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Degree project

Dynamic modelling of electricity arbitrage for single- family homes

*Assessing the cost-effectiveness of implementing
Energy Storage and Demand-Side Load Management.*



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Summary

Access to affordable, reliable, and modern energy is essential for advancing various sectors within society, including agriculture, business, communications, education, healthcare, and transportation. These sectors all play crucial roles in promoting the sustainable development of society. The availability of modern energy sources is also necessary for addressing objectives such as poverty alleviation, economic growth, and improved living standards. Governments worldwide prioritize energy security to ensure the reliability and stability of their energy supply systems, which in turn supports sustainable development goals.

In the context of electricity, arbitrage trading involves taking advantage of existing price variations within electricity markets. When effectively capitalizing on electricity price area differentials, the strategy results in cost savings for electricity consumption, effectively serving as an energy efficiency measure for building energy performance. The primary objective of electricity arbitrage is to purchase electricity during periods of low demand and relatively lower wholesale spot prices (typically off-peak hours) and utilize it during periods of high demand and higher electricity prices (peak hours). The report conducted financial modelling for energy storage systems and demand-side load management for electricity arbitrage trading in single-family homes. The analysis included two different energy storage systems: a thermal energy storage system and a battery energy storage system. Additionally, electricity spot cost reduction was compared between electricity arbitrage trading and traditional energy efficiency measures such as air-to-water and ground-source heat pumps.

The report's findings indicated that air-to-water and ground-source heat pumps emerged as the most economically viable choices for reducing electricity spot costs, irrespective of the studied electricity price area. The thermal energy storage system, employing an insulated hot water storage tank, ranked the third most efficient in achieving cost savings. The battery energy storage system, represented by a lithium home battery system, demonstrated the lowest rate of cost saving among the analyzed energy efficiency measures.

The financial modelling highlighted the economic potential for thermal energy storage systems, particularly in southern Sweden's electricity price areas SE3 and SE4. On the other hand, no economically viable options for battery energy storage systems were identified, regardless of the studied electricity price area. As a results, the report recommends utilizing thermal energy storage systems and implementing demand-side load management as strategies to hedge against future electricity price volatility.



Sammanfattning

Tillgång till prisvärd, pålitlig och modern energi är avgörande för att främja olika sektorer inom samhället, inklusive jordbruket, näringsliv, informationsteknik, utbildning, sjukvård och transport. Dessa sektorer spelar alla avgörande roller i att främja samhällets hållbara utveckling. Tillgången till moderna energikällor är också nödvändig för att uppnå mål som fattigdomsbekämpning, ekonomisk tillväxt och förbättrade levnadsvillkor. Myndigheter över hela världen prioriterar energisäkerhet för att säkerställa tillförlitligheten och stabiliteten i sina energiförsörjningssystem, vilket i sin tur stöder hållbara utvecklingsmål.

Inom kontexten av elektricitet, handlar arbitrage om att dra nytta av befintliga prisvariationer inom elmarknaden. Genom att effektivt utnyttja prisskillnader som existerar i olika elprisområden och tidsperioder kan man generera kostnadsbesparingar för sin elförbrukning. En förutsättning för att generera dessa kostnadsbesparingar är att man implementerar laststyrning. Syftet med arbitrage är att köpa el under perioder med låg efterfrågan och relativt lägre priser och använda den under perioder med hög efterfrågan och högre elpriser. Rapporten genomförde finansiell modellering för energilagringssystem och laststyrning i ett enfamiljshus. Analysen inkluderade två olika energilagringssystem: ett termiskt energilagringssystem och ett batteri energilagringssystem. Kostnadsbesparingar jämfördes även med traditionella energieffektiviseringsåtgärder såsom luft- och bergvärmepumpar.

Rapportens resultat indikerade att luft- och bergvärmepumpar framstod som de mest ekonomiskt lönsamma alternativ för att minska kostnader, oavsett vilket elprisområde som studerats. Det termiska energi lagringssystemet, som använder en ackumulatortank, var de tredje mest effektiva sättet att uppnå kostnadsbesparingar. Batteri energilagringssystem, representerat av ett litium hembatteri, visade den lägsta kostnadsbesparingen bland de analyserade energieffektiviseringsåtgärder.

Den finansiella modelleringen drog slutsatsen att det fanns betydande ekonomiska potential för termiska energilagringssystem, särskilt inom elprisområdena SE3 och SE4 i södra Sverige. Å andra sidan identifierades inga ekonomiskt lönsamma alternativ för batteri energilagringssystem, oavsett de studerade elprisområdena. Rapporten rekommenderar således termiska energilagringssystem och laststyrning som kostnadseffektiva åtgärder mot framtida prishöjningar i elpris.



Abstract

In the context of electricity, arbitrage trading involves taking advantage of existing price variations within electricity markets. The report conducted financial modelling for energy storage systems and demand-side load management for electricity arbitrage trading in single-family homes. The analysis included two different energy storage systems: a thermal energy storage system and a battery energy storage system. Additionally, electricity spot cost reduction was compared between electricity arbitrage trading and traditional energy efficiency measures such as air-to-water and ground-source heat pumps.

The report's findings indicated that air-to-water and ground-source heat pumps emerged as the most economically viable choices for reducing electricity spot costs, irrespective of the studied electricity price area. The thermal energy storage system, employing an insulated hot water storage tank, ranked the third most efficient in achieving cost savings. The battery energy storage system, represented by a lithium home battery system, demonstrated the lowest rate of cost saving among the analyzed energy efficiency measures.

The financial modelling highlighted the economic potential for thermal energy storage systems, particularly in southern Sweden's electricity price areas SE3 and SE4. On the other hand, no economically viable options for battery energy storage systems were identified, regardless of the studied electricity price area. As a results, the report recommends utilizing thermal energy storage systems and implementing demand-side load management as strategies to hedge against future electricity price volatility.

Key words: Electricity arbitrage trading, intraday electricity market, energy storage system, demand-side load management, single-family homes, Nord Pool, building performance simulation (IDA Indoor Climate and Energy), financial modelling.



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// Ahmed Ali



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1 Introduction

The introduction begins by providing a background to the thesis subject and a project description. Following this, it outlines the aim, purpose and the report's scope and limitations.

1.1 Background

In 1987, the United Nations published the Brundtland report, also called *Our Common Future*, which introduced the concept of sustainable development and described it as: "Development that meets the needs of the present without compromising the ability of future generations to meet their own needs [1]". Over the years, particularly after the publication of the Brundtland report, sustainable development has expanded its scope to encompass a more comprehensive definition, considering a wider range of factors, including economic, social, ecological, and cultural dimensions. This broader definition has contributed to shaping the sustainable development goals, which seek to "provide a shared blueprint for peace and prosperity for people and the planet, now and into the future [2]."

Access to affordable, reliable, and modern energy is essential for advancing various sectors within society, including agriculture, business, communications, education, healthcare, and transportation. These sectors all play crucial roles in promoting the sustainable development of society. The availability of modern energy sources is also necessary for addressing objectives such as poverty alleviation, economic growth, and improved living standards. Governments across the world prioritize energy security to ensure the reliability and stability of their energy supply systems, which in turn supports sustainable development goals. In a world where de-industrialization or de-modernization is impractical, addressing climate change through mitigation and adaptation is critical for sustainable development. [3], [4]

Figure 1 illustrates the global primary energy consumption by fuel source between 2000 and 2022, measured in exajoules (EJ) [5]. Measuring primary energy consumption includes accounting for the energy used by end-users as well as the losses that arise during fuel processing, thermal conversion, transmission, and distribution.

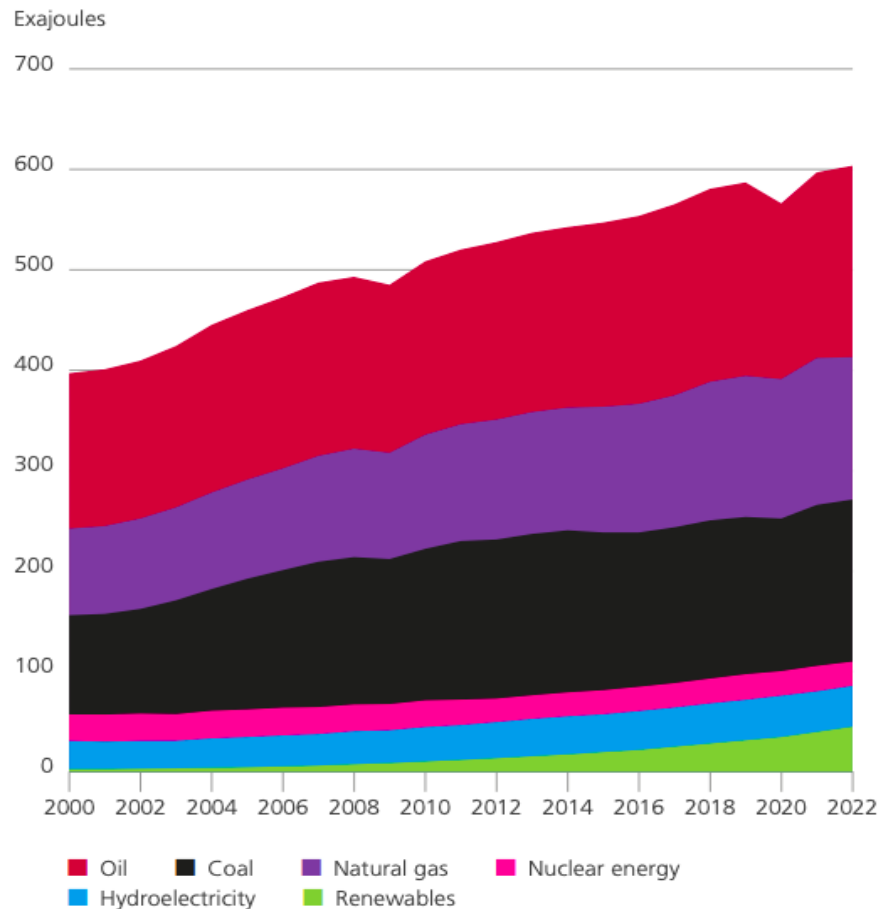


Fig. 1. Global primary energy consumption by fuel source [5].

In the European Union, buildings collectively contribute to approximately 40% of the energy consumption, and account for nearly 36% of greenhouse gas emissions [6]. The overall energy consumption of a building throughout its life cycle can be divided into two main components: embodied energy and operational energy. Embodied energy refers to the energy content of all the materials used in the building and the energy consumption during technical installations, construction/demolition, and renovation. Operational energy refers instead to the energy required to run the building in its day-to-day operation.

Much of the life cycle energy consumption of a building occurs in its day-to-day operation, at around 80-90 % of total energy use [7]. Electricity consumption for building operations currently represents 55% of the global electricity consumption [8]. Implementing energy efficiency measures in buildings can effectively reduce energy consumption or enhance the cost-effectiveness of energy performance while maintaining or even improving the quality of services provided, contributing to the sustainable development of the building sector.

1.2 Project description

Sweden's electrical grid is connected to the larger continental European grid, enabling electricity trading, and establishing a pan-European electricity marketplace. The inherent volatility observed in electricity markets can be attributed to various factors, including electricity demand, the availability of generation sources, fuel costs, geographic location, weather conditions, regulatory policies, transmission and distribution capabilities, and power plant availability. Within Sweden, the electricity market is divided into four distinct price areas, each characterized by its specific pricing dynamics. Figure 2 shows a map of Sweden, including the different electricity price areas. [9], [10]

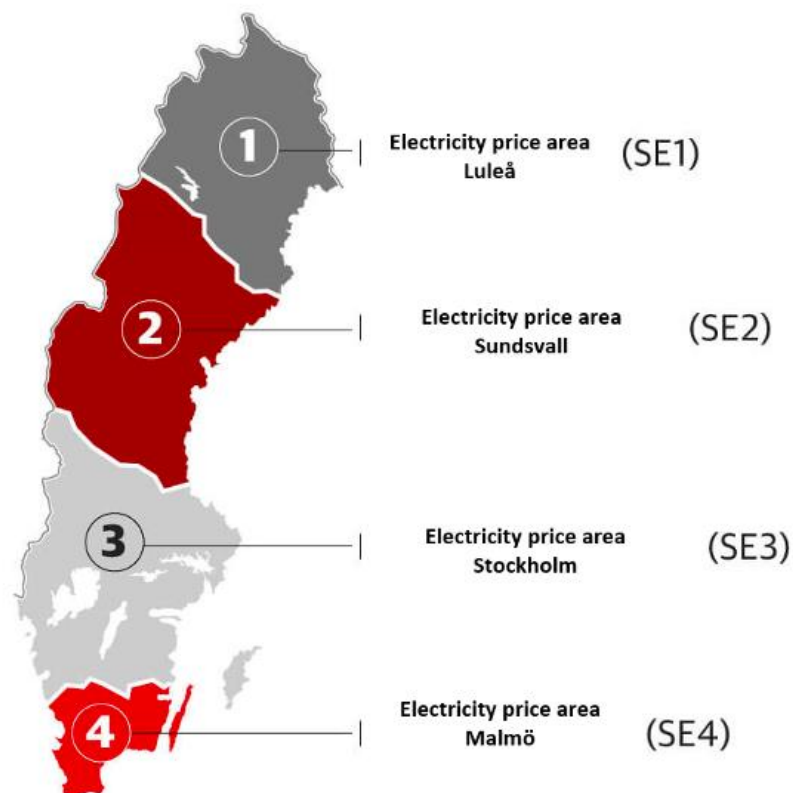


Fig. 2. A map of the different electricity price areas in Sweden [11].

In Sweden, an estimated 1.450 million single-family homes rely on electricity for heating and hot water. These homes employ various heating methods, including electric resistance heating and heat pump technologies, either individually or in combination. When considering that the average annual demand for heating and hot water in these single-family homes amounts to 16,000 kilowatt-hours (kWh), their collective electricity demand totals 2,648 megawatts (MW), accounting for roughly 6% of Sweden's total installed electricity capacity. [12], [13]



The estimated total electricity demand for heating and hot water in single-family homes assumes that all households have an equal annual demand for heating and hot water, with power consumption evenly distributed. However, this assumption needs to be revised due to variations in the efficiency of heating systems among these homes. Additionally, certain houses rely solely on electricity for part of their heating needs while using non-electric energy sources like biofuels for the rest. The equal distribution assumption also has limitations because energy usage fluctuates throughout the seasons and at different times of the year, leading to an uneven distribution of electricity demand.

Nevertheless, this figure underscores the substantial impact single-family homes have on the overall national electricity demand. To provide some context, the estimated electricity demand for heating and hot water in single-family homes surpasses the capacity of Sweden's largest power station, the Ringhals nuclear power plant, with its 2,204 MW installed generation capacity. [14]

This thesis will primarily focus on electricity arbitrage for single-family homes, specifically assessing the financial impact of shifting heating and hot water electricity demand to off-peak hours. The primary approach employed in the research involves implementing energy storage systems and demand-side load management strategies to leverage price differentials in the intraday electricity markets.

1.3 Aim and purpose

The purpose of the research is to quantify the financial impact of electricity arbitrage trading within a simulated single-family home. The report conducts an analysis of energy efficiency measures that involve energy storage systems and demand-side load management. This analysis specifically focuses on thermal and battery energy storage systems, as well as the concentration of electricity consumption during off-peak hours to leverage price differentials in the intraday electricity spot market.

The study aims to contribute to the understanding of intraday electricity arbitrage trading. It achieves this aim by employing simulation software (IDA-ICE), initially designed to evaluate building energy performance and consider the energy dynamics of electricity price areas in Sweden, particularly in electricity price areas SE1, SE2, SE3, and SE4. Ultimately, the study aims to identify cost-effective strategies households can implement to reduce their electricity costs.



1.4 Scope and limitations

The research's scope includes financial modelling for investments in energy storage system for electricity arbitrage trading. The aim is to compare the electricity spot cost savings with other energy efficiency measures, such as air-to-water and ground-source heat pumps. The electricity demand is derived from a building simulation model, created using input parameters commonly associated with actual Swedish single-family homes.

The electricity spot cost modeling is constructed based on hourly price data between 2020 and 2022, sourced from the European power exchange Nord Pool. Regarding the financial modelling, electricity spot price forecasting is restricted to three predefined scenarios of price development. The geographical scope of the modeling is confined to the electricity price areas in Sweden, encompassing price areas SE1, SE2, SE3, and SE4.

The report analyzes two energy storage system for electricity arbitrage trading: thermal and battery energy storage system. The report refrains from discussing the use of control systems for process management of charging, storage, and discharge, which capitalize on price differentials in the electricity markets. The focus solely rests on the monetary value associated with load shifting, assuming a highly reliable control system for the designated operations.

2 Theoretical background

This chapter provides a theoretical background necessary for understanding the outcomes of the thesis.

2.1 Electricity supply in Sweden

The electricity generation mix in Sweden predominantly relies on hydropower and nuclear power, which together contribute to about 75% of the total generation capacity as of 2022. Wind power, combined heat and power (CHP), and solar power supplement the remaining generation capacity. [15]

This electricity generation mix places Sweden among the countries with the least carbon-intensive electricity sectors in the world; only a fraction of the electricity generated in Sweden is provided by fossil fuels [16]. Sweden is a net exporter of electricity, maintaining alternating and direct current connections with several countries, including Norway, Denmark, Finland, Germany, Poland, and Lithuania [17]. In 2022, the nation's total electricity generation reached 170 terawatt-hours (TWh), with a net export of 39.4 TWh. Figure 3 illustrates the electricity generation in Sweden, measured in TWh. [15]

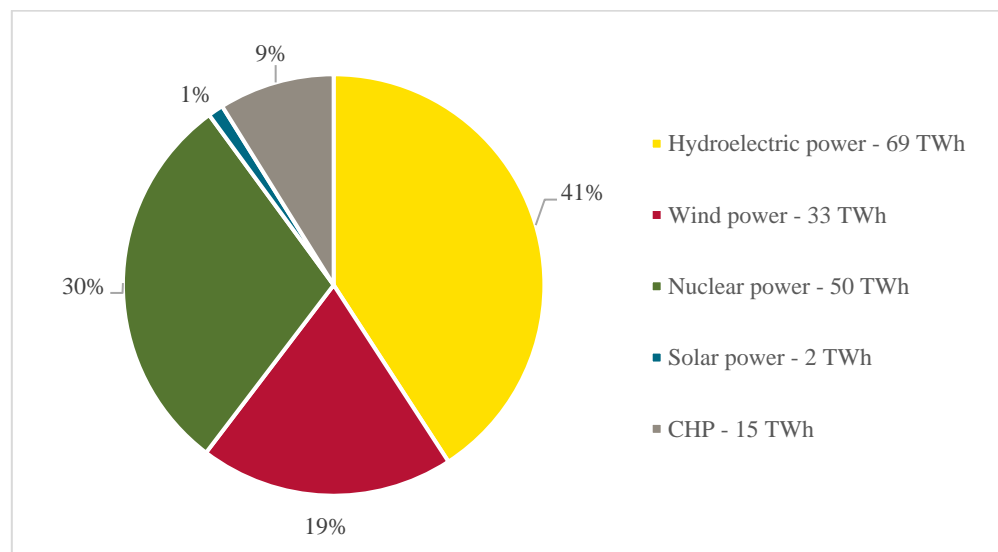


Fig. 3. Electricity generation in 2022, categorized by energy source. [15].

Electricity generation must constantly match the existing electricity demand in the market, as limited large-scale energy storage capacity is available. The collective electricity generation capacity can be categorized into three main groups: dispatchable, non-dispatchable, and operating reserves. Dispatchable energy sources like nuclear energy, hydropower, and CHP constitute the bulk of Sweden's electricity generation, representing a combination of stability and flexibility. Non-dispatchable generation sources, including wind and solar PV, are prominent in newly connected energy sources. These sources are characterized by intermittent power output, reflecting a less stable and flexible

power output than dispatchable energy sources. Operating reserves can be viewed as backup electricity generation resources that can be dispatched during periods of excess demand. Standard operating reserves in Sweden are often fossil fuel power plants including oil- and natural gas-fired power stations. [18]

2.1.1 Wind power development in Sweden

Wind power development in Sweden has been characterized by significant growth and expansion. A rapid capacity increase in wind power can be seen, growing from 2,000 MW in 2010 to 14,278 MW by 2022 and electricity generation from wind power was measured at 33,987 gigawatt-hours (GWh) in 2022, up from 2,487 GWh in 2010. [19]

To promote the sustainable development of wind power in Sweden, the Swedish Energy Agency (Energimyndigheten) and the Swedish Environmental Protection Agency (Naturvårdsverket) have jointly formulated a national strategy for wind power development. The national strategy envisions a total demand of 100 TWh of wind power development by 2040, with 80 TWh from onshore wind installations [20]. The trends in the development of wind power in Sweden between 2010 and 2022 can be seen in Figure 4, illustrating the number of installed wind turbines, the installed capacity measured in MW, and the electricity generation measured in GWh [19].

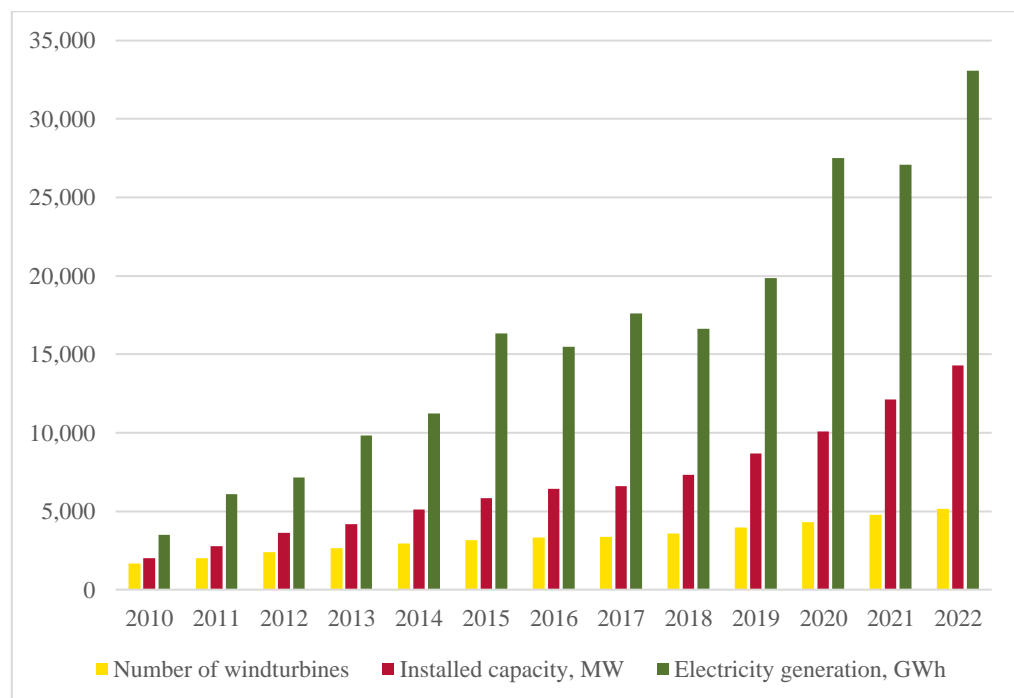


Fig. 4. Number of installed wind turbines, the installed capacity, and the electricity generation for wind power in Sweden [19].



Wind power contributes to the generation mix as a non-dispatchable energy source with intermittent power production. This intermittency results from the variable and dynamic nature of wind availability across different regions involved in power generation. The quantification of wind power generated by a wind turbine relies on specific parameters, including air density, the cross-sectional area of the wind turbine's blades, and wind velocity. Equation 1 outlines the calculation for wind power generation, expressed in watts (W). [21]

$$P = \frac{1}{2} * \rho * A * v^3 \quad (1)$$

Where:

P = the power output generated from the wind turbine (W)

ρ = the density of the air $\left(\frac{\text{kg}}{\text{m}^3}\right)$

A = the cross-sectional area of the wind turbine (m^2)

v^3 = the wind speed $\left(\frac{\text{m}}{\text{s}}\right)$

2.1.2 European electricity market (Nord Pool)

Nord Pool is Europe's largest electricity market and provides data on generation, transmission, consumption, and wholesale electricity spot prices in the pan-European power market. The Nord Pool electricity market gives weight to transparency in electricity pricing, stating that their products are "a transparent and reliable power price produced within our markets every hour, every day." Appendix 1 visually represents the online database containing historical electricity spot prices accessible via the Nord Pool website. [22]

The prices quoted by Nord Pool represent a share of the total electricity cost for single-family homes. Electricity prices from Nord Pool refer to electricity spot rates, which, when combined with grid usage fees and energy taxes, make up the total cost of electricity. Equation 2 shows the calculation of total electricity cost, which is the sum of the three components. The cost is quoted in Swedish kronor. [23]

$$C_{\text{ToT}} = C_S + C_G + C_T \quad (2)$$

Where:

C_{ToT} = the total cost of electricity for single-family homes (kr)

C_S = the spot cost of electricity (kr)

C_G = the grid usage fees (kr)

C_T = the energy tax (kr)

According to Swedenergy (Energiföretagen), a non-profit organization representing energy supply, distribution, sales, and storage companies, predicting electricity spot costs has become increasingly difficult. Electricity prices in several European countries have experienced significant increases, with various factors contributing to this phenomenon. These factors include heightened natural gas costs, limited availability of nuclear power, reduced hydropower output caused by recurring droughts, the unpredictable nature of intermittent renewable energy resources, a decline in conventional fossil fuel-based power generation, and the strain experienced by power and auxiliary services. [24]

Rising electricity costs have a more profound effect on single-family homes that rely on electric heating systems. This is primarily because heating expenditures correlate more strongly with electricity rates than alternative heating methods like district heating, biomass-fired boilers, and solar heating. Figure 5 illustrates electricity spot price development from January 2020 to December 2022, containing all price areas in Sweden (SE1, SE2, SE3, and SE4). Electricity spot prices are measured in kronor per megawatt-hours (MWh). [25].

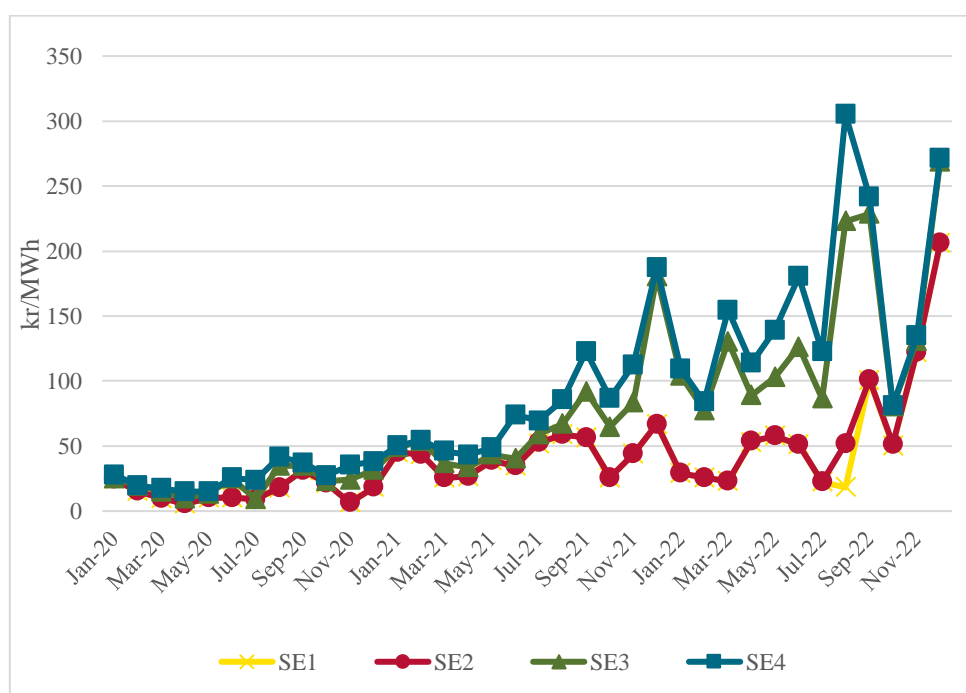


Fig. 5. Monthly average electricity spot prices in Sweden by price area (SE1, SE2, SE3, and SE4) [25].

2.1.3 Available electricity contracts in Sweden

Three main types of electricity contracts are available for single-family homes in Sweden: fixed, floating, and hourly rate contracts. Floating and hourly rate contracts are directly linked to the intraday electricity spot market, which means that contract holders are exposed to the continuous volatility of electricity markets. On the other hand, fixed-rate contracts offer insulation from price volatility in the electricity spot market. This is possible through a fixed electricity rate but typically includes a risk premium to protect against market volatility. [26]

Hourly rate contracts, introduced in 2012 following a Swedish government initiative, enabled single-family homes to engage in electricity arbitrage trading. These electricity contracts permit the measurement of electricity consumption on an hourly basis without incurring extra fees, a crucial component for taking advantage of price differentials in the intraday electricity markets. Consequently, an hourly rate contract represents the sole pricing mechanism for single-family homes to facilitate electricity arbitrage trading. [27]

Statistics Sweden, a government agency under the Ministry of Finance, produces official statistics in decision-making, research, and public discourse. Since February 2023, they have included data on the share of hourly rate electricity contracts in Sweden. The majority of end users have floating rate contracts, accounting for 53% of the overall electricity contracts. Fixed rate contracts account for 17% of the total, while hourly contracts constitute 10.4%. The remaining 20% comprises various other contract types, encompassing designated contracts and long-term power purchase agreements. Figure 6 illustrates the distribution of electricity contracts in Sweden. [28]

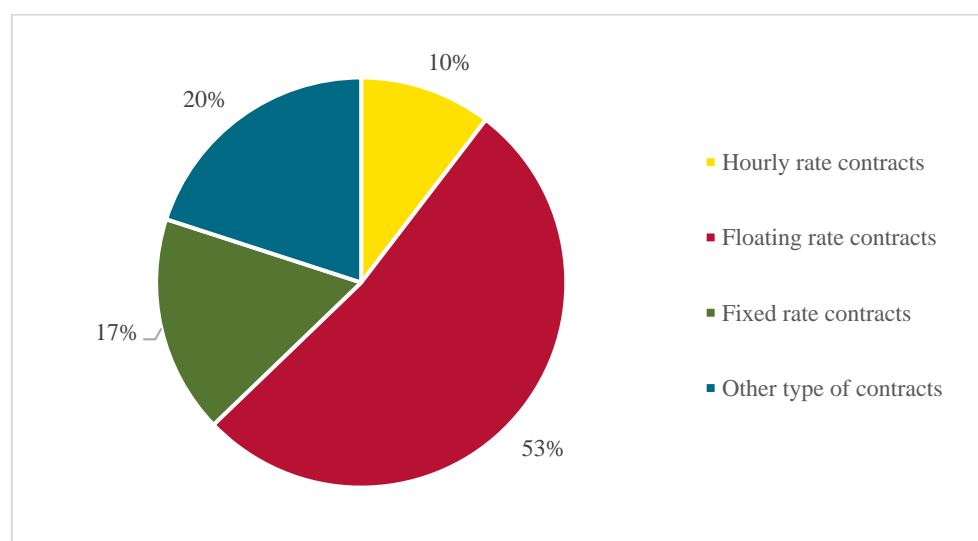


Fig. 6. Share of different electricity contracts in Sweden as of February 2023 [28].

2.1.4 Merit order effect in energy markets

The merit order curve within energy markets describes the sequence in which electricity generation sources respond to electricity demand. This order is determined by the marginal cost of electricity generation, with the lowest-cost energy sources being dispatched first, and as demand increases, facilitates with higher marginal costs are brought online to meet power demand. In the context of electricity generation, the marginal cost refers to the additional cost of generating one more unit of electricity. Generation sources with high marginal costs, such as natural gas power plants, are only dispatched during periods of excess electricity demand or when more cost-effective alternatives are unavailable. The primary objective of the merit order curve in energy markets is to manage the supply of electricity efficiently and economically. Figure 7 provides a visual representation of the merit order curve, with spot prices measured in cost per MWh. The spot price is set by the highest operational cost among available electricity generation sources [29], [30], [31]

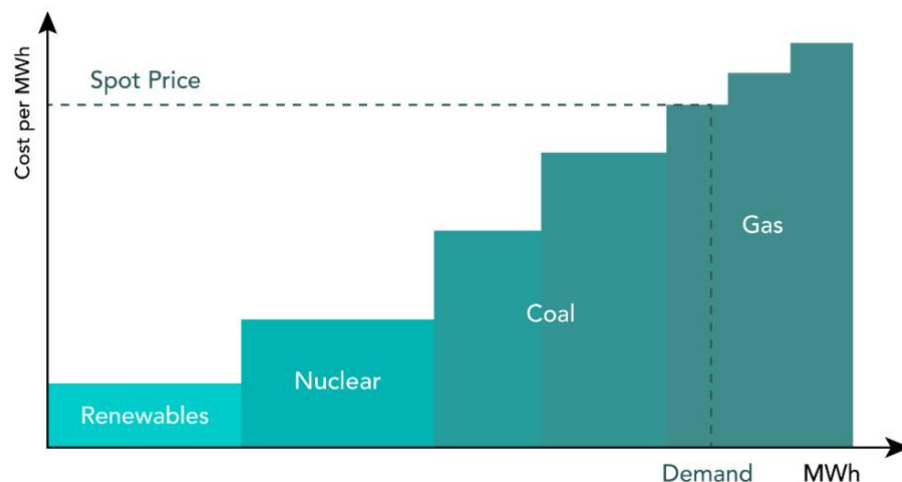


Fig. 7. Merit order curve in energy markets. [32]

2.2 Energy consumption in the building sector

The building and service sector in Sweden accounts for approximately 40% of the total energy consumption [33]. In the year 2022, the sector had a total energy consumption of 140 terawatt-hours (TWh) [33]. Within this sector, the combined energy consumption for heating and hot water in single-family homes amounted to 31.7 TWh, with 16 TWh of this energy sourced from electricity. This electricity consumption for heating and hot water in single-family homes constitutes 10% of the nation's total electricity production. [33], [12]

On average, single-family homes in Sweden consume around 16,000 kilowatt-hours (kWh) of energy per year for heating and hot water. The energy use varies depending on the construction year of the building, whereas buildings built more recently have lower energy use for heating and hot water. Homes constructed before 1940 have a higher average energy consumption of around 18,000 kWh per year, while those built after 2011 are more energy efficient, with an annual energy consumption of approximately 10,000 kWh. Figure 10 visually represents this data through a bar chart, showcasing the average annual energy consumption for heating and hot water in single-family homes. The chart categorizes this consumption data based on the year of construction of the homes. [12]

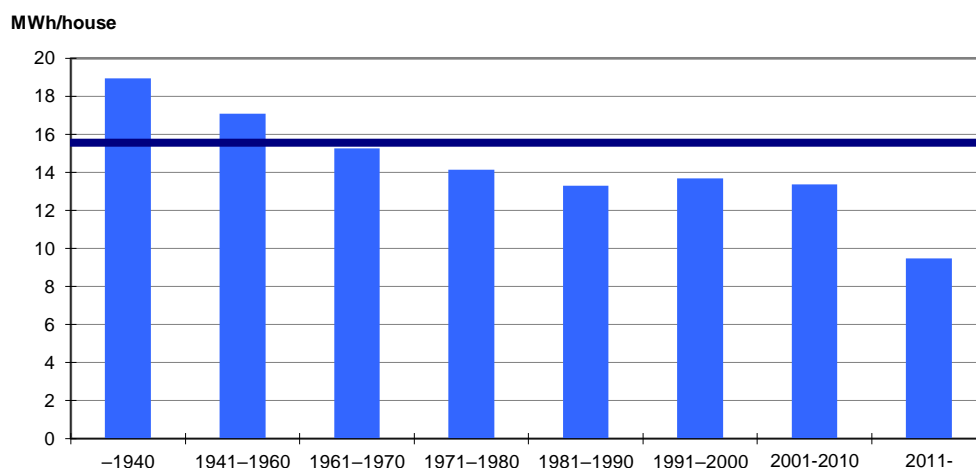


Fig. 8. Average annual energy consumption for heating and hot water in single-family homes [12].

For accurate comparisons of energy consumption data across different years, it's essential to consider a temperature correction factor in the calculations. This correction factor accounts for variations in energy consumption due to milder or harsher winters in specific years. By incorporating a temperature correction factor based on temperature data, typically spanning 30 years, energy consumption comparisons become more precise. [34]

2.2.1 Thermal comfort and indoor air quality

Thermal comfort is regarded as crucial in building energy performance and significantly impacts occupant comfort, well-being, and thermal discomfort. It is essential for buildings to be designed to ensure thermal comfort when they are occupied; according to the guidelines from Boverket [The Swedish National Board of Housing, Building, and Planning], a minimum operative temperature of 18 degrees Celsius is recommended. Discomfort has been shown to affect concentration, cognitive ability, and memory, among others. [35]

Indoor air quality is defined as the total levels of pollutants within the building envelope. Poor indoor air quality has been shown to give rise to irritation in occupants' respiratory systems. To obtain acceptable indoor air quality, effective ventilation systems need to be in place to replace pollutants with fresh air. Swedish building regulations specify that the minimum ventilation rate for return airflow should be 0.35 liters per second per square meter. [35]

2.2.2 Electric heating systems

Household energy consumption encompasses various uses such as heating and hot water, cooling, cooking, lighting, electrical appliances, and other end-users. Energy consumption data for households in the European Union (EU) reveals that 63% of the energy is allocated to heating, 15% to domestic hot water, 15% to lighting and electrical appliances, 6% to cooking, 0.5% to space cooling, and 1% to other applications. Outside temperatures notably influence the demand for heating; as outdoor temperatures drop, the need for heating increases to maintain indoor thermal comfort. Figure 9 presents the energy consumption distribution in EU households, categorized by intended end-use. [36]

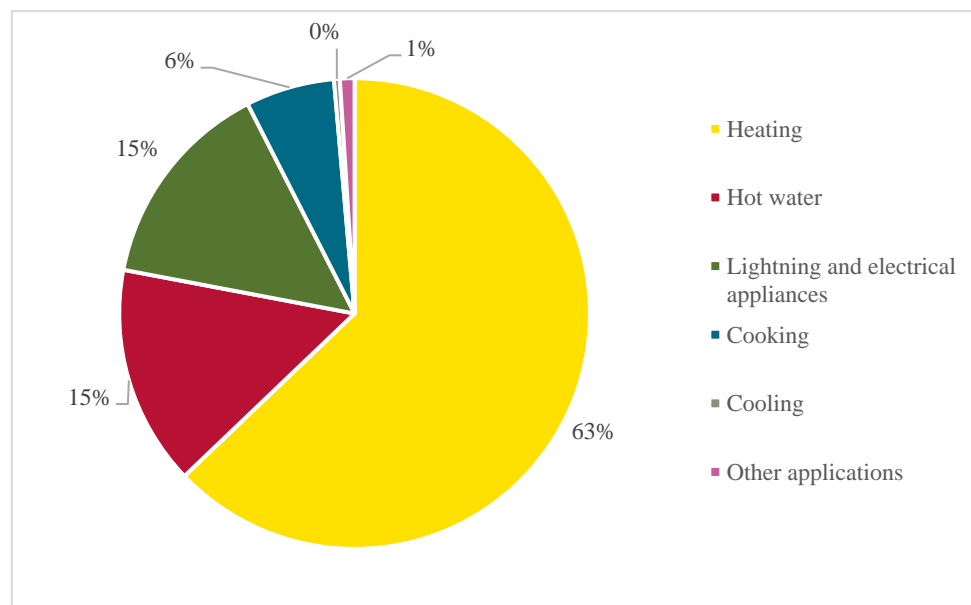


Fig. 9. Energy consumption in EU households [36].



Electric heating systems in single-family homes are predominantly divided into electric resistance heating and heat pump technologies. Electric resistance heating generates heat when an electric current flows through a conductor characterized by high resistance. This process radiates heat energy into the surrounding environment at an efficiency rate of 100% (COP=1). Control systems, typically in the form of thermostats, regulate heat output, maintaining the desired indoor temperature. The Coefficient of Performance (COP) for a heating system signifies the efficiency of heat generation in relation to the electricity consumption, as depicted in equation 3. [37]

$$\text{COP} = \frac{\text{Delivered heat energy}}{\text{Electricity input}} = \frac{Q}{W} \quad (3)$$

Where:

Q = delivered heat energy (W)

W = electricity input (W)

A heat pump represents a mechanical heating system that transfers heat between system boundaries, often in the opposite direction of spontaneous heat flows. These systems have key components such as a compressor powered by electrical energy, an expansion valve, an evaporator, a condenser, and a refrigerant. The heat transfer process between system boundaries depends on the refrigerant undergoing a complete vapor compression refrigeration cycle, involving stages of compression and expansion of refrigerant, changing its state from liquid to vapor to facilitate heat transfer. Heat pumps typically outperform electric resistance heating in terms of efficiency, with COP values above one, indicating an efficiency rate higher than 100 %. [37]

2.2.3 Heat distribution systems

Two primary methods for heat distribution within single-family homes are hydronic heating systems and radiant heating systems. In hydronic heating systems, water serves as the medium for transferring heat throughout a structure, while radiant heating systems relies on the radiant heat emitted by hot surfaces to provide warmth to the building. Buildings outfitted with hydronic heating systems offer an opportunity to integrate thermal energy storage systems into the building, facilitating electricity arbitrage trading. [38]

It is important to emphasize that while all homes equipped with electric heating systems can participate in electricity arbitrage trading, cost-effectiveness can vary significantly. Greater returns are anticipated for less efficient heating systems, whereas systems characterized by high efficiency and lower electricity consumption are likely to yield comparatively lower returns for electricity arbitrage trading.

2.3 Electricity arbitrage trading

In the context of electricity, intraday arbitrage trading involves taking advantage of price variations within electricity markets. If successful, the strategy results in cost savings for electricity, which can be viewed as an energy efficiency measure within a building. Electricity arbitrage trading in buildings relates to optimizing electricity purchases in response to existing energy market dynamics. Unlike other energy efficiency measures that permanently reduce overall consumption, electricity arbitrage trading does not permanently reduce the building's energy consumption; rather, it aligns energy consumption with hours of lower electricity prices. [39]

Load management strategies include two primary techniques: supply-side load management and demand-side load management. Supply-side load management focuses on optimizing electricity generation, transmission, and distribution processes to ensure efficient operations and achieve a lower leveled cost of electricity. Demand-side load management involves implementing strategies at the end user's premises to control and modify electricity load patterns. Demand-side load management often include offering monetary incentives to encourage end users to invest in energy-efficient equipment and practices. Figure 8 illustrates the process of shifting electricity consumption load shifting. [40], [41]

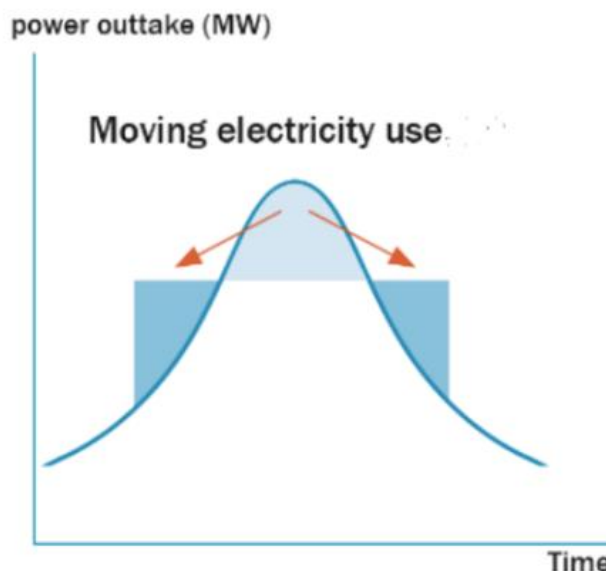


Fig. 10. Process of shifting electricity consumption between time periods [42].

Sweden has four primary electricity trading markets: forward and futures markets, day-ahead markets, intraday markets, and balancing markets. Forward and futures markets enable long-term trading, allowing electricity consumers to lock in prices for up to 10 years into the future. This type of trading primarily occurs in financial markets and is commonly done through power purchase agreements and over-the-counter trading. The difference

between forward and futures market is that forwards are customized agreements between two parties while futures are standardized contract traded in an organized exchange. [43], [42]

On the other hand, day-ahead markets facilitate trading within a shorter timeframe, typically between 12 and 36 hours before delivery. In day-ahead markets, electricity trading occurs at financially binding day-ahead prices for the following day. The minimum bid volume for the day-ahead market is 100 kW, which excludes single-family homes from trading due to this volume requirement being larger than their typical electricity needs. [44]

Intraday markets serve as spot markets, allowing trading up to 1 hour before delivery. Intraday market prices form the basis for pricing in floating and hourly rate electricity contracts. Notably, the intraday market has no minimum bid volume requirement, making it accessible for residential consumer trading. Prices are set based on the first-come, first-served principle. [45]

Balancing markets are primarily operated by the transmission system operator, in this case, Svenska Kraftnät [Swedish Power Grid], and are used for regulating frequency in the electricity grid. [46]

Effectively engaging in intraday electricity arbitrage trading requires participation in the intraday market to capitalize on price differentials between peak and off-peak periods. Furthermore, successful implementation of intraday electricity arbitrage trading for buildings relies on the presence of an energy storage system and demand-side load management. Figure 9 illustrates the various electricity trading markets, with the main distinctions being the timeframe and the types of market participants involved.

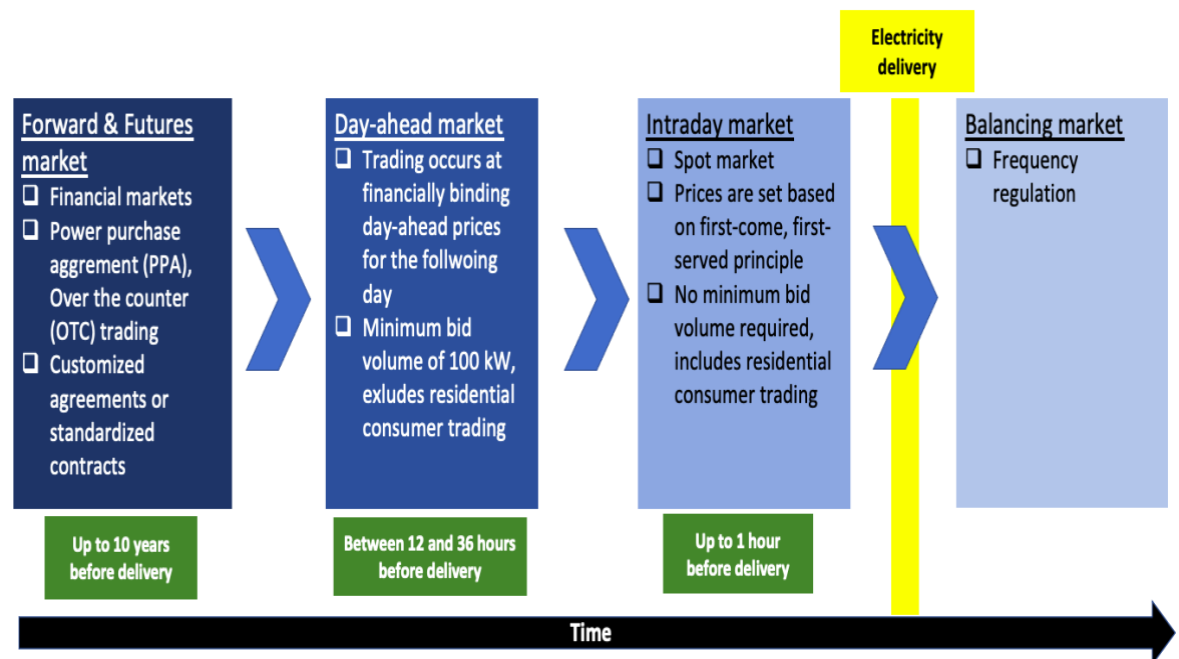


Fig. 11. Electricity trading markets in Sweden.



2.4 Energy storage

Energy can be stored using several methods, and energy storage technologies encompass various systems. Energy storage is a technology that enables the capture of energy generated at one time for use at a later period. Energy storage systems can store energy in various forms, including chemical, kinetic, and thermal energy, and subsequently convert them back into useful forms of energy. The advantages of energy storage include storing excess energy or taking advantage of more economical energy rates for later use, especially during periods of energy scarcity or higher energy tariffs. Energy storage systems play a pivotal role in the future development of renewable energy resources by enhancing the economic value of investments through addressing the intermittent nature of specific renewable energy resources. This chapter offers an in-depth exploration of thermal energy storage systems. [47]

2.4.1 Thermal energy storage system

Thermal energy storage systems can be designed to allow the storage of generated heat and cold to be used later, providing a mechanism to manage energy demand and enhance overall energy efficiency. Different types of storage methods for thermal energy storage systems include - sensible (air, water, and underground thermal energy storage), latent (employing phase change materials), and thermochemical (centered around chemical reactions). [48]

Thermal energy storage systems represent a mature and well-established technology with numerous systems and practical applications in commercial use today. In Europe, large-scale thermal energy storage systems are extensively utilized as heat storage solutions for district heating networks. These systems are charged during periods of low heat demand and then discharged to meet higher heat demand, reducing peak loads for the district heating network and achieving a balance between demand and supply curves. [49]

The thermal energy storage process cycle consists of three stages: charging, storage, and discharging. The thermal energy storage system is charged via a heat exchanger in the charging phase, with heat supplied from an external heat source. Subsequently, it retains the stored thermal energy for the intended duration and then discharges the accumulated energy to its final utilization through another heat exchanger. Figure 13 illustrated the energy flow across the different changes in the process cycle of thermal energy storage system.

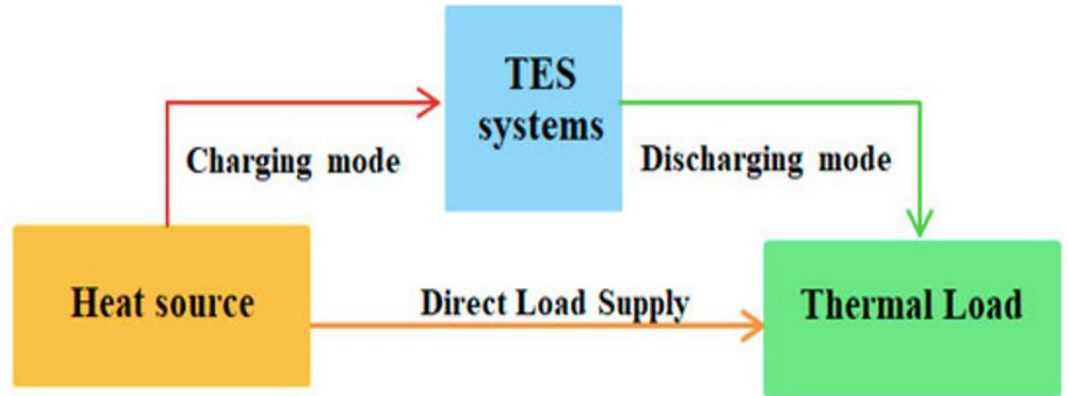


Fig. 12. Energy flow for thermal energy storage systems process cycle [49].

In the charging phase, we can characterize the energy balance as the difference in internal energy between the fluid enthalpy at the inlet (H_a) of the heat exchanger, and its outlet (H_b), while also taking into account the rate at which thermal energy is lost ($Q_{loss,1}$) from the thermal energy storage to the surrounding environment. The energy balance for the loading stage can be expressed using Equation 4.

$$\Delta U_1 = \dot{m}(h_a - h_b) - Q_{loss,1} \quad (4)$$

Where:

ΔU_1 = change in internal energy during the charging phase (W)

\dot{m} = mass flow rate for heat-transfer fluid ($\frac{\text{kg}}{\text{s}}$)

h_a = fluid enthalpy at the inlet of the thermal energy storage during charging phase ($\frac{\text{Joule}}{\text{kg}}$)

h_b = fluid enthalpy at the outlet of the thermal energy storage during charging phase ($\frac{\text{Joule}}{\text{kg}}$)

$Q_{loss,1}$ = heat loss to the surrounding environment during charging phase (W)

In the storage phase, the energy balance can be described by the relationship between the energy stored during the charging period (ΔU_2) and the energy lost to the surroundings during the storage phase (Q_2). Equation 5 presents the energy balance equation for the storage phase.

$$\Delta U_2 = Q_{loss,2} \quad (5)$$

Where:

ΔU_2 = change in internal energy during the storage phase (W)

Q_2 = heat loss to the surrounding environment during storage phase (W)



For the discharge period, the energy balance can be formulated as the change in internal energy between outlet (H_d) and inlet (H_c) temperature of the fluid enthalpy and the energy lost during the discharge. Equation 6 shows the energy balance during the discharge period:

$$-\Delta U_3 = \dot{m}(h_d - h_c) + Q_{loss,3} \quad (6)$$

Where:

ΔU_3 = change of internal energy of the thermodynamic system during the discharge phase (W)

h_d = fluid enthalpy at the outlet of the thermal energy storage during discharge phase $\left(\frac{\text{Joule}}{\text{kg}}\right)$

h_c = fluid enthalpy at the inlet of the thermal energy storage during discharge phase $\left(\frac{\text{Joule}}{\text{kg}}\right)$

Q_3 = heat loss to the surrounding environment during discharge phase (W)

The overall energy efficiency can subsequently be described according to equation 7:

$$\eta = 1 - \frac{\sum_{i=1}^3 Q_{loss,i}}{\dot{m}(h_a - h_b)} \quad (7)$$

Where:

$\sum_{i=1}^3 Q_{loss,i}$ = total heat loss for each phase in the thermal energy storage process cycle (W)

η = energy efficiency for the complete thermal energy storage process cycle

2.4.1.1 Sensible heat storage

Sensible heat storage is a method of storing energy by increasing the internal energy of a heat-transfer fluid. It is characterized by the storage of energy within a medium that does not undergo a phase transition. The energy capacity is a function of the temperature difference between the heat storage and the surrounding environment to which heat can be transferred, combined with the thermophysical properties of the heat-transfer fluid (density and specific heat capacity) and the volume of storage. Sensible heat energy in storage can be computed with equation with equation 8. [48]

$$\Delta Q_{sensible} = \rho V \int_{T_C}^{T_H} c_p(T) dT \quad (8)$$

Where:



$\Delta Q_{\text{sensible}}$ = the sensible energy stored (W)

ρ = the density of heat-transfer fluid $\left(\frac{\text{kg}}{\text{m}^3}\right)$

V = the volume of the heat storage system (m^3)

c_p = the specific heat capacity of the heat-transfer fluid medium $\left(\frac{\text{J}}{\text{K}}\right)$

dT = the temperature difference between the heat storage and the surrounding environment (K)

Sensible heat storage has been widely employed in various applications due to their simplicity and reliability. One notable advantage of sensitive thermal energy storage is its versatility, as it can be integrated into different sectors, such as industrial processes, residential heating and cooling, and grid energy management. By efficiently capturing excess heat during periods of low demand and releasing it when demand is high, sensible heat storage helps to balance energy consumption and reduce the strain on power generation during peak hours. This adaptability and proven performance make sensible heat storage valuable in pursuing sustainable and efficient energy utilization across diverse industries. [49]

2.4.1.2 Thermochemical energy storage

Thermochemical energy storage is a storage method that utilizes chemical reactions to both accumulate and discharge thermal energy. Thermochemical energy storage relies on reversible chemical reactions to store and release thermal energy. In the charging phase, thermal energy is absorbed by reactants to drive an endothermic reaction, resulting in products with a higher energy content. The energy stored within the chemical bonds of these products can later be utilized through a triggering mechanism, initiating an exothermic reaction and thus releasing the stored thermal energy. Figure 9 illustrates the chemical reactions in the thermochemical energy storage process between substance A (discharged material) and B (charged material), outlining the chemical reactions that occur when accumulating thermal energy and, subsequently, the chemical reactions that discharge thermal energy. [48]

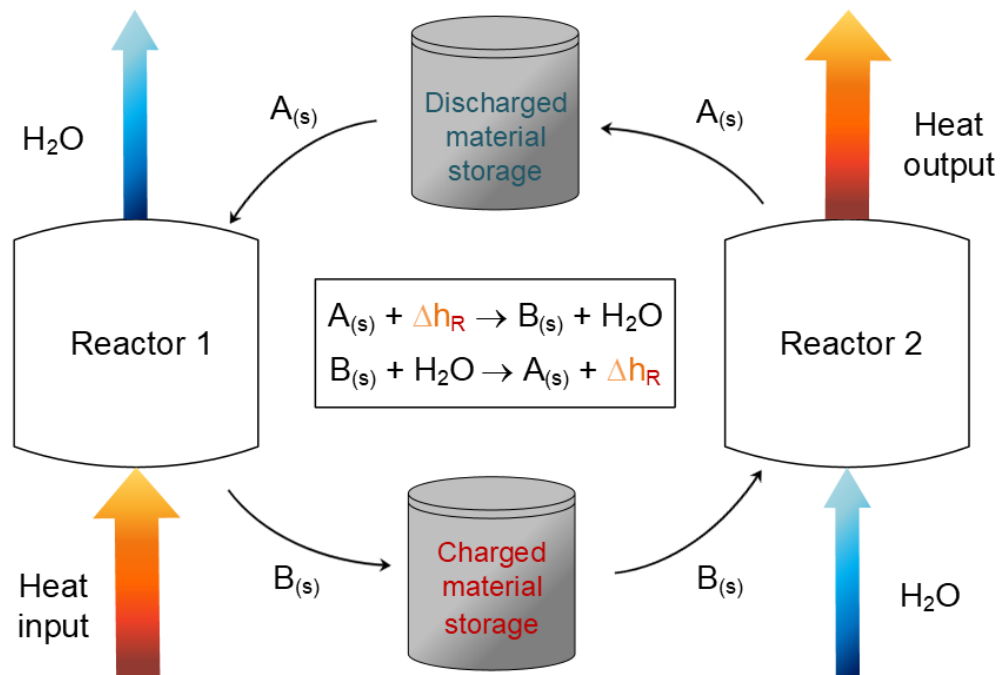


Fig. 13. General principal process for thermochemical energy storage between substance A (discharged material) and B (charged material) [50].

2.4.1.3 Latent thermal energy storage

Latent thermal energy storage is an energy storage method that stores energy in a storage medium that undergoes a phase change during the process cycle. Latent thermal energy storage utilizes phase change materials to store and release thermal energy during a phase change process transitioning between its solid and liquid states. [48]

Phase change materials exhibit unique properties that make them ideal for latent thermal energy storage applications. These materials can absorb or release large amounts of thermal energy during the phase change, also known as heat of transformation, while maintaining a constant temperature. The characteristic of phase change materials ensures that energy is efficiently stored during the transition from solid to liquid and vice versa. Phase change materials are selected based on their phase change temperature, heat capacity, and compatibility with the intended application. [51]

2.5 Energy storage systems for single-family homes

The study evaluates two energy storage systems intended for intraday electricity arbitrage trading: thermal energy storage utilizing insulated hot water storage tank and electrochemical energy storage, specifically lithium home battery system. Figure 10 presents an energy flowchart illustrating the conceptual operation of electricity arbitrage trading within the individual households. The house on the left represents the energy flow for a thermal energy storage system, while the house on the right presents the energy flow for a battery energy storage system.

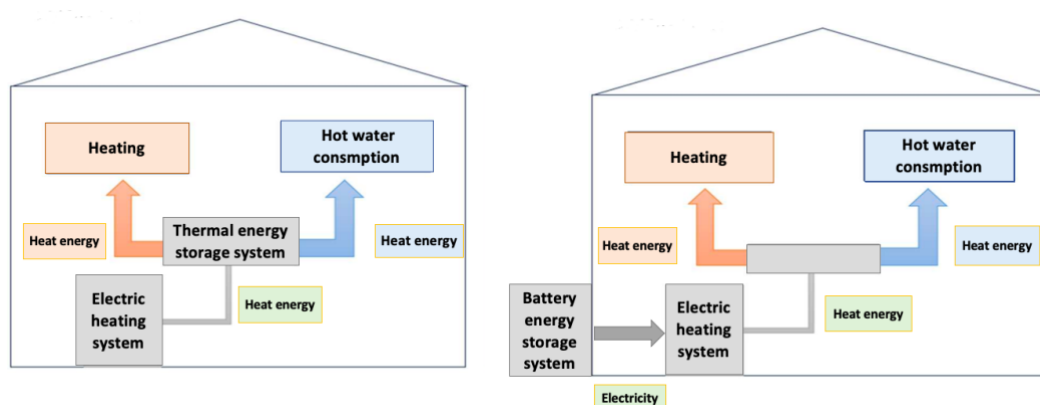


Fig. 14. An energy flowchart illustrating the conceptual operation of electricity arbitrage trading within individual households.

2.5.1 Insulated hot water storage tank

Insulated hot water storage tanks can store sensible thermal energy for later utilization when charged from a heat source. The energy stored in the tank is influenced by various factors, including the water volume, the temperature difference between the heated water and the surrounding environment where heat can be transferred, and the thermal transmittance value (U-value) associated with the insulation material. [52]

The management of heat loss is a critical consideration for insulated hot water storage tanks. Several factors impact heat loss, including the choice of insulation material, thickness, tank surface area, and duration over which heat loss occurs. Minimizing heat loss from insulated hot water storage tanks is paramount for enhancing energy efficiency and reducing overall energy consumption. A minimum of 150 mm mineral wool is recommended, as any less leads to excessive heat loss impacting the economic feasibility of the energy storage system. [53]

Following consultations with energy and climate advisors at the municipal agency, the report has assessed a tank capacity of 1000 liters as appropriate. Real-world experience indicates that this size aligns well with the available space in single-family homes. Appendix 2 includes an engineering drawing with measurements of the analyzed insulated hot water storage tank. [54]



2.6 Climate and Energy Policy

This section presents an introduction to Climate and Energy policy related to building energy efficiency.

2.6.1 EU Energy performance of buildings directive (2002/91/EC) and Sweden's Integrated National Energy and Climate plan

The Energy Performance of Buildings Directive is a legislative framework in the EU that intends to promote energy efficiency and the adoption of renewable energy in existing and newly built buildings. Promoted policies are intended to help achieve; a higher energy efficiency and fossil-free building sector by the year 2050, create a stable environment for investment decisions regarding the energy performance of buildings, and enable consumers and businesses to make more informed decisions regarding reduced energy cost and energy consumption. [55]

A set of building standards also supports Energy Performance of Buildings Directive called the energy performance of buildings standards. The European Committee for Standardization manages the standards, enabling a system of energy performance certificates for buildings. Energy performance certificates provide information on a building's energy consumption and are used as reference tools for regulatory requirements set by member states on building energy performance. [56]

Sweden has introduced a range of policies and measures to influence greenhouse gas emissions, both directly and indirectly. These strategies include regulatory approaches involving general economic instruments like carbon dioxide taxes and emissions trading. Additionally, Sweden has supplemented these strategies with specific measures designed to support technological advancements, facilitate market entry, and eliminate barriers associated with new energy technologies. In Table 4, you can find an overview of climate and energy policy goals from Sweden's Integrated National Energy and Climate Plan. [57], [58]

Table 1. An overview with key climate and energy policy objectives from Sweden's national energy and climate plan [58].

Target	Target year	Reference year
Sweden will not have any net emissions of greenhouse gases into the atmosphere and should thereafter achieve negative emissions	2045	1990
Reduction of -75 percent of emissions from sectors outside the EU emission trading system	2040	1990
Reduction of -70 percent of emissions from domestic transport	2030	2010
100 percent renewable electricity production	2040	-
Sweden's energy use is to be 50 percent more efficient	2030	2005



2.6.2 The Swedish Energy Agency and the Energy and Climate Municipal Advisory in Blekinge and Tingsryd

The Swedish Energy Agency is a Swedish government Agency under the Ministry of Climate and Enterprise. The agency works to promote energy efficient technology and investments in sustainable energy. As the most significant public financier and facilitator of energy efficient technology and sustainable energy, the agency is responsible for managing the energy transition on behalf of the Swedish government. Management of the energy transition involves approaches to support research and development, innovation, business development, commercialization, and internationalization of Swedish energy innovations. [59]

The agency is responsible for publishing official energy statistics. The purpose of the energy statistics is to provide an overall picture of the energy system and the progression of the energy sector. The collection of energy statistics includes areas like climate and energy policy, electricity market, district heating, biofuel, fossil fuels, residential and service sector, industry, transport, and global energy trends. [60]

The Energy and Climate Municipal Advisory in Blekinge and Tingsryd is a municipal advisory agency that offers support and advice on energy efficiency and reduction of environmental impact. The advisory targets the private sector, small and medium enterprises, cooperatives, and housing associations. The advisory offers cost-free service that is funded by the Swedish Energy Agency and is cooperation between 5 different municipalities in Blekinge and Tingsryd region. The advisory covers questions like energy efficiency, choice of heating system, additional insulation, change of windows, information about solar power, electric cars and charging stations, environmental cars, biofuels, electricity consumption, and subsidies for energy investment. [61]

2.6.3 Financial aid for energy efficiency measures in buildings

Historically, subsidies have been available in Sweden to promote energy efficiency in residential buildings, including multi- and single-family homes. These subsidies have varying funding structures; some come from the EU and others from national governmental agencies. Usually, specific requirements must be met to qualify for subsidies meant to promote energy efficiency in buildings. Examples of energy efficiency measures can be upgrading the heating system or improving the thermophysical characteristics of the building envelope. [62]

Several Swedish commercial banks also offer energy loans for improving energy efficiency in single-family homes. The loans are specific regarding what they can be used for but mainly include upgrading the heating system, renovating windows, additional insulation, and installing solar panels. Effective annual interest rates, loan period, and loan amount can vary between the banks but generally offer better loan terms than consumer loans. [63]



2.7 Previous studies

In this section, an overview of two prior studies conducted in the field of electricity arbitrage is provided.

2.7.1 An assessment of European electricity arbitrage using storage system

"An assessment of European electricity arbitrage using storage systems" is a report by F. Nunez, D. Canca, and A. Vargas published in 2021. The report analyses the viability of the electricity arbitrage business with lithium-ion batteries for a sample of European countries. The authors explain that adding renewable generation capacity to the energy mix will bring an "unmanageable nature" to the energy system, increasing price volatility and making the development of arbitrage business models that take advantage of increasing price fluctuations more interesting. According to the study, the effectiveness of electricity arbitrage is strongly influenced by daily price variations (differences between maximum and minimum prices throughout the day) and technical and economic characteristics of the electrical storage system. The conclusions provided by the study can be used by entrepreneurs, regulators, and technology research centers to determine in which country the business of battery arbitrage is profitable.

To determine the best energy purchase and sale strategy for each country, an optimization trading model based on Linear Mixed-Integrated programming was developed by the authors to optimize the arbitrage strategy. Cash-flows obtained from the optimization model were then used to calculate two financial indicators: Net Present Value (NPV) and Internal rate of return (IRR). The methodology used in the report focused on developing a method based on market information, technical information, and financial information to compare the business of electricity arbitrage with lithium-ion batteries for 24 European countries.

The report's findings show that energy arbitrage is not considered a profitable business for any of the studied countries, considering the investment cost used in the report for lithium-ion batteries. However, if battery technology continues the advancement trends in performance and price, energy arbitrage will be profitable for all the sample countries in a few years. The report also concludes that there are differences in the profitability of the electricity arbitrage business between the sample countries, where some countries offer more profitability than others. Additional variables affecting the profitability of the electricity arbitrage business are the investment cost, tax requirements in each country, and daily price variations. [64]



2.7.2 Arbitrage analysis for different energy storage technologies and strategies

“Arbitrage analysis for different energy storage technologies and strategies” is a report written by X. Zhang, C. Qin, E. Loth, Y. Xu, X. Zhou, and H. Chen published in 2021. The report investigates the potential economic advantages of electricity arbitrage for three different energy storage technologies. Energy storage technologies examined in the report include lithium-ion batteries, compressed air energy storage, and pumped hydro storage. Energy storage systems are proposed as a viable solution to addressing the challenges of integrating renewable energy sources into the power grid. By balancing power supply with demand, these systems enhance the value of intermittent renewables, resolving the problematic nature of their fluctuating power output. Energy storage systems benefit power grid resilience but have vital challenges, including cost, scale, and effectiveness.

The methodology used in the report to determine potential benefits for stakeholders investing in the energy storage system is first to develop an arbitrage strategy framework that considers storage technologies with different overall efficiencies and life cycle costs. Secondly, a techno-economic analysis is performed based on energy storage investment costs and fixed and variable operation and maintenance costs. Hourly electricity price data is collected from the California Independent System Operator (CAISO) in the United States to estimate the potential economic performance of the developed electricity arbitrage strategy.

The report concludes that pumped hydro storage is most cost-effective for electricity arbitrage in large-scale energy storage applications but is limited in increasing capacity due to concerns with appropriate site conditions when developing dams. Compressed air energy storage was more cost-effective than lithium-ion batteries but required more technology development before widespread usage. [65]



3 Methodology

3.1 Literature review

The research was initiated with a literature review, which analyzed various sources, including articles from scientific databases, electricity wholesale price data, websites, regulatory agencies, and theoretical books. Recurring interviews with energy and climate advisors at the Municipal Energy and Climate Advisory in Blekinge and Tingsryd supplemented the research, contributing with industry-specific knowledge about energy efficiency and energy efficiency measures in buildings. Additionally, interviews were held with the thesis advisor from Linnæus University, improving the research with relevant feedback and a thorough understanding of building energy performance simulations.

3.2 Building performance simulation software (IDA-ICE)

IDA Indoor Climate and Energy (IDA-ICE) is building performance simulation software used for multi-zone simulation applications for the study of thermal indoor climate as well as the energy consumption of the entire building. The developers ensure that the software “*accurately models the building, its systems, and controllers - ensuring the lowest possible energy consumption and the best possible occupant comfort.*” IDA-ICE software allows for input of building technical parameters to produce output with tables, charts, reports, and plots on zone heat and energy balances, heat and mass transfer, indoor air quality, and energy demand. Figure 14 shows marketing material highlighting aspects of IDA-ICE software. [66]

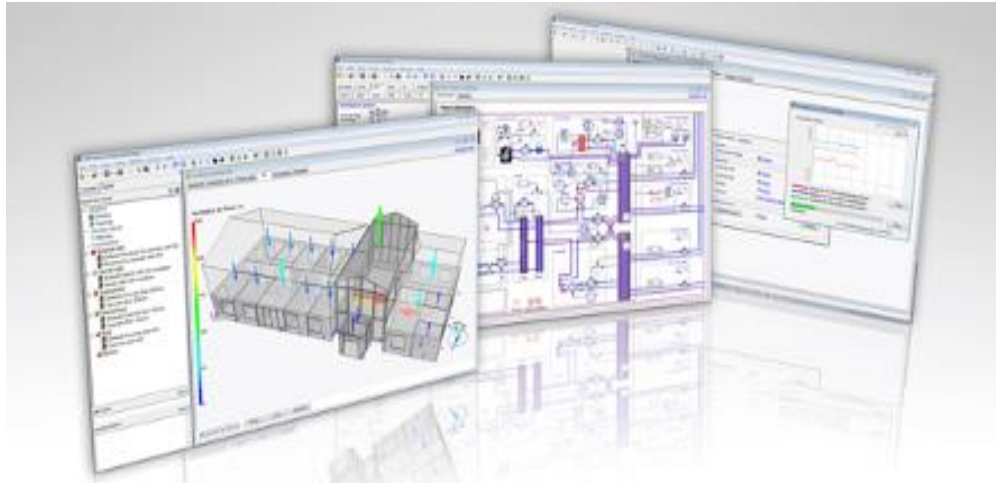


Fig. 15. Marketing material from IDA-ICE [66].

The IDA-ICE software performs hourly calculations of electricity consumption required for heating within the building simulation model. Estimating the electricity spot cost associated with heating and hot water in a single-family home relies on gathering historical price data and aligning it with the corresponding electricity consumption in the simulation. We operate under the assumption of a linear relationship between electricity consumption and heating costs. In simpler terms, we consider that the electricity spot cost for heating is directly proportional to the simulated electricity consumption, as outlined in Equation 9.

$$C_H(E_H) = C \times E_H \quad (9)$$

Where:

C_H = electricity spot cost for heating, including heating and hot water consumption (kr)

C = electricity spot cost per unit of consumption $\left(\frac{\text{kr}}{\text{kWh}}\right)$

E_H = electricity consumption for heating, including heating and hot water consumption (kr)

3.3 Case study single-family home design

The single-family home in this case study is a theoretical building designed to mimic the characteristics of a real single-family home found in Sweden. It is created using input parameters commonly associated with actual Swedish single-family homes. The floor plan of this simulated building is based on technical drawings, as depicted in Figure 16, which represent the typical layout of a Swedish single-family home.

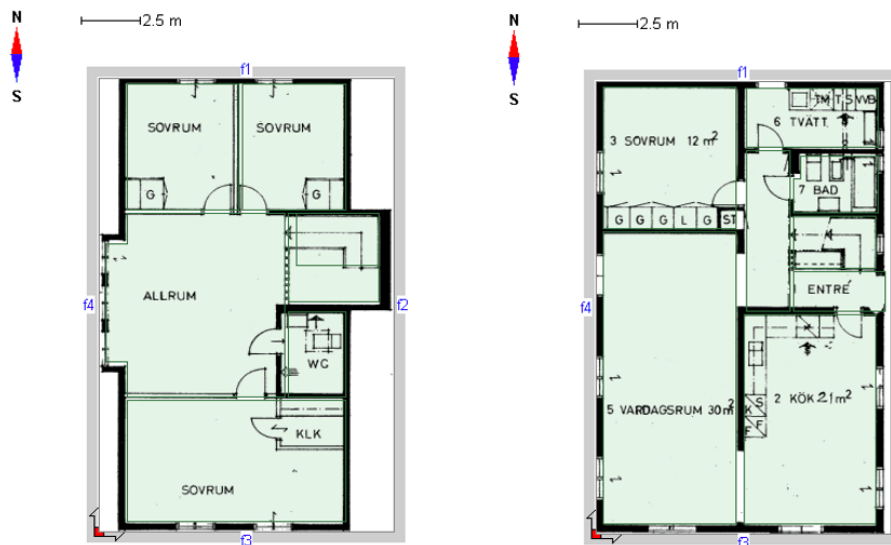


Fig. 16. Floor plan of the case study single-family home.

This building is structured into two levels: a ground floor and an upper floor. It features four bedrooms, two living rooms, two bathrooms, and one laundry room. The exterior of the building is assumed to be covered with wood paneling, as shown in Figure 17.

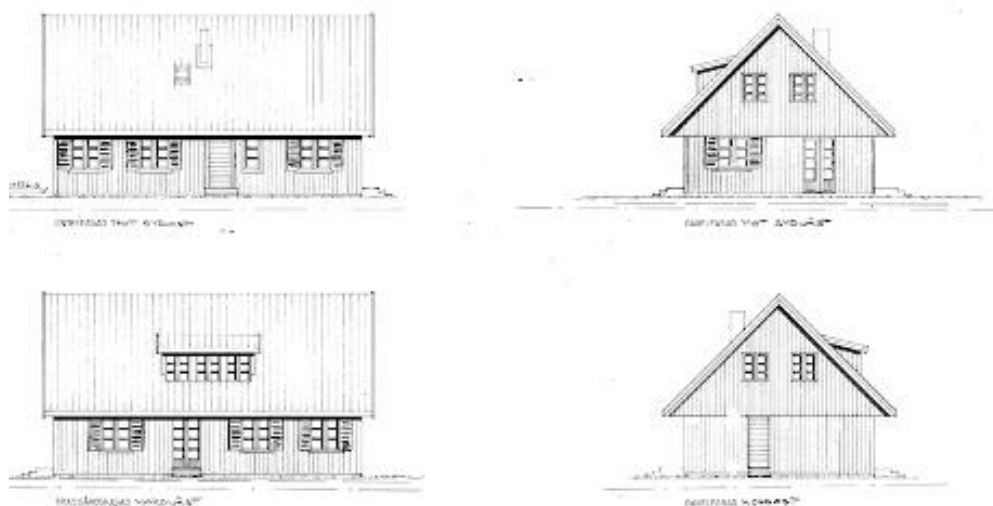


Fig. 17. Front view and sideview of the case study single-family home.



3.4 Building simulation model and assumptions

The building simulation model relies on several input parameters for various categories, such as generator efficiency for standard heating and cooling systems, domestic hot water consumption, and air handling units. A detailed summary of input parameters can be found in Table 2.

Table 2. General data input parameters for case study single family home.

Parameter	Value	Reference
Location	Luleå, Sundsvall, Stockholm, & Malmö	
Climate	Luleå, Sundsvall, Stockholm, & Malmö	IDA-ICE
Wind profile	Suburban	IDA-ICE
Holidays	Public holiday in Sweden	Wikipedia
Carrier for heating, cooling and domestic hot water	Electric heating	IDA-ICE
COP Heating	1	IDA-ICE
COP Cooling	-	
COP Domestic hot water	1	IDA-ICE
Average hot water use	60 L/ per occupant and day	Energimyndigheten
Standard ventilation unit with heat recovery (FTX)	0.35 L/(s m ²)	BBR29

The construction materials used in the building simulation model, and their thermophysical properties were determined based on input data from IDA-ICE resource database. Table 3 provides an overview of the building construction and thermophysical properties of construction material, including thickness, thermal conductivity, density, and specific heat capacity.



Table 3. Building construction and thermophysical properties of construction material.

Building elements	Material	Thickness (mm)	Thermal conductivity (W/m K)	Density (kg/m ³)	Specific heat capacity (J/ kg K)
Basement slab towards ground, 357 mm	Chip board	22	0.13	1000	1300
	Light insulation	335	0.036	20	750
Basement wall toward ground, 225 mm	Gypsum	35	0.22	970	1090
	Frames cc600+cross, insulation	195	0.052	92	2010
	Wood	25	0.14	500	2300
External floors, 357 mm	Chip board	22	0.13	1000	1300
	Light insulation	335	0.036	20	750
Internal floors, 303 mm	Wood	10	0.14	500	2300
	Chip board	22	0.13	1000	1300
	Frames cc600, insulation	245	0.044	56	1720
	Gypsum	26	0.22	970	1090
	Gypsum	35	0.22	970	1090
	Frames cc600+cross, insulation	195	0.052	92	2010
External walls, 255 mm	Wood	25	0.14	500	2300
	Gypsum	52	0.22	970	1090
	Air gap	64	0.17	1,2	1006
Internal walls, 146 mm	Light insulation	30	0.036	20	750
	Light insulation	365	0.036	20	750
	Wood	22	0.14	500	2300
Roof, 400 mm	Gypsum	13	0.22	970	1090
	Wood	8	0.14	500	2300
	Aluminum	2	237	2710	0.91
	Light insulation	25	0.036	20	750
Door, 35 mm					



The operational schedule of the building, encompassing occupancy, lighting, and equipment, is set to mirror typical household living patterns. In practical terms, this translates to the simulation software assuming that occupants are away from 08:00 to 15:00 on weekdays, partially absent between 15:00 and 17:00, and present at home throughout the weekends. The number of occupants in the households is estimated at four people.

The building simulation model's dimensions comprise a floor area of 196 square meters and a volume of 480 cubic meters, see appendix 3 for a 3D visualization. The windows comprise 6.4% of the building envelope area, totaling 14 windows. The windows integrated into the building simulation model were double-glazed. Each window is accompanied by a water radiator with a designed power output of 0.8 kW. The U-value for the building envelope was 0.4457 W/(m² K). Table 4 shows a breakdown of building specific parameters provided by IDA-ICE.

Table 4. Building simulation model specific parameters.

Category	Value	Unit
Heated floor area	192	m ²
Volume	480	m ³
Building envelope area	392	m ²
Windows area per envelope area	6.4	%
Average U-value building envelope	0.4457	W/(m ² K)
Average U-value windows	2.9	W/(m ² K)

3.5 Sensitivity analysis

Because the operational lifespan of each energy efficiency equipment assessed in the report extends beyond the timeframe covered by the collected price data, electricity spot price forecasting was practiced for the financial modeling. The sensitivity analysis examines three distinct scenarios regarding future electricity spot price development. The initial scenario assumes a 2% annual growth in hourly electricity spot prices; the second scenario anticipates a yearly increase of 5%, and the third scenario estimates an annual increase of 10%. The calculation of the electricity spot price involved determining the mean cost of spot prices between 2020 and 2022 and then multiplying it by the predetermined growth rate, as outlined in Equation 10:

$$COE_n = \frac{(COE_{2020} + COE_{2021} + COE_{2022})}{3} \times (1 + g)^n \quad (10)$$

Where:

COE_{2020} = the spot cost of electricity in year 2020 $\left(\frac{kr}{kWh}\right)$

COE_{2021} = the spot cost of electricity in year 2021 $\left(\frac{kr}{kWh}\right)$

COE_{2022} = the spot cost of electricity in year 2022 $\left(\frac{kr}{kWh}\right)$

g = the scenario of predetermined annual growth rate of electricity spot cost

n = the number of years for electricity spot price forecasting

For a detailed breakdown of the projected electricity spot prices based on these scenarios across all price areas in Sweden (SE1, SE2, SE3, & SE4), please refer to Appendix 3.

3.6 Financial modelling: IRR, NPV, DCF, Payback Period

The financial modelling of electricity arbitrage trading involved incorporating various performance metrics for respective energy systems. Performance metrics can be seen summarized in Table 6. These metrics are derived from the existing commercial technologies within the Swedish energy market. When assessing the economic viability of investing in these systems, we factor in the tax deduction available for the installation costs (specifically, labor expenses) associated with energy-efficient equipment, known as "ROT-avdrag", as both systems are eligible for this tax benefit. However, the investment assessment did not include an additional tax deduction applicable to battery storage systems. This decision was made because this tax incentive is only granted when the installation is combined with a solar system. The model examined in this case study comprises a standalone energy storage system and does not integrate a solar system.

Table 5. Economic metrics considered in the financial modelling of respective energy storage system.

Parameter	Insulated hot water storage tank	Lithium home battery storage
Storage capacity	1000 liters (92 kWh) ¹	14 kWh ²
Available energy storage capacity	90 kWh ¹	13.5 kWh ²
Life span	25 years ³	15 years ³
Initial investment outlay (Material cost)	47 833,00 kr	79 800,00 kr
Cost for installation and delivery (Labor cost)	14 349,90 kr	23 940,00 kr
Tax relief	- 4 304,97 kr	- 7 182,00 kr
Cost for operation and maintenance	-	-
Total cost	57 877,93 kr	96 558,00 kr

In addition to the computation of cost savings for electricity expenses, the report included supplementary financial metrics to evaluate the economic prospects of electricity arbitrage trading. The report included financial metrics such as the internal rate of return (IRR), net present value (NPV), discounted cash flow (DCF) model, and payback period for the two energy storage systems.

¹ According to product "EKS 1000 – Nibe".

² According to product "Powerwall 2 – Tesla".

³ According to industry knowledge from manufacturers and suppliers.



The internal rate of return (IRR) is a financial metric used to assess the profitability of an investment or project. It measures the rate at which the project's cash flows, both positive and negative, will result in a net present value (NPV) of zero. In other words, it is the interest rate at which the project's inflows and outflows break even. [67]

If the calculated IRR is higher than the required rate of return or the cost of capital, the project is considered profitable and may be a good investment. On the other hand, if the IRR is lower than the required rate of return, the project might not be financially sound. Comparing the IRR to the cost of capital helps decide whether the project should be pursued. The internal rate was calculated according to equation 11:

$$0 = NPV = -C_0 \sum_{n=1}^n \frac{C_f}{(1 + IRR)^n} \quad (11)$$

Where:

NPV = the net present value of the investment through its lifetime discounted to today's value

C_f = the cash flow gained per period

n = the number of periods into the future

IRR= the discount rate which results in a net present value of zero

C_0 = the initial investment cost

The report utilizes a discount cash flow model that employs a seven percent discount rate to discount the free cash flow generated from the cumulative savings in electricity spot costs resulting from electricity arbitrage trading. The report also includes a payback period calculation to determine the years required for the cumulative cash savings to recover the initial investment cost of the energy storage system. Payback period was calculated according to equation 12.

$$\text{Payback period} = \frac{\text{Initial investment cost}}{\text{Cash flow gained per period}} \quad (12)$$



3.7 Validity and reliability of research methodology

The quality of a well-constructed report regarding electricity arbitrage trading in the single-family homes market depends on its ability to quantify cost savings accurately. The analysis focused on three critical factors: electricity consumption for heating and hot water, electricity spot costs, and the investment cost associated with installing an energy storage system. The assessment accuracy for these three factors dictates the validity of the report and its analysis. The manual input of historical electricity prices also introduced the potential for errors, meaning any inaccuracies in cost calculations could be linked to the accuracy of manually input data.

4 Results and analysis

This section presents results and analysis of the report.

4.1 Advantages and disadvantages of energy efficiency measures

Table 6 presents advantages and disadvantages of the analyzed energy efficiency measures in single-family homes.

Table 6. Advantages and disadvantages for each energy efficiency measure.

EEM	Advantages	Disadvantages
Insulated hot water storage tank	<ul style="list-style-type: none"> • Possibility of storing excess heat energy, allowing for electricity arbitrage trading • Cost-effective, particularly in terms of initial investment cost 	<ul style="list-style-type: none"> • Space requirements for installment can be a limitation for homes with limited space • Limited hot water capacity because of the tank's finite volume capacity • Standby heat loss occurs over time because of insulation imperfections
Lithium home battery storage	<ul style="list-style-type: none"> • Possibility of storing excess electrical energy, allowing for electricity arbitrage trading • If paired with solar systems can access tax deductions, lowering initial investment costs 	<ul style="list-style-type: none"> • High initial investment cost • The battery's capacity and performance may degrade with time, requiring replacement • Limited storage capacity
Air-to-water source heat pump	<ul style="list-style-type: none"> • Permanently improves energy efficiency, resulting in lower energy consumption and cost • Lower initial investment cost compared to ground source heat pump • Installation flexibility by not requiring ground loops, which is advantageous in areas where drilling is not possible 	<ul style="list-style-type: none"> • High initial investment cost. • Seasonal efficiency variations: When the outside temperature drops, the system may experience lower efficiency • Noise generation may be prevalent in the fans that draw in air from the surrounding environment
Ground source heat pump	<ul style="list-style-type: none"> • Permanently improves energy efficiency, resulting in lower energy consumption and cost • Higher seasonal efficiency as the ground extracts and transfers heat experiences lower temperature variation • Long lifespan and low maintenance 	<ul style="list-style-type: none"> • High initial investment cost • Space requirements for the ground loop and required site suitability • Design and installation complexity, considering factors like soil composition and thermal conductivity

4.2 Historical electricity spot price analysis

Price data collected for price areas SE1, SE2, SE3, and SE4 within Sweden consisted of hourly spot rates spanning 2020, 2021, and 2022. The dataset resulted in 105,216 price quotations. The findings reveal that intraday electricity spot prices show an increasingly noticeable pattern over the observed timeframe, with distinct peak and off-peak periods. Electricity prices from 2022 in price areas SE3 and SE4 showed a clear distinction between peak and off-peak periods. The initial peak occurred during the morning hours, approximately from 06:00 to 13:00. The second peak can be seen between 16:00 and 21:00. A price reduction was observed in the interval between 13:00 and 16:00. However, this decrease is overshadowed by the price decline observed between 00:00 and 05:00.

The observed trends in these electricity markets over a 24-hour cycle substantiate the fundamental principle underpinning electricity arbitrage trading strategies – the existence of price differentials in the intraday electricity markets. This trend suggests promising opportunities for future investments in energy storage systems and demand-side load management, especially if the observed trends in electricity price volatility continue. Figure 18-21 illustrates annual median electricity spot prices for each hour during a 24-hour cycle, measured in kronor per kilowatt. The figures are divided by each price area in Sweden (SE1, SE2, SE3, and SE4).

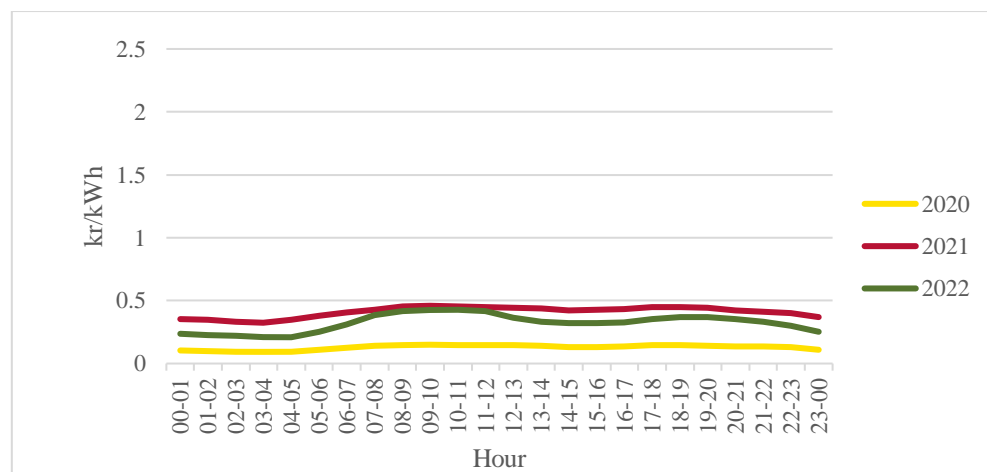


Fig. 18. Annual median spot prices for each hour in electricity price area SE1 during 2020, 2021, and 2022.

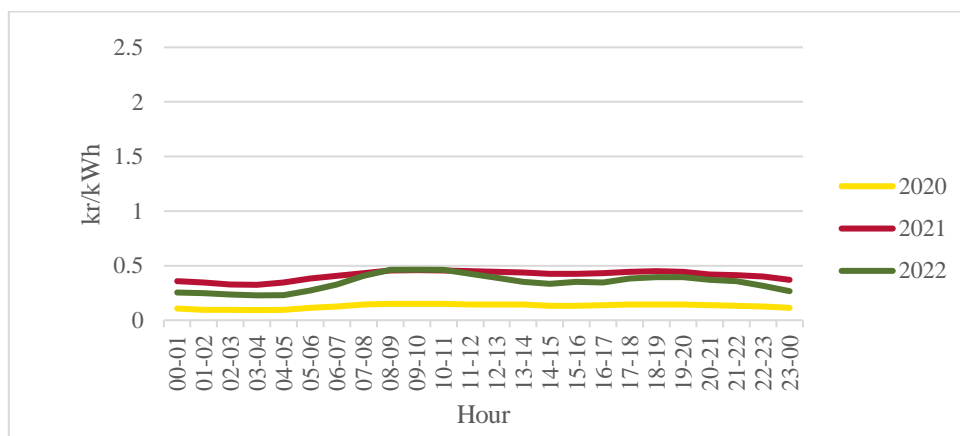


Fig. 19. Annual median spot prices for each hour in electricity price area SE2 during 2020, 2021, and 2022

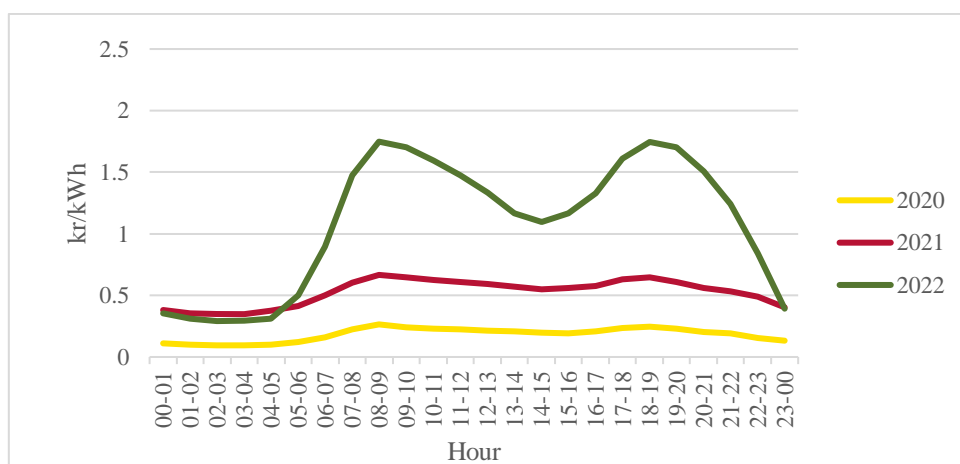


Fig. 20. Annual median spot prices for each hour in electricity price area SE3 during 2020, 2021, and 2022.

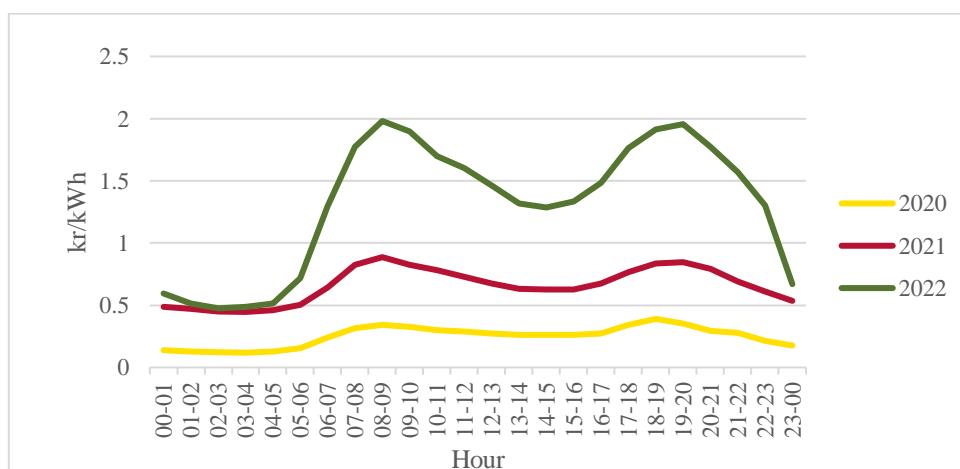


Fig. 21. Annual median spot prices for each hour in electricity price area SE4 during 2020, 2021, and 2022.



Table 8 presents an overview of historical electricity spot price statistics for the period under observation. It includes key metrics such as the number of samples, median hourly spot price, maximum hourly spot price, minimum hourly spot price, and standard deviation.

Table 7. Electricity Spot Price Statistics Across All Price Areas in Sweden for the Years 2020, 2021, and 2022, including Median, Maximum, Minimum Prices, and Standard Deviation.

Year	Price area	Number of samples	Median hourly spot price (kr/kWh)	Maximum hourly spot price (kr/kWh)	Minimum hourly spot price (kr/kWh)	Standard deviation
2020	Luleå (SE1)	8784	0.127	1.970	-0.018	12.00 %
	Sundsvall (SE2)	8784	0.127	1.970	-0.018	12.00 %
	Stockholm (SE3)	8784	0.174	2.592	-0.018	19.95 %
	Malmö (SE4)	8784	0.235	2.592	-0.020	20.80 %
2021	Luleå (SE1)	8760	0.409	3.711	-0.020	29.71 %
	Sundsvall (SE2)	8760	0.409	3.711	-0.020	29.77 %
	Stockholm (SE3)	8760	0.417	6.486	-0.020	61.02 %
	Malmö (SE4)	8760	0.647	6.486	-0.020	65.44 %
2022	Luleå (SE1)	8760	0.313	6.432	-0.022	85.69 %
	Sundsvall (SE2)	8760	0.328	6.432	-0.022	87.02 %
	Stockholm (SE3)	8760	0.994	8.513	-0.022	137.42 %
	Malmö (SE4)	8760	1.301	8.513	-0.022	150.28 %

The findings also reveal that over the observed timeframe, electricity price areas SE1 and SE2 demonstrate a consistently strong correlation in electricity spot prices, irrespective of the specific year. Electricity price areas SE3 and SE4 exhibit a strong correlation as well, like the correlation between SE1 and SE2. Price areas located in the northern Sweden (SE1 and SE2) and those situated in the south (SE3 and SE4) show a declining correlation in electricity spot prices between each other. The most significant decline in correlation is observed between price areas SE1 and SE4, with the correlation value for hourly electricity spot prices dropping from 0.519 in 2020 to 0.470 in 2021 and further to 0.451 in 2022.

4.3 Electricity consumption for heating and hot water in building simulation model

The COP values for the ground source heat pump and the air-to-water source heat pump employed in the simulation were 4 and 3.6, respectively. You can find figures illustrating simulated heat losses through the building envelope for each of the simulated locations in Appendix 6.

In Malmö (SE1), the annual electricity consumption for heating and hot water in the base model, was 13,347 kWh. In Stockholm (SE2), it was 14,166 kWh per year. In Sundsvall (SE3), it amounted to 18,007 kWh per year, while in Luleå (SE4), it reached 21,228 kWh per year. From May until September, the annual purchased energy for electrical heating used to maintain the minimum indoor temperature remained relatively stable across the simulated locations. However, during winter, there was a noticeable increase in demand for electrical heating, with higher energy consumption observed in the locations further north, especially in Luleå and Sundsvall. Figure 22 illustrates a bar chart for the annual electrical energy consumption for heating, encompassing heating and hot water consumption, measured in kilowatt-hours.

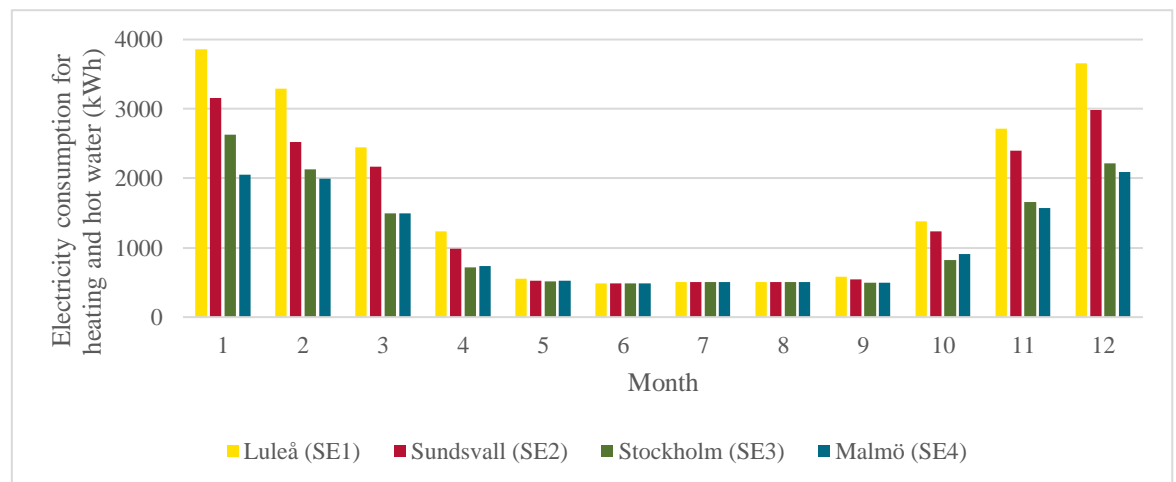


Fig. 22. Electricity consumption for heating and hot water in the building simulation model.

4.4 Electricity consumption for energy efficiency measure

The results indicate that, when comparing simulated energy efficiency measures, those incorporating energy storage systems and demand-side load management had a limited impact on reducing annual purchased energy for electrical heating, as the overall energy consumption remained unchanged. In contrast, the energy efficiency measures featuring heat pump installation significantly reduced electrical energy consumption, with an average decrease of 65.5% and 62.7% observed for ground and air-to-water source heat pumps across all simulated locations. Generally, energy consumption tended to be higher in northern locations. However, this did not necessarily translate to lower electricity spot costs, as historical price data shows that electricity prices have historically been lower in the northern areas (SE1 and SE2).

For the simulated energy efficiency measures in Luleå SE1, integrating an insulated hot water storage tank and demand-side load management led to an annual electrical energy consumption of 21,652 kWh, encompassing heating and hot water. On the other hand, the energy efficiency measures incorporating a lithium home battery storage in the same price area recorded an electricity consumption of 22,289 kWh. In Sundsvall (SE2), the annual electricity consumption was 18,367 kWh for an insulated hot water storage tank and 18,907 kWh for a lithium home battery storage. In Stockholm (SE3), the respective values were 14,449 kWh and 14,874 kWh. In Malmö (SE4), the annual electricity consumption was 13,614 kWh for an insulated hot water storage tank and 14,015 kWh for a lithium home battery storage.

The simulated energy efficiency measures that integrated air-to-water and ground-source heat pumps demonstrated significant reductions in annual electricity consumption for heating and hot water. In Luleå, the ground source heat pump had an annual electricity consumption of 7,786 kWh, while the air-to-water source heat pump consumed 9,230 kWh. In Sundsvall, the electricity consumption was 6,437 kWh for the ground source heat pump and 7,088 kWh for the air-to-water source heat pump. In Stockholm, it was 4,708 kWh for the ground source heat pump and 5,001 kWh for the air-to-water source heat pump. In Malmö, the respective values were 4,385 kWh and 4,545 kWh. Figure 23-26 visually represents the annual electricity consumption for the simulated energy efficiency measures in all simulated locations, measured in kilowatt-hours.

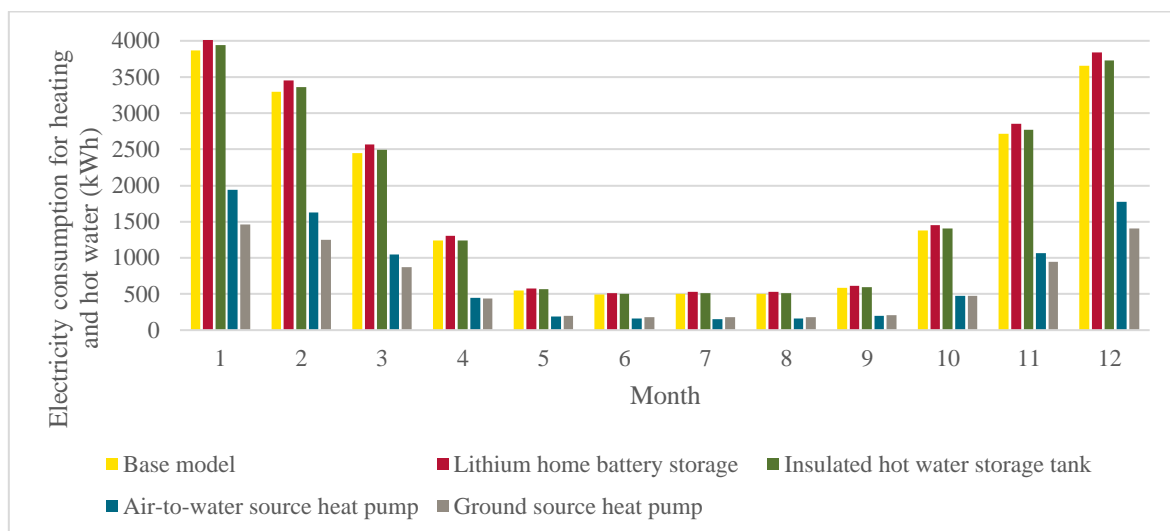


Fig. 23. Electricity consumption for heating and hot water in the simulated base model and energy efficiency measures in Luleå (SE1).

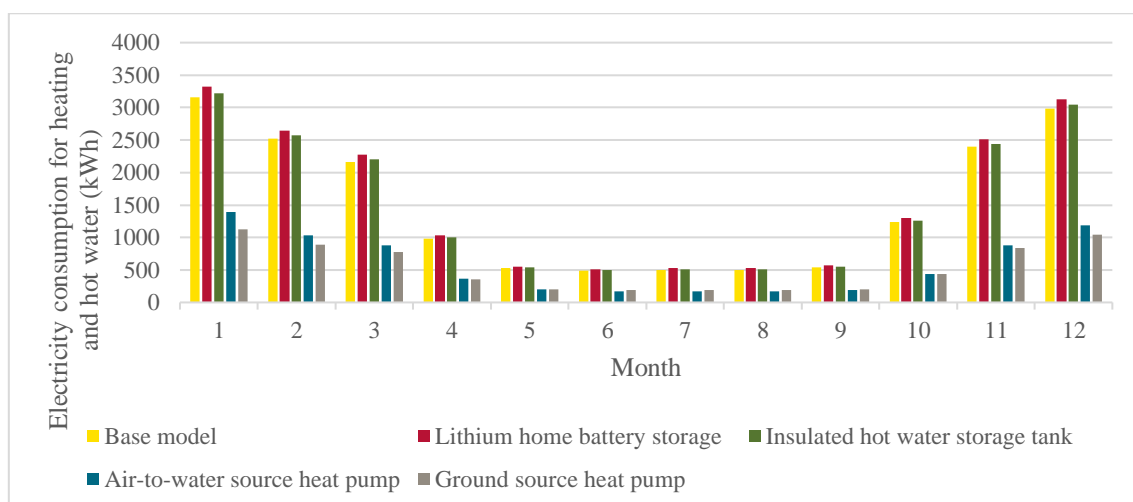


Fig. 24. Electricity consumption for heating and hot water in the simulated base model and energy efficiency measures in Sundsvall (SE2).

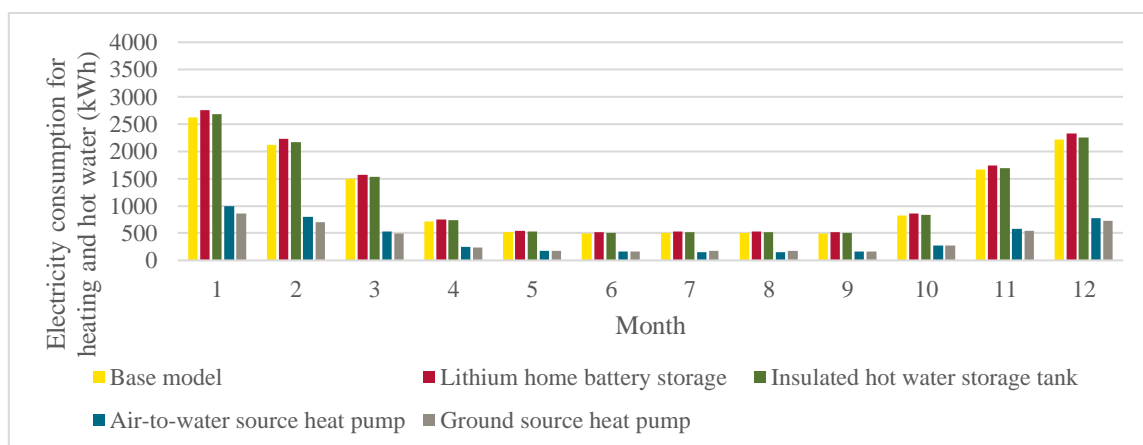


Fig. 25. Electricity consumption for heating and hot water for the simulated base model and energy efficiency measures in Stockholm (SE3).

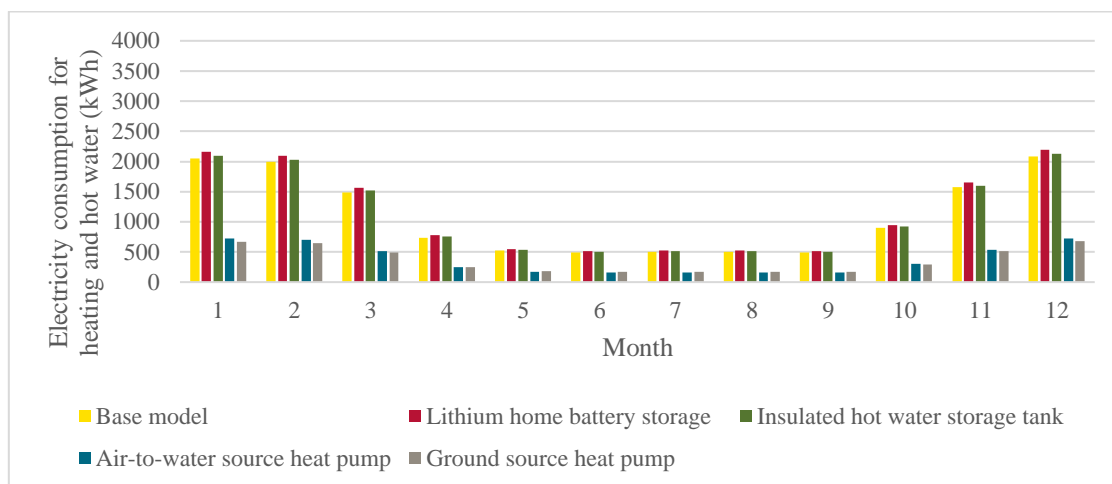


Fig. 26. Electricity consumption for heating and hot water in the simulated base model and energy efficiency measures in Malmö (SE4).

4.5 Electricity spot cost modelling

Electricity arbitrage trading incorporating thermal energy storage systems displayed higher electricity cost savings than battery energy storage systems. The thermal energy storage system achieved an average reduction of 44% in electricity spot costs in the southern regions (SE3 and SE4) from 2020 to 2022 and a 29 % reduction in the northern price regions (SE1 and SE2). In comparison, the lithium home battery storage yielded significantly lower reductions in electricity spot costs, with a decrease of 14% in the southern price regions and 4% in the north price regions.

Among the evaluated energy efficiency measures, the ground-source heat pump simulation in Malmö (SE4) proved to be the most cost-effective in reducing electricity spot costs, leading to electricity cost savings of 2,436 kr in 2020, 7,598 kr in 2021, and 13,507 kr in 2022. On the other hand, the lithium home battery storage simulated in Luleå (SE1) exhibited the least potential for reducing electricity spot costs among all the analyzed energy efficiency measures. In 2020, the electricity spot cost was only 149 kr lower than the base model, followed by a reduction of 280 kr in 2021 and a further decrease of 627 kr in 2022.

In 2022, the simulated thermal energy storage system in Malmö (SE4) achieved a 43% reduction in electricity spot costs, while the ground source heat pump, considered the most cost-effective choice, realized a more substantial 67% reduction. This highlights the cost-effectiveness of electricity arbitrage trading strategies utilizing thermal energy storage systems, especially when their investment cost is only one-third that of a heat pump system.

Figure 27-30 presents figures illustrating the annual simulated electricity spot costs in kronor for the base and energy efficiency measures throughout 2020, 2021, and 2022. These figures are categorized based on the simulated location.

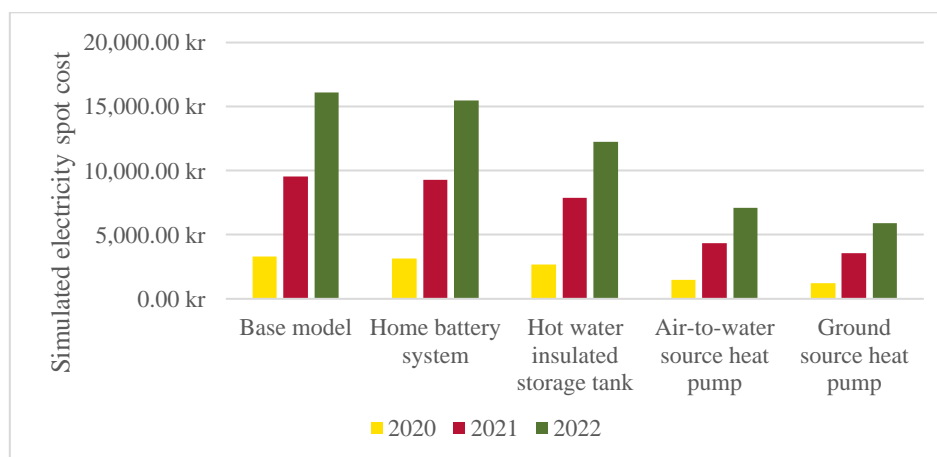


Fig. 27. Electricity spot cost modelling for the base model and energy efficiency measures based on simulated electricity consumption and historical price data from SE1 price area.

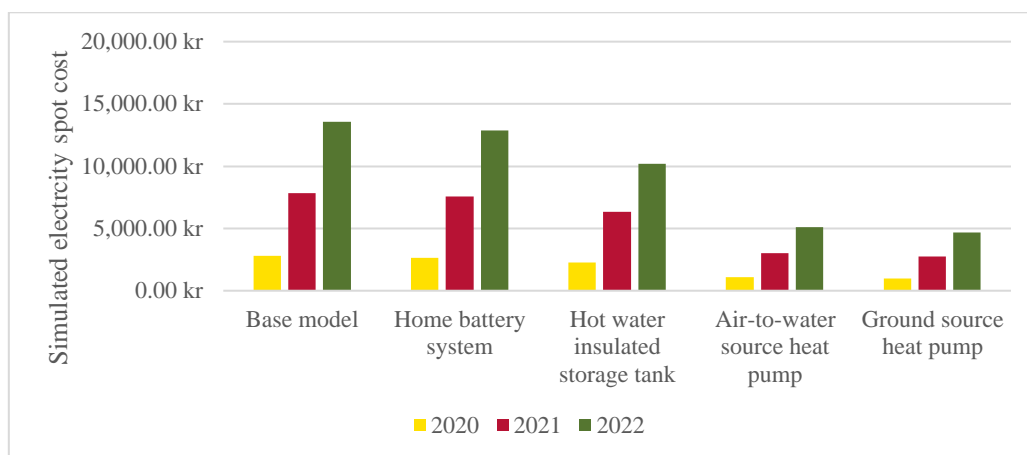


Fig. 28. Electricity spot cost modelling for the base model and energy efficiency measures based on simulated electricity consumption and historical price data from SE2 price area.

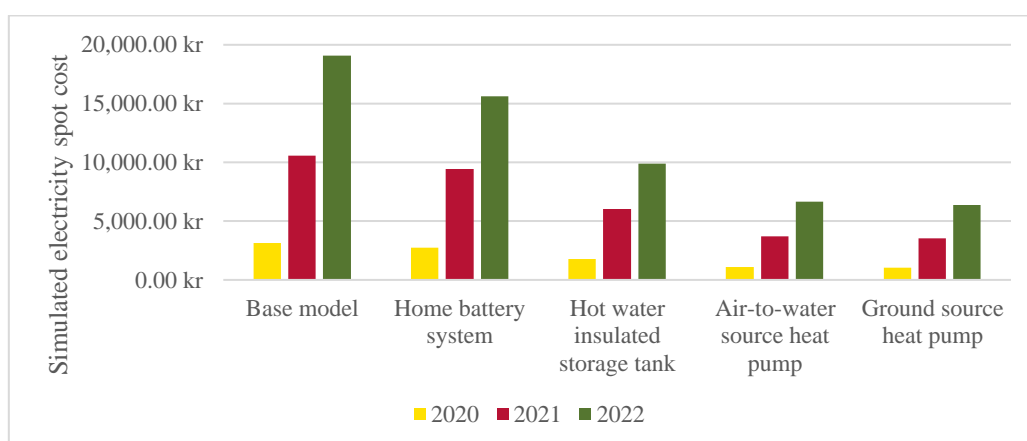


Fig. 29. Electricity spot cost modelling for the base model and energy efficiency measures based on simulated electricity consumption and historical price data from SE3 price area.

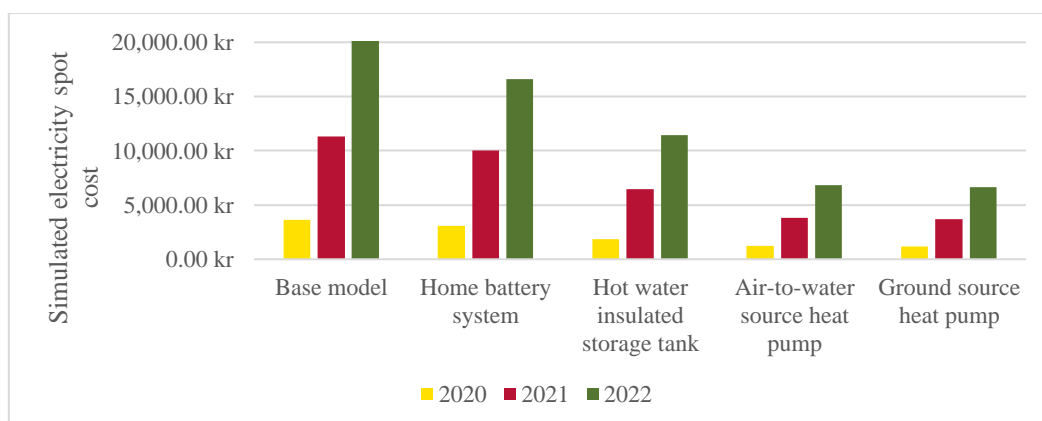


Fig. 30. Electricity spot cost modelling for the base model and energy efficiency measures based on simulated electricity consumption and historical price data from SE4 price area.

4.6 Financial modelling of electricity arbitrage trading

The financial modeling of energy storage and demand-side load management for electricity arbitrage trading provides a partial assessment of intraday electricity arbitrage trading within the single-family homes market. This partial evaluation stems from the fundamental concept that the electricity spot cost constitutes only a portion of the total electricity expenses for single-family homes. Nevertheless, the results highlight that the internal rate of return associated with electricity arbitrage trading, specifically concerning electricity spot costs, is influenced by various factors, including the electricity price area, the chosen trajectory for future electricity price trends, and the specific characteristics of the energy storage system, particularly its storage capacity.

4.6.1 Internal rate of return, discounted cash flow model and payback period.

Among the electricity arbitrage models, a thermal energy storage system utilizing a insulated hot water storage tank offered a higher internal rate of return over the equipment's lifespan. In contrast, lithium home battery storage resulted in a non-positive internal rate of return regardless of the electricity price area studied and the chosen scenario of future electricity price development.

The internal rate of return for thermal energy storage peaked at 18% in price area SE4. Regions SE3 and SE4 consistently outperformed regions SE1 and SE2, indicating more robust economic performance for thermal energy storage systems in the southern price areas of Sweden. The highest internal rate of return was observed in scenario three, where an 18% return was computed for scenario three, including projecting electricity spot prices with a consistent annual increase of 10% within the SE4 electricity price area. In contrast, no positive IRR and NPV were calculated for the battery energy storage system, regardless of the future electricity spot price development.

For a detailed visualization of the internal rate of return for thermal energy storage systems in each simulated location and future electricity price development, please refer to Figures 31-33.

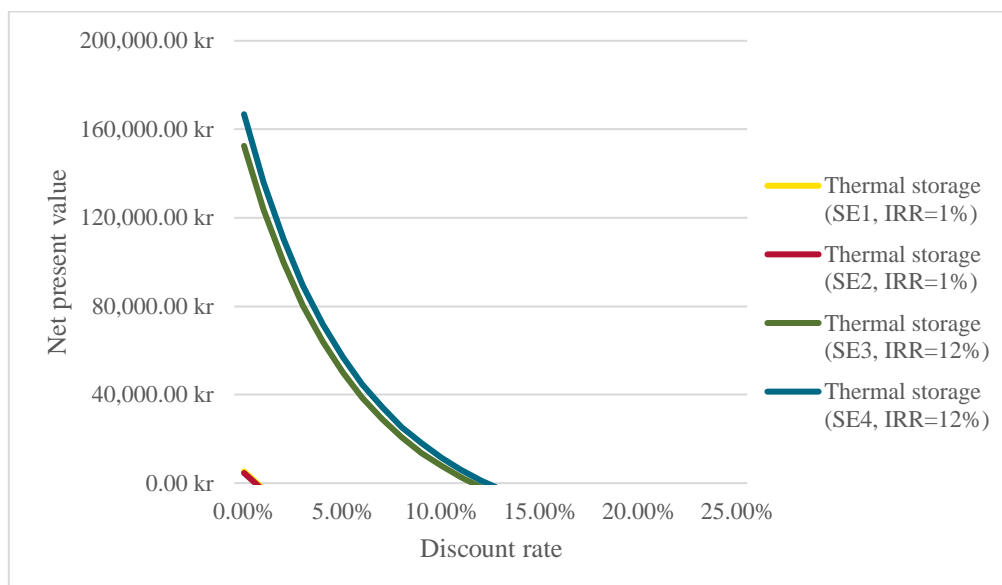


Fig. 31. Internal rate of return for thermal energy system and demand-side load management in price areas (SE1, SE2, SE3, and SE4) for scenario one, which entails consecutive annual growth rates of 2% in hourly electricity spot prices

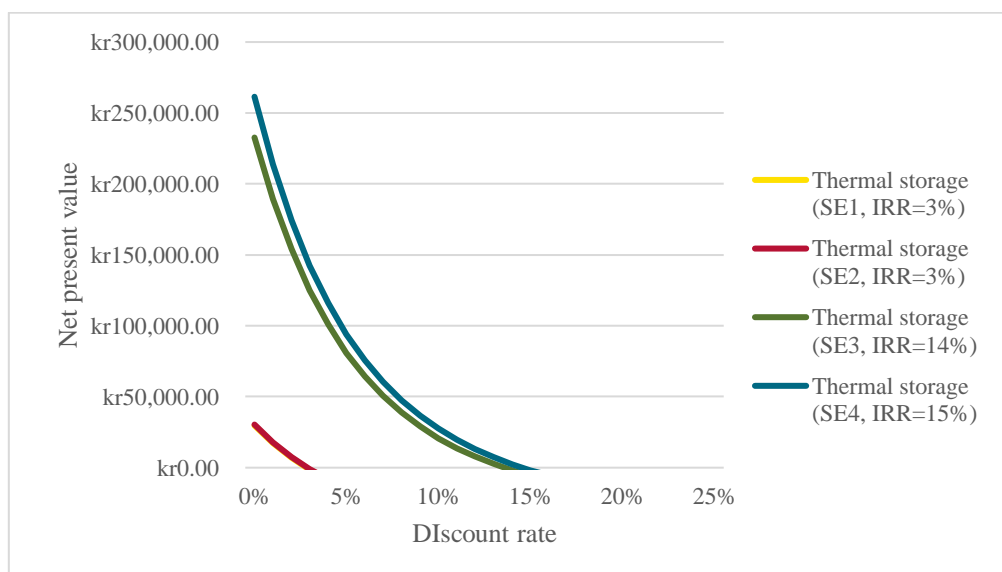


Fig. 32. Internal rate of return for thermal energy system and demand-side load management in price areas (SE1, SE2, SE3, and SE4) for scenario two, which entails consecutive annual growth rates of 5% in hourly electricity spot prices

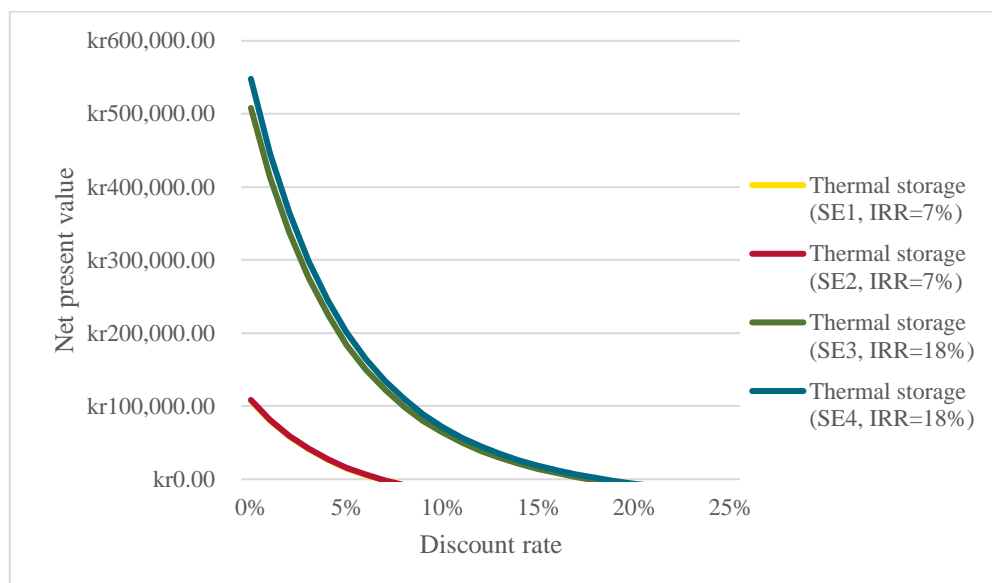


Fig. 33. Internal rate of return for thermal energy system and demand-side load management in price areas (SE1, SE2, SE3, and SE4) for scenario three, which entails consecutive annual growth rates of 10% in hourly electricity spot prices

The discounted cash flow model utilized a discount rate of 7 % for its calculation. For the thermal energy storage system, all scenarios within the electricity price area SE3 and SE4 yielded positive net present value at the 7 % discount rate. The scenario yielding the highest net present value was identified as scenario three within price area SE4, totaling 134,170 kr, with a corresponding payback period of 7.3 years. The lowest net present value was observed in scenario one within price area SE3, amounting to 28,860 kr, and it was associated with a payback period of 8.7 years.

For an overview of the discounted cash flow (DCF) figures at a 7% discount rate and the associated payback periods for thermal energy storage systems in price areas SE3 and SE4, see Table 7.

Table 7. DCF at 7 % discount rate and payback period for thermal energy storage system in electricity price areas SE3 and SE4, organized by scenario of consecutive annual growth rates in electricity spot prices.

Price area	Financial metrics	Scenario 1	Scenario 2	Scenario 3
Stockholm (SE3)	DCF	28 860 kr	50 500 kr	122 100 kr
	Payback period	8.7 years	8.3 years	7.6 years
Malmö (SE4)	DCF	34 240 kr	60 360 kr	134 170 kr
	Payback period	9.3 years	7.9 years	7.3 years

5 Discussions and conclusions

This chapter discusses the outcomes and analysis presented in the report. The chapter finishes with a conclusion and a suggestion for future work.

5.1 Modeling electricity arbitrage

I set forth two primary objectives when writing my bachelor's thesis in energy and environmental engineering. The first objective was to gain an understanding of electricity arbitrage trading within the single-family homes market by utilizing energy storage systems and demand-side load management. To achieve this, I developed a rule-based intraday electricity arbitrage trading model based on energy dynamics observed in the Swedish electricity market from 2020 to 2022. The primary aim of this model was to quantify the economic benefits associated with shifting electricity demand to off-peak periods to take advantage of lower wholesale electricity spot prices. The results of this model showed the economic potential of adjusting electricity consumption patterns, particularly in conjunction with positive electricity price volatility trends. However, it is important to note that this model is specifically designed for intraday trading and hourly rate contracts, as this is the only contract allowing single-family homes to capitalize on intraday price differentials. Hourly rate contracts constitute 10 % of the electricity contracts in Sweden, highlighting the untapped opportunities within the electricity markets for consumers to realize potential benefits from electricity arbitrage trading.

My second objective was identifying practical strategies single-family homes could adopt to reduce their electricity expenses. Within the report, an analysis was conducted to quantify the cost-effectiveness of four distinct energy efficiency measures. Two of these models incorporated energy storage systems and demand-side load management (specifically, a thermal energy storage system and a battery energy storage system), while the other two models integrated heat pump installations (a ground source heat pump and an air-to-water source heat pump). The report computed cost savings for each of these energy efficiency models and performed financial modeling for electricity arbitrage trading, including financial metrics such as IRR (Internal Rate of Return), NPV (Net Present Value), DCF (Discounted Cash Flow), and the payback period. The findings highlighted the economic potential of adopting energy storage systems and demand-side load management for electricity arbitrage trading. These strategies effectively mitigate potential future electricity price volatility for electrically heated single-family homes, presenting a viable hedging opportunity for households seeking to manage their electricity costs.

5.2 Limitations of the modelling

The analysis conducted in the report is a simplified model for evaluating the economic potential of electricity arbitrage trading rather than a comprehensive assessment of investment performance. A complete investment evaluation would necessitate using an actual residence for a cost-benefit analysis rather than a hypothetical one, as employed in the report. Furthermore, this real-world scenario should account for the total electricity cost structure, encompassing grid usage fees and energy taxes. Achieving a more precise electricity load demand pattern is also essential. Incorporating a temperature correction factor could further enhance the investment performance evaluation, ensuring an accurate measurement of energy costs.

Another critical aspect to consider is the daily energy storage capacity requirements. The energy storage needs for a hot summer day and a cold winter day would naturally differ, as milder external temperatures would demand less energy storage for heating. Factoring in this variability in daily energy storage requirements in the investment performance assessment would prevent issues like tank overflow or battery overcharging, thereby limiting excess electricity costs. This approach would provide a more precise cost structure for the electricity arbitrage trading model. One way to achieve this is by implementing a smart energy system that continually monitors real-time weather data to optimize energy storage capacity. This smart energy system could also efficiently manage electricity purchases, ensuring a consistent alignment of load demand with off-peak periods, even when these off-peak hours deviate from the typical schedule. In the most favorable scenario, such a service would be provided by a third party actively optimizing electricity purchases on behalf of the customer to enhance the cost-effectiveness of building energy performance.

The modeling of electricity arbitrage identified specific off-peak hours between 00:00 and 05:00, which offered favorable cost-saving potential for charging the energy storage system. Within the model, an assumption was made that the charging would occur between 02:00 and 04:00, during which the maximum power output was only constrained by the capacity of the energy storage system. This implied that it was possible to draw the highest power output during the charging window without incurring additional costs. The rationale behind charging the energy storage system during this specific timeframe stemmed from the fact that it was identified as a typical off-peak period. Additionally, it was deemed more practical for the thesis to employ a rule-based strategy for demand-side load management, which involved a straightforward, predefined charging period instead of a non-rule-based strategy that continuously adjusted the charging period.

5.3 Cost and benefit of electricity arbitrage trading

Initially, it is important to note that the cost-effectiveness of energy storage and demand-side load management in electricity arbitrage is contingent upon volatile energy market dynamics. These market dynamics generate price differentials in the electricity market, which makes electricity arbitrage trading for buildings an appropriate energy efficiency measure for reducing energy cost. Without such financial incentives to capitalize of price disparity, there would be no compelling reason to invest in energy storage system and demand-side load management.

The modeling of energy storage systems and demand-side load management strategies for their application in electricity arbitrage trading has yielded insights into the economic viability of electricity arbitrage trading in single-family homes. The findings of this report states that a difference in economic feasibility exists between the two energy storage system: thermal and battery energy storage. The primary factors contributing to this variation in economic performance are the different energy storage capacities and the initial investment costs associated with each energy storage system.

Limitations of thermal energy storage systems lie in their compatibility with buildings that have hydronic heating systems. In contrast, the battery energy storage system offers versatility by being suitable for integrating into buildings equipped with hydronic and radiating heating systems, as the technology is not mutually exclusive. Regarding shifting load demand for heating and hot water in buildings with hydronic heating systems, thermal energy storage systems offer the most cost-effective solution for electricity arbitrage trading, more so than battery energy storage systems.

The report also analyzed the energy storage systems in each of the electricity price areas in Sweden. As electricity demand is higher in the south of the country (SE3 and SE4) and supply is more constrained compared to the north (SE1 and SE2), this area experiences greater market volatility. Prices also tend to be higher, which positively impacts the economic performance of electricity arbitrage trading. This paper argues that electricity arbitrage trading with thermal energy storage system can result in positive internal rate of return and net present value when considering electricity spot cost in price areas SE3 and SE4 but would result in a negative equivalent metrics in price areas SE1 and SE2. For price areas in the north, the papers argue that investment in heat pump installation would be a more beneficial energy efficiency measure in terms of electricity cost savings. The calculated internal rate of returns and net present value is understood to be higher than the case for an actual house, as more cost would be incurred because of inclusion of tax and grid usage fees, ultimately lowering any expected return.



5.4 Conclusions

The report has analyzed two energy storage systems suitable for electricity arbitrage trading, comparing them with two conventional energy-efficiency measures for single-family homes. Of the analyzed energy systems, installing ground-source heat pumps led to the most significant decrease in electricity spot cost.

Conclusions drawn from the report highlight the role of thermal energy storage systems in profitable intraday electricity arbitrage trading. For the energy storage system, the report concluded that the thermal energy storage system was more cost-effective in reducing electricity costs than the battery energy storage system. The report concluded the thermal energy storage system had a positive net present value at 7 % discount rate for electricity price areas SE3 and SE4. In contrast, the battery energy storage system provided no positive net present value at 7 % discount rate, in any of the studied price areas and scenarios.

5.5 Suggestions on future work

Suggestions for future work include evaluating investment performance in the context of an actual residential property, considering grid usage fees and energy taxes. Additionally, there is room for further enhancement of the rule-based electricity arbitrage model to optimize the exploitation of price differentials, thus leading to more accurate evaluations of cost structures.



6 References

- [1] World Commission on Environment and Development, "Our common future (Brundtland report)," United Nations, 1987.
- [2] United Nations, "The 17 goals," [Online]. Available: <https://sdgs.un.org/goals>.
- [3] Global Energy Assessment Writing Team, "'Energy, Poverty, and Development'," in *Global Energy Assessment: Toward a sustainable future*, Cambridge University press, 2012, pp. 151-190.
- [4] International Energy Agency, "Energy security: Reliable, affordable access to all fuels and energy sources," [Online]. Available: <https://www.iea.org/topics/energy-security>.
- [5] Energy Institute, "Statistical Review of World Energy 2023," 72nd edition, 2023.
- [6] European Commission, "Energy efficiency in buildings," [Online]. Available: https://commission.europa.eu/news/focus-energy-efficiency-buildings-2020-02-17_en.
- [7] T. Ramesh, R. Prakash and K. Shukla, "Life cycle energy analysis of buildings: An overview," *Energy and buildings*, vol. 42, no. 10, pp. 1592-1600, 2010.
- [8] United Nations Environment Programme, "2020 Global status report for buildings and construction: Towards a zero-emissions, efficient and resilient buildings and construction sector," *Buildings Global Status Report*, 2020.
- [9] European Union, "Electricity market design," [Online]. Available: https://energy.ec.europa.eu/topics/markets-and-consumers/market-legislation/electricity-market-design_en.
- [10] US Energy Information Administration, "Electricity explained: Factors affecting electricity prices," [Online]. Available: <https://www.eia.gov/energyexplained/electricity/prices-and-factors-affecting-prices.php>.
- [11] J. Nilsson, "Skånska politiker kräver stöd till elkonsumenter i syd [Skåne politicians demand support for electricity consumers in the south]," *Dagens Nyheter*, Stockholm, 2022.
- [12] Energimyndigheten [Swedish Energy Agency], "Energistatistik för småhus [Energy statistics for single-family homes]. 2021.
- [13] Svenska Kraftnät [Swedish Power Grid], "Kraftbalansen på den svenska elmarknaden [Power Balance in the Swedish Electricity Market]," 2022.
- [14] Vattenfall, "Ringhals," [Online]. Available: <https://powerplants.vattenfall.com/sv/ringhals/>.
- [15] Energimyndigheten [Swedish Energy Agency], "Minskad elanvändning under 2022 [Reduced electricity consumption in 2022]," 2022.



- [Online]. Available:
<https://www.energimyndigheten.se/nyhetsarkiv/2023/minskad-elanvandning-under-2022-i-sverige/>.
- [16] International Energy Agency, "Energy Policies of IEA Countries: Sweden 2019 Review," 2019.
- [17] Svenska Kraftnät [Swedish Power Grid], "Svergies elnät [Swedens Electricity Grid]," [Online]. Available: <https://www.svk.se/om-kraftsystemet/oversikt-av-kraftsystemet/sveriges-elnat/>.
- [18] R. Mishan, M. Abdelmalak, M. Egan, A. Sobhy and M. Benidris, "Dispatchable, Non-dispatchable, Reserve and Arbitrage Power within PV-Storage Intergrated Grid," in *IEEE Kansas Power and Energy Conference (KPEC)*, Manhattan, KS, USA, 2023.
- [19] Energimyndigheten [Swedish Energy Agency], "Vindkraftstatistik [Wind power statistics]," 2023.
- [20] Energimyndigheten [Swedish Energy Agency], "Nationell strategi för en hållbar vindkraft [National strategy for sustainable wind power]," 2021.
- [21] H. Alvarez, "Vindenergi [Wind Power]," in *Energiteknik del 1 [Energy technology part 1]*, Lund, Studentlitteratur, 2006, pp. 240-245.
- [22] Nord Pool, "About us," [Online]. Available: <https://www.nordpoolgroup.com/en/About-us/>.
- [23] Konsumenternas Energimarknadsbyrå [Consumer Energy Market Agency], "Elräkningen [Electricity bill]," [Online]. Available: <https://www.energimarknadsbyran.se/el/dina-avtal-och-kostnader/elrakningen/>.
- [24] Energiföretagen [Swedenergy], "Kundens elkostnader [The customers electricity cost]," [Online]. Available: <https://www.energiforetagen.se/energifakta/elsystemet/elhandel-marknad/for-dig-som-ekund/kundens-elkostnader/>.
- [25] Nord Pool, "Market data," [Online]. Available: <https://www.nordpoolgroup.com/en/Market-data1/#/nordic/table>.
- [26] Energimarknadsinspektionen [The Swedish Energy Markets Inspectorate], "Avtalstyp och elområde [Contract type and electricity area]," [Online]. Available: <https://www.ei.se/konsument/el/elavtal/elhandelsavtal/olika-avtalstyper>.
- [27] Regeringskansliet [Swedish Government Offices], "Timmättnig för aktiva elkonsumenter [Hourly measurement for active electricity consumers]," Klimat och näringslivsdepartementet [Ministry of Climate and Enterprise], Stockholm, 2012.
- [28] Statistikmyndigheten [Statistics Sweden], "Fördelning av avtal på olika avtalstyper - Procentuell fördelning av avtal på olika avtalstyper [Distribution of contracts by different contract types - Percentage distribution of contracts by different contract types]," [Online]. Available: <https://www.scb.se/hitta-statistik/statistik-efter->



amne/energi/prisutvecklingen-inom-energiomradet/elpriser-och-elavtal/pong/tabell-och-diagram/tabeller-over-manadsvarden/fordelning-av-avtal-pa-olika-avtalstyper/.

- [29] M. Savolainen and R. Svento, "Assessment of Deregulation Process," in *Modern Energy Markets: Real-Time Pricing, Renewable Resources and Efficient Distribution*, John Wiley Sons Inc, 2014, pp. 14-17.
- [30] P. Krugman and R. Wells, "Marginal cost," in *Microeconomics*, New York, Worth Publishers, 2021.
- [31] P. Deane, C. Eid, S. Collins, G. B. R. Hartel, D. Keles and W. Fichtner, "Quantifying the "merit-order" effect in European electricity markets," French Institute of International Relations, 2015.
- [32] Squeaky Clean Energy Group, "Understanding power markets: Merit order and marginal pricing," [Online]. Available: <https://www.squeaky.energy/blog/understanding-power-markets-merit-order-and-marginal-pricing>.
- [33] Energimyndigheten [Swedish Energy Agency], "Energiläget 2022 [State of energy in 2022]".
- [34] Sveriges meteorologiska och hydrologiska institut [Swedish Meteorological and Hydrological Institute], "Guide normalsårskorrigerig - värme [Guide for normal annual temperature correction - heating]".
- [35] Boverket [Swedish National Board of Housing, Building, and Planning], "Boverket byggregler och klimatanpassnign [Swedish National Board of Housing, Building, and Planning regulations and climate adaptation]," Boverket, Karlskorna, 2018.
- [36] Eurostat, "Energy use in households in 2020," European Commission, [Online]. Available: <https://ec.europa.eu/eurostat/web/products-eurostat-news/-/ddn-20220617-1>.
- [37] H. Alvarez, "Kylmaskin- och värmepumpprocess [Refrigeration and Heat Pump Process]," in *Energiteknik 1 [Energy technology part 1]*, Lund, Studentlitteratur, 2006, pp. 310-314.
- [38] Y. Cengel and A. Ghajar, Heat and Mass Transfer: Fundamentals & Applications, McGraw-Hill Education, 2020.
- [39] D. Bunn and S. Kermer, "Statistical arbitrage and information flow in an electricity balancing market," *The Energy Journal*, vol. 42, no. 5, 2021.
- [40] United Nations Industrial Development Organization, "Supply-side management," United Nations.
- [41] United Nations Industrial Development Organization, "Demand-side management," United Nations.
- [42] Swedish Energy Markets Inspectorate, "Measures to increase demand-side flexibility in the Swedish electricity system," Eskilstuna, 2017.



- [43] Energimarknadsinspektionen [The Swedish Energy Markets Inspectorate], "Elmarknaden [Electricity market]," [Online]. Available: <https://ei.se/konsument/el/sa-har-fungerar-elmarknaden>.
- [44] Svenska Kraftnät [Swedish Power Grid], "Dagen före-marknaden – fysisk handel med el [The day-ahead market - physical electricity trading]," [Online]. Available: <https://chat.openai.com/c/b1b801b5-b812-439e-bfb6-3a84a5891602>.
- [45] Nord Pool, "Intraday market," [Online]. Available: <https://www.nordpoolgroup.com/en/the-power-market/Intraday-market/>.
- [46] Svenska Kraftnät [Swedish Power Grid], "Balansmarknaden [Balancing markets]," [Online]. Available: <https://www.svk.se/om-kraftsystemet/om-elmarknaden/balansmarknaden/>.
- [47] M. Sterner and I. Stadler, Handbook of Energy Storage, Springer-Verlag Berlin and Heidelberg GmbH Co. KG, 2019.
- [48] H. Ali, F. Jamil and H. Babar, Thermal Energy Storage: Storage Techniques, Advanced Materials, Thermophysical Properties and Applications, Springer, 2021.
- [49] D. Enescu, G. Chiccom, R. Porumb and G. Seritan, "Thermal Energy Storage for Grid Applications: Current Status and Emerging Trend," *Energies*, vol. 13, no. 340, 2020.
- [50] Restore Technology, "Thermochemical Energy Storage," [Online]. Available: <https://www.restore-dhc.eu/about-restore/thermochemical-energy-storage/>.
- [51] A. Shurma, V. Tyagi, C. Chen and D. Buddhi, "Review on thermal energy storage with phase change materials and applications," *Renewable and Sustainable Energy Reviews*, vol. 13, no. 2, p. 2009.
- [52] H. Alvarez, "Värmeöverföring [Heat transfer]," in *Energiteknik 1 [Energy technology part 1]*, Lund, Studentlitteratur, 2006, pp. 360-444.
- [53] Energimyndigheten [Swedish Energy Agency], "Ackumulatortankar: Får värmen att räcka längre [Accumulator tanks: Make the heat last longer]," Energimyndigheten, 2011.
- [54] R. Ahlman and D. Hägerby, Interviewees, *How to model size for insulated hot water storage tank size in single-family homes*. [Interview]. 2023.
- [55] European Commission, "Energy performance of buildings directive," [Online]. Available: https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficient-buildings/energy-performance-buildings-directive_en.
- [56] Consultancy and Services on the Energy Performance of Buildings, "EPB Standards - Background," [Online]. Available: <https://epb.center/epb-standards/background/>.
- [57] Regeringskansliet [Government Offices of Sweden], "Mål för energipolitiken [Goals for energy policy]," [Online]. Available:

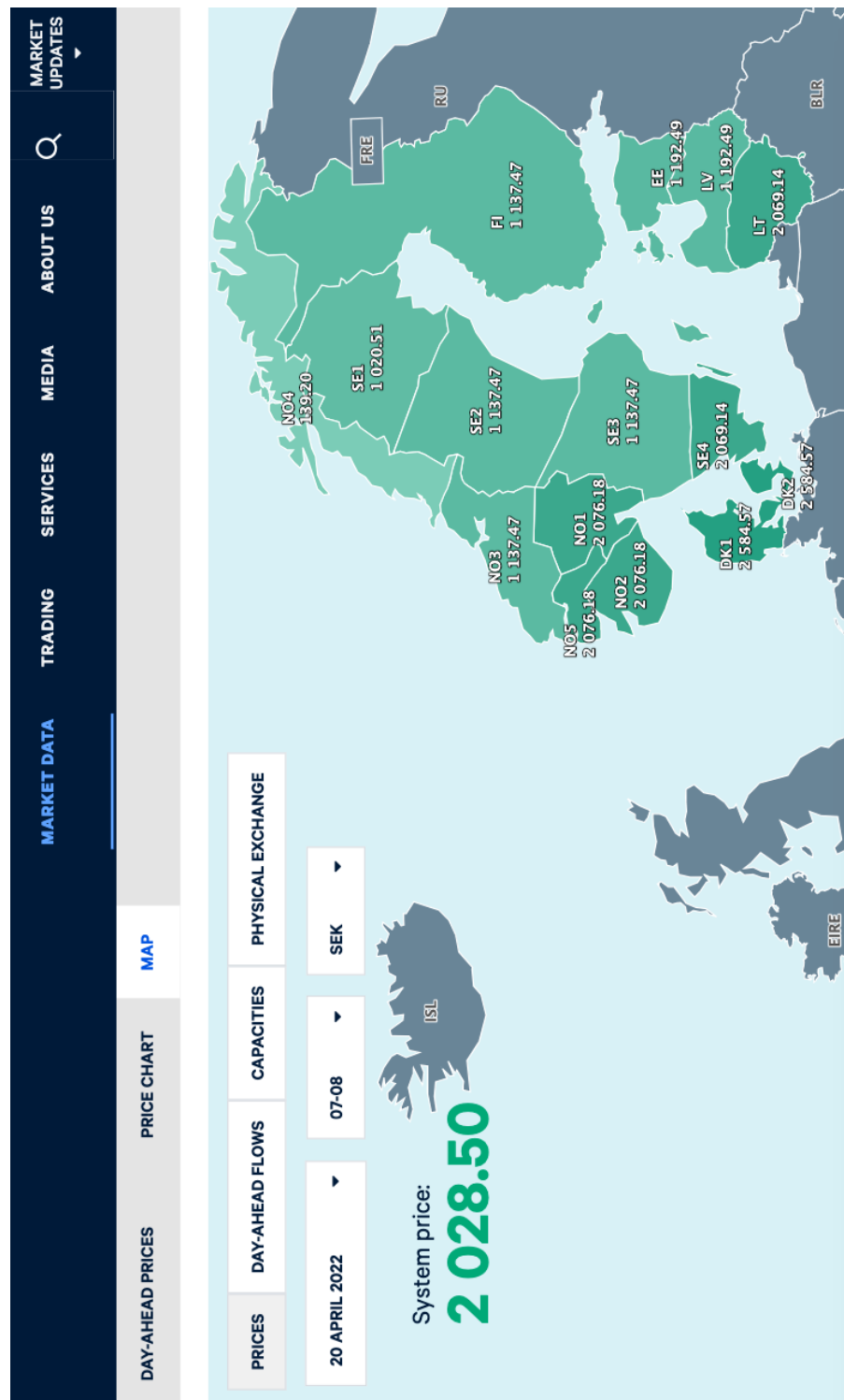


<https://www.regeringen.se/regeringens-politik/energi/mal-och-visioner-for-energi/>.

- [58] Ministry of the Environment and Energy (Sweden), "Sweden's draft integrated national energy and climate plan," Government Offices of Sweden, 2018.
- [59] Swedish Energy Agency, "Business Development and Commercialization," [Online]. Available: <https://www.energimyndigheten.se/en/innovations-r--d/business-development-and-commercialisation/>.
- [60] Energimyndigheten [Swedish Energy Agency], "Statistik [Statistics]," [Online]. Available: <https://www.energimyndigheten.se/statistik/>.
- [61] Energi- och klimatrådgivningen i Blekinge och Tingsryd [Energy and Climate Advisory in Blekinge and Tingsryd], "Energieffektivisering [Energy efficiency]," [Online]. Available: <https://www.karlskrona.se/energi--och-klimatradgivning/energieffektivisering/>.
- [62] Boverket [Swedish National Board of Housing, Building, and Planning], "Finansieringsstöd [Financial support]," [Online]. Available: <https://www.boverket.se/sv/energiguiden/energirenovera-smahus/2.lonsamhet/finansiering/>.
- [63] Nordea, "Energilån [Energy loans]," [Online]. Available: <https://www.nordea.se/privat/produkter/lan/energilan.html>.
- [64] F. Nunez, D. Canca and A. Vargas, "An assesment of European electricity arbitrage using storage systems," *Energy*, vol. 242, 2022.
- [65] X. Zhang, C. Qin, E. Loth, Y. Xu, X. Zhou and H. Chen, "Arbitrage analysis for different energy storage technologies and strategies," *Energy Reports*, vol. 7, pp. 8198-8206, 2021.
- [66] IDA Indoor Climate and Energy, "Case studies," [Online]. Available: <https://www.equa.se/en/ida-ice/case-studies>.
- [67] J. Berk and P. DeMarzo, "Financial Decision Making and the Law of One Price: Present Value and the NPV Decision Rule," in *Corporate Finance*, New York, Pearson education, 2020, pp. 100-104.

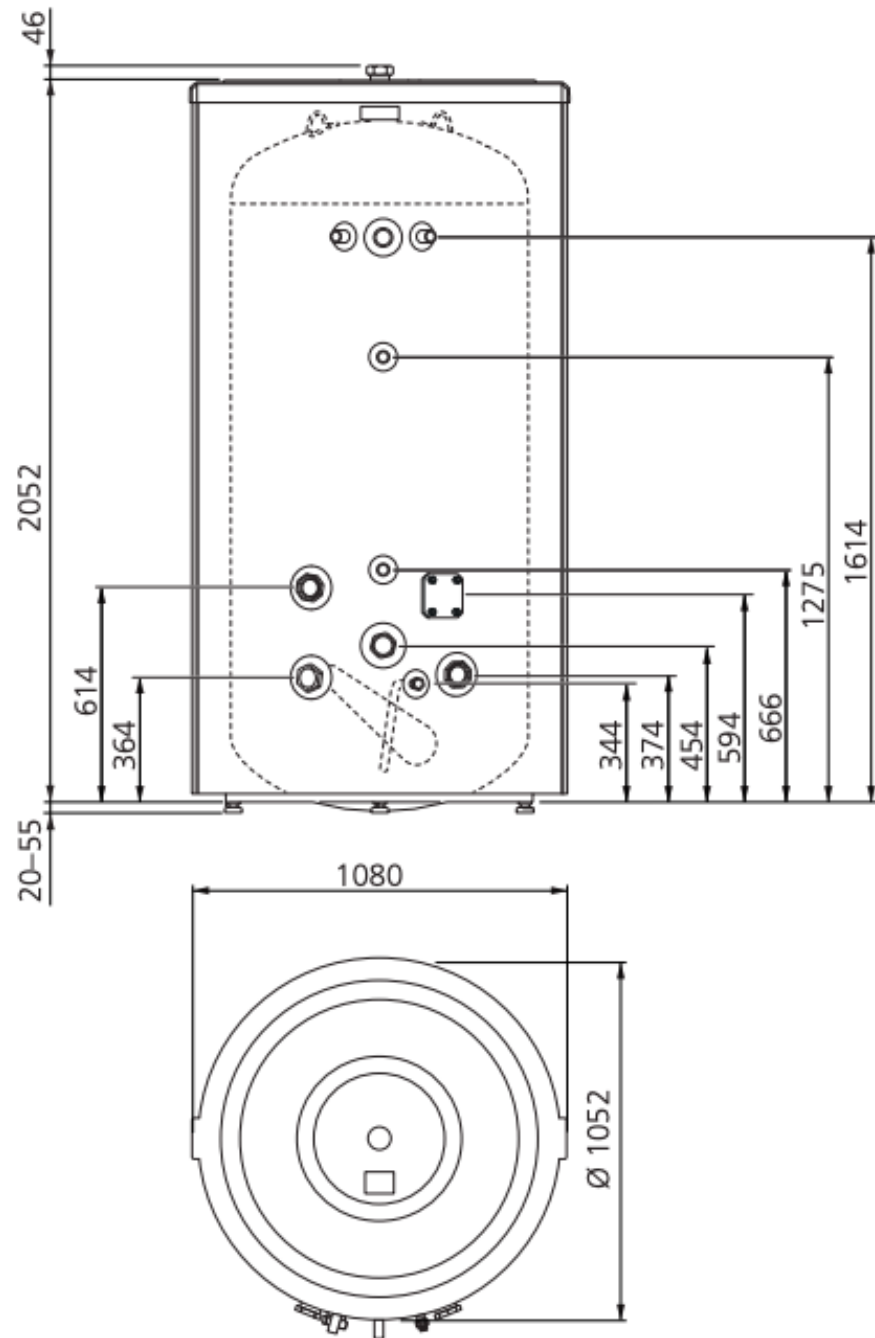


Appendix 1: Nord pool online database containing historical electricity spot prices



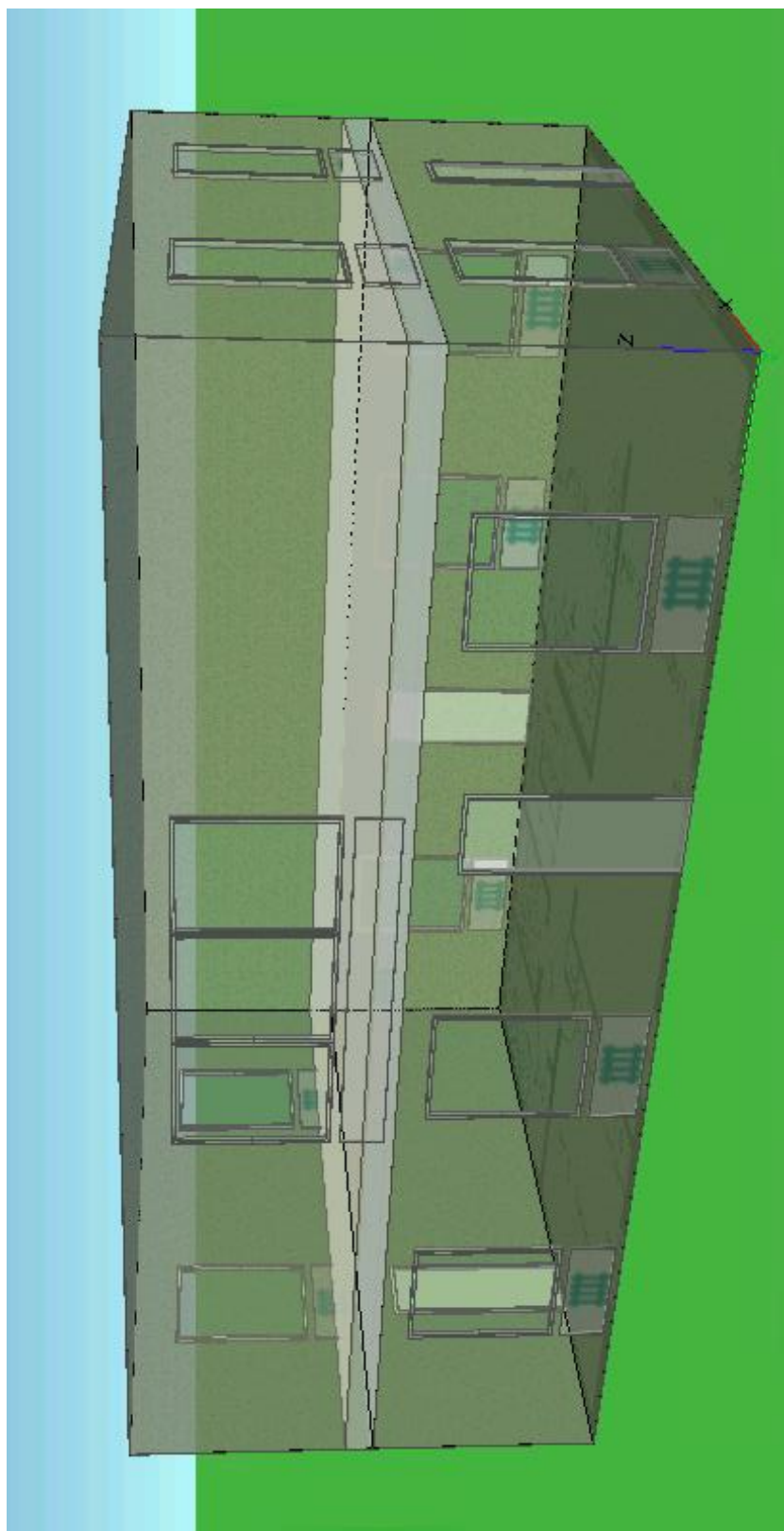
Appendix 2: Engineering drawing of insulated hot water storage tank⁴

EKS 1000



⁴ Model EKS 1000 from Nibe. Measurements are in millimeter (mm).

Appendix 3: 3D visualization of building model simulation





Appendix 4: Price statics for forecasted electricity spot prices according to each scenario and price area

Table 8. Price statistics for forecasted electricity spot prices calculated by applying an annual increase of 2 % for electricity price area SE1.

Year	Median hourly spot price (kr/kWh)	Maximum hourly spot price (kr/kWh)	Minimum hourly spot price (kr/kWh)	Standard deviation
2023	0.296	3.009	0.035	35.05%
2024	0.302	3.069	0.036	35.75%
2025	0.308	3.130	0.037	36.47%
2026	0.314	3.193	0.037	37.20%
2027	0.320	3.257	0.038	37.94%
2028	0.327	3.322	0.039	38.70%
2029	0.333	3.388	0.040	39.48%
2030	0.340	3.456	0.041	40.26%
2031	0.347	3.525	0.041	41.07%
2032	0.353	3.595	0.042	41.89%
2033	0.361	3.667	0.043	42.73%
2034	0.368	3.741	0.044	43.58%
2035	0.375	3.816	0.045	44.46%
2036	0.383	3.892	0.046	45.34%
2037	0.390	3.970	0.047	46.25%
2038	0.398	4.049	0.048	47.18%
2039	0.406	4.130	0.048	48.12%
2040	0.414	4.213	0.049	49.08%
2041	0.422	4.297	0.050	50.06%
2042	0.431	4.383	0.051	51.07%
2043	0.439	4.471	0.052	52.09%
2044	0.448	4.560	0.054	53.13%



Table 9. Price statistics for forecasted electricity spot prices calculated by applying an annual increase of 5 % for electricity price area SE1.

Year	Median hourly spot price (kr/kWh)	Maximum hourly spot price (kr/kWh)	Minimum hourly spot price (kr/kWh)	Standard deviation
2023	0.304	3.097	0.036	36.08%
2024	0.320	3.252	0.038	37.89%
2025	0.336	3.414	0.040	39.78%
2026	0.352	3.585	0.042	41.77%
2027	0.370	3.764	0.044	43.86%
2028	0.389	3.953	0.046	46.05%
2029	0.408	4.150	0.049	48.36%
2030	0.428	4.358	0.051	50.77%
2031	0.450	4.576	0.054	53.31%
2032	0.472	4.804	0.056	55.98%
2033	0.496	5.045	0.059	58.78%
2034	0.521	5.297	0.062	61.72%
2035	0.547	5.562	0.065	64.80%
2036	0.574	5.840	0.069	68.04%
2037	0.603	6.132	0.072	71.44%
2038	0.633	6.438	0.076	75.02%
2039	0.665	6.760	0.079	78.77%
2040	0.698	7.098	0.083	82.70%
2041	0.733	7.453	0.088	86.84%
2042	0.769	7.826	0.092	91.18%
2043	0.808	8.217	0.096	95.74%
2044	0.848	8.628	0.101	100.53%



Table 10. Price statistics for forecasted electricity spot prices calculated by applying an annual increase of 10 % for electricity price area SE1.

Year	Median hourly spot price (kr/kWh)	Maximum hourly spot price (kr/kWh)	Minimum hourly spot price (kr/kWh)	Standard deviation
2023	0.319	3.244	0.038	37.80%
2024	0.351	3.569	0.042	41.58%
2025	0.386	3.926	0.046	45.74%
2026	0.425	4.318	0.051	50.31%
2027	0.467	4.750	0.056	55.35%
2028	0.514	5.225	0.061	60.88%
2029	0.565	5.748	0.067	66.97%
2030	0.622	6.323	0.074	73.67%
2031	0.684	6.955	0.082	81.03%
2032	0.752	7.650	0.090	89.14%
2033	0.827	8.415	0.099	98.05%
2034	0.910	9.257	0.109	107.85%
2035	1.001	10.183	0.120	118.64%
2036	1.101	11.201	0.132	130.50%
2037	1.211	12.321	0.145	143.55%
2038	1.332	13.553	0.159	157.91%
2039	1.466	14.908	0.175	173.70%
2040	1.612	16.399	0.193	191.07%
2041	1.773	18.039	0.212	210.18%
2042	1.951	19.843	0.233	231.19%
2043	2.146	21.827	0.256	254.31%
2044	2.360	24.010	0.282	279.74%



Table 11. Price statistics for forecasted electricity spot prices calculated by applying an annual increase of 2 % for electricity price area SE2.

Year	Median hourly spot price (kr/kWh)	Maximum hourly spot price (kr/kWh)	Minimum hourly spot price (kr/kWh)	Standard deviation
2023	0.301	3.009	0.041	35.56%
2024	0.307	3.069	0.042	36.27%
2025	0.313	3.130	0.043	37.00%
2026	0.320	3.193	0.044	37.74%
2027	0.326	3.257	0.045	38.49%
2028	0.333	3.322	0.046	39.26%
2029	0.339	3.388	0.047	40.04%
2030	0.346	3.456	0.048	40.85%
2031	0.353	3.525	0.049	41.66%
2032	0.360	3.595	0.050	42.50%
2033	0.367	3.667	0.051	43.35%
2034	0.374	3.741	0.052	44.21%
2035	0.382	3.816	0.053	45.10%
2036	0.390	3.892	0.054	46.00%
2037	0.397	3.970	0.055	46.92%
2038	0.405	4.049	0.056	47.86%
2039	0.413	4.130	0.057	48.81%
2040	0.422	4.213	0.058	49.79%
2041	0.430	4.297	0.059	50.79%
2042	0.439	4.383	0.060	51.80%
2043	0.448	4.471	0.062	52.84%
2044	0.456	4.560	0.063	53.89%



Table 12. Price statistics for forecasted electricity spot prices calculated by applying an annual increase of 5 % for electricity price area SE2.

Year	Median hourly spot price (kr/kWh)	Maximum hourly spot price (kr/kWh)	Minimum hourly spot price (kr/kWh)	Standard deviation
2023	0.310	3.097	0.043	36.60%
2024	0.326	3.252	0.045	38.43%
2025	0.342	3.414	0.047	40.36%
2026	0.359	3.585	0.049	42.37%
2027	0.377	3.764	0.052	44.49%
2028	0.396	3.953	0.054	46.72%
2029	0.415	4.150	0.057	49.05%
2030	0.436	4.358	0.060	51.51%
2031	0.458	4.576	0.063	54.08%
2032	0.481	4.804	0.066	56.79%
2033	0.505	5.045	0.069	59.62%
2034	0.530	5.297	0.073	62.61%
2035	0.557	5.562	0.077	65.74%
2036	0.585	5.840	0.080	69.02%
2037	0.614	6.132	0.084	72.47%
2038	0.645	6.438	0.089	76.10%
2039	0.677	6.760	0.093	79.90%
2040	0.711	7.098	0.098	83.90%
2041	0.746	7.453	0.103	88.09%
2042	0.783	7.826	0.108	92.50%
2043	0.823	8.217	0.113	97.12%
2044	0.864	8.628	0.119	101.98%



Table 13. Price statistics for forecasted electricity spot prices calculated by applying an annual increase of 10 % for electricity price area SE2.

Year	Median hourly spot price (kr/kWh)	Maximum hourly spot price (kr/kWh)	Minimum hourly spot price (kr/kWh)	Standard deviation
2023	0.325	3.244	0.045	38.35%
2024	0.357	3.569	0.049	42.18%
2025	0.393	3.926	0.054	46.40%
2026	0.432	4.318	0.059	51.04%
2027	0.476	4.750	0.065	56.14%
2028	0.523	5.225	0.072	61.76%
2029	0.575	5.748	0.079	67.93%
2030	0.633	6.323	0.087	74.73%
2031	0.696	6.955	0.096	82.20%
2032	0.766	7.650	0.105	90.42%
2033	0.842	8.415	0.116	99.46%
2034	0.927	9.257	0.127	109.41%
2035	1.019	10.183	0.140	120.35%
2036	1.121	11.201	0.154	132.39%
2037	1.233	12.321	0.170	145.62%
2038	1.357	13.553	0.187	160.19%
2039	1.492	14.908	0.205	176.21%
2040	1.642	16.399	0.226	193.83%
2041	1.806	18.039	0.248	213.21%
2042	1.986	19.843	0.273	234.53%
2043	2.185	21.827	0.301	257.98%
2044	2.403	24.010	0.331	283.78%



Table 14. Price statistics for forecasted electricity spot prices calculated by applying an annual increase of 2 % for electricity price area SE3.

Year	Median hourly spot price (kr/kWh)	Maximum hourly spot price (kr/kWh)	Minimum hourly spot price (kr/kWh)	Standard deviation
2023	0.605	3.992	0.041	61.97%
2024	0.617	4.071	0.042	63.21%
2025	0.629	4.153	0.043	64.48%
2026	0.642	4.236	0.044	65.77%
2027	0.655	4.321	0.045	67.08%
2028	0.668	4.407	0.046	68.42%
2029	0.681	4.495	0.047	69.79%
2030	0.695	4.585	0.048	71.19%
2031	0.709	4.677	0.049	72.61%
2032	0.723	4.770	0.050	74.06%
2033	0.738	4.866	0.051	75.54%
2034	0.752	4.963	0.052	77.06%
2035	0.767	5.062	0.053	78.60%
2036	0.783	5.164	0.054	80.17%
2037	0.798	5.267	0.055	81.77%
2038	0.814	5.372	0.056	83.41%
2039	0.831	5.480	0.057	85.08%
2040	0.847	5.589	0.058	86.78%
2041	0.864	5.701	0.059	88.51%
2042	0.881	5.815	0.060	90.28%
2043	0.899	5.931	0.062	92.09%
2044	0.917	6.050	0.063	93.93%



Table 15. Price statistics for forecasted electricity spot prices calculated by applying an annual increase of 5 % for electricity price area SE3.

Year	Median hourly spot price (kr/kWh)	Maximum hourly spot price (kr/kWh)	Minimum hourly spot price (kr/kWh)	Standard deviation
2023	0.605	3.992	0.041	61.97%
2024	0.635	4.191	0.044	65.07%
2025	0.667	4.401	0.046	68.32%
2026	0.700	4.621	0.048	71.74%
2027	0.735	4.852	0.050	75.33%
2028	0.772	5.094	0.053	79.09%
2029	0.811	5.349	0.056	83.05%
2030	0.851	5.617	0.058	87.20%
2031	0.894	5.897	0.061	91.56%
2032	0.939	6.192	0.064	96.14%
2033	0.986	6.502	0.067	100.95%
2034	1.035	6.827	0.071	105.99%
2035	1.087	7.168	0.074	111.29%
2036	1.141	7.527	0.078	116.86%
2037	1.198	7.903	0.082	122.70%
2038	1.258	8.298	0.086	128.84%
2039	1.321	8.713	0.090	135.28%
2040	1.387	9.149	0.095	142.04%
2041	1.456	9.606	0.100	149.14%
2042	1.529	10.087	0.105	156.60%
2043	1.605	10.591	0.110	164.43%
2044	1.686	11.121	0.115	172.65%



Table 16. Price statistics for forecasted electricity spot prices calculated by applying an annual increase of 10 % for electricity price area SE3.

Year	Median hourly spot price (kr/kWh)	Maximum hourly spot price (kr/kWh)	Minimum hourly spot price (kr/kWh)	Standard deviation
2023	0.652	4.305	0.045	66.83%
2024	0.718	4.735	0.049	73.52%
2025	0.789	5.209	0.054	80.87%
2026	0.868	5.730	0.059	88.96%
2027	0.955	6.303	0.065	97.85%
2028	1.051	6.933	0.072	107.64%
2029	1.156	7.626	0.079	118.40%
2030	1.271	8.389	0.087	130.24%
2031	1.399	9.228	0.096	143.26%
2032	1.539	10.150	0.105	157.59%
2033	1.692	11.165	0.116	173.35%
2034	1.862	12.282	0.127	190.68%
2035	2.048	13.510	0.140	209.75%
2036	2.253	14.861	0.154	230.73%
2037	2.478	16.347	0.170	253.80%
2038	2.726	17.982	0.187	279.18%
2039	2.998	19.780	0.205	307.10%
2040	3.298	21.758	0.226	337.81%
2041	3.628	23.934	0.248	371.59%
2042	3.990	26.327	0.273	408.75%
2043	4.390	28.960	0.301	449.62%
2044	4.828	31.856	0.331	494.58%



Table 17. Price statistics for forecasted electricity spot prices calculated by applying an annual increase of 2 % for electricity price area SE4.

Year	Median hourly spot price (kr/kWh)	Maximum hourly spot price (kr/kWh)	Minimum hourly spot price (kr/kWh)	Standard deviation
2023	0.756	4.096	0.041	65.88%
2024	0.771	4.178	0.042	67.20%
2025	0.787	4.262	0.043	68.54%
2026	0.803	4.347	0.044	69.91%
2027	0.819	4.434	0.045	71.31%
2028	0.835	4.522	0.046	72.74%
2029	0.852	4.613	0.047	74.19%
2030	0.869	4.705	0.048	75.68%
2031	0.886	4.799	0.049	77.19%
2032	0.904	4.895	0.050	78.73%
2033	0.922	4.993	0.051	80.31%
2034	0.940	5.093	0.052	81.91%
2035	0.959	5.195	0.053	83.55%
2036	0.978	5.299	0.054	85.22%
2037	0.998	5.405	0.055	86.93%
2038	1.018	5.513	0.056	88.67%
2039	1.038	5.623	0.057	90.44%
2040	1.059	5.736	0.058	92.25%
2041	1.080	5.850	0.059	94.09%
2042	1.102	5.967	0.060	95.97%
2043	1.124	6.087	0.062	97.89%
2044	1.146	6.208	0.063	99.85%



Table 18. Price statistics for forecasted electricity spot prices calculated by applying an annual increase of 5 % for electricity price area SE4.

Year	Median hourly spot price (kr/kWh)	Maximum hourly spot price (kr/kWh)	Minimum hourly spot price (kr/kWh)	Standard deviation
2023	0.779	4.217	0.043	67.82%
2024	0.818	4.427	0.045	71.21%
2025	0.858	4.649	0.047	74.77%
2026	0.901	4.881	0.049	78.51%
2027	0.946	5.125	0.052	82.43%
2028	0.994	5.382	0.054	86.55%
2029	1.043	5.651	0.057	90.88%
2030	1.096	5.933	0.060	95.43%
2031	1.150	6.230	0.063	100.20%
2032	1.208	6.541	0.066	105.21%
2033	1.268	6.868	0.069	110.47%
2034	1.332	7.212	0.073	115.99%
2035	1.398	7.572	0.077	121.79%
2036	1.468	7.951	0.080	127.88%
2037	1.542	8.349	0.084	134.27%
2038	1.619	8.766	0.089	140.99%
2039	1.700	9.204	0.093	148.04%
2040	1.785	9.665	0.098	155.44%
2041	1.874	10.148	0.103	163.21%
2042	1.968	10.655	0.108	171.37%
2043	2.066	11.188	0.113	179.94%
2044	2.169	11.747	0.119	188.94%



Table 19. Price statistics for forecasted electricity spot prices calculated by applying an annual increase of 10 % for electricity price area SE4.

Year	Median hourly spot price (kr/kWh)	Maximum hourly spot price (kr/kWh)	Minimum hourly spot price (kr/kWh)	Standard deviation
2023	0.816	4.417	0.045	71.05%
2024	0.897	4.859	0.049	78.15%
2025	0.987	5.345	0.054	85.97%
2026	1.086	5.880	0.059	94.56%
2027	1.194	6.468	0.065	104.02%
2028	1.314	7.114	0.072	114.42%
2029	1.445	7.826	0.079	125.86%
2030	1.590	8.608	0.087	138.45%
2031	1.748	9.469	0.096	152.29%
2032	1.923	10.416	0.105	167.52%
2033	2.116	11.458	0.116	184.28%
2034	2.327	12.603	0.127	202.70%
2035	2.560	13.864	0.140	222.97%
2036	2.816	15.250	0.154	245.27%
2037	3.098	16.775	0.170	269.80%
2038	3.407	18.453	0.187	296.78%
2039	3.748	20.298	0.205	326.46%
2040	4.123	22.328	0.226	359.10%
2041	4.535	24.561	0.248	395.01%
2042	4.989	27.017	0.273	434.52%
2043	5.488	29.718	0.301	477.97%
2044	6.036	32.690	0.331	525.76%

Appendix 5: Simulated energy loss through building envelope measured in kilowatt-hours

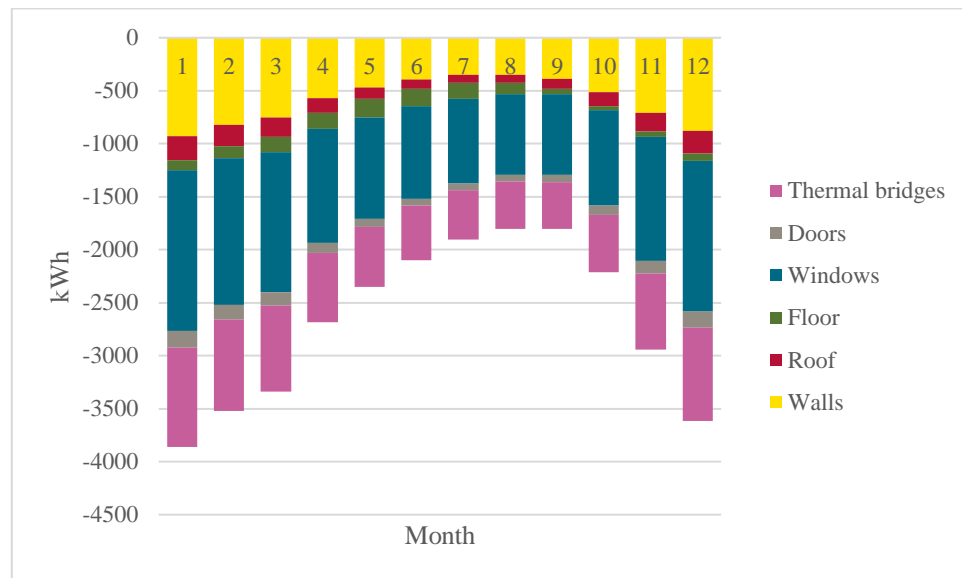


Fig. 34. Heat loss through building envelope for building simulation model within Luleå (SE1).



Fig. 35. Heat loss through building envelope for building simulation model within Sundsvall (SE2).

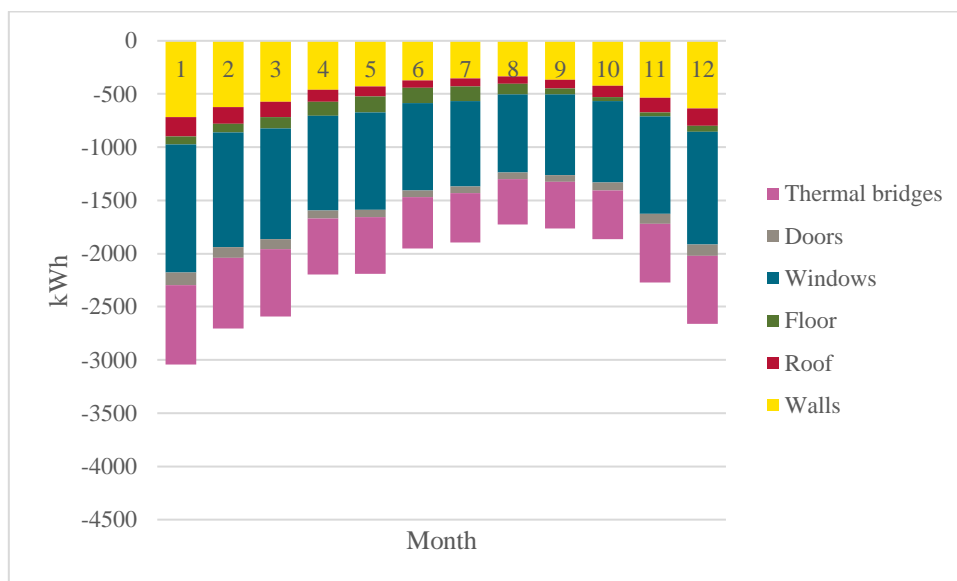


Fig. 36. Heat loss through building envelope for building simulation model within Stockholm (SE3).

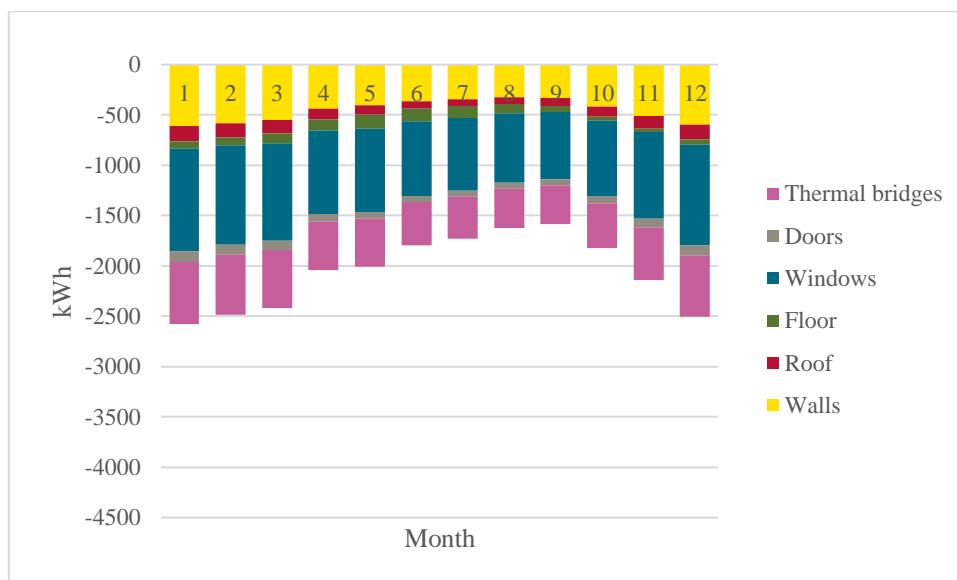


Fig. 37. Heat loss through building envelope for building simulation model within Malmö (SE4).



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