchenko, Odenberger, Göransson and Johnsson, 2017).

The different technologies used require different types of fuels, in the year 2021, 69% of the heat from district heating was provided by recovered waste energy and 24% from renewable sources such as biofuels. The remaining heat demand was mainly produced from fossil fuelled heat production. Important to note is that the percentages of different fuels used are highly dependent on the year investigated, an increase in total or peak heat demand results in a higher percentage of fossil fuel required (Gothenburg Energy, 2022). Naturally, the district heating network load strongly correlates with the outside temperature. This results in heat load variations being larger during winter periods, and the highest peaks are covered by heat-only boilers based on fossil fuels. Today more than 17 000 buildings are connected, and district heating provides almost 90% of all Gothenburg's heating demand (Gothenburg Energy, n.d.).

### 2.1.1 Supply and demand fluctuations DH

Typical heat load patterns of Swedish district heating systems can be placed in two categories. Either, by two characteristic peaks over the day, one in the morning and one in the afternoon. The other load pattern has a significant dip during the day due to large diurnal outdoor temperature differences (Gadd & Werner, 2013). The two categories are often divided over the year, occurring during winter and in the autumn/spring period respectively, the pattern categories can be seen in Figure 2.

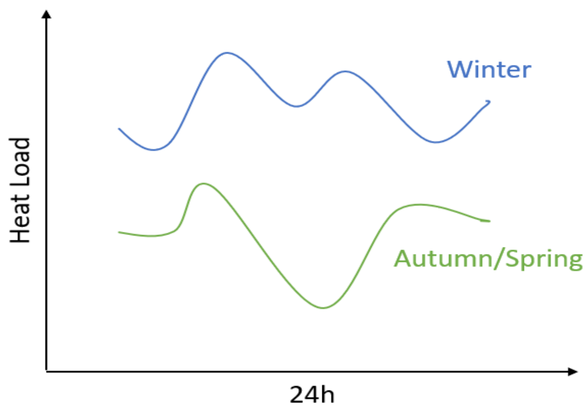



*Figure 2, Seasonal heat load pattern characteristics*

In the Gothenburg district heating system, during the coldest days of the year the peak heat generation units are in operation to cover the two daily peaks (Gothenburg municipality, 2021). A benefit of reducing the daily heat load variations is that less peak power capacity and expensive fuels are needed, resulting in a lower system cost (Gadd & Werner, 2013). The conclusion of Ingvarson Olsson and Werner (2008) article was that the building block in Gothenburg's municipality can handle the daily heat load variations of the local district heating network. Romanchenko et. al. (2018) agrees and indicate that every building can be utilized to act as short-term storage of heat for the district heating network. Using the short-term storage of buildings can decrease the daily net-load variations by 20% of the district heating network. Another conclusion by Romanchenko et al. (2018) is that using thermal energy storage of buildings as a demand response can reduce the utilization of peak HOBs through less fluctuating heat demand. With a reduction in the usage of fossil-based heat only boilers, buildings can play a significant role in reducing the carbon dioxide footprint of Gothenburg's district heating network. Werner (2017) states that increased industrial demand for biomass and focus on material recycling instead of waste incineration restrict the fuel source for district heating. However, a decreased heating demand in the building sector due to the near-zero energy requirements can ease the risk of heat source shortage.

### 2.1.2 Price model district heating

The price model for district heating in Gothenburg is based on energy consumption, peak power demand, and the temperature of the returning water (Gothenburg Energy, n.d.). The power tariff is based on a step function, where an increased power demand results in less variable cost but increased fixed annual cost. The peak power is expressed by the three highest average diurnal energy consumptions, further known as three diurnal peak averages (TDPA). The *winter* season includes January, February, March, and December. A*utumn/Spring* includes April, October, and November and the remaining months are counted as *Summer*.

*Table 1, District heating energy prices for different seasons.*
*Source: Gothenburg Energy*

| Period | Energy Price (SEK/kWh) |
|---|---|
| **Winter** | 0.508 |
| **Autumn/Spring** | 0.346 |
| **Summer** | 0.087 |

*Table 2, District heating power tariff based on annual three diurnal peak averages (TDPA).*
*Source: Gothenburg Energy*

| Power (kW TDPA) | Fixed Annual Cost (SEK) | Variable Cost (SEK/kW TDPA) |
|---|---|---|
| **0–100** | 9 235 | 880 |
| **101–250** | 14 285 | 830 |
| **251–500** | 28 090 | 775 |
| **501–1000** | 58 150 | 715 |
| **1001–2500** | 123 215 | 650 |
| **> 2500** | 298 285 | 580 |

## 2.2 District cooling network in Gothenburg

The district cooling network in Gothenburg is based on three types of generation technologies: free cooling, absorption heat pumps, and cooling compressors. The centralised cooling units use cold water from Göta Älv, waste energy from refineries, and bio-based labelled electricity, which in the present day is considered carbon neutral according to industry standards. Like the DH network, Gothenburg Energy is both the infrastructure owner and energy supplier. The total amount of energy provided through district cooling is significantly less than district heating (Gothenburg Energy, 2022).

### 2.2.1 Supply and demand fluctuations DC

The district cooling network of Gothenburg is in an expansion phase where the incentives to be connected have increased. This has resulted in the project "Vision Fjärrkyla 2030" by Gothenburg Energy, where the capacity is projected to be increased from 65MW to 148 MW (Gothenburg municipality, 2021). Stricter regulations on energy usage and global warming have resulted in higher demand for cooling alternatives in commercial buildings (SMHI, 2021; Werner, 2017).

The base supply to cover district cooling demand is the utilisation of absorption heat pumps powered by the recovery of waste heat from municipal waste incineration plants or refineries. During the summer period in Gothenburg, the demand for district cooling is largest, and the free cooling from Göta Älv (Sea Water) is not possible to utilize due to high water temperatures. The peaks in the summer where the waste heat is insufficient, compressor cooling powered by electricity is utilised to satisfy the demand. Additionally, during the autumn/spring the seawater temperature is often too high to utilise, and the waste heat is needed for the DH network. Therefore, compressor cooling is the primary resource of district cooling during this period (Gunasekara, S.H. et. al, 2019).

### 2.2.2 Price model district cooling

The price model for district cooling in Gothenburg is based upon energy consumption, peak power demand, and volumetric flow. The power tariff basis is a step function, where a larger power output results in less variable cost but increased fixed annual cost presented in Table 4. The power cost is derived from the annual maximum power peak with an hourly resolution. The energy consumption cost is dependent on seasonal pricing per kWh seen in Table 3. It also includes a volumetric flow cost component of 0.65 SEK per cubic meter (Gothenburg Energy, n.d.).

*Table 3, District cooling energy prices for different seasons.*
*Source: Gothenburg Energy*

| Period | Energy Price [SEK/kWh] |
|---|---|
| **Winter** | 0.145 |
| **Autumn/Spring** | 0.260 |
| **Summer** | 0.340 |

*Table 4, District cooling power price based on the annual maximum power demand.*
*Source: Gothenburg Energy*

| Max Power (kW) | Fixed Annual Cost (SEK) | Variable Cost (SEK/kW) |
|---|---|---|
| **0–100** | 18 500 | 750 |
| **101–250** | 34 500 | 590 |
| **251–500** | 67 000 | 460 |
| **501–1000** | 99 500 | 395 |
| **1001–2000** | 119 500 | 375 |

## 2.3 Electricity system Gothenburg

The local electricity grid in Gothenburg in present-day does not experience electricity congestion. The limiting factor is the amount of electricity that can be transferred into the city. Even though the grid presently does not experience difficulties in capacity, increased demand for electricity in society will most likely bring congestion challenges within the foreseeable future (Gothenburg Energy, 2022). The transmission capacity is better suited than in other large cities in Sweden, but the power demand expansion expected with increased population, electrification of the transport sector, new electricity-intensive data centres, and extensive harbour operation indicates potential difficulties in the future (Teran Öman, A et al., 2021; Sweco, 2020).

The supply of electricity is typically made by various power production technologies. The order in which these technologies are providing electricity mainly depends on the capacity, supply costs, and operation costs. The merit order curve is ordered from the least expensive to the most expensive technology and describes how the energy demand will be met by suppliers over the year, see Figure 3. This indicates that when electricity price peaks, the total electricity demand surpasses the capacity of cheaper alternatives, and to sustain power balance more expensive technologies are dispatched to fulfil the demand (Morthost et al., 2010).

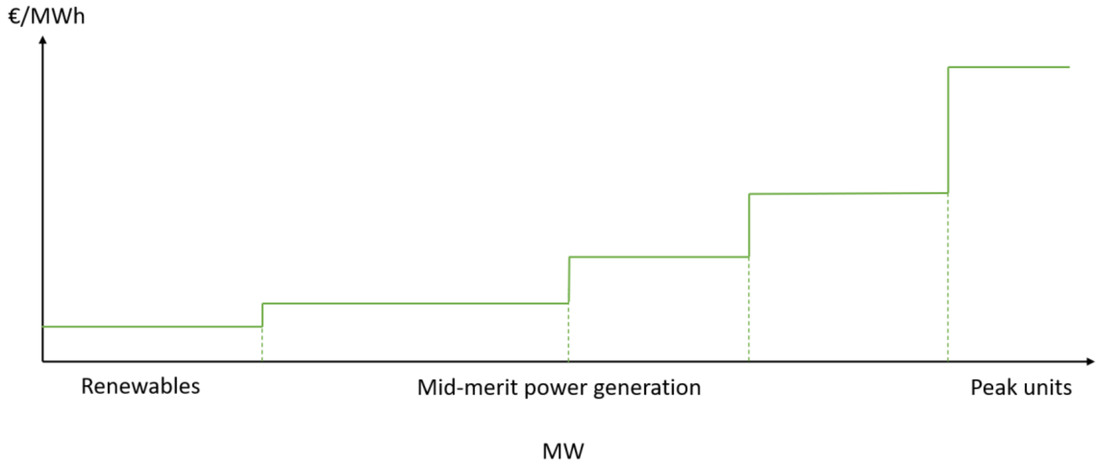



*Figure 3, Merit order curve*

In Sweden year 2019, electricity production mainly originated from six production technologies. In recent years there has been a significant increase in wind power production (Swedish Energy Agency, 2021). A further expansion of intermittent power sources increases volatility in the electricity price. How the net electricity production in Sweden has developed since 1970 can be seen in Figure 4.

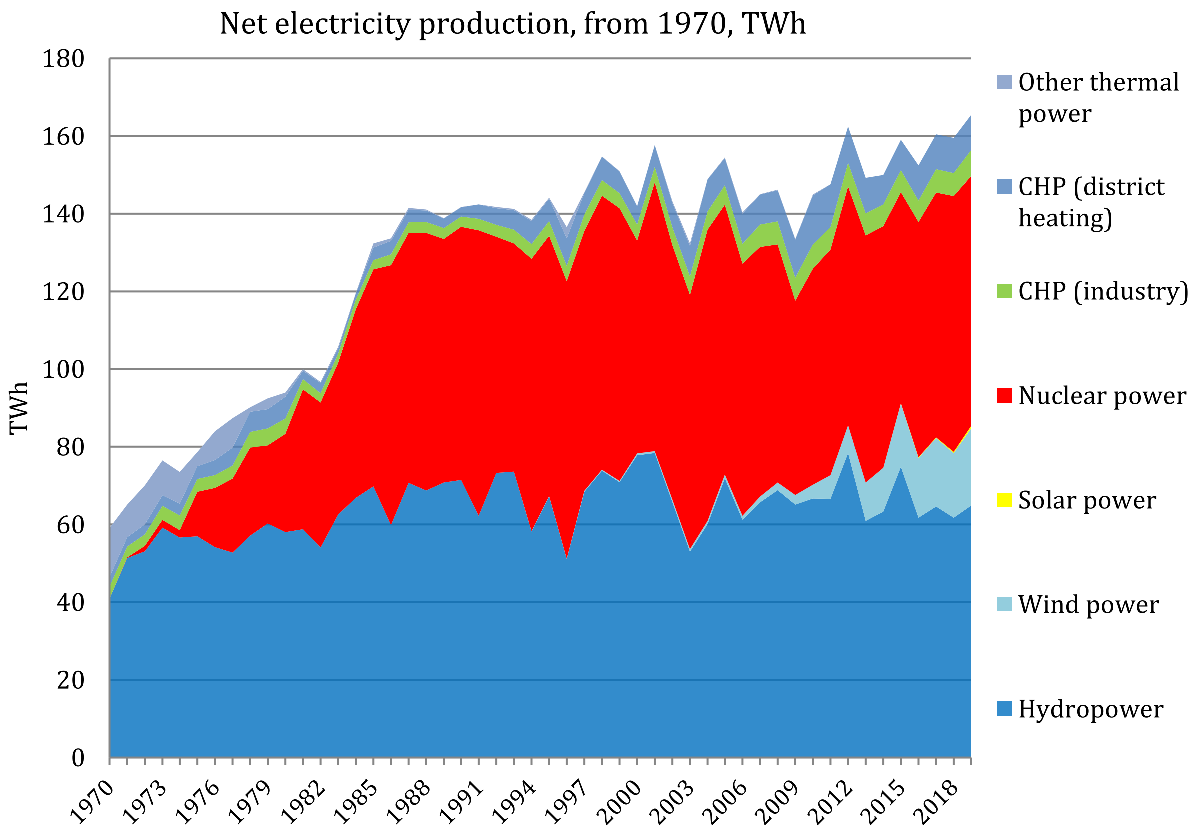



*Figure 4, Net electricity production in Sweden, excluding electricity generated off-grid. Source: Swedish Energy Agency and Statistics Sweden data*

### 2.3.1 Supply and demand fluctuations electricity

A rule of thumb for the Swedish electricity production is that during hours when wind power generation is low there is a need to import electricity in the price region SE3, where Gothenburg is situated. The import can consist of electricity generated by either coal or gas power plants in Germany or Poland. Any local installations of renewable electricity generation can have a substantial value in reducing carbon dioxide emissions (Gothenburg municipality, 2021).

Demand response programs are a way to create economic incentives for consumers to reduce or shift their electricity consumption during peak periods. Real-time pricing, critical peak pricing, and variable pricing are examples of demand response strategies. In combination with electricity information/control user systems, it is considered a valuable resource for grid modernisation (U.S Department of Energy, n.d). Increased demand for regulating power production technologies will follow the integration of renewable energy sources. Price-based demand response can be used to reduce the need for new regulating power. However, depending on the implementation the effect could vary, for example, Sweden's power system is divided into different areas which not necessarily experience system peak load simultaneously. This leads to an increased system demand locally, resulting in a further need for electricity system reinforcement (Steen D et al., 2012).

Shifting electricity consumption to a low-price period has been shown to have a clear correlation with increased use of renewables, especially wind power. Only shedding load during the highest electricity price hours resulted in the increased use of variable renewable energy (Lund et al., 2015).

Interviews with stakeholders within the energy and building sector suggest there is little financial benefit in participating in demand response programs. Most investigated stakeholders agree that this relatively unexplored territory needs further incentives to allow wide-scale participation (Bulut et al., 2015).

Communication between the stakeholders is important to allow sufficient planning for increased power needs to streamline condition evaluation and bring forth relevant issues (Teran Öman, A et al., 2021). Buildings in a future energy system will be an active player in the energy market, due to the development of energy trade, energy flexibility demand, local electricity production, and energy storage alternatives. For this transition to happen, cooperation between stakeholders in the building and energy sector needs improvement. The viewpoint where CO2 reduction measures are crucial is shared between the stakeholders and may induce cooperation opportunities (Bulut et al., 2015).

### 2.3.2 Price model Electricity

The electricity bill for Gothenburg's consumers has two main components, grid cost, and electricity trading. The grid cost includes transfer cost per kWh, energy transfer tax (0.36 SEK/kWh), and power cost based on the monthly peak on an hourly resolution. There are some differences in the grid cost depending on the fuse size see Table 5. The electricity trading is based on the intraday market spot electricity price presented by Nord Pool. How the intraday market spot electricity price (used as electricity trading price in this thesis) varied in SE3 over the year 2021 can be seen in Figure 5.

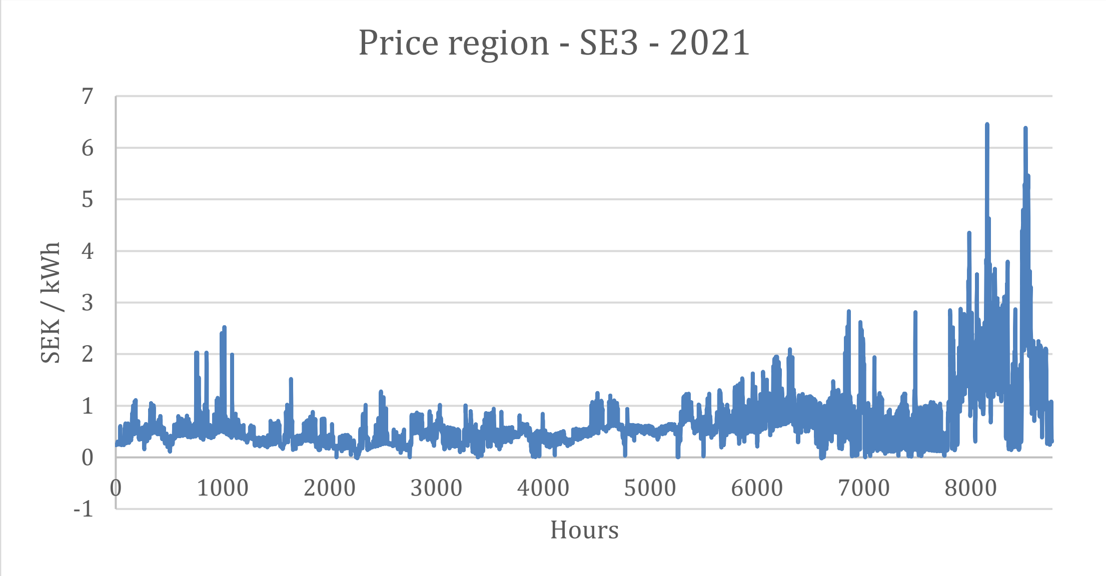



*Figure 5. Intraday market spot electricity price for price region SE3 with hourly resolution. Source: Nord Pool*

*Table 5, Electricity grid price model of Gothenburg local grid. Source: Gothenburg Energy*

| *Fuse* | *Fixed Monthly Cost (SEK)* | *Transfer Cost (SEK/kWh)* | *Power Cost (SEK/kW)* |
|---|---|---|---|
| ***<63A*** | *94* | *0.0166* | *29 (TPA)* |
| ***>63A*** | *555* | *0.075* | *49.3* |

## 2.4 Building energy balance

All energy flows have to be accounted for when studying the energy balance over the building envelope, including solar heat gains and heat losses to the surroundings (Abel & Elmroth, 2007). The inputs to the system are energy from district heating, district cooling and electricity, which are used to fulfil indoor climate requirements and operating systems tasks, see Figure 6.

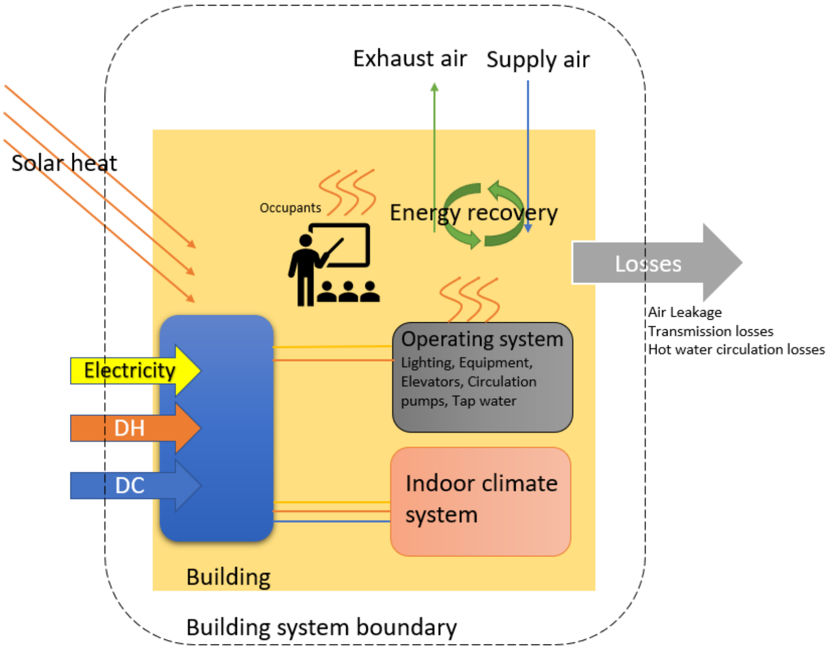



*Figure 6. Building system description and its system boundary.*

The total energy balance contains several categories of energy flows depending on origin, which equals the total energy demand $E_{tot}$. The overall energy balance of a building is presented in Equation 1.

*Equation 1, Overall annual energy balance over building*

$$E_{tot} = Q_{t,loss} + Q_{air,loss} + Q_{hwc,loss} + Q_{vent} + Q_{cool} + Q_{hw} + W_{p,el} + W_{b,el} - Q_{gain} - Q_{solar}$$

Internal heat gain, $Q_{gain}$, in an office building mainly originates from equipment, lighting, and occupancy during operating hours. Solar radiation through windows converts to heat on all affected surfaces. For rooms that have external walls and/or windows, $Q_{solar}$ accounts for a large part of the rooms heat surplus. The energy needed for heat removal, $Q_{cool}$, is mainly used by either ventilation systems or chilled surfaces using cold-water. $Q_{air,loss}$ is defined as the heat losses due to leakage through the envelope or natural ventilation. $Q_{hw}$ is the heat for hot water usage, where the $Q_{hwc,loss}$ is the distribution losses through the pipes supplying hot water in the building. The energy for electricity usage is split into business electricity and property electricity depending on the specific purpose, $W_{b,el}$ and $W_{p,el}$ respectively (Elmroth, 2007).

By using a heat recovery ventilation system, the demand of heating and cooling is reduced because of energy recovered from exhaust air. Equation 2 is used to explain the heat that is removed through air by the ventilation system. Often in non-residential buildings the ventilation system air flow is reduced during non-occupied hours (Elmroth, 2007).

*Equation 2, Heat removed by the ventilation*

$$Q_{vent} = \rho * c * \dot{V} * [T_i - (T_o + \eta_T (T_i - T_o))]$$

The overall heat transfer coefficient, also known as the U-value, of a building part is specified as the perpendicular thermal transmittance through the individual part per Kelvin. (Elmroth, 2007). The U-value is the measure to evaluate the insulation capacity, where a lower value indicates less heat transmission. The determination of a U-value is the inverse sum of all the thermal resistances for all layers of the specified part, see Equation 3. Equation 4 explains the transmission loss through a single building part.

*Equation 3, U-value equation derived by the total thermal resistance of a single part.*

$$U = \frac{1}{R_{tot}}$$

*Equation 4, Transmission losses through a single part*

$$q_{t,loss} = U * A * (T_i - T_o)$$

Thermal inertia is the heat capacity of thermal mass by a building to store heat within its envelope (Verbeke and Audenaert, 2018). Large thermal mass has less dependency on temperature changes outside the envelope. Furthermore, the duration to store heat is dependent on the temperature but cannot be quantified by a single parameter. For climates with large temperature fluctuations, large thermal inertia can reduce the demand for heating. Buildings with high heat capacity, low air flows, and good heat recovery has higher thermal inertia (Forslund & Forslund, 2021). Buildings with high thermal inertia have higher demand to remove heat through cooling.

## 2.5 Building performance & indoor climate requirements

Boverket's measure of energy performance is the primary energy number (EP, kWh/m2 Atemp) see Equation 5. Where the area, $A_{temp}$, consists of areas heated to at least 10°C. Each energy carrier is considered different in respect to effectiveness is multiplied by a weight factor $PE_i$. The weight factor for district heating, district cooling and electricity is 0.7, 0.6, and 1.8 respectively. Also, depending on the geographical location, $F_{geo}$, in Sweden the heating component is slightly altered to account for climate differences and district heating infrastructure available. The factor for geographical location in Gothenburg is 0.9.

*Equation 5, Equation for the primary energy number.*

$$EP = \frac{\sum_{i=1}^{3} \left( \frac{E_{heat}}{F_{geo}} + E_{cool} + E_{hot\,water} + E_{el} \right) x\ PE_i}{A_{Temp}}$$

The electricity accounted for in the primary energy number is only the electricity needed to run the property installations, called property electricity, such as HVAC, elevators, and property lighting (Boverket, 2021).

A building with sufficient heat performance needs adequate insulation to reduce heat transfer over the building envelope (Boverket, 2021). With some exceptions due to cultural heritage and functionality, the guidelines for building components' overall heat transfer coefficients are presented in Table 6.

*Table 6, Recommended U-values for adequate insulation for specific building envelope components, excluding thermal bridges. Source: Boverket*

| **U-values for specific building components** *[W/m²K]* | |
|---|---|
| $U_{roof}$ | *0.13* |
| $U_{wall}$ | *0.18* |
| $U_{floor}$ | *0.15* |
| $U_{window}$ | *1.2* |
| $U_{exterior\ door}$ | *1.2* |

The average overall heat transfer coefficient of the building is a measure to understand the insulation performance of a single building. It includes all thermal bridges and building components U-values. The equation for the total average heat transfer coefficient is described in Equation 6. Note that Equation 6 is modified to where all thermal bridges are added as a factor in the U-value. $A_{envelope}$ is the area that confines the tempered area.

*Equation 6, Total average heat transfer coefficient.*

$$U_{average} = \frac{\sum_{i=1}^{n} U_i A_i}{A_{envelope}}$$

In addition to the energy performance, there are regulations regarding indoor climate in commercial buildings. The used source to validate adequate measures of indoor comfort is the Swedish Work Environment Authority and Boverket. Which source that is used for an individual validation category are declared with their respective area in the Method chapter.

## 2.6 IDA Indoor Climate and Energy

IDA Indoor Climate and Energy is a simulation software of a building's energy performance developed by EQUA Simulation AB. IDA ICE can simulate specific heating, specific cooling, and energy consumption. The software can model annual energy consumption and performs it with a dynamic multi-zone strategy. By importing a local data file, IDA can model variations in location and climate (EQUA Simulation AB, n.d.).

A user of IDA ICE can set up a model with variations of input parameters and create 3D zones. The zone modelling is often performed by importing a BIM file or a DWG file as a framework. Simulating chosen parameters in the IDA ICE software creates a non-linear system of equations and solves them for every defined time step. EQUA Simulation states that it can be hard to guarantee the result of a simulation and that a non-linear equation system can have none or more than one solution. The software has been validated and certified by industry standards to ensure acceptable values with correct inputs (EQUA Simulation AB, 2018).

## 2.7 Demand Side Management (DSM)

The definition of demand side management is modifications in the end-user consumption patterns to allow more efficient operational behaviour in energy systems (Behrangrad, 2015). The utilisation of DSM has increased in popularity in recent years due to the electricity technological advances, need for intermittent power sources, and deregulation of electricity market.

The concept was introduced by the Electric Power Research Institute and defined as "*systematic utility and governing activities designed to change the amount and/or timing of the customer's use of electricity for the collective benefit of the society, the utility, and its customers*." Alteration of the load curve according to specific need is commonly categorised in load management objectives and energy efficiency measures. The two categories are different in energy use, where load management mainly alters the load shape, and energy efficiency can be described as energy conservation which reduces total consumption (World Bank, 2005).

Demand side management is applicable in several different forms. The load curve is specific to the operational pattern and/or structural features of an object where a favourable utilisation requires knowledge regarding the current load curve and the intended result (Lund et al., 2015). Some commonly used load pattern alterations are load shifting, peak shaving, and energy conservation visualised in Figure 7. The load strategies presented does not necessarily occur singularly, and multiple effects can be accomplished

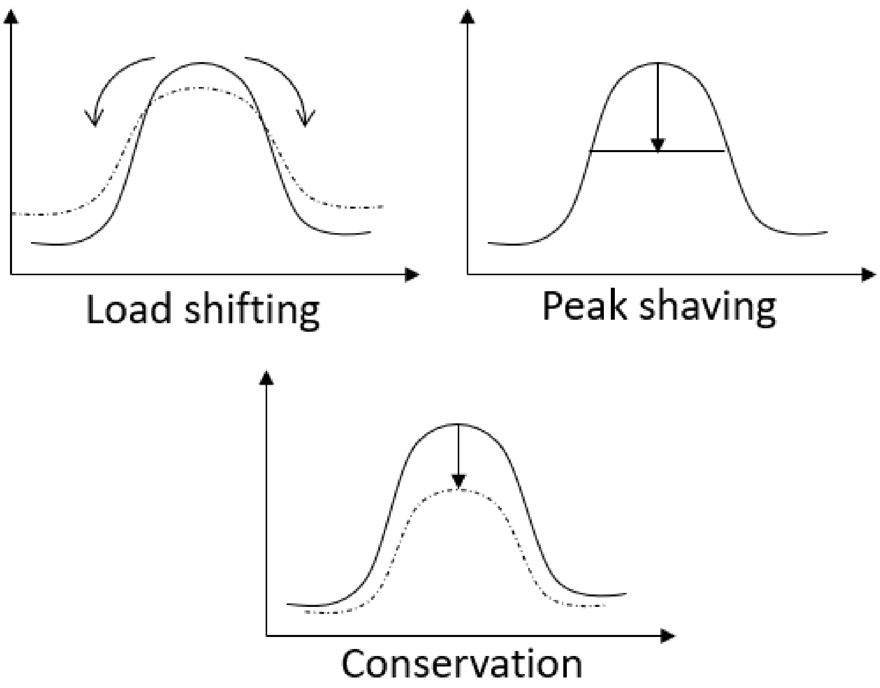



*Figure 7, Load curve visualisation with specific load management strategies, how the building load is distributed and altered over time. Based on Lund et al, 2015.*

Basically, demand side management is a broad term that includes all alternating actions in loads made by end-users, the criteria being that a certain outcome is planned. When referring to actions and activities in response to an event, as identifying peak load hours in the system, the more specific term is demand response (Darwazeh et al., 2022).

### 2.7.1 Load management measures for heating/cooling

The Swedish Government displays in their report “Sveriges tredje nationella strategi för energieffektiviserande renovering”, some cost-efficient strategies for energy-saving measures in the residential building sector (Ministry of Infrastructure, 2021). Effective measures can be additional façade insulation, roof insulation, and changing the windows of the building envelope. Kamel & Memari (2016) concludes that improved façade and roof insulation are energy conservation measures, but the percentage of energy savings is dependent on the building properties. Renovation of residential buildings by replacing building parts which reduce the overall heat transfer coefficient also reduces the annual energy consumption (Mata et., al, 2013).

#### 2.7.1.1 Global temperature adjustment

Global temperature adjustment (GTA) is meant to reduce energy consumption mainly during peak load events in the system. The concept allows operators to adjust the indoor temperature to reduce energy usage, which means that during heating seasons the temperature lowered and during cooling seasons it is increased to reduce the momentary energy load in the building. GTA can be implemented by using an absolute setpoint adjustment or if possible divided into the most suitable zones in the building to control. The concept is the same in regard to a building connected to district heating where a radiator output is reduced during the peak time (Darwazeh et al., 2022).

#### 2.7.1.2 Insulation of envelope

A decrease in the overall heat transfer coefficient result in less transmission losses. To achieve a low overall heat transfer coefficient, the insulating building part consists of layers of several materials with low thermal conductivity (Petersson, B-Å., 2003). Common methods to increase the thermal resistance is to increase the thickness of the material or exchanging materials with lower thermal conductivity (Haliu, G. 2021). However, an increased insulation property may imply problems with surface condensation.

#### 2.7.1.3 Windows

The primary purpose for windows in a building is to utilise the solar irradiation and provide the tenants with enough daylight (Petersson, B-Å, 2003). However, the most critical heat transmission losses of an office building are regularly through the windows (Zhao et al, 2015). Therefore, the overall heat transfer coefficient for windows is important to the total building envelope heat balance. An important property for studying windows is its g-value. The g-value specifies how much of the solar radiation that is accounted as heat gain within the building envelope through the window (Pilkington, 2021). For a building located in a cold climate region it is important to use the solar heat to reduce the yearly heating demand (Kamel & Memari, 2016).

#### 2.7.1.4 Blinds

Buildings with a large proportion of windows can use blinds to reduce heat gain from solar radiation and therefore reduce the demand for cooling and cooling power (Zhao et al, 2015). The most effective method to reduce the solar heat is using dynamic external blinds, which enables efficient use depending on the season. (Warfvinge & Dahlbom, 2010).

### 2.7.2 Li-Ion Battery

Li-ion batteries store electric energy as chemical energy, and the electrification of society presents further applications for this battery technology in the form of electricity storage in large scale and electric vehicles. A grid integrated battery management system can provide increased grid reliability, load management possibilities, and frequency regulation. (Danish Energy Agency, 2020).

Production of 1Wh li-ion batteries is, on average, causing emissions of 110g $CO_{2\,eq}$ and requires 328Wh of energy, including mining. Also, the materials used in the cathode contains toxic metals which create ethical concerns due to in health risks and bad work conditions in the mining industry (Danish Energy Agency, 2020).

The expected lifetime often depends on using the battery within its most efficient span. According to Danish Energy Agency (2020), the state of charge should be kept above at least 10% to not rapidly degrade the battery's total energy capacity. Wikner & Thriringer (2018) complements with that Li-ion batteries should avoid a high state of charge level to prolong their lifetime.

The battery system roundtrip efficiency is defined as the losses on the conversion path through the battery. The Danish Energy Agency (2020) presents a summary of the grid-scale battery storage capacity available today, see Table 7.

*Table 7, Li-ion battery technical data.*
*Source: Danish Energy Agency (2020)*

| ***Li-Ion battery technical data*** | |
|---|---|
| **Max storage capacity for one unit (MWh)** | 6 |
| **Max output capacity for one unit (MW)** | 18 |
| **Max input capacity for one unit (MW)** | 3 |
| **Charge efficiency (%)** | 98 |
| **Discharge efficiency (%)** | 97 |
| **Lifetime (Years & Cycles)** | 20 & 14 000 |
| **Variable O&M (€2015/MWh)** | 2 |
| **Specific investment (M€2015/MWh)** | 1.042 |

#### 2.7.2.1 Utilisation of Li-ion Battery

It is important to specify the reason for the implementation of battery storage since the control strategy varies between the different measures possible. The repayment period for the installation is also very long, and various areas of use need to be combined to motivate the initial investment. Life cycle assessments are also crucial because the production and recycling of batteries leads to environmental impacts (Energikontor Sydost, 2021).

Utilisation of battery as energy storage reduce a buildings power demand during a given time. It reveals the possibility for a smaller fuse, which lead to lowered electricity grid costs. If the battery is combined with linking between multiple buildings, it also leads to further grid benefits and system services. The Danish Energy Agency (2021) refers to batteries as a promising technology to enable energy transition and provide additional opportunities to renewable integration with a wide range of applications such as: peak load shaving, transmission congestion relief and frequency regulation.

Lowered electricity cost is possible through strategic purchasing of electricity when the price is low and utilising the charged-up electricity when the price increase. The economics regarding battery installations solely for this purpose has shown non-profitable. However, with increased variations in electricity prices and the declining investment cost for batteries, the future can present a different result (Energikontor Sydost, 2021).

### 2.7.3 Photovoltaic Panels

Photovoltaic (PV) panels convert solar energy in the form of sunlight into electric energy. Each solar panel, or solar module, consists of many PV cells, which typically do not produce more than one or two watts each. Several connected panels create a solar array and increase the total power output.

To utilise solar energy from photovoltaics, they need to be included in a system, which also consists of mounting structures and components transforming the electricity into the desired current form (U.S. Department of Energy, n.d.).

The energy output of a solar panel is highly dependent on the irradiation intensity, operational angle, module temperature, and solar radiation spectral distribution. Therefore, the classification is based upon a set of laboratory standard test conditions, which corresponds to irradiation of 1000W/$m^2$ perpendicular to the panel surface and 25°C cell temperature (Danish Energy Agency, 2020).

The power output for a horizontal panel depends on the hourly global horizontal irradiance (GHI) per $m^2$ for a defined location multiplied by panel efficiency, see Equation 7 (Hornsberg & Bowden, 2019). The global horizontal irradiance is defined as the total solar irradiation on a horizontal plane. GHI is the combination of direct normal irradiance and diffuse horizontal irradiance. A panel tilted toward the sun's direction increases the irradiation to the panel surface.

*Equation 7, Solar power per square meter for a horizontal panel.*

$$\frac{W}{m^2} = GHI * \eta_{PV}$$

Photovoltaic panels have great properties for the transition to a climate-neutral energy system. In 2018 commercial buildings were together with residential buildings the two largest market segments of the technology. Reindl & Palm (2021) present some barriers for non-residential buildings in the Swedish taxation rules regarding electricity production. If peak production hours surpass 500kW, it is no longer tax-free to consume the locally produced electricity. This becomes a limitation for property owners with a large capacity of solar panel installations within their building stock. The everchanging economic subsidies also make accurate investment predictions difficult and hamper expansion of solar panel utilisation.

# 3 Method

The modelling scenarios were constructed with specific parameter data changes in IDA ICE or MATLAB to represent a technical action. Each scenario will in this section be described in terms of change in relation to the Reference Case. The technical actions were also evaluated based on literature reviews to answer the research question about energy system impact with wide-scale utilisation and its implications in a current or future energy system.

## 3.1 Modelling Reference Case

The method to create the model was based on office input data from Sveby (2013), BBR and BEN2 guidelines. All input data to the Reference Case model creation is presented in Chapter 4. The energy performance of the Reference Case was evaluated by the primary energy number (Equation 5), the specific heating and cooling demand, power peaks, and the average overall heat transfer coefficient $U_{average}$ (Equation 6). The heat load variations were expressed using the annual relative daily heat load variations presented by Gadd and Werner (2013), seen in Equation 8.

*Equation 8, Annual relative daily variation.*

$$G_a = \frac{\frac{1}{2}\sum_{h=1,d=1}^{8760,365}|P_h - P_d|}{P_a * 8760} * 100\%$$

The district heating, district cooling, and electricity price models, described in Section 2, were directly implemented with the energy consumption patterns to decide the operating costs and act as a reference in monetary values to the model scenarios. All heating and cooling demand in the building was fulfilled by district heating and district cooling. The volumetric flow was assumed to constitute 10% of the total operating costs for district cooling, as presented by Gothenburg Energy (n.d.). The return temperature to the district heating system was assumed to not affect the operating cost. For every price model, all sales tax and energy tax were excluded.

## 3.2 Modelling scenarios

Each technical action coupled with the heating and cooling system of the office building went through a yearly parameter investigation in IDA ICE. The comparison to the Reference Case was performed by studying the effect of energy peaks, specific heating/cooling demand, energy demand, operating costs, and annual relative daily heat load variations. The solar panel installation and battery storage model scenarios were annually simulated individually and as a combined scenario by MILP modelling in MATLAB.

### 3.2.1 Increased envelope insulation

To study the effects of increased envelope insulation the U-values of the exterior walls and roof were decreased. The reduction magnitude was suggested by GICON from a reference project as the currently best practice available. The new U-value studied for the exterior walls and roof was 0.13 W/m$^2$ K and 0.078 W/m$^2$ K respectively with a 30% increase for thermal bridges included. The original values from the Reference Case can be found in Table 11. The comparison to the Reference Case also included the average overall heat transfer coefficient.

### 3.2.2 Window exchange

To analyse the impact of a window exchange, the U-value of all windows in the IDA ICE model was changed to 0.78 $W/m^2 K$. All other parameters of the individual window were maintained constant. The overall heat transfer coefficient was chosen from a high-performance window presented by Pilkington’s window catalogue (2021) with sun protection and energy-saving functionality. The comparison to the Reference Case also included the average overall heat transfer coefficient.

### 3.2.3 External Blinds

To investigate the influence of external blind usage, the window g-factor was multiplied by 0.14 and all other values remained constant. The chosen blind was a default blind in IDA ICE database and was applied to all windows connected to ambient air. Each blind was controlled by the sunlight reflecting on the corresponding window.

### 3.2.4 Global temperature adjustment

The global temperature adjustment (GTA) was simulated by separately altering the heating and cooling setpoint for all modelled zones. The heating setpoint was reduced to a constant 20°C and the cooling setpoint increased to 26°C, from SVEBY (2013) as the minimum and maximum recommended temperature for office indoor climate.

### 3.2.5 Combined Measures

The technical actions were combined to examine the Reference Case to a “best available building envelope” case. The used technical actions in the combined measures scenario were the increased envelope insulation, windows exchange, and the use of sun controlled external blinds during the summer period. The comparison to the Reference Case also included the average overall heat transfer coefficient.

### 3.2.6 Energy Storage – Li-Ion Battery

Battery storage implementation was made with two different control strategies, *load shifting* and *peak shaving*, see Figure 6 for visual description and below for application technique. Input parameters consisted of the total electricity load curve generated by the Reference Case, the regional (SE3) electricity spot price of 2021 provided by Nord Pool, and Gothenburg Energy’s local electricity grid cost. A minimum cost objective function was applied in MATLAB through MILP variable optimisation to investigate the different battery strategies. The grid power cost was not minimised but instead added to the electricity cost from the objective function. Each load management strategy was simulated with five different battery storage capacities in the range of 300 – 1500kWh. Note that the charging and discharging capacity was kept as a constraint with equal relation to the battery size. The battery technical data can be found in Table 7.

*Load shifting* was used to evaluate the potential benefit for controlling the netload based on electricity spot price. Load shifting, in this case, does not result in complete peak removal, but only a load shift in time during high electricity price hours. The method was constrained to avoid higher peaks than original simulated demand in the Reference Case, which was expressed as a potential congestion risk from a local electricity grid perspective during the interview with GENAB. General balance constraints are described in Section 3.2.6.1 and complementary variables and constraints can be found in Appendix D.

*Peak shaving* used the battery capacity to fully "shave" electricity peak load as a measure to reduce power cost. The power cost for current over 63A from Gothenburg Energy is based upon the highest peak for each month. Therefore, the aim was to reduce monthly peak height as much as possible for a given battery size. General balance and constraints are described in Section 3.2.6.2, and complementary variables and constraints can be found in Appendix D.

#### 3.2.6.1 MATLAB Modelling Load Shifting

The minimum cost objective function for the load shifting strategy is described in Equation 9 as subject to the netload and battery charging pattern. The electricity balance constraints can be seen in Equation 10, where the $Netload_t$ describes the total need for purchased electricity at a given hour t. The battery was implemented with parameters and variable constraints following the Danish Energy Agency summary seen in Section 2.7.2. To avoid increased power peaks in comparison to the Reference Case, a subset was created including all hours for each month to constraint the amount of purchased electricity, see Equation 12. The battery state of charge over time ($SOC_t$) was an optimisation variable that accounted for battery efficiencies, see Equation 11. To ensure the life expectancy of 20 years and 14000 cycles, the battery $SOC_t$ was constrained within the span of 20-90% of max capacity.

*Equation 9, Objective function for operation cost minimisation.*

$$TC_{min} = \sum_t Netload_t * P_{el,t} + O\&M_{bat} * Ch_t$$

*Equation 10, Building electricity balance.*

$$Netload_t - D_t - Ch_t + Dch_t = 0$$

*Equation 11, Battery state of charge with charging and discharging efficiencies.*

$$SOC_t - SOC_{t-1} - Ch_t * E_c + Dch_t * \frac{1}{E_d} = 0$$

*Equation 12, Peak constraint*

$$Netload_{t,m} \leq Max\ D_m$$

#### 3.2.6.2 MATLAB Modelling Peak Shaving

The objective function for peak shaving was to accomplish a minimised monthly netload peak, Equation 13. To accomplish peak shaving, an optimisation variable factor was added to the peak constraint, see Equation 14. Note that the objective function for peak shaving did not rely on electricity price nor variable battery cost when minimising peak load. Therefore, the peak shaving strategy was a two-step optimisation program to first accomplish the minimum monthly peak load factor, $Shave_m$, and remaining battery capacity to use the load shifting objective function in a second step, see Equation 9.

*Equation 13, Objective function for monthly minimum netload peak.*

$$PeakLoad_{min} = \sum_{m} Shave_{m}$$

*Equation 14, Inequality constraint to accomplish lowest monthly peak load.*

$$Netload_{t,m} \leq Shave_{bat,m} * Max\ D_{m}$$

### 3.2.7 Solar Panel Installation

The available area to install photovoltaic panels was assumed to be 1000 $m^2$, to considering the roof available for ventilation fan rooms, other installations, and maintenance work. The PV installation aimed to utilise the produced electricity to meet building demand rather than selling to grid and the tilt angle 45° was therefore chosen to match the electricity generation and demand curve. The panel efficiency, $\eta_{PV}$, was set to 19%.

The power output possible per square meter was based on SMHI meteorological data from 2021 with an hourly resolution of the global horizontal irradiance in Gothenburg. The geographical location point used was (57.6715°, 11.9575°) with a height above the mean sea level of 104 meters. When calculating the electricity generated with panel tilt the GHI was divided by cos (45°) to model a larger PV area towards the sun. However, utilising this formula will overestimate the diffuse horizontal irradiation which is independent of panel tilt. Therefore, to receive a more realistic electric power output the hourly generated power was reduced by 20%, based on reference projects performed by GICON.

#### 3.2.7.1 MATLAB PV implementation with battery storage

When combining the solar panel installation with the battery storage, the solar produced energy was added to Equation 10. The building electricity balance was changed to an inequality constraint, to allow for negative netload when solar energy generation surpassed Reference Case demand, see Equation 14. The electricity that surpassed the building demand was used to charge the battery or sold to the grid at spot price with the addition of 0.03SEK/kWh, the current local grid compensation from Gothenburg Energy.

*Equation 14, Solar Panel building electricity inequality.*

$$Netload_{t} - D_{t} + PVgen_{t} - Ch_{t} + Dch_{t} \geq 0$$

### 3.2.8 Sensitivity Analysis

To study the result robustness regarding the heating/cooling system, the occupant and equipment density were doubled per square meter tempered area. The goal of this sensitivity analysis was to understand how the total energy consumption and peaks were influenced by increased office productivity.

The battery results were tested with different electricity price scenarios. The prices were received from Nord Pool and two different price regions were tested, SE1 and Denmark East. SE1 have less intermittent electricity price due to the high penetration of low-cost production units, wind power and large regulating hydropower, often with a large surplus to export. (The Swedish Energy Markets Inspectorate, n.d.). The other scenario was designed to simulate higher electricity price volatility. Denmark East is largely powered by wind with conventional power plants as base power. In conditions with low wind power production, Denmark East is dependent on trade from other countries (Danish Energy Agency, 2022). Less predictable total power production due to the system configuration induces more price variations in this region.

The battery control strategy sensitivity in relation to the local electricity grid price model was analysed by implementing a fully power-based price model design. which has already been adopted by another Swedish local grid owner. The power cost is based on seasonal power tariffs. Peak shaving and load shifting were analysed in the same way as earlier described but the power cost was doubled during the period between November to March and the transferring cost was removed.

## 3.3 Interviews

The overarching goal of the qualitative interviews was to understand the local stakeholder landscape within the energy sector and its relation to the building sector. The main questions asked were to investigate of how peak load events affect different stakeholders. A semi-structured interview format was constructed to allow the interviewees to express themselves more freely (Trost, 2010).

The questions were sent to the interviews by e-mail at least a week before the scheduled interview date. By presenting the questions before the time of the interview, it may allow for a more comprehensive interview quality (Trost, 2010). In Appendix A, the questions that are covered in the interviews are presented. The questions were formed to fit the interviewee's position of work and conducted in Swedish.

Two technical managers within the building sector, as well as one operation engineer within the local electricity grid were interviewed, see Table 8. All the interviews were conducted and recorded with Microsoft Teams and measured approximately 30 minutes each. The people interviewed all accepted that the interview was recorded.

*Table 8, Interview date, information of the interview subject's role and organisation.*

| ***Date*** | ***Name and Job Title*** | ***Organization*** |
|---|---|---|
| ***Interview 1 – 18/2 - 2022*** | *Andreas Hassel – Technical Manager* | *Platzer AB – Property Owner* |
| ***Interview 2 – 4/3 – 2022*** | *Ann Helen Ejdervik – Operation Engineer* | *GENAB – Local grid Owner* |
| ***Interview 3 -14/3 – 2022*** | *Anders Björling – Technical Manager Nationally* | *Castellum AB – Property Owner* |

# 4 Model Creation IDA ICE

The data used to create the Reference Case model in IDE ICE is presented in this chapter. The model is described in two sections: building characteristics and operational input. From floor plan drawings of an office building, a generalised model of an office was constructed within the IDA ICE sketching tool. The climate data file in this report was a generated data file from SMHI based on the years 1981 – 2010 in Gothenburg promoted by Sveby (n.d.), which include wind conditions, temperature, and solar irradiation (coordinates: 57.6715°, 11.9575°) 104 meter above sea level, with an hourly resolution.

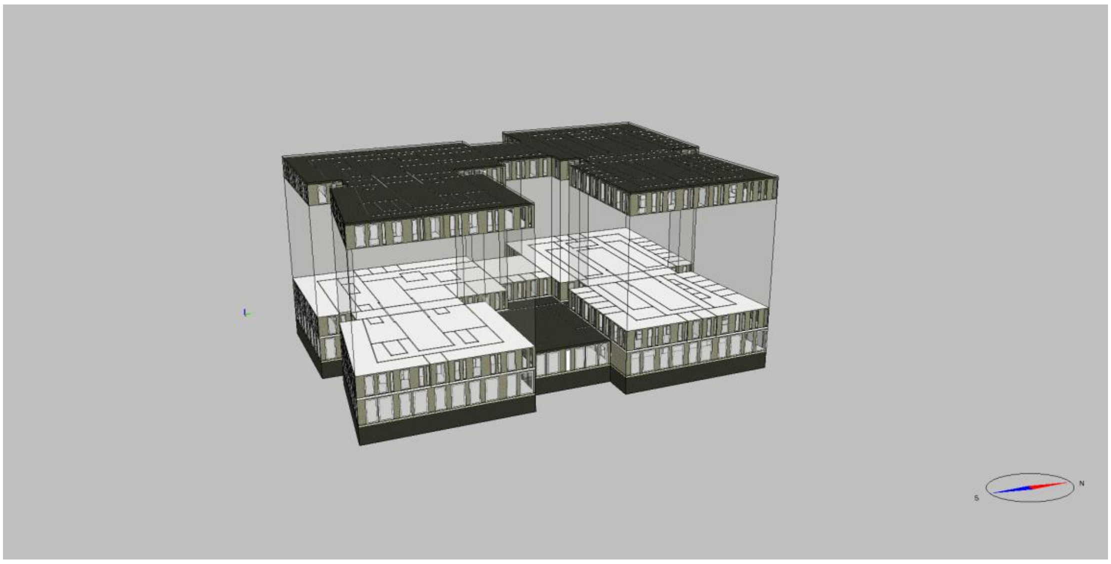


*Figure 8, Reference Case model visualisation from IDA ICE.*

## 4.1 Building characteristics

The model consists of eight levels over four bodies connected with pathways, see Figure 9. The model consists of three floorplan characteristics included in the tempered area, identified as entrance plan, standard plan, and top floor. These three have unique properties in terms of their connection to ambient air and the garage. The standard plan constitutes six out of eight levels. The entrance floor includes an entrance zone, see Table 10 for a description of each modelled zone and a visualisation of the floor plan layout, see Figure 10. The modelled garage stretches beneath the entire building as a single model zone.

*Table 9. Building characteristics for IDA ICE Reference Case.*

| Building Characteristics | |
|---|---|
| ***Total height*** | *29.4 meter* |
| ***Number of floors*** | *8* |
| ***Floor height*** | *3.6 meters (First level 4.2 meters)* |
| ***Total tempered area*** | *22671 $m^2$* |
| ***Floorplan area:*** | *2805 $m^2$ (First level 3126 $m^2$)* |
| ***Glass fraction:*** | *26% of envelope – 52% of façade* |
| ***Number of zones*** | *189* |

*Table 10, Zone description for each floor plan.*

| Name | | Description |
|---|---|---|
| ***Façade office*** | | *An office room with one or more external walls.* |
| ***Cell office / Conference*** | | *An office room where all walls are internal walls.* |
| ***Corridor*** | | *A pathway that is meant to connect the buildings different areas. Connected to each other with openings.* |
| ***Open office*** | | *Area in the building envelope that is connected to other areas with corridors. The open office consists both of internal and external walls.* |
| ***Core*** | | *The core is an area where elevators, staircase, kitchens, toilets, and storage.* |
| ***Entrance*** | | *Only located on the first level and is removed from other floor plans.* |

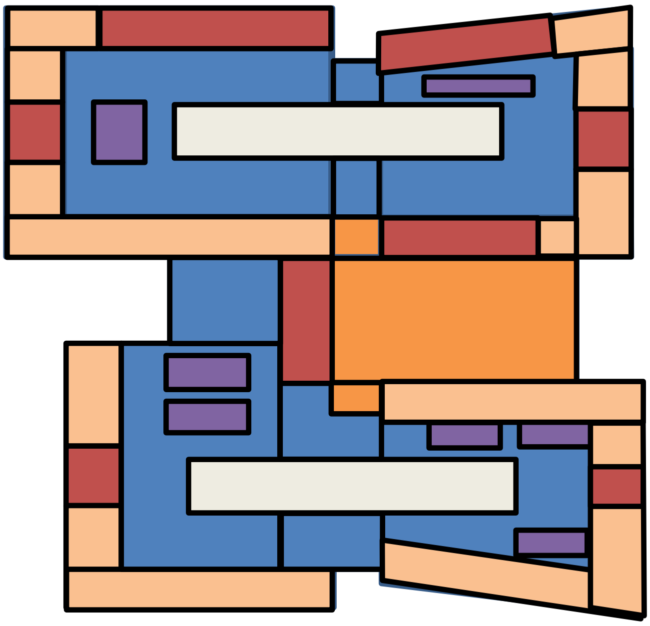


*Figure 9, Zone layout visualisation, see Table 10 for colour coding.*

Characteristics of the building parts, except windows, were only described in terms of their U-value with an added 30% of thermal transmittance to cover for thermal bridges. In Table 11, the overall heat transfer coefficients used in the Reference Case are listed with a brief description. Most of the values follow the recommendations from BBR, presented previously in Table 6. Some U-values were not described in BBR, these U-values were suggested by GICON based upon earlier projects of relative similarity. For entrance door and internal parts, the IDA ICE standards were used due to negligible impact on energy performance. The windows for the Reference Case used BBR recommendations for U-value and the g-value was based on Pilkington's (2021) energy-saving window. For all windows, an internal blind was installed with a g-value factor of 0.5. Note that the g-value and g-value factor are two different parameters.

Table 11, Overall heat transfer coefficients used in the Reference Case model, including thermal bridges.

| | U-value ($W/m^2K$) | Description |
|---|---|---|
| External wall | 0.234 | All walls in contact with outside air (BBR) |
| Internal wall | 1.707 | Connection between two zones (IDA standard) |
| Window | 1.56 | All windows (g-value: 0.43) |
| Roof | 0.169 | Horizontal roof (BBR) |
| Internal floor | 1.551 | Floor between two levels (IDA standard) |
| Entrance level floor | 0.195 | Connected to the garage's roof (GICON) |
| Garage wall | 0.39 | Wall connected to ground (GICON) |
| Garage floor | 0.26 | Floor connected to ground (GICON) |
| Inner door | 1.56 | Scheduled open during office hours (IDA standard) |
| Entrance door | 1.56 | Modelled entrance door (IDA standard) |

## 4.2 Operational input

An ideal heater and an ideal cooler were created for every zone, this was to ensure that the indoor temperature requirements were met for every time step. All energy supplied for heating and cooling purposes was provided by district heating and district cooling with an efficiency of 90%.

The heating setpoint was a variable setting with 22°C during occupied hours and 20°C during the remaining hours and the cooling setpoint set constant to 24.5°C. The indoor temperature was based on Sveby (2013) and within the Swedish Work Authority (2021) recommendations for indoor climate for offices with light clothing standards.

### 4.2.1 Ventilation

When designing the ventilation, all zones had equal supply and return airflow per square meter and the entire building was supported by an HRV Variable Air Volume (VAV) ventilation system. The specific fan power was $1.5 kW/m^3 s$ and was equally distributed between the supply and exhaust system. The heat recovery efficiency was 85%.

The minimum airflow during operational hours was set to $0.35 l/s\ m^2$, which according to Sveby (2013), is the required general ventilation. The supply air temperature was decided to 18°C which originates from 17°C due to pressure losses in the supply fan. The ventilation system was controlled by temperature, and the dimensioned airflows are presented in Table 12. Sveby (2013) recommended airflow that varied between 1.2 – 2.8 $l/s\ m^2\ A_{temp}$ depending on operational specifics. To accommodate a realistic value between air cooling and water cooling the maximum airflow was set by iterating simulations and GICON recommendations.

Table 12, Minimum and maximum air flows for the HRV VAV ventilation system.

| | Maximum air flow (VAV) | Minimum air flow (VAV) |
|---|---|---|
| Office area | $1.40\ l/s\ m^2$ | $0.35\ l/s\ m^2$ |

### 4.2.2 Occupancy

To implement realistic patterns for office equipment usage, lighting, and climate control were based on the occupancy level. The occupancy was set to one person per $20m^2$ $A_{temp}$ (Sveby, 2013) and simulated with a ramping function for the natural time difference in workers' arrival/departure. The function implements a linear increase/decrease of occupants during the first and last two working hours with Sveby (2013) suggesting 70% as normal occupancy. The ramping function was mimicked in the equipment schedule. Facility lighting and electricity to maintain servers were assumed crucial for building functionality and therefore scheduled to always run at rated capacity, see Table 13. Sveby (2013) highlights that the electricity consumption of office equipment is around 15% outside office hours, which was also included in the model. The occupancy schedule was assumed to reoccur throughout the year. The total hours of occupancy were 2115 in accordance with BEN2.

*Table 13, Schedule descriptions for occupants, lighting, equipment, servers, and fans.*

| ***Schedules*** | |
|---|---|
| ***Occupants*** | *07:00 – 17:10 (70% & 15%)* |
| ***Lighting tenant*** | *07:00 – 17:00 (100% & 15%)* |
| ***Lighting facility*** | *Always on* |
| ***Equipment*** | *07:00 – 17:10 (70% & 15%)* |
| ***Servers*** | *Always on* |
| ***Fans*** | *07:00 – 19:00 (100% & 15%, Temp. cont.)* |

### 4.2.3 Electricity

It was assumed that the entire office building shared one electricity meter with a fuse larger than 63A. The zones were modelled with various equipment installed. The lighting required for essential facility functions and tenant operation was modelled separately, see Table 13 for schedule and Appendix B for power requirement. For zone-specific equipment power usage see Appendix B Table B1.

### 4.2.4 Losses and additional energy consumption

The energy losses that were accounted for by adding the mean loss throughout the year are listed in Table 14. Diurnal variations regarding these losses and consumption patterns were therefore not considered. The hot water circulation loss was estimated by assuming an energy loss of 6W per meter and an estimated piping length of 700 meters inside the building boundary. In the model, the additional losses and energy consumption added were assumed to not contribute to the internal heat gains. However, they were included in the demand and operating costs. The office building was assumed to contain six elevators with a yearly electricity usage of $5.5MWh_{el}$/elevator (Sveby, 2013).

*Table 14, Losses and/or additional energy consumption per Atemp that IDA does not consider.*

| Losses & Additional energy consumption | |
|---|---|
| **Natural ventilation losses (DH)** | 4 $kWh/m^2$ $A_{temp}$ (BEN2) |
| **HWC losses (DH)** | 1.65 $kWh/m^2$ $A_{temp}$ (GICON) (700m piping) |
| **Hot water usage (DH)** | 2 $kWh/m^2$ $A_{temp}$ (BEN2) |
| **Elevators (Electricity)** | 1.45 $kWh/m^2$ $A_{temp}$ (Sveby) (6 Elevators) |
| **Circulation pumps (Electricity)** | 3.35 $kWh/m^2$ $A_{temp}$ (GICON) |

# 5 Summary of Interviews

This chapter consists of an interview summary to identify the current stakeholder landscape. The four different areas that are discussed cover the overlapping interests. Each section within this chapter will describe the actual area and summarise the viewpoints analysed. The questions asked in the interviews are listed in Appendix A.

### 5.1.1 Status in Gothenburg for the electricity congestion

During the interview conducted with GENAB, the local grid owner in Gothenburg, it was expressed that the local grid does not currently experience a power shortage or insufficient transmission capacity and refers to SWECO‘s (2020) mapping of Sweden’s regional grid investments. Increased electrification will present future challenges where the conventional strategy for supply and demand needs to change. At the same time, it was clear that the responsibility for guiding this electrification should not fall on the energy end-users.

The property owners indicate that the more intermittent electricity prices have resulted in significantly more expenses for electricity consumption. Some prerequisites for electricity connection in the central city of Gothenburg have changed. I.e., connecting a newly built building to a higher voltage level grid was a solution to avoid local grid congestion. The introduction of electric vehicle (EV) charging in existing buildings has been a challenge. However, with phase balancing of electricity, the problem has momentarily been solved. In older commercial buildings, electric cooling has and will be replaced with district cooling, if possible, to leave the potential for EV charging.

### 5.1.2 Current electricity price model and a future perspective

GENAB works to reduce the risk of an eventual power capacity shortage. Until 2027, GENAB is switching out old cables in the local grid to new larger ones with higher transmission capacity. The energy price model has a power tariff depending on the size of the fuse installed and peak load consumption. Future development of the energy price models tends to increase the percentage of the cost based on power, which creates an economic incentive to reduce peak power for end-users. In January 2022, GENAB started a pilot project, a local flexibility market named Effekthandel Väst. The project includes around 300 units, and its minimum regulatory power is 0.1 MW. The local grid owner, one day ahead, advises the participants to sell or buy power to stabilize the grid with economic compensation.

The increased power tariffs by the local grid owners are now impacting the property owners' technical energy decisions. Five Swedish local grid owners and Castellum designed a power strategy highlighting twelve actions to reduce peak load. It focuses on power optimization to benefit the electricity grid and the property owners.

### 5.1.3 Potential for commercial buildings to the local electricity grid

Peak loads in the Gothenburg local grid occur during the coldest outdoor temperatures, mainly in the morning and afternoon. Efficient measures to handle the peak loads during these hours are thermal energy storage and the use of batteries. However, batteries must be dimensioned to not introduce new peaks in the system for an overall beneficial application. Commercial buildings can also serve a purpose in the future with local flex markets, either with li-ion battery storage or if equipped with heating from electricity. Vehicle to grid is also a strategy expected to have great potential for load levelling and electricity congestion relief. Battery storage installations today are prevented by the lack of economic value, but the future potential is possible. Another comment was that batteries as a resource is limited and possibly serve a better primary purpose in other sectors.

The property owners emphasise the importance of good communication between local grid owners and property owners with a large building stock. From a future perspective, the communication and collaboration between property owners and local grid owners need improvements. Property owners need to be open with solutions that are available from their viewpoint, likewise for the grid owners. Property owners have the tools to be a part of local-flex markets because they can regulate their electricity consumption. Some examples were either delaying the start of the ventilation unit or installing a dynamic power monitor.

### 5.1.4 Use of heating and cooling in buildings

Platzer provided an example of one of their energy optimisation strategies, “green leases”, where tenants cooperate with the property owner to reduce energy consumption and operating costs. The green leases are currently not considering peak loads. Castellum has considered altering the global temperature setpoint of the heating or cooling and restraining their max power to decrease the stress of the energy networks. There is also an economic factor for property to reduce power requirements due peak-based power tariffs. For maintenance and renovation of the current building stock, the measures taken for the building envelope primarily focus on energy conservation. However, it was mentioned that the envelope updates require high investment costs and are not a simple operation in relation to the reduction of operating expenses.

# 6 Results

In this chapter, the results from all model scenarios described in Chapter 3 are presented with tables and graphs. Similar to the rest of the report structure, the heating/cooling system is decoupled from the electricity system in the result presentation.

## 6.1 Reference Case simulation

The presented data in this section describes the simulated Reference Case with a summary of key figures that can be seen in Table 15. The annual demand for heating and cooling was highly dependent on the season. In the Reference Case, cooling energy was almost exclusively utilised during summer, when the energy peaks occurred due to high outdoor temperatures. Heating was mainly needed in the winter and has diurnal variations based on indoor temperature, occupancy, and equipment schedules. Presented with an hourly resolution in Figure 11 is the annual demand for heating and cooling, including heat transfer efficiencies.

Electricity consumption in July, illustrated in Figure 12, showcases variations in electricity consumption for a month. The variations occurred in regular diurnal patterns following equipment, HVAC, and lighting utilisation. The annual simulation follows a similar electricity pattern with a slight monthly difference in peak load.

*Table 15, Summary of key energy figures obtained from the Reference Case model.*

| Summary | Max (kW) | W/m2 | Energy (MWh) | kWh/m2 |
|---|---|---|---|---|
| District Heating | 676 | 30 | 370 | 16 |
| District Cooling | 780 | 34 | 209 | 9 |
| Total Electricity Consumption | 256 | 11 | 982 | 43 |
| Electricity Property | 57 | 3 | 280 | 12 |
| Primary Energy Number | 40 kWh/m$^2$ A temp a year | | | |
| U-average | 0.55 W/ m$^2$K | | | |
| $G_a$ | 21% | | | |

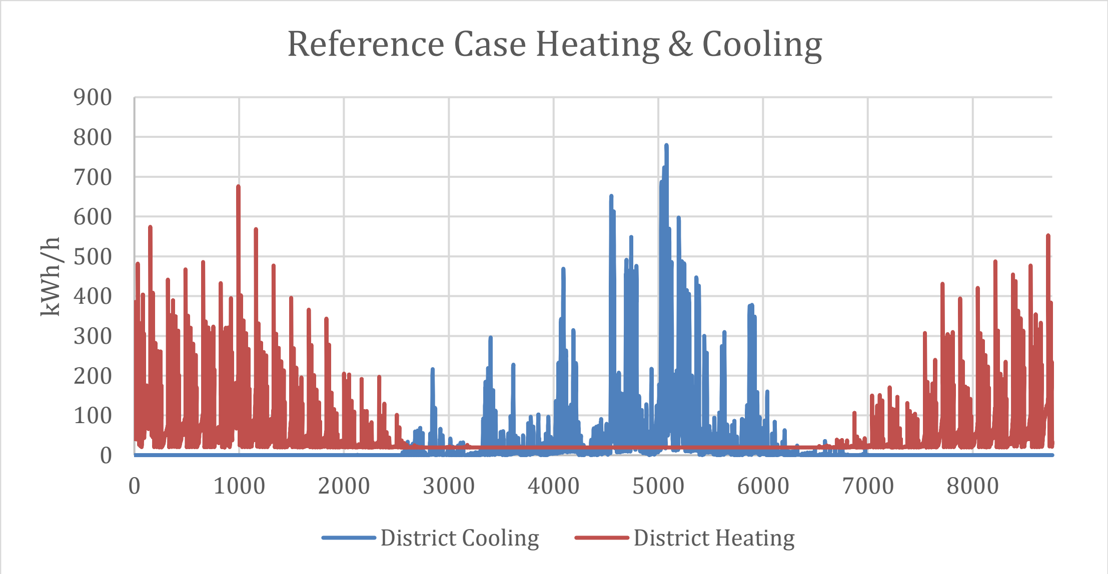



*Figure 10, Hourly load for DH & DC for heating and cooling in the Reference Case simulation.*

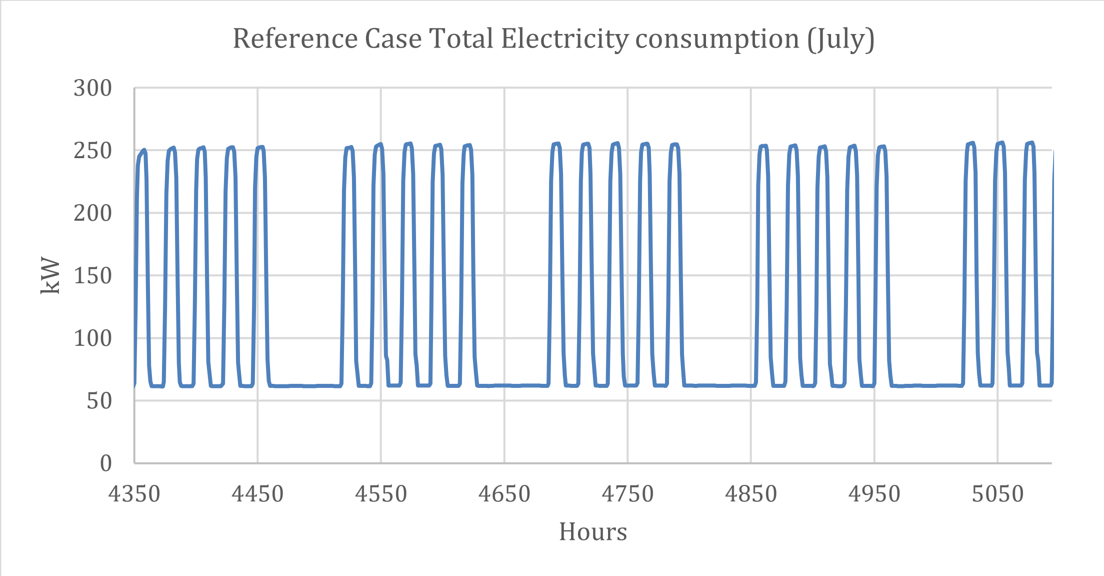



*Figure 11, Electricity demand curve for July from the Reference Case simulation.*

### 6.1.1 Operating Costs Reference Case

The operating cost was based on the Reference Case consumption pattern and the price models presented separately in Chapter 2. The power cost and fixed cost for district cooling were derived from the maximum peak in Table 15. The district heating power cost and fixed cost were based on the three diurnal peak averages (TDPA) displayed in Figure 13. The price dimensioning monthly electricity peaks can be observed as the blue curve in Figure 16.

In Table 16, the operating costs for the different energy types are shown, and the total operating cost over the simulated year was 1802 kSEK.

*Table 16, Operating cost for Reference Case.*

| | *Electricity* | *District Heating* | *District Cooling* |
|---|---|---|---|
| ***Energy cost*** | *828* | *145* | *59* |
| ***Power cost*** | *144* | *145* | *308* |
| ***Fixed cost*** | *7* | *14* | *100* |
| ***Flow*** | | | *52* |
| ***Total*** | *979* | *304* | *519* |
| ***% Of Total*** | *54%* | *17%* | *29%* |

## 6.2 Heating and cooling results

The following sections will present the results from studying parameter changes in the IDA ICE model scenarios.

### 6.2.1 Heating and cooling model scenarios result graphs

This section presents the result from simulations in graphs with evaluated parameters displayed in bars for comparing the technical actions. In Figures 13 & 14, the dark blue bars represent the maximum energy peak experienced due to heating or cooling.

Purple bars represent the total energy used annually for each investigated scenario. In Figure 13, the teal bars are added to clarify the power cost dimensioning TDPA for district heating. The following sections will refer to these two figures for result interpretation regarding load comparisons.

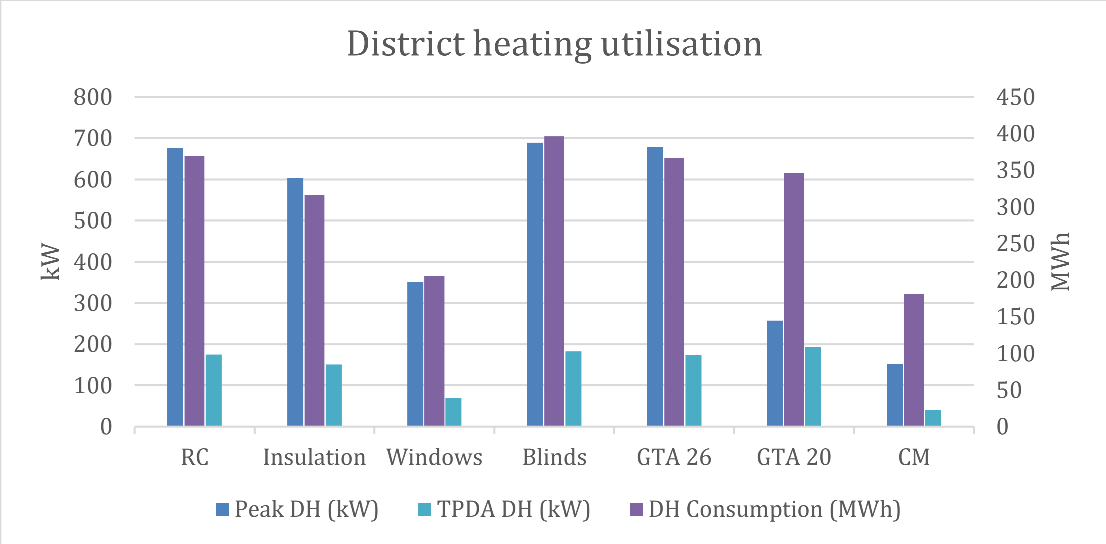



*Figure 12, Model scenario simulations for District Heating utilisation. RC = Reference Case, CM = Combined Measures.*

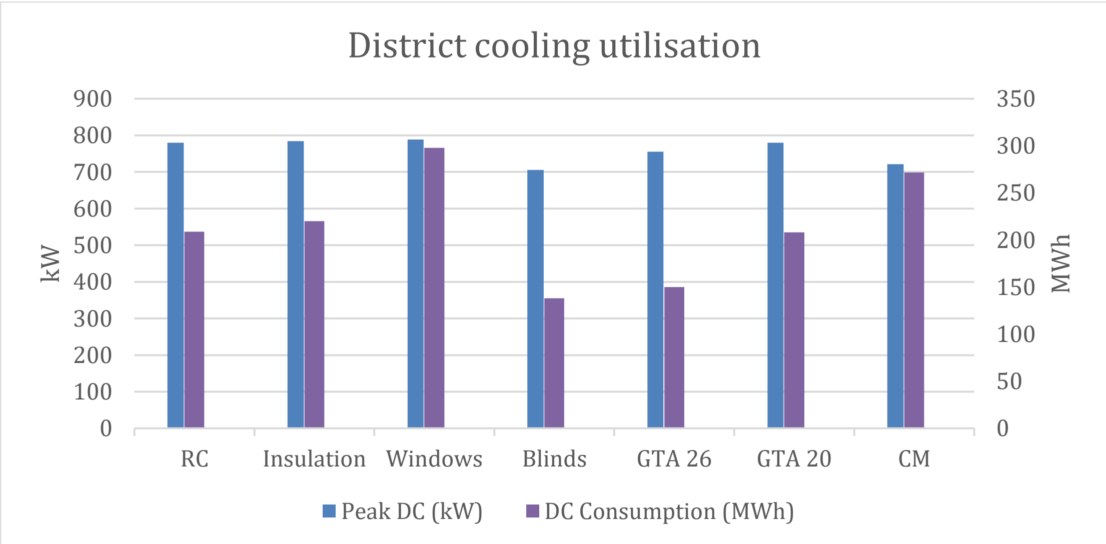



*Figure 13, Model scenario simulations for District Cooling utilisation. RC = Reference Case, CM = Combined Measures.*

All the load management measures are in Figure 15 presented in stacked bars for total operating cost based on district heating and district cooling in the modelled building. The total cost for heating includes the red and blue bars, and the cooling consists of the green and purple bars. The fixed cost is included in the power cost for both cases, but the flow cost for district cooling is excluded.

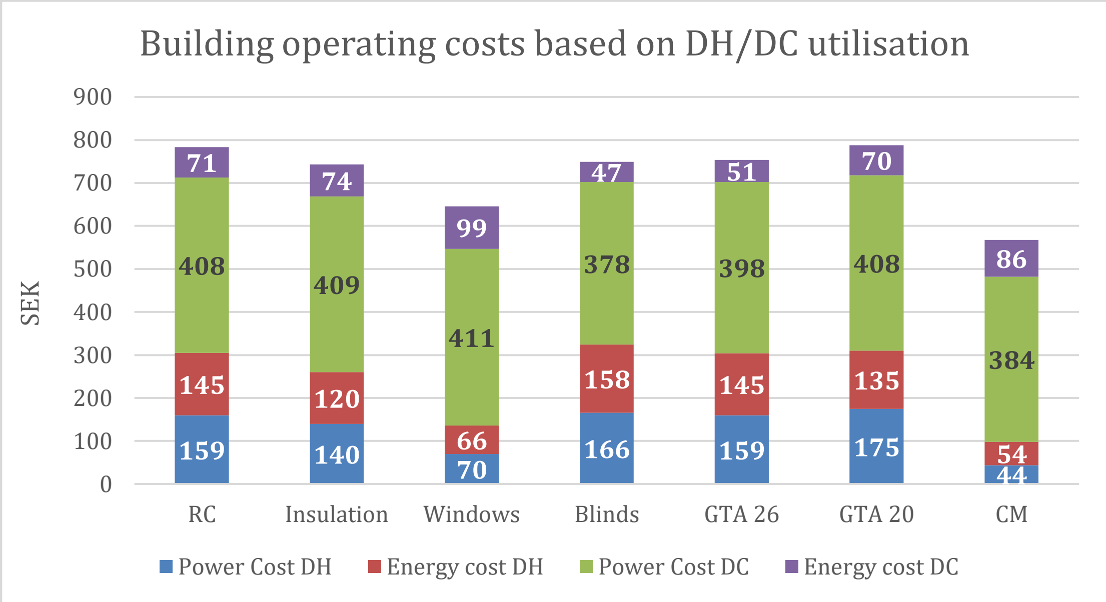



*Figure 14, Building operating costs based on district heating and district cooling utilisation for each model scenario. Fixed costs included in Power Cost. Flow cost excluded for DC.*

### 6.2.2 Increased envelope insulation

With increased envelope insulation, the average overall heat transfer coefficient was decreased to 0.50 W/m$^2$K. Increased insulation showed a reduction in total heat used and peak load, see Figure 13. Lowered heat transmission through the building envelope correlates with building thermal inertia and reduced need for supplied heat. Additionally, the annual relative daily heat load variations were reduced by 2%. As shown in Figure 14, there was an annual increase in district cooling utilisation, originating from the summer and autumn/spring. A reduced average overall heat transfer coefficient increased cooling demand due to internal heat gains. The yearly distribution of energy consumption can be seen in Appendix E, Figure E5.

The reduction of heating operating costs consisted of a lower TDPA and less energy purchased. The modelling scenario showed a marginal increase in cooling cost. Since the power cost for DC is derived from the highest peak that occurs in the summer, the power increase during autumn/spring did not affect the power tariff. The DH/DC operating cost was decreased by 5%.

### 6.2.3 Window exchange

The total window area constituted 26% of the envelope area and accounted for the highest thermal transmission loss in the Reference Case. The window exchange resulted in an average overall heat transfer coefficient of 0.34 W/m$^2$K, and a substantial reduction in TDPA and heat consumption, see Figure 13. The daily relative annual heat load variation was reduced to 7%, a decrease of 14%. An increase in cooling energy and power consumption originated from more accumulated heat in the building and required more heat removal.

The window exchange simulation resulted in a lower heating cost but an increased cooling cost. However, the total expenses for heating and cooling were reduced by 17%, see Figure 15. The annual load curves for heating and cooling can be found in Appendix E, Figure E2.

### 6.2.4 External Blinds

The use of sun-controlled external blinds that reduce the system g-value for all windows resulted in the most reduction for cooling energy peaks and consumption, shown in Figure 14. Additionally, this technical action creates higher heating energy peaks during the heating periods, as shown in Figure 13. Also showcased by 1% increased annual relative heat load variation. External blind utilisation for managing peak load needed seasonal planning since solar heat was desired during colder seasons.

The power tariff, which was the majority of the total operating cost, was reduced see Figure 15. Further, a large portion of the district cooling cost is fixed and was not affected by the decreased need for cooling power. The decrease in district cooling cost exceeded the district heating expenses with a total reduction of operating cost by 4%.

### 6.2.5 Global Temperature Adjustment – Heating setpoint 20°C

Figure 13 shows that a reduced global heating setpoint significantly reduced the maximum peak load for heating and decreased heat load variations by 9%. However, an increased price-setting TDPA resulted in no reduced power costs. As presented in Figure 15, it had some effect on the total consumption of district heating. However, even though the amount of heat was reduced, it was outweighed by the increased power tariff. This modelling scenario showed a negligible effect on the cooling loads and cost, see Figure 14. The DH/DC operating cost did barely deviate from the Reference Case.

Reducing the temperature below 21°C is currently not a recommended action in office buildings, according to the Swedish Work Authority (2021), due to the decreased satisfaction of indoor climate. Therefore, it is not considered a permanent action but can act as a temporary measure within the regulation parameters presented in BBR, where a maximum of 80 work hours that deviates from recommended indoor temperature is allowed.

### 6.2.6 Global Temperature Adjustment – Cooling setpoint 26°C

Increased cooling setpoint to 26°C reduced the cooling demand and maximum power peak shown in Figure 14. An additional effect was a 1% reduction of daily relative annual heat load variations during the spring/autumn when more heat was allowed to accumulate in the building during the day.

The technical action primarily reduced energy consumption, which was only a minor part of the district cooling costs. It also indicated a lower district heating usage during the autumn/spring and allowed for a 4% reduction in heating and cooling cost operating costs.

The indoor temperature is not recommended to exceed 25°C to be of satisfactory level in an office building, according to the Swedish Work Authority. An adjustment of the global indoor temperature should be temporary with the same reasoning as for decreased heating setpoint.

### 6.2.7 Combined Measures

The effects of implementing the model scenarios: envelope insulation, external blinds, and window exchange are explained in this section. The combination resulted in an average overall heat transfer coefficient of 0.29 W/ $m^2$K. There was a reduction in the power peaks of heating and cooling, the energy demand for heating was reduced, but the cooling demand increased. Due to the low heat demand, the annual relative daily heat load variations were only 2%. Increased building thermal inertia resulted in a more yearly spread utilisation of district cooling. The hourly heating and cooling load curve distribution are presented in Appendix E, Figure E1.

The reduction in operating costs primarily originated from reduced heating demand, see Figure 15. Even though the cooling demand increased over the year, the operating cost for district cooling was reduced due to the peak reduction. The overall heating and cooling expenses were reduced by 27%.

## 6.3 Electricity Results

The electricity results are divided into three different parts. The first is solar panel installation, the second on li-ion battery storage, and the last part is a combination of the two.

### 6.3.1 Solar Panel Installation

The highest electricity peak demand occurred mid-day during the summer and overlapped with the peak solar production. Allowing for high percentage utilisation of solar PV produced electricity. Electricity generated by the solar panels was always primarily used to fulfil the building demand before considering selling electricity to the grid. The total electricity produced by the solar panel system equalled 193 MWh, of which 92% was utilised within the building boundary. Displayed in Figure 16 are the monthly peaks in the Reference Case with the addition of solar PV installation. The monthly maximum peaks were reduced by an average of 8% but did not show peak shaving capacity during the winter. The peak reductions experienced were primarily due to diffuse horizontal irradiance and provided a steady flow of electricity independent of the weather. The total energy purchased was reduced by 18%, with a maximum power output from the PV system that equalled 190kW.

The total reduced cost for electricity purchased equalled 139.4 kSEK, excluding transferring taxes. The energy that could not be utilised directly was valued at 6.2 kSEK based on electricity spot price + 0.03SEK/kWh.

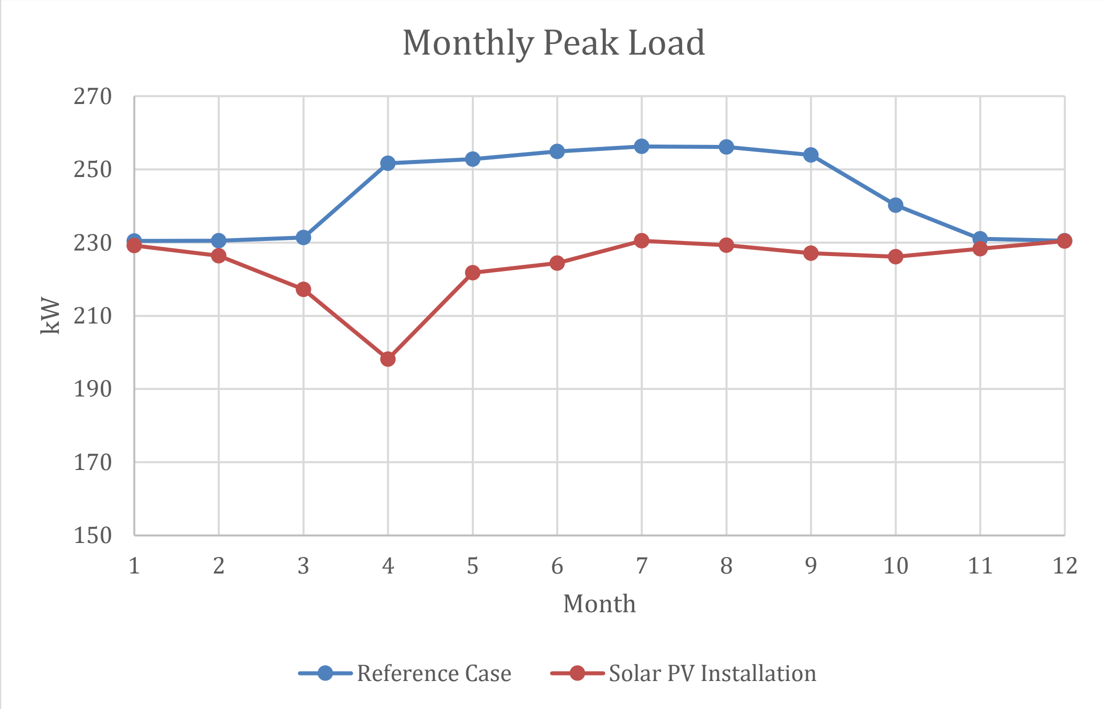



*Figure 15, Monthly peak load comparison with Solar PV installation and Reference Case.*

## 6.3.2 Energy Storage – Li-Ion Battery

The presentation of the li-ion battery will include the variable operating cost and losses as electricity cost since it automatically follows the battery system installation. The electricity utilisation will inevitably slightly increase due to the batteries' round trip efficiency.

### 6.3.2.1 Operating Cost

Figure 17 visualises the effect on electricity cost in relation to control strategy and battery size. The battery implementation showed, with both strategies, a reduction in the building operating costs following an increased battery capacity. The smaller investigated batteries were more profitable when using the peak shaving strategy. However, the reduced load demand variations of the building limit the effectiveness of this strategy with larger battery capacities.

The point where a further expansion of battery was no longer profitable for peak shaving in relation to power cost was around 1200kWh in battery storage capacity, where the fully charged battery can cover large quantities of daily demand. The load shifting strategy still accomplishes further savings with a diminishing trend.

Operating cost reduction was present when using both techniques of load management. In Section 2.7.2, there is further information regarding other areas of economic value, such as the need for a smaller fuse and the possibility of participation in demand response programs. I.e., GENAB's pilot project with the local flex market "Effekthandel Väst" can add value to properties with installed batteries.

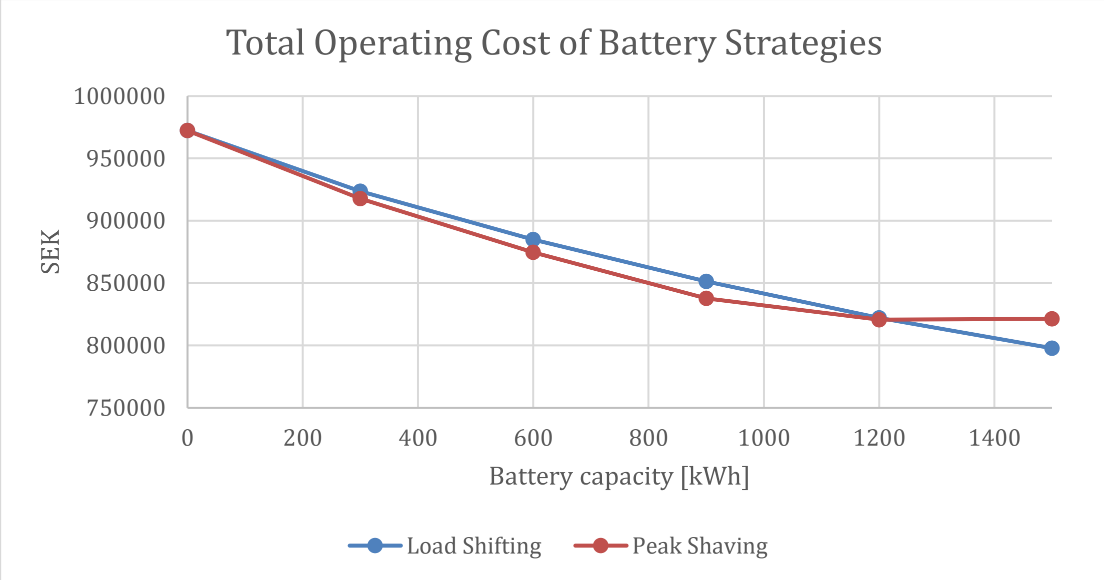



*Figure 16, Total operating cost of load shifting and peak shaving.*

#### 6.3.2.2 Building Electricity Load Effects

When the *peak shaving* strategy was used, the highest peak in the building electricity demand decreased significantly. The peak shaving strategy with a battery storage capacity of 300 - 1500kWh provided a yearly peak load average reduction of 12 - 45%, respectively. Diurnal variations were almost removed when the battery storing capacity surpassed 1200kWh. When the charged battery can fulfil a large portion of building electricity demand for the occupancy hours, the annual load duration curve is significantly flattened. In Figure 18, three annual load duration curves corresponding to battery size are presented.

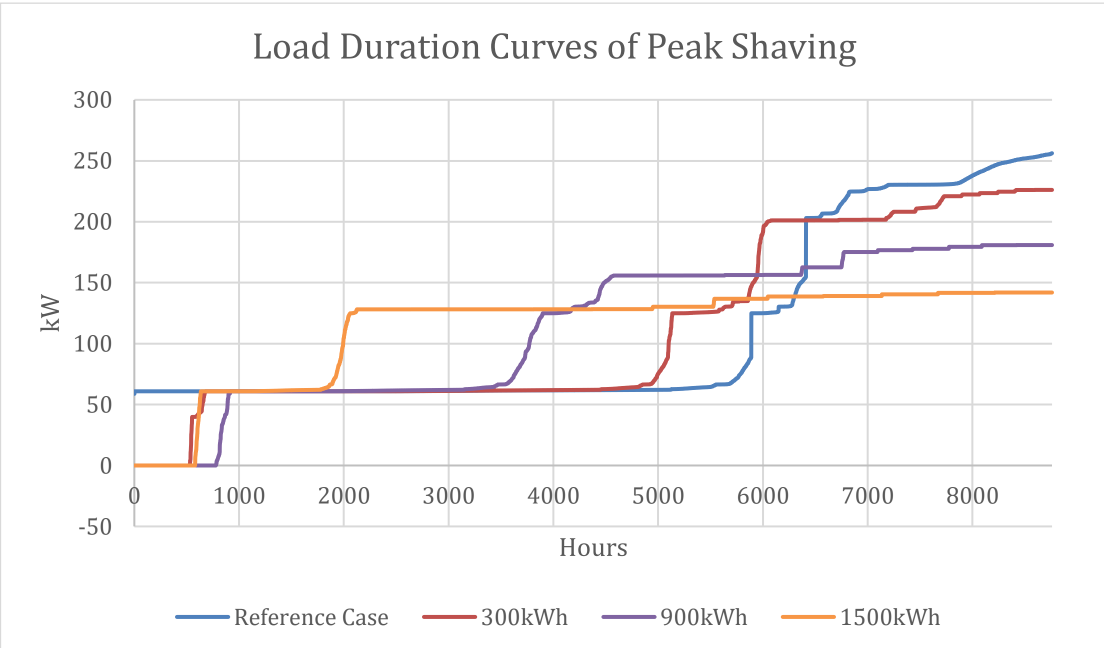



*Figure 17, Load duration curves with peak shaving.*

When utilising the *load shifting* strategy, the direct impact on the building electricity load was correlated to the hourly electricity price. Instead of reducing the highest peak load, the netload was reduced during electricity price peaks. Therefore, the monthly peak loads were not reduced compared to the Reference Case regardless of battery size. This strategy created higher intermittency in the building netload even though the periodic highest peak load was constant. In Figure 19, it can be observed in the annual load duration curves that with load shifting, there were more fluctuations with more hours with high and low netload.

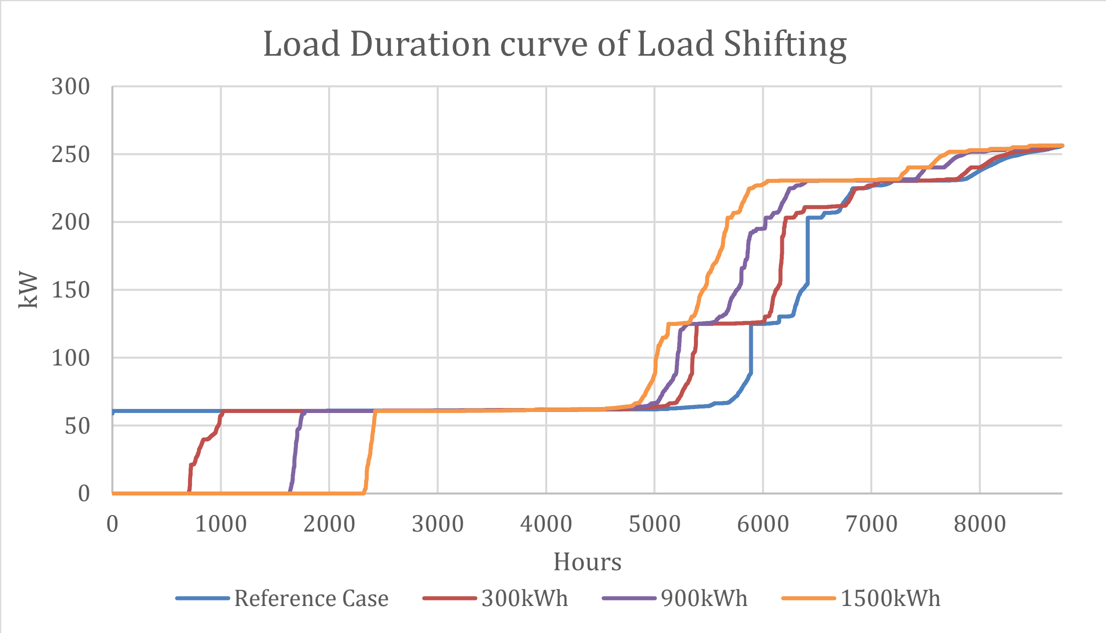



*Figure 18, Load duration curves for load shifting.*

### 6.3.3 Combined Effect of Solar Panels & Energy Storage

Presented in this section are the combined effect of utilising both solar panels and a li-ion battery. When implemented, the goal was to utilise the battery for maximum use of solar power produced in combination with load shaving and load shifting.

#### 6.3.3.1 Operating Cost

The combination between solar panel installation and energy storage shows an increased capacity for peak shaving compared to the individual results. When the battery size surpassed 900kWh, there was no longer profitability for further expansion with peak shaving intended. However, the load shifting strategy still showed the same trend diminishing of increase of savings for each enlargement of battery storage capacity, see Figure 20.

As mentioned in Section 6.3.1, the electricity available for selling without storage was 6.2kSEK. With the 300kWh battery, this was reduced by approximately 50%. Continued increase of battery size leads to full solar electricity utilisation for the building at 1500kWh capacity. Note that the electricity selling point was not an optimised variable and was only sold if it could not be utilised to fulfil building demand or be charged into the battery, independent of the current electricity price.

Results regarding solar panels and battery storage presented in this chapter suggest that the profitable aspect of this combination was the solar panels. Battery storage is more valuable to specific needs in power reduction than cost-reducing control measures.

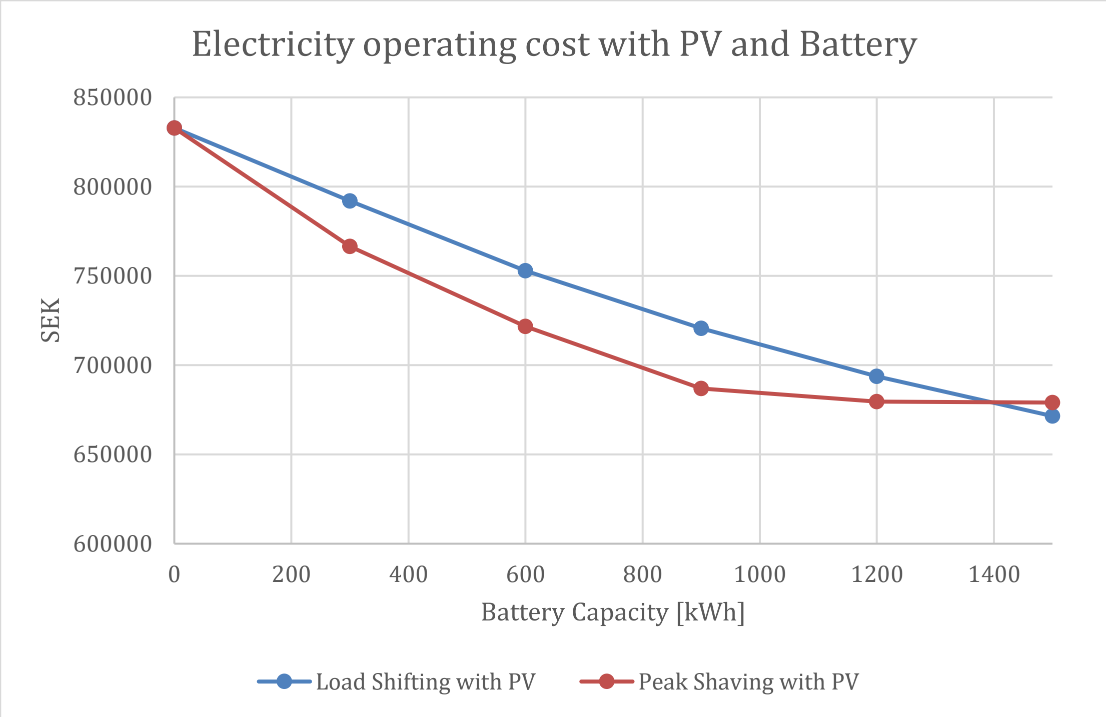



*Figure 19. Electricity operating cost with PV and Battery with the two tested battery strategies.*

#### 6.3.3.2 Building Electricity Load Effects

When analysing the load duration curves while using *peak shaving*, see Figure 21, it is visible that the battery storage complements the solar PVs. Especially during the summer months when the generation of electricity is the highest. A battery storage capacity interval of 300 - 1500kWh provided an average yearly peak load reduction of 23 - 52%, respectively. Less battery storage capacity is needed for an equal amount of peak load reduction compared to an individual battery installation. Therefore, the point when peak shaving loses effectiveness occurs at smaller battery capacities and can be observed by comparing the difference between 900kWh and 1500kWh in Figure 21.

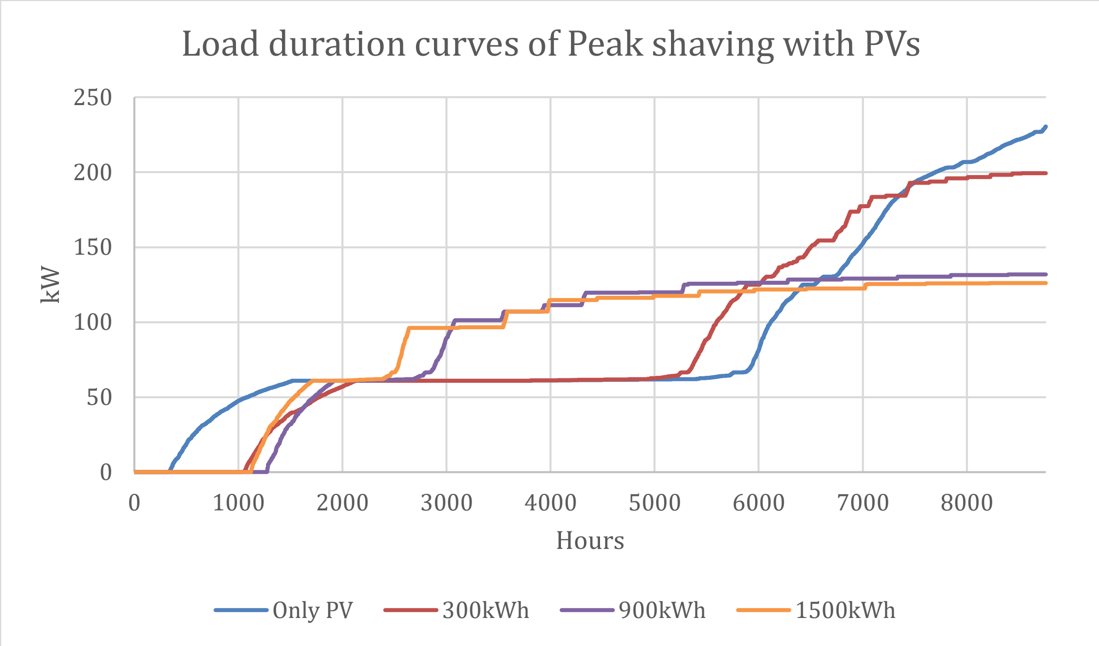


*Figure 20, Load duration curves of Peak shaving with PV.*

*Load shifting* was ineffective for reducing the monthly peak with solar PVs. With the same implemented constraints regarding maximum building netload, the battery nullified the peak load reduction accomplished by the stand-alone PVs. The load duration curves for different battery storage capacities with load shifting can be seen in Figure 22.

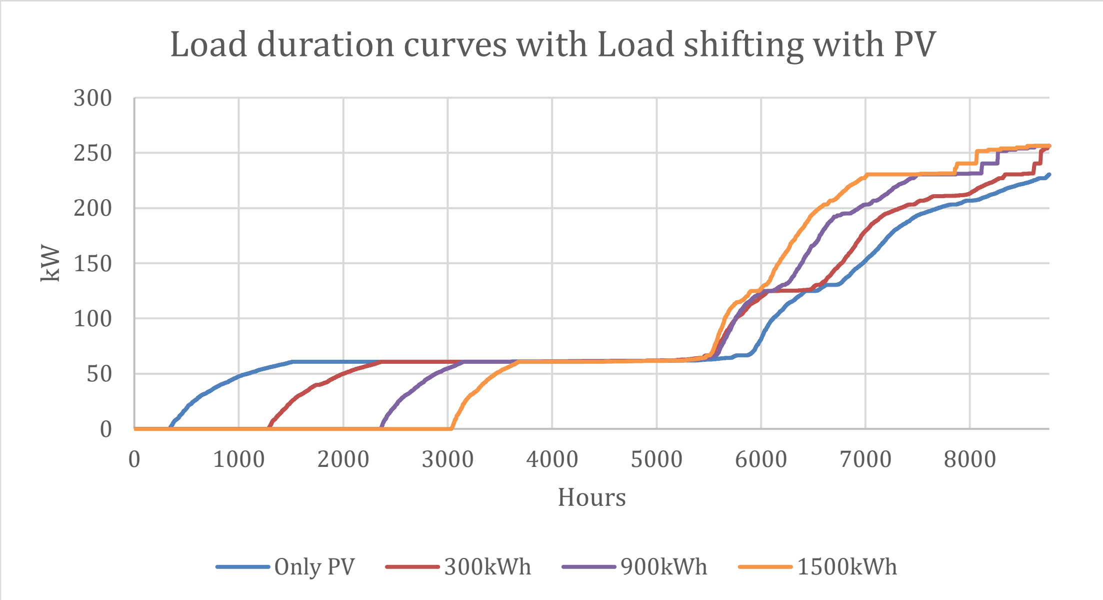


*Figure 21, Load duration curves of Load shifting with PV.*

## 6.4 Sensitivity Analysis

In the following sections, the robustness of the results earlier presented is analysed. The electricity and heating/cooling systems are investigated by altering parameters likely to change over time.

### 6.4.1 Occupancy and Equipment impact

The sensitivity simulation was aimed to investigate changes in occupancy norms. The input parameters occupancy and equipment had an influence on the building's energy usage, see Table 17. The increase in occupancy and equipment density provided additional internal gain that increased cooling demand and lowered heating demand. The same effect but less was noticed on the peak load for the systems. Another observation was that the daily relative annual heat load variation was reduced in unison with heating demand. Note that the increased need for cooling resulted in more property electricity needed for the indoor climate system.

The energy demand and the heat load variation in the building were highly affected by increased occupancy and equipment. Since occupancy and equipment use are correlated in office operation, the need for individual investigation of the parameters was therefore derived superfluous.

*Table 17, Key figures from sensitivity analysis of double equipment and occupancy, in comparison with Reference Case.*

| | *Max (kW)* | *W/m2* | *Energy (MWh)* | *kWh/m2* |
|---|---|---|---|---|
| ***District Heating*** | *544 (-20%)* | *42* | *266 (-28%)* | *12* |
| ***District Cooling*** | *946 (+21%)* | *24* | *340 (+63%)* | *15* |
| ***Total Electricity Consumption*** | *314 (+23%)* | *14* | *1 186 (+21%)* | *52* |
| ***Electricity Property*** | *59 (+3%)* | *3* | *289 (+4%)* | *13* |
| ***Primary Energy Number*** | *41 kWh/m$^2$ A temp a year* | | | |
| ***$G_a$*** | *14% (-6%)* | | | |

### 6.4.2 Electricity Price impact

The Reference Case electricity results are based on the spot electricity price in the SE3 price region year 2021 provided by Nord Pool. To investigate the result in an aspect of this parameter, the electricity spot price was implemented in two additional scenarios. Electricity prices that were registered during the same year in Denmark East and the price region SE1. The Denmark East electricity system allows for higher price volatility and SE1 with a more stable electricity price curve. For a view of yearly electricity price curves for the different price regions, see Appendix C.

#### 6.4.2.1 Denmark East

In comparison to the results shown in Section 6.3.2, the trend of a diminishing increase in electricity cost savings remains. However, as seen in Figure 23, a high electricity price volatility favoured the method of load shifting at a smaller battery size. This suggested that high price volatility indicates more savings through utilising the battery capacity in load shifting through price indicators rather than peak shaving.

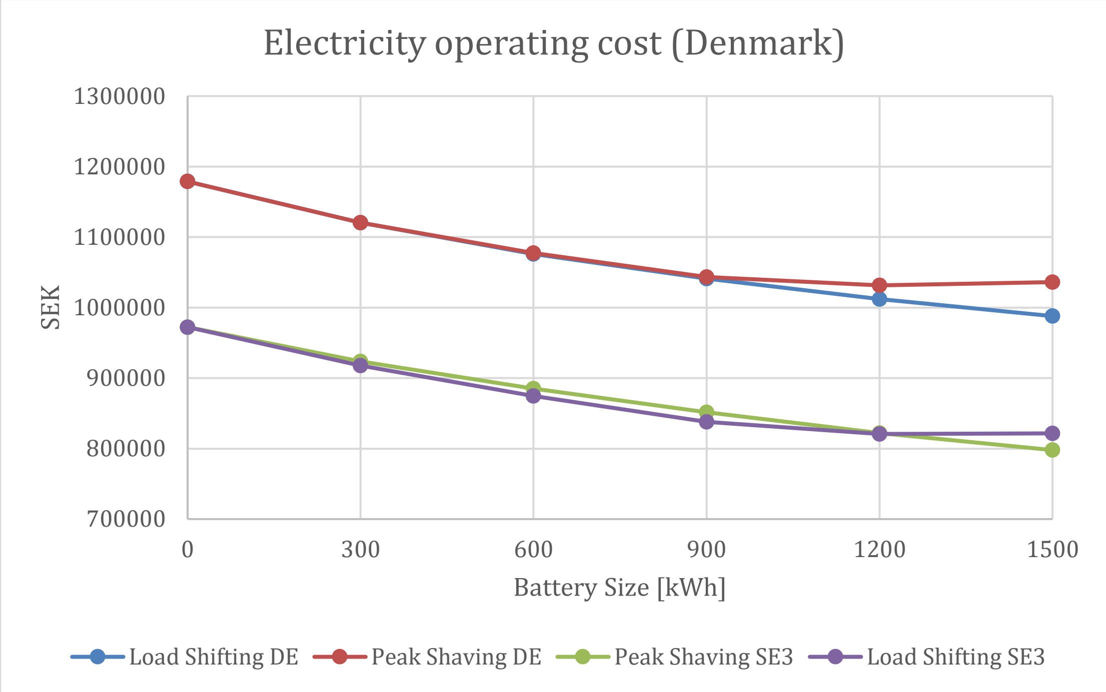



*Figure 22, Sensitivity analysis comparison between Denmark and SE3 electricity spot price.*

#### 6.4.2.2 Sweden SE1

Figure 24 shows the result with electricity prices in SE1 during 2021 and visualises the opposite effect that increased volatility in electricity price suggested. The peak shaving control method has, in this case, increased effectiveness compared to load shifting. Fewer variances in the electricity price give less opportunity to utilise the battery load shifting method. However, for both controlling strategies, the total electricity cost savings is reduced and provide less economic incentive to use a battery installation for load management.

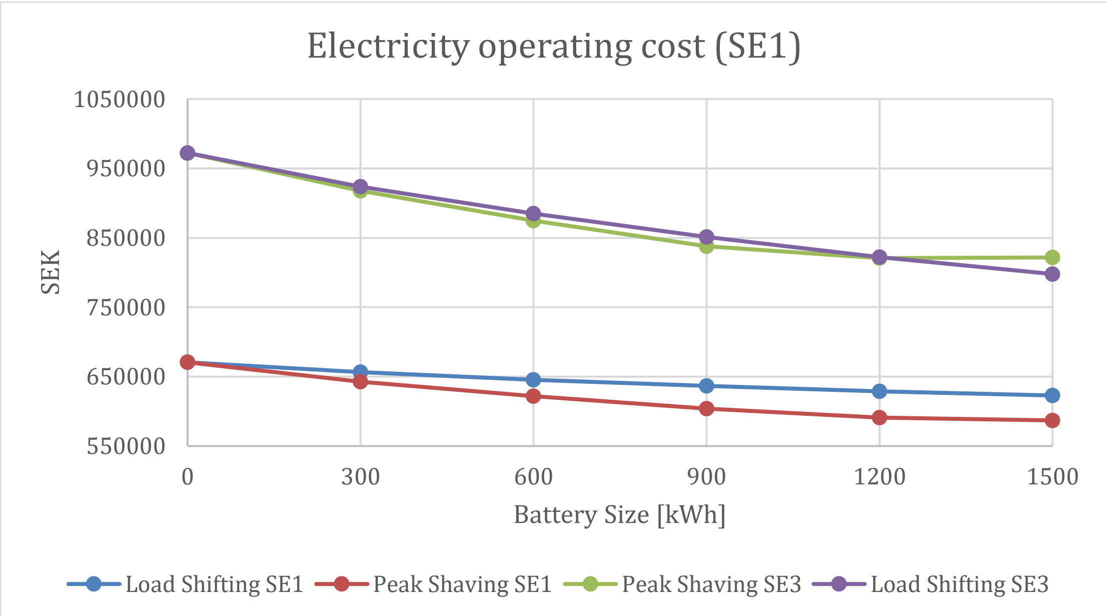



*Figure 23, Sensitivity analysis comparison between SE1 and SE3 electricity spot price.*

### 6.4.3 Electricity Grid Pricing Model

The Gothenburg Energy pricing models have been used exclusively throughout the simulations and calculations made in this thesis. However, in this sensitivity analysis, the local electricity grid cost was assumed to be entirely power-based. The price model is purposed to avoid sudden peak demand scenarios.

Using a fully power-based grid cost provided further incentive to utilise the peak shaving strategy while the load shifting stayed relatively equal to the SE3 case. The similarities between the curves suggested no significant impact on the battery installation profitability trends with either used control strategies. In Figure 25, the cost reductions maintain a similar pattern in relation to battery size and control strategy. However, the difference between the control strategies was magnified when a power-based grid price model was used.

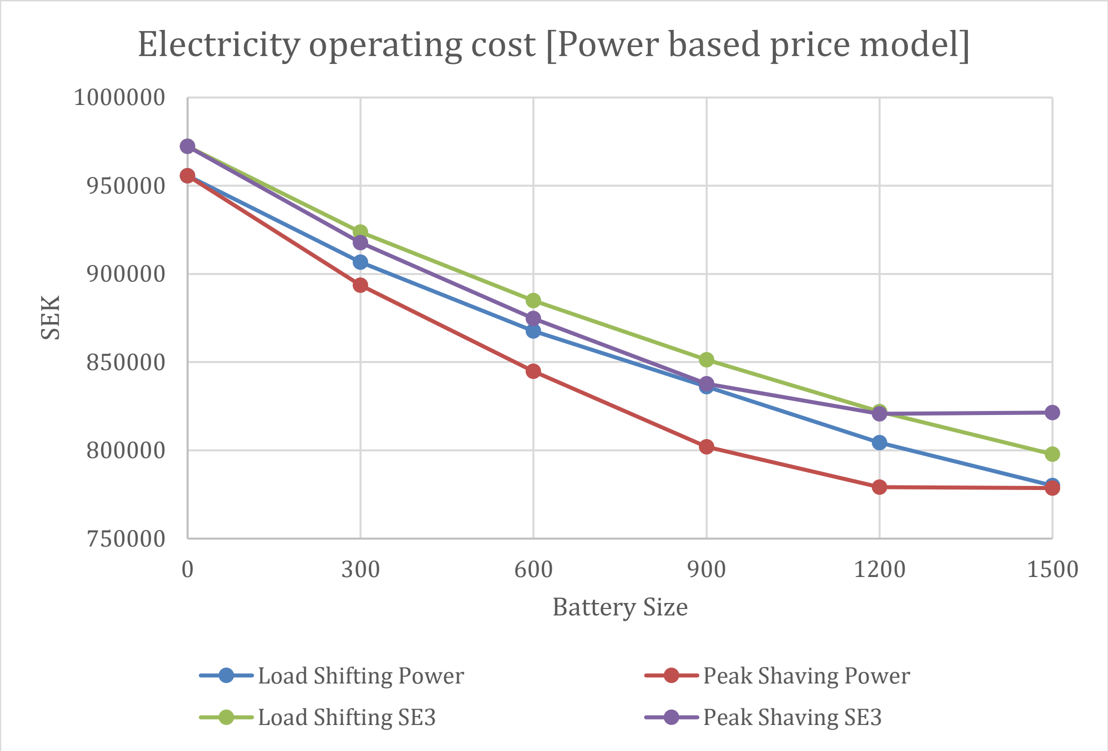



*Figure 24, Sensitivity analysis results of total electricity for a power-based price model.*

# 7 Result Analysis & Discussion

This chapter contains an analysis of the results from Chapter 6 based on a literature review and answers the research questions regarding energy system impact and its development in relation to the technical actions. The last section in this chapter contains a general discussion of assumption and demarcation impact.

## 7.1 Energy system perspective: District heating

The results of the modelled scenarios showed a decrease in heat demand and daily load variations in the individual building. Apart from the global temperature adjustments, the investigated actions require extensive investment when applied to existing buildings. Reduced operating costs can be an insufficient incentive for wide-scale implementation of the technical actions investigated. The future commercial office buildings will be less dependent on the district heating system and present significantly lower heat peaks during winter. Better heat performance in existing and new office buildings can play an important role in reducing daily load variations, total system cost, and carbon emissions in the district heating network.

In a similar system context, a reduction of the indoor temperature can be a viable strategy to reduce heating peaks and annual relative daily heat load variations. Especially during the autumn/spring period in times of large temperature swings. Less volatile heat demand requires less peak generation, which in turn, results in reduced emissions. However, there are no economic incentives for peak reduction during autumn/spring, even though the effects of peak reduction can reduce the total system costs.

The district heating price model in Gothenburg is designed by Gothenburg Energy. With reduced demand, it can impact a future price model. Another concern regarding the district heating future is that a large portion of the energy on a yearly basis is supplied by waste heat from refineries. The development of the fossil-based industry is ambiguous, and other waste heat streams may need to be utilised, i.e., data centres or electric vehicle battery production. However, a future decreased heating demand in commercial buildings may be a solution to the loss of heating sources.

## 7.2 Energy system perspective: District cooling

The reduction of cooling loads in the autumn/spring does not provide any economic incentives for property owners due to the power tariff design, that only considers the annual maximum peak. To reduce the operating costs during autumn/spring, focusing on energy conservation measures is the only viable strategy. The use of blinds and global temperature adjustment to 26°C was the best option to reduce cooling demand and peaks.

Gothenburg Energy currently promotes an expansion of the district cooling network for the city core. It aligns with the result of this thesis, which suggests that the future office building will experience an increase in cooling demand. The purpose of the district cooling network is to have a centralised system to improve overall efficiency. Current building regulations attempt to promote the utilisation of district cooling networks with a low weight factor in the primary energy number calculation. Large existing commercial buildings connecting to the district cooling network can enable more efficient use of electricity in the city core. By avoiding electric cooling machines, the electricity grid capacity can be used for other purposes.

The district cooling network is dependent on excess heat from fossil industries and waste incineration when the water temperature of Göta Älv’s is too high. Even though the current carbon dioxide equivalent calculations suggest zero emissions from district cooling, a reduction of fossil-based products in society may require the DC network to find other sources of excess energy. Furthermore, during the autumn/spring, the access to free cooling originating from Göta Älv is limited, which may induce further electricity consumption in the centralised cooling system to satisfy demand. Therefore, decreasing peak demand during the autumn/spring can have great system benefits, even though irrelevant in economic aspect for the property owner today. With less energy supplied by free cooling and waste energy, the future price model of DC utilisation can be uncertain.

## 7.3 Energy system perspective: Electricity

### 7.3.1 Solar PV impact

Using solar panels for peak load reduction requires knowledge about the operational patterns in the building. In the Reference Case, the highest electricity demand always occurs mid-day with full occupancy and the most significant internal gain from solar heat. Naturally, the time when electricity from solar PVs is most useful is during these full-occupancy hours.

Solar PVs have already seen wide-scale implementation on commercial and residential buildings. As described in Section 2.7.3, there are limitations to the power production allowed before the electricity produced locally is no longer tax-free. However, the results of this thesis suggest that PV panels with less than 500kW peak power allow for significant savings for property owners.

Solar panels are a great way to mitigate carbon dioxide emissions in the energy sector. Single installations locally are not expected to impact the energy system significantly but provide savings in terms of bought electricity in buildings utilised. In a wide-scale implementation scenario, it would require a response strategy from the supply side since production from many local PV customers will peak simultaneously. The development of flexibility in the supply and demand of electricity can manage the intermittence solar panels would introduce. However, with increased implementation, the marginal value of the PV generated electricity sold to the grid can be decreased and reduce economic profitability due to a merit order effect.

### 7.3.2 Battery storage

The control strategy for the battery needs to be optimised to fit the actual situation. The peak shaving program in this thesis searches for the lowest peak load that can be guaranteed during a specific month. This method of control is not always the desired peak shaving strategy. When used as a utility for the electricity system, there are some periods where the shaving capacity is more desirable for a specific load scenario rather than accomplishing a lower monthly peak.

Load shifting strategies are positive since the last technology in the merit order, which induces the highest electricity price, often has a substantially higher environmental impact. Avoiding these high electricity price hours allows for lower carbon emissions in the electricity system and more efficient use of variable renewable power generation. Battery performance and utilisation will likely improve as the energy from renewable energy sources increases.

The peak shaving strategy provides more direct benefits for the Gothenburg's local electricity grid in a wide-scale implementation compared to load shifting. Batteries could solve power capacity complications and allow the building sector with an implementable load management measure. Complementing the local grid with peak shaving alternatives can reduce the need for infrastructural expansion.

The expected increase in electricity price volatility is an aspect that favours future usage of battery storage to accomplish operating savings. In the Swedish power system, with a continued increase in variable renewables, the trend of heightened price intermittency is expected. Some grid owners in Sweden have begun to present opportunities to participate in flexibility demand programs in the form of smart charging of electric vehicles, both for private and businesses. Commercial facilities with an installed battery storage capacity will be a potent regulator for the local electricity system.

Wide-scale battery usage in the present system with the sole purpose in reducing operating costs is not likely. High investment costs on li-ion batteries make the current fluctuations in energy price insufficient as an economic incentive. Also, production of the battery units on a large scale with circumstances presented today is hard to accommodate in a sustainable manner. Therefore, it has to be thoroughly investigated in which societal sector li-ion batteries can be most useful.

## 7.4 Assumptions & Demarcations

The single location used for outdoor climate makes it hard to evaluate the level of applicability in other parts of Sweden. The outdoor temperature is of great importance concerning the effectiveness of the technical actions, especially within the boundary of district heating and district cooling systems. Furthermore, the centralised infrastructure for heating and cooling is not always present and not applicable to all locations.

During late July and the beginning of August and holiday seasons in Sweden, a large portion of people are on vacation and demand for heating, cooling, and electricity during this time may be reduced for office buildings. These momentary dips in energy demand are excluded in this thesis, which otherwise would be noticeable on the load curves presented. The cost for heating based on the building's return water temperature is not considered, but according to Gothenburg Energy (2022), the return water temperature usually affects the operating cost by +-5%.

Input parameter impact is always crucial to understand when utilising simulation software. The climate data file used in IDA ICE was based on the yearly averages from 1981 – 2010, and more recent fluctuations in climate are unnoticeable. Electricity prices fluctuate on an annual and daily basis. In addition to the magnified fluctuations due to increased renewables in the electricity system, future supply and demand changes are difficult to interpret due to the high system complexity. Rapid decarbonisation and electrification are examples of factors that influence the energy system landscape. This uncertainty in electricity price development resulted in the use of recent data.

The simulation was performed in IDA ICE with a predefined outside climate, electricity demand, and internal heat for the simulation. In a real case, this data is hard to estimate beforehand, which makes precise decisions concerning load management difficult. Similar reasoning can be derived in the MATLAB optimisation model, where the basis of battery optimisation refers to an accurate prediction of electricity price and demand development to create an optimal solution.

None of the simulations in IDA ICE has an upper limit constraint of the power output from district heating, district cooling or electricity. The model simulation was designed to meet the building demand in every time step, which indicates that the building energy system is over-dimensioned. Furthermore, the assumptions and data used for electricity consumption patterns in the office building do not consider spontaneous operational actions.

The Reference Case aimed to create a generalised office building. However, the variations in results due to operating inputs, further described in Section 6.4.1, demonstrated significant impact. Even though generalised values were used for the Reference Case creation, the results become case-specific. Building specifications are rarely identical, and the technical actions applied in this thesis can have a different impact on another type of envelope structure, operating patterns, and system boundaries. However, the foundation of the result of this thesis contains industry standards, regulations, and recommendations which should provide more similarities to the general case than a single case study.

The annual simulation time of the IDA ICE exceeded 24 hours. The primary problems of the long simulation were the size and number of zones created. A more comprehensive yearly analysis by the trial-and-error method of the technical actions would have been helpful for investigating more detailed parameter impacts.

# 8 Conclusions

The technical actions investigated in this thesis show a widespread effect on the office building load demand. Most measures accomplished reduced operating costs through load management and energy conservation but need further incentives to prove economically feasible on a wide scale for property owners. Regulation and guidelines regarding energy use and stakeholder cooperation will likely set the base for how buildings can interact with the energy system in the future.

Temporary control measures, such as global temperature adjustments, show potential for reductions concerning energy load and peak generation utilisation. Decreased thermal transmittance reduces heat consumption and peak load but increases the need for cooling. The increased cooling demand is concluded to have a minor impact compared to the reduced carbon emissions from more efficient utilisation of heating. The expansion of the district cooling network aligns with building sectorial development. However, the future district cooling energy sources for Gothenburg are not evident due to societal decarbonisation.

Installation of solar PVs reduces the amount of energy purchased and the electricity peak load due to the overlap between operational pattern and PV production. Battery energy storage can provide the energy system with crucial flexibility improvements. Depending on the control strategy chosen, it will affect the monthly peak load variations for the building in various ways. Development of demand response programs, increased volatility in electricity price, and declining battery investment prices will create a future energy landscape where batteries contribute with flexibility to support variable renewable energy production.

## 8.1 Recommendations for future work

This thesis has considered several different technical actions, which in most cases have promising results for property owners operating costs and energy system efficiency. However, no investment computation is performed, which can be promising complementing work, especially for the most promising measures.

During the interviews, the property owners expressed the importance of effort within the indoor climate for the tenants. In the report, the indoor climate effects have not been covered in an extensive manner. The load management measures investigated in this report, especially concerning heating and cooling, require further work to evaluate how they impact the indoor climate.

Battery storage applications need further investigation to allow for sufficient incentives. Examples are how the local flex market introduction can provide more economic incentives for the property owner or utilise an electrical vehicle fleet as the foundation instead of stationary battery storage.

# 9 References


Behrangrad, M. 2015. A review of demand side management business models in the electricity market. *Renewable and Sustainable Energy Reviews,* 47. pp. 270-283.

Boverket. 1994. *Boverket´s handbook on Concrete Structures BBK 94*, Volume 1. Karlskrona, Sweden: Byggavdelningen, Boverket p. 185.

Boverket, 2021. *Boverkets byggregler (2011:6) – föreskrifter och allmänna råd*. https://www.boverket.se/sv/lag–ratt/forfattningssamling/gallande/bbr---bfs-20116/ [Accessed 8 March 2022].

Boverket, 2021. *Boverkets föreskrifter och allmänna råd (2016:12) om fastställande av byggnadens energianvändning vid normalt brukande och ett normalår*. https://www.boverket.se/sv/lag--ratt/forfattningssamling/gallande/ben---bfs-201612/ Hämtad 2022-05-24.

Bulut, M., Odlare, M., Stigson, P., Wallin, F. and Vassileva, I. 2015. Buildings in the future energy system – Perspectives of the Swedish energy and buildings sectors on current energy challenges. *Energy and Buildings*, 107, pp. 254-263.

C.B.Honsberg and S.G.Bowden, 2019. *Photovoltaics Education Website, Solar Radiation of Tilted Surfaces*. < https://www.pveducation.org/ > [Accessed 21 April 2022].

Danish Energy Agency, 2020. *Technology Data for Energy Storage*. Esbjerg, Denmark: Danish Ministry of Climate, Energy and Utilities.

Darwazeh, D., Duquette, J., Gunay, B., Wilton, I. and Shillinglaw, S. 2022. Review of peak load management strategies in commercial buildings. *Sustainable Cities and Society*, 77, pp. 1-16. Available at: <https://www.sciencedirect.com/science/article/pii/S2210670721007599> [Accessed 16 February 2022].

Energiforsk. 2016. *Innovativ teknik för kombinerad fjärrkyla och fjärrvärme. (Report 2016:318)*

Energikontor Sydost, 2021. *Batterilagring i byggnader – en vägledning*.

EQUA Simulation AB, n.d. *IDA ICE.* <https://www.equa.se/se/ida-ice> [Accessed 28 May 2022].

EQUA Simulation AB, 2018. *User Manual IDA Indoor Climate and Energy v4.8.* Solna, Sweden.

Forslund, J., Forslund, G. 2021 *Bästa inneklimat till lägsta energikostnad.* 4th edn. Svensk Byggtjänst.

Gadd, H., Werner, S. 2013. Daily heat load variations in Swedish district heating systems. *Applied Energy*, 106, pp 47-55.

Gothenburg Energy, n.d. *Flexibilitet*. <https://www.goteborgenergi.se/foretag/flexibilitet> [Accessed 17 February 2022].

Gothenburg Energy. n.d. *Här finns fjärrkyla*. <https://www.goteborgenergi.se/foretag/fjarrkyla/har-finns-fjarrkyla> [Accessed 26 May 2022].

Gothenburg Energy. n,d. *Klimatneutral och driftsäker fjärrvärme*. https://www.goteborgenergi.se/i-var-stad/artikelbank/klimatneutral-och-driftsaker-fjarrvarme> [Accessed 3 May 2022].

Gothenburg Energy. n.d. *Miljövärden*. <https://www.goteborgenergi.se/kundservice/dokument-blanketter/miljovarden-for-fjarrvarme-och-fjarrkyla?C=90705654> [Accessed 27 April 2022].

Gothenburg Municipality. 2021. *Göteborgs Stads energiplan 2022–2030.* <https://tinyurl.com/mr37h8r5> [Accessed 19 April 2022].

Gunasekara, S.H., Martin, V., Edén, T. Sedeqi, F., Tavares, M., and Nardone, P.S.M.. 2019. Distributed cold storages for district cooling in Sweden - The current context and opportunities for the cold supply expansion. *Eurotherm Seminar #112: Advances in thermal energy storage*, University of Lleida, Spain, 15-17 May, 2019.

Hailu, G. 2021. Energy systems in buildings. *Energy Services Fundamentals and Financing*, pp.181-209.

Kamel, E., Memari, A, M. 2016. Different methods in building envelope energy retrofit. *3rd residential bulduing design & construction Conference.* Penn State, University Park, 2-3 March, 2016.

Lund, P., Lindgren, J., Mikkola, J. and Salpakari, J. 2015. Review of energy system flexibility measures to enable high levels of variable renewable electricity. *Renewable and Sustainable Energy Reviews*, 45, pp.785-807.

Mata, E., Kalagasidis, A, S., and Johnsson, F. 2013. Energy usage and technical potential for energy saving measures in the Swedish residential building stock. *Energy Policy*, 55, pp. 404–414.

Ministry of Infrastructure. 2021. *Sveriges tredje nationella strategi för energieffektiviserande renovering*. Swedish Government, pp. 28–33.

Morthost, P., Ray, S., Munksgaard, J. and Sinner, A. 2010. *Wind energy and electricity prices. Exploring the 'merit order effect'*. <https://inis.iaea.org/search/search.asplx?orig_q=RN:43000625> [Accessed 19 April 2022].

Olsson Ingvarson, L.C., & Werner, S. 2008. Building mass used as short term heat storage. *The 11th International Symposium on District Heating and Cooling.* Reykjavik, Iceland, 31 August– 2 September 2008.

Pilkington. 2021. *Glasfakta 2021.* <https://www.pilkington.com/-/media/pilkington/site-content/sweden/glasfakta/gf-2021-se.pdf> [Accessed 21 April 2022].

Romanchenko. D. 2018. *The future load curve of the Swedish building stock – Interactions between the heating load and district heating.* Licentiate of engineering Thesis, Chalmers University of Technology.

Romanchenko, D., Kensby, J., Odenberger, M. and Johnsson, F., 2018. Thermal energy storage in district heating: Centralised storage vs. storage in thermal inertia of buildings. *Energy Conversion and Management*, 162, pp. 26-38.

Romanchenko, D., Odenberger, M., Göransson, L. and Johnsson, F. 2017. Impact of electricity price fluctuations on the operation of district heating systems: A case study of district heating in Göteborg, Sweden. *Applied Energy,* 204, pp.16-30.

Steen, D., Tuan, L. and Bertling, L. 2012. *Price-Based Demand-Side Management for reducing peak demand in electrical distribution systems – with examples from Gothenburg. Nordic Conference on Electricity Distribution System Management and Development*. Helsinki, September 2012.

Svenska Kraftnät. 2021. *Scenarier för elsystemets utveckling fram till 2050*. <https://www.svk.se/siteassets/om-oss/rapporter/2021/langsiktig-marknadsanalys-2021.pdf> [Accessed 16 February 2022].

Sveby.org. 2013. *Brukarindata för kontor*. <https://www.sveby.org/wp-content/uploads/2013/06/Brukarindata-kontor-version-1.1.pdf> [Accessed 20 April 2022].

Sveby.org. 2022. *Klimatdata filer för 2021.* <https://www.sveby.org/okategoriserad/klimatdatafiler-for-2021/> [Accessed 3 May 2022].

Sweco. 2020. *Kartläggning av hur planerade nätinvesteringar avhjälper kapacitetsbrist i elnätet.*

Swedish Energy Agency. 2021. *Energy in Sweden Facts and figures*. <http://www.energimyndigheten.se/en/facts-and-figures/statistics/> [Accessed 19 April 2022].

Swedish Work Authority. 2021. *Temperatur och klimat*. <https://www.av.se/inomhusmiljo/temperatur-och-klimat/> [Accessed 3 May 2022].

Teran Öman, A., Lintorp, A., Åker, J., Boberg, A. and Stenberg, J. 2020. *Kartläggning och analys av elförsörjningssituationen i Västra Götaland*. Lansstyrelsen. <shorturl.at/wAWY3> [Accessed 16 February 2022].

Trost, J. 2010. *Kvalitativa intervjuer*. Lund: Studentlitteratur.

U.S. Department of Energy, n.d. *Demand Response*. Washington, DC: Office of Electricity. < *https://www.energy.gov/oe/activities/technology-development/grid-modernization-and-smart-grid/demand-response>* [Accessed 27 April 2022]

World Bank, 2005. *Primer on Demand-Side Management: With an Emphasis on Price-Responsive Programs*. <http://hdl.handle.net/10986/8252> [Accessed 26 April 2022].

U.S. Department of Energy, n.d. *Solar Photovoltaic Technology Basics*. Washington, DC: Office of Energy Efficiency & Renewable Energy. <*https://www.energy.gov/eere/solar/solar-photovoltaic-technology-basics*> [Accessed 27 April 2022]

Verbeke, S. and Audenaert, A., 2018. Thermal inertia in buildings: A review of impacts across climate and building use. *Renewable and Sustainable Energy Reviews,* 82, pp. 2300-2318.

Warfvinge & Dahlbom, 2010. Projektering av VVS-installationer. Lund: Studentlitteratur AB

Werner, S. 2017. District heating and cooling in Sweden. *Energy,* 126, pp-419-429.

Wikner, E. and Thiringer, T. 2018. Extending Battery Lifetime by Avoiding High SOC. *Applied Sciences*, 8(10), p. 1825.

Zhao, M., Künzel, H.M., Antretter, F. 2015. Parameters influence the energy performance of residential bulduings in different Chinese climate zones. *Energy and Buildings*, 96, pp. 64-75.

# **Appendix A** – Summary of interview questions

1. *What is your opinion if Gothenburg currently has a problem with capacity shortage for electricity?*

2. *What is your role in a potential electricity capacity shortage?*

3. *Who do you believe will be the responsible actor for coordinating measures to prevent a potential capacity shortage?*

4. *Who do you believe should be responsible to coordinate resources in an eventual electricity capacity shortage?*

5. *Is there any communication between the local grid owner and property owners for optimization of power peaks?*

6. *What are the largest challenges to a local grid owner with increased penetration of renewables?* – Question was only asked to the local grid owner.

7. *How do you believe the composition for a future price model between power and energy will be designed?*

8. *What type of actions do you use in your current property block to reduce power peaks? For all energy sources. If not, what hinders you from doing it?* – Question was only asked the property owners.

9. *Do you cooperate with other actors to optimise power peaks for buildings?*

# **Appendix B** - Input electricity data to the IDA ICE model

*Table B1, Input equipment + lighting for the different zone types.*

| | Lighting [W/m2] | Equipment [W/m2] | Equipment/Occupant | Total Area | Equipment (See table below) |
|---|---|---|---|---|---|
| **Facade office** | 10 | 5.42 | 108.4 | 2278 | 2 Monitors + 1 Laptop |
| **Cell office** | 10 | 16.17 | 323.4 | 920 | 2 Monitors + 1 Workstation |
| **Landscape office** | 10 | 5.42 | 108.4 | 6528 | 2 Monitors + 1 Laptop |
| **Conference** | 10 | 7.05 | 141 | 1638 | 1 TV |
| **Corridor + Entrance** | 10 | 0.7 | 14 | 8907 | Other equipment, microwaves oven etc. |
| **Core** | 4 | 0.9 | 18 | 2490 | Servers |

*Table B2, Individual component for electric equipment.*

| Power usage at 100% and its source, see electricity schedule in Table 13. | | | |
|---|---|---|---|
| **Monitor** | 21.7 | W | Dell P2720DC \| Dustin.se |
| **Laptop** | 65 | W | Lenovo ThinkPad X1" \| Dustin.se |
| **Workstation** | 280 | W | HP Z2 G5 \| Dustin.se |
| **TV** | 141 | W | Samsung QE85Q60A 85"\| Dustin.se |
| **Servers** | 0.9 | W/m2 | See reference list Sveby (2013) |
| **Other** | 0.7 | W/m2 | Assumed |
| **Lighting data** | | | From Sveby (2013) |

# **Appendix C** – Electricity spot price variations for price regions of SE1 and East Denmark in 2021

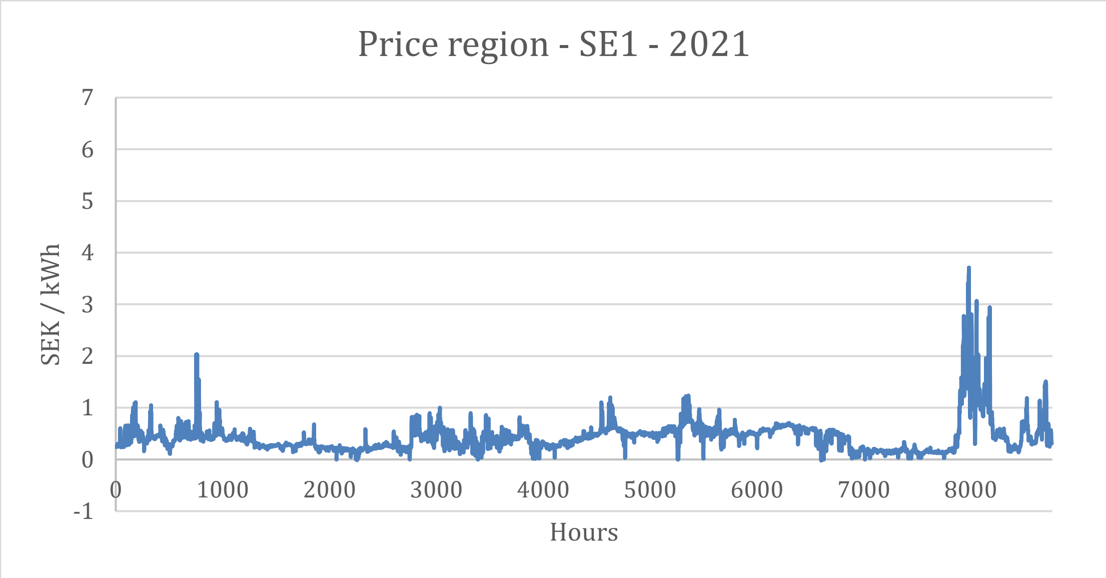



*Figure C1, Spot market electricity price for SE1 of 2021 provided by the Intraday Market. Source: Nord Pool.*

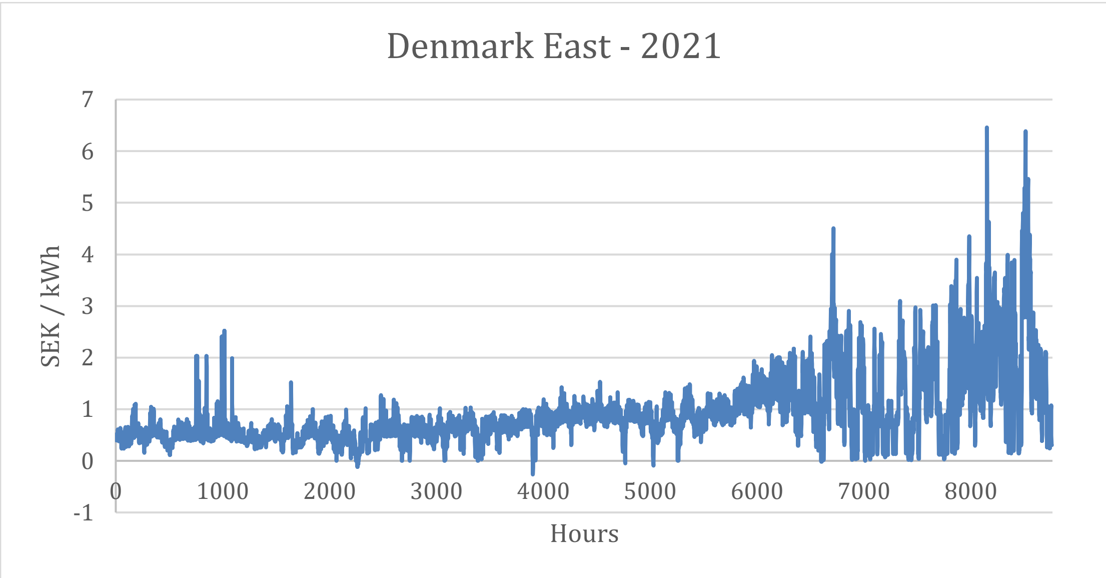



*Figure C2, Spot market electricity price for Denmark East of 2021 provided by the Intraday Market. Source: Nord Pool.*

# Appendix D - MATLAB notations and additional constraints

*Table D1, Indexes, parameters, and variables for linear programming.*

| ***Indexes*** | ***Parameters*** | ***Variables*** |
|---|---|---|
| t = time [hour] | $D_t$ – Building electricity demand at hour t [kWh/h] | TC – Total Electricity Cost [SEK/year] |
| m = month [1, 12] | $P_{el,t}$ – Electricity price at hour t [kWh/h] | $Netload_t$ – Building net electricity demand |
| | $SOC_{max}$ – Maximum battery storage capacity [kWh] | $Ch_t$ – Battery charging at hour t [kWh/h] |
| | $PVgen_t$ – PV generated electricity at hour t [kWh/h] | $Dch_t$ – Battery discharging at hour t [kWh/h] |
| | $E_c$ – Battery charging efficiency | $SOC_t$ – Battery state of charge [kWh] |
| | $E_d$ – Battery discharging efficiency | $Shave_m$ – Monthly building load shaving factor |
| | $O\&M_{bat}$ – Variable cost for battery [SEK/kWh] | PeakLoad – Sum of monthly load shaving factors |

***Additional variable constraints:***

Global netload constraint:

$$0 \leq Netload_{t,m} \leq D_{t,m}$$

Battery maximum charging constraint:

$$0 \leq Ch_t \leq \frac{SOC_{max}}{2}$$

Battery maximum discharging constraint:

$$0 \leq Dch_t \leq SOC_{max} * 3$$

Battery state of charge constraint:

$$0.2 * SOC_{max} \leq SOC_t \leq 0.9 * SOC_{max}$$

Battery cycles per year constraint (Cycles 14000 & Lifetime 20 years):

$$\sum_t \left(\frac{Ch_t}{SOC_{max}}\right) \leq \left(\frac{Cycles}{Lifespan}\right)$$

# **Appendix E** – Annual load curves from model scenarios in IDA ICE

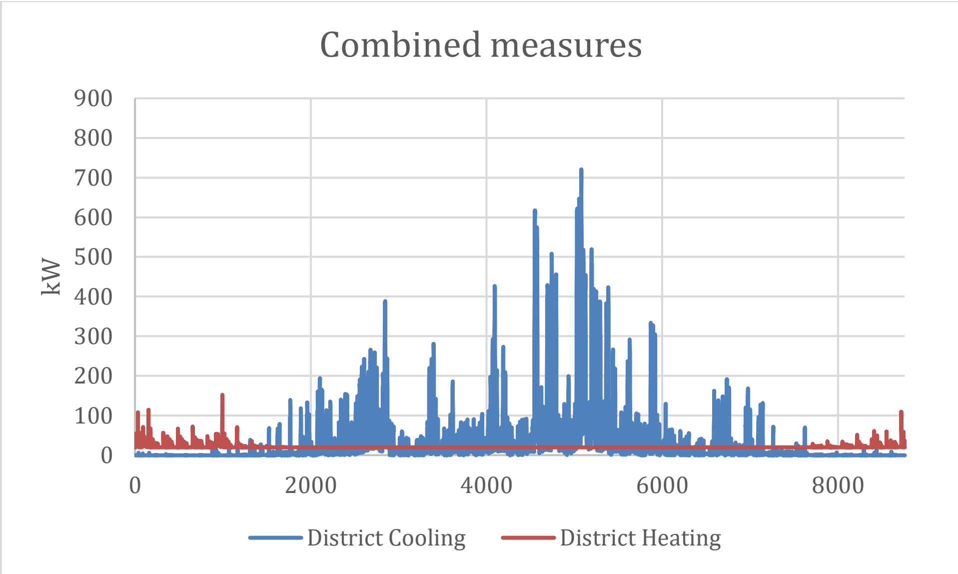



*Figure E1, Full year hourly load demand for the "Combined measures" scenario.*

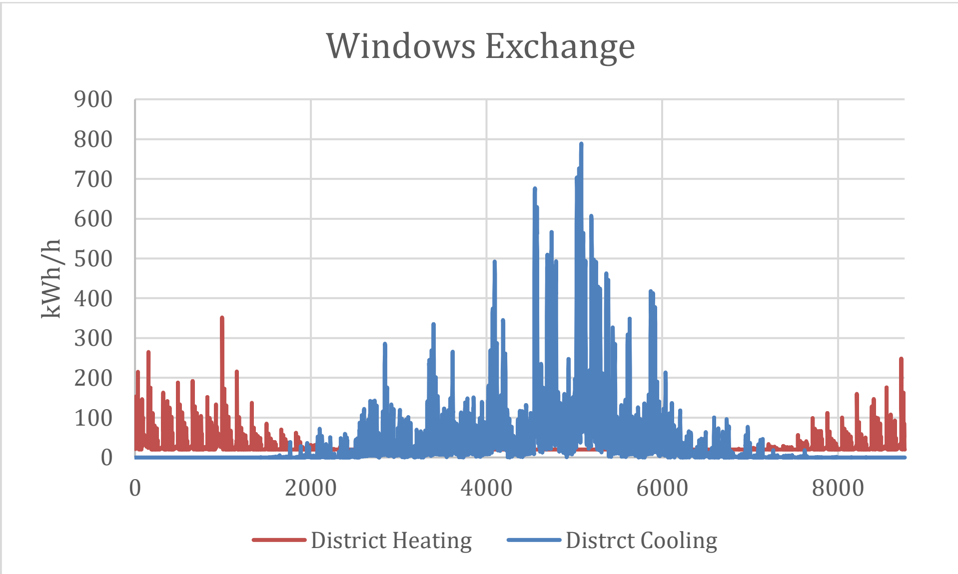



*Figure E2, Full year hourly load demand for the "Windows Exchange" scenario.*

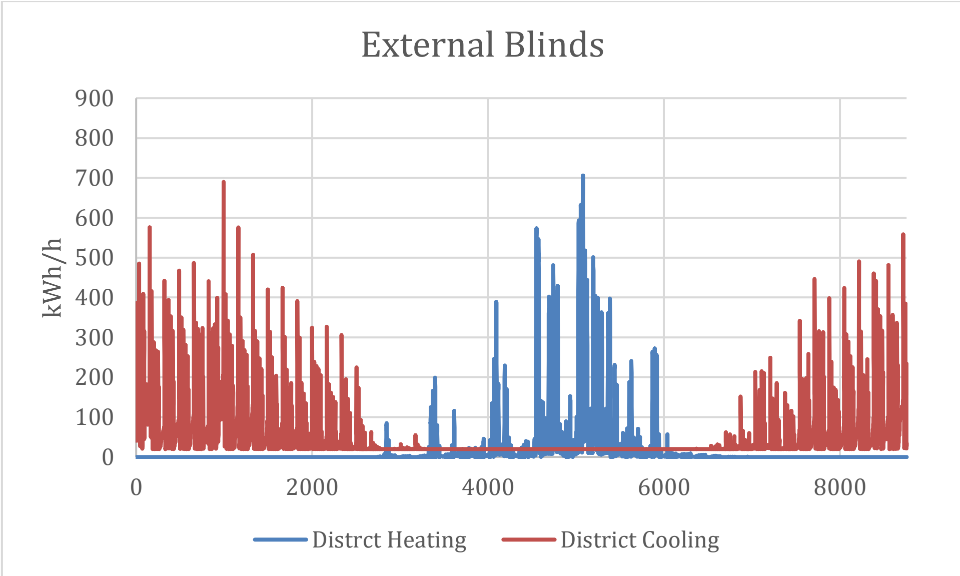



*Figure E3, Full year hourly load demand for the "External Blinds" scenario.*

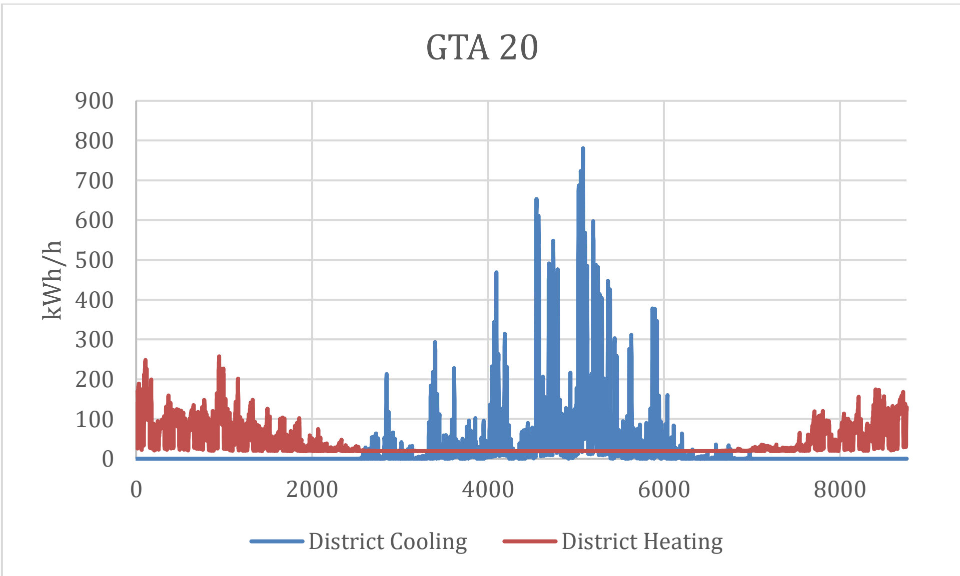



*Figure E4, Full year hourly load demand for the "GTA 20" scenario.*

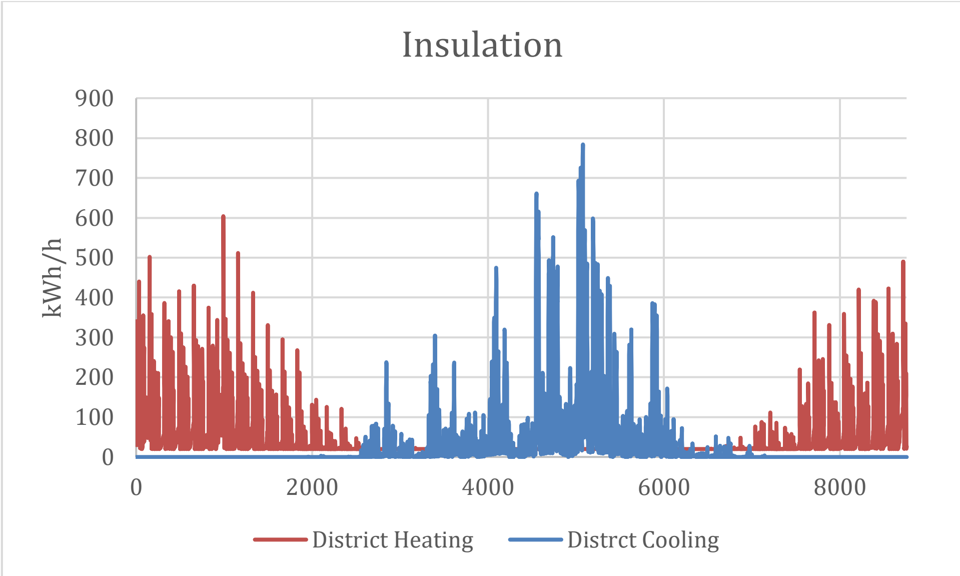


*Figure E5, Full year hourly load demand for the "Insulation" scenario.*

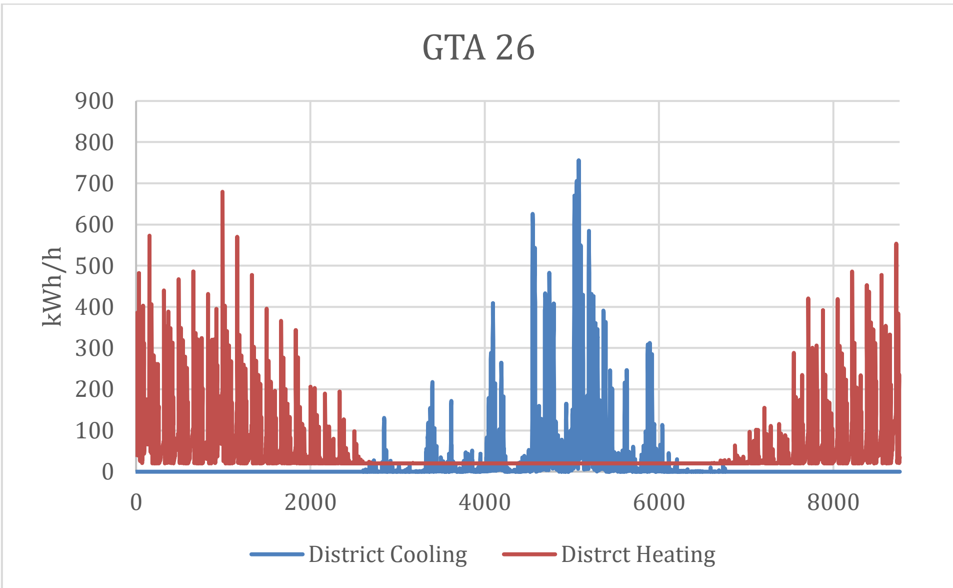


*Figure E6, Full year hourly load demand for the "GTA 26" scenario.*

DEPARTMENT OF ARCHITECURE AND CIVIL ENGINEERING
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2022
www.chalmers.se