Optimization and Analysis of Sector Coupled Flexible Energy System

Evaluation of Sector Coupling and Energy Storage Methods

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Acknowledgements

This project is a 15-credit degree project, and is a final project of the 180-credit electrical engineering program at Chalmers University of Technology in Gothenburg. The work was performed over a period of six months, for the consulting company, Bengt Dahlgren AB, in urban planning. The goal of the project has been to investigate and evaluate how energy storage and sector coupling solutions can be used to contribute to more flexible, cost efficient and fossil-free energy system as well as to reduce power peaks.

We would like to extend a big gratitude to our supervisors at Bengt Dahlgren AB, Martin Ekelund and Christopher Carrwik who have been a great support for us in the project. From the company we would also like to thank Peder Eriksson for sharing his expertise with us. Finally, we would like to thank David Steen at the department of Electrical Engineering at Chalmers, who has been our supervisor and examiner.

Anna Pardo and Julia Ratka Gothenburg, June 2026

Abstract

Modern civilization is dependent on electricity, often generated from fossil fuels. Meanwhile, the global transition toward renewable energy sources and decarbonization has led to an increased demand for flexible energy systems. Challenges such as power peaks, fluctuating electricity prices, limited grid capacity, and the increasing share of renewable energy sources require buildings to be designed in a way that it becomes capable of controlling, storing, and shifting energy use over time.

This report describes a scenario-based study that investigates sector coupling solutions and electrical energy storage methods with the goal to asses their potential to reduce power peaks and enhance local energy flexibility. The scenarios are simulated in Python for Power System Analysis (PyPSA) software. The data was obtained from a literature study as well as from a property project by Bengt Dahlgren AB. This study also evaluates the solutions from economical- and environmental perspectives.

The results indicate that there are various storage methods that contribute to a more flexible energy system, particularly when combined with local power production and sector coupling. After simulating the scenarios, the findings in the report suggest that many technologies, such as hydrogen tanks and Vehicle to grid (V2G), are a key component to a transition of industries and heavy vehicles to fossil-free. However, based on analysis of the results, they are technologies that need further development and standardization in order to be a viable alternative.

After evaluation from a technical- , environmental- and economical perspective, the results suggest that the accumulator tank in combination with heat pumps is the most optimal alternative for the property area investigated in this study. Furthermore, integration of solar photovoltaic cells seems to contribute to a reduction of power peaks by being a support to the grid, mostly during the days with many sun hours.

Overall, the findings suggest that integrated system solutions, such as battery storage systems, thermal tanks, hydrogen tanks, have the potential to reduce peak demand and improve the utilization of renewable energy sources. Thermal tank scenario, that turned out to be the most optimal scenario in the study, offers economic and environmental benefits, while it also reducing power peaks. The heat demand can be met, without using the grid, by using the energy stored in the tank.

Keywords: sector coupling, energy flexibility, renewable energy sources, decarbonization

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Terminology

- VRES - Variable Renewable Energy Sources
- SC - Sector Coupling
- EV - Electric Vehicles
- G2V - Grid-to-Vehicle
- V2G - Vehicle-to-Grid
- EES - Electrical Energy Storage
- BESS - Battery Energy Storage Systems
- PV - Photovoltaic
- IC engines - Internal Combustion engines
- FC - Fuel Cell
- PyPSA - Python for Power System Analysis
- HFC - Hydrofluorocarbon
- HVAC - Heating, Ventilation, and Air Conditioning
- CapEx - Capital Expenditure
- Battery SOC - Battery State of Charge

1 Introduction

As a result of the Paris Agreement and the global push toward decarbonization [1], the demand for flexible energy systems has increased. This, in a civilization highly reliable on electricity, introduces new conditions for how buildings and real estate areas should be planned and designed. These requirements concern both overarching issues related to the electricity grid and energy production, as well as solutions on a construction level. Challenges such as power peaks, fluctuating electricity prices, limited grid capacity, and the ambition to increase the share of variable renewable electricity sources (VRES) imply that buildings increasingly need to be able to control, store, and shift energy use over time.

Discussion regarding energy storage systems (ESS) often centers around battery systems. However, these systems are associated with high investment costs, significant climate impact, and technical complexity. This motivates an investigation of alternative and potentially more resource-efficient solutions. Sector coupling (SC) is one such alternative, where interaction between heating, cooling, and electricity systems can contribute to flexibility without extensive investments.

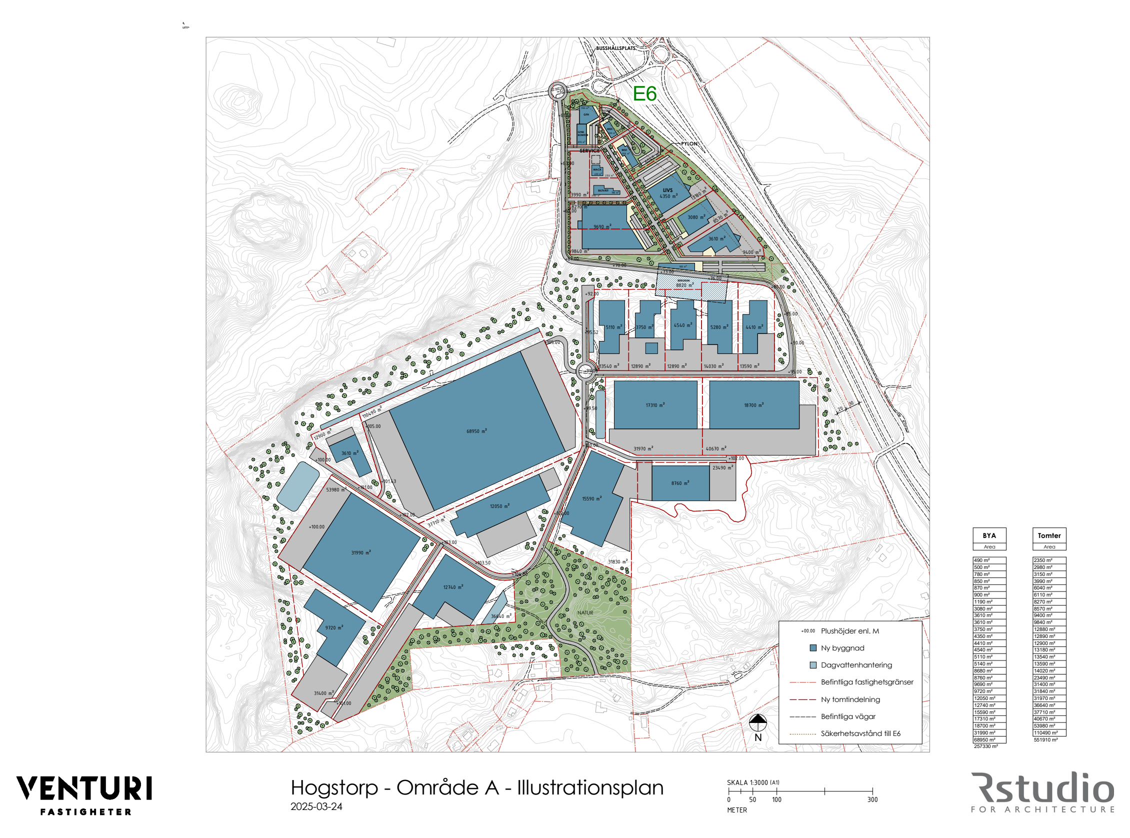
Furthermore, it is important to analyze the benefits of local flexibility that arise higher up in the energy system, for example in the form of reduced or balanced power demand. This includes highlighting both economic and climate-related aspects, such as impacts on power-related costs, resilience, utilization of renewable electricity, and the cost and climate consequences of different solutions.

This project intends to, through a literature study supported by data from a property project and simulations, evaluate different solutions in order to assess their potential to reduce power peaks, enhance local energy flexibility, and contribute to a resilient, cost-efficient, and low-carbon energy system. The analysis is based on a property project, where the energy analysis and planning for the area is performed by Bengt Dahlgren AB, from which data will be utilized.

1.1 Description of the Area

The Illustration plan of the area Hogstorp made by Bengt Dahlgren AB can be seen in the Figure 1.1 below.

The property project is in Hogstorp in Gothenburg and has a potential exploitation of 350.000 square meters (sqm) gross area, with an estimated exploitation figure of 0.5. The area is meant to contain warehouses, logistics, light industries, service, charging infrastructure, batteries. The



BYA Area	Tomter Area
490 m²	2350 m²
500 m²	2980 m²
780 m²	3150 m²
850 m²	3990 m²
870 m²	6040 m²
900 m²	6110 m²
1190 m²	8270 m²
3080 m²	8570 m²
3610 m²	9400 m²
3610 m²	9840 m²
3750 m²	12880 m²
4350 m²	12890 m²
4410 m²	12900 m²
4540 m²	13180 m²
5110 m²	13540 m²
5140 m²	13590 m²
8680 m²	14020 m²
8760 m²	23490 m²
9690 m²	31400 m²
9720 m²	31840 m²
12050 m²	31970 m²
12740 m²	36640 m²
15590 m²	37710 m²
17310 m²	40670 m²
18700 m²	53980 m²
31990 m²	110490 m²
68950 m²	551910 m²
257330 m²	

Figure 1.1: Illustration plan of the area Hogstorp made by Bengt Dahlgren AB.

regional and local network are owned by the company Vattenfall. This area is planned as part of a wider integrated project , with phased expansion, innovative technical solutions, ecological vision and potentially be a testbed for future systems. Since this area is close to the E6 motorway, it is meant to have road-oriented service and restaurant offering.

This area is split into two areas, area A and area B, where area A is further divided into two areas, lower plateau and upper plateau. The lower plateau is intended to have a central green space leading to restaurants and also be walkable. It is also meant to have moderately sized business buildings with focus on sustainability, traditional constructions and wood and stone from the site.

The upper plateau should contain greenery as a natural element in the environment, with both existing and newly planted greenery. This project only considers area A which can be seen in Figure 1.1.

1.2 Purpose

The purpose of this project is to investigate and evaluate how energy storage and sector coupling solutions such as thermal storage tanks, thermal storage in the building structure, and control of heat pumps can be used in order to reduce power peaks, enhance local energy flexibility, and contribute to a resilient, cost-efficient, and low-carbon energy system. Furthermore, it is meant to evaluate said methods from an economical- as well as environmental perspective. All this is intended to be done through simulations and analysis of various scenarios.

Thereby objectives are:

- Identify and analyze possible measures for power reduction and power balancing through sector coupling, such as:
  - Thermal storage tanks
  - Flexibility and control of heat pumps
  - Hydrogen storage tanks
  - Battery storage
  - Vehicle to grid
  - Operational optimization between heating and electricity
- Assess how much power reduction or balancing is technically possible at the area level.
- Evaluate costs and climate impact of different solutions and compare these with the achieved benefits for both property owners and the electricity grid.
- Discuss resilience, security of supply, and the potential to support the grid during periods of high load.

1.3 Delimitations

The evaluation made in this project is based on literature and available operational data, and does thereby not include long-term forecasting or experimental testing.

Furthermore, as a result of rapid development of technologies in this field, there is limited access to reliable data on investment cost as well as long term effect and lifespan of the products. Hence, several estimates in this study are based on global data.

Moreover, there is a wide range on possible energy storage methods and system configurations. It is thereby not possible to asses all potential solutions. Consequently, this study is limited to a selected number of scenarios. Furthermore, the study is based on assumptions made regarding potential energy usage.

Certain assumptions were required, since the area is not a real area yet. Firstly, the power- and energy-demands are estimated for the year 2035 by Bengt Dahlgren AB, where the load may actually look different in the future. The solar data is taken from 2020 in PVGIS, where it also may look different in 2035. This is a delimitation since it can lead to over-dimensioning of the load and therefore cause over-dimensioning by the simulations for different scenarios built in this project.

Secondly, the exact prices of the different scenarios cannot be determined with exact certainty either as it depends on materials used, the supplier or provider of the technology. Since the simulations highly depends on the investment cost this can lead to misleading simulation outputs for the different scenarios. Furthermore, operational costs are not included in the study due to time limitations as well as difficulty finding information on the newer technologies.

2 Background Material

This section incorporates information on the theoretical concepts necessary for subsequent analysis.

2.1 Electricity Grid

An electricity grid is an infrastructure network, covering a wide geographical area, used for electricity delivery from producers to consumers. It is a network of synchronized producers and consumers where they are linked by transmission lines as well as distribution lines. Those are managed by one or more control centers [2].

Such a system consists of power plants where electricity production takes place, usually by usage of electromechanical generators. As, the electricity is usually produced far from where it is needed, transmission lines are used for electrical transmission. The transmission lines in Sweden are stepped up by step-up transformers a high voltage of 220kV or 400kV [2].

The electricity is later distributed using step-down transformers to transform the voltage to utilization voltage safe and appropriate for use by individual customers. In Sweden the distribution lines consist of regional and local grids where the regional grids are connected to transmission lines and transport the electricity further to local level. The regional grid have a voltage 130kV whereas local grids have a voltage 400V[2].

2.2 Photovoltaic Cells

An alternative for renewable energy sources is solar energy. Photovoltaic (PV) cells are used to convert solar energy into electricity on an atomic level through a process called photovoltaics[3] . The cells are made of semiconducting material. When photons strike a cell, some of the particles are absorbed within the photoelectric material. The energy absorbed loosens the electrons negatively charged components which makes them flow freely, resulting in production of a current. [3] Nevertheless, as other RES, it is also characterized by a stochastic nature as it is highly dependent on the climate and weather. Thereby flexibility and storage becomes of great importance.

Most commercial solar PV modules have an efficiency of 21.13%, where inverters that convert the electricity from solar panels (direct current) into household electricity (alternating current) so that it can be used at home have an efficiency of 98.6% [4]. Solar PV have a lifespan between

20-30 years [5].

2.3 Energy Flexibility in Energy System

Flexibility is a term that describes the extent to which a power system can adjust to the electricity demand or generation in reaction to both anticipated and unanticipated variability[6]. In other words it indicates whether the system can reliably sustain power supply when facing sudden disturbances or mismatches between generation and demand. As integration of VRES increases, the need for more flexible energy systems becomes essential in order to create a balanced system. It is important to achieve balance, meaning that the demand should not exceed the production and the production should not be greater than the demand.

Modern civilization is to large extent dependent on electricity generated from fossil fuels. Although the goal is transition to energy generation using VRES, the shift introduces various challenges - one of the main challenges being the stochastic nature of VRES. VRES are irregular and non-constant over time as they are highly dependent on climate conditions. This is where the term flexibility is shown to be of great importance[6]. Power system flexibility is essential to manage said uncertainty and variability of generation. One of the main subsequent issues in connection to the stochastic nature of VRES becomes the mismatch between demand and supply which can jeopardize reliability of power system networks. There are deficiencies in terms of storage capacities - hence it becomes challenging to counteract the mismatch.

Furthermore, an unreliable electricity supply has cascading effects on socio-economic activities[7]. Several studies in Europe demonstrate that the capacity and utilization of VRES is low due to monthly variations[7]. This in turn results in seasonal or even interannual structural imbalances in energy supply which in turn can cause fluctuations in electricity prices [7].

Thereupon, it is of great importance to find sources of flexibility for decarbonization and efficiency of the entire energy system while maintaining the security of supply to the area, which is highly emphasized by The European Commission [8].

In order to reach net zero, it is important to make a deep analysis of flexibility needs, to find the most optimal method where we can exploit sector-coupling or energy system integration, which can benefit system resilience and cost-effectiveness.

2.3.1 Spatio-Temporal flexibility

Spatial flexibility deals with geographic mismatches in supply and demand across geographic locations[9]. While VRES have a significant role in decarbonization of an energy system, it is complex to find an ideal solution. The complexity comes from the fact that integrating VRES to great extent, can challenge the power system due to their temporal fluctuations and geographical dispersion [10].

Temporal flexibility on the other hand deals with the time-dependent variability. The different time scales on which flexibility can be evaluated are long-term (more than a year), medium-term (annual, weekly and daily) and short-term (intraday). Matching supply and demand is uncertain as VRES development is difficult to predict which has to do with the earlier mentioned stochastic nature of the VRES, as well as the evolution of customer habits and economic growth[9].

2.4 Sector Coupling and Integration Methods

Sector Coupling (SC) is a concept of connection and interaction of various energy sectors with the aim to increase flexibility of supply, demand and storage. Current research on smart energy systems aims to overcome the challenges of balancing energy over time, which arise from the intermittent feed-in of RES through the use of smart energy systems. SC encompasses purposeful connection and interaction of demanding energy sectors, sectors with high energy consumption and high energy requirements, and the mechanism itself requires connection of at least two sectors[11]. The integration provides flexibility to energy systems and helps simultaneously manage energy consumption of various systems.

This method refers to electrification of energy systems, and emerges as a potentially efficient strategy for emission reduction with the goal of decarbonization of the power sector. Electrification can occur directly or indirectly. Direct electrification indicates an increase in electricity consumption through technologies that directly consume electricity. Indirect electrification depends on the consumption of fuels produced by electricity such as electrolysis which is a method to produce hydrogen by splitting water molecules into hydrogen and oxygen using electricity. This method can effectively reduce emissions that direct electricity cannot mitigate. Electricity is converted to another form which adds flexibility, storage or transportability[12].

2.4.1 Heat pumps

Heat pumps provide renewable energy, by condensing and utilizing thermal energy that already exists and using it for cooling and heating [13]. The pump absorbs the heat from the outside through a fluid called refrigerant, that then evaporates into gas. A compressor compresses the refrigerant gas, increasing the pressure and temperature. The hot refrigerant passes through a heat exchanger inside the building and releases heat indoor[14]. This is a technology that works well for providing heating and cooling for homes, offices, industries or shops.

The highest efficiency is achieved with series counterflow configurations of several heat pumps, as the work input for each compressor is reduced, the efficiency of the heat pumps increases [15].

Heat pumps are a sustainable technology for heating and cooling. Nevertheless, faults can occur. Heat pumps use refrigerants, which are usually hydrofluorocarbons (HFCs) their leaking can lead to massive emissions of greenhouse gases [16]. Underfilling the refrigerant can also negatively affect the pumps' capacity, energy consumption and performance [16]. There are different types of heat pumps, such as air source and ground source heat pumps.

2.4.1.1 Air source heat pumps

Air source heat pumps are installed where circulating air is present, e.g. on roofs, they can be used for room cooling and heating, but can also be connected to the water heating system to provide hot water during the cooling cycle [13].

2.4.1.2 Ground source heat pumps

Ground source heat pumps utilize the even temperature below the ground, which means that this pump is not exposed to fluctuating temperatures, unlike the air source heat pump. The refrigerant fluid instead travels though pipes buried in the ground, absorbing the heat from the surrounding ground. If seasonal temperatures drop below -1 to -2 degrees Celsius, ground-based heating and cooling may be more suitable than air source heat pumps [13].

2.4.2 Electric boiler

Electric boilers produce heat using electricity while being compact and quiet [17]. Electric boilers perform well compared to gas or oil boilers, but heat pumps are significantly more energy efficient than electric boilers. Electric boilers have an efficiency between 95% and 99.9%, and are often used as a supplementary option for heating in residential areas [18]. In comparison heat pumps have an efficiency around 250-400% [19], depending on temperature and operating conditions.

2.4.3 Vehicle to Grid

Coupling the electricity and transportation sector which can be referred to as vehicle to grid. [11] Increasing electrification of the transport sector by electric vehicles (EV) serving as consumers or storage of excess electricity. Bidirectional charging, V2G, means that the electric car's battery not only receives electricity when charging (G2V) but also has the ability to store and feed electricity back into the grid when needed.

When an electric vehicle is parked and connected to the grid, the stored energy can be fed back into the grid, increasing the stability and capacity of the electricity grid. This also benefits the car owner who can sell the electricity. This method increases the ability to stabilize the electricity system, by creating the possibility for flexible energy storage and backup power.

Given the increased influx of electric cars, and the requirement to reduce fossil fuels, this solution can currently overload the grid. Due to uncoordinated charging processes that will produce unwanted peaks, stress on distribution transformers, overloading of lines, this will lead to increasing system losses and voltage deviations. This can be avoided by using coordinated charging processes (G2V) where charging is done during off-peak hours during the night. By shifting or reducing peak load on the grid, losses in the distribution grid are reduced and the lifespan of transformers is improved, which leads to increased grid reliability [20].

There is great importance in where charging stations are placed to increase accessibility but also the impact on the local grid [21].

2.4.4 Power-to-X

Electricity can be processed into other energy carriers that are flexible in their use and storage, but also used in other sectors directly. The method where electrical energy is converted into various products is called Power-to-X (PtX). Synonymous with all PtX applications is Power-to-Gas (PtG), which utilizes renewable electricity to produce hydrogen through the electrolysis of water. The hydrogen can then be used directly as an energy carrier or converted into methane, syngas, electricity, chemicals, or liquid fuels [22].

2.5 Storage

Energy storage systems (ESS) play an essential role in terms of enhancement of utilization of VRES. This provides a potential solution of variability caused by the intermittent nature of VRES. Such storage systems charge during off-peak periods and discharge when a need emerges, and thereby meet peak demands [23].

2.5.1 Thermal Energy Storage

An alternative for achieving more flexible energy systems as well as increase utilization of RES is thermal energy storage (TES). These systems are designed to store heat energy by cooling, melting, condensing or vaporizing substances. Such a system usually consists of a storage medium as well as equipment for heat injection and extraction to-and from the used medium. Medium used in a TES can either be naturally occurring, for instance the ground, or it can be artificial, such as a container such as a water tank [24].

TES is widely used for both industrial purposes, where required temperatures can at times be very low, as well as heating in buildings. Accumulator tank is a storage solution for heat storage in heating systems. It stores excess heat generated by heating systems in order for it to be used later when it is needed. Accumulator tanks are usually insulated and are available in various sized and insulation types with the goal to increase compatibility with various energy systems with various applications [25].

This method can effectively reduce the mismatch between energy supply and demand by storing thermal energy for use at a later time.[24]. This means that when heat production is higher than the demand, the excess heat can be stored in the thermal tank. Later the energy stored in the thermal tank can be used when the demand is high, instead of drawing power from the grid.

2.5.2 Battery Energy Storage Systems

Battery storage systems (BESS) play an essential role in increasing performance of solar PV cells and thereby contribute to an increased usage of VRES. This method has gained popularity over the years - particularly in residential areas, electrical vehicle charging stations as well as large scale grid connected systems. BESS are used to store electrical energy for later use in for further power system operations. In other words, the goal is to charge the battery and then discharge it when the need arises. This method can improve grid flexibility as well as reduce power peaks[26]. Currently, most focus lies on lithium-ion batteries as they are highly efficient, their costs are declining and there is flexibility in use meaning that it can be used in various ways.

Furthermore, power loss due to degradation is one challenge when using BESS. This occurs as a result of operation in a power system, self discharge, overall usage of the battery, well as stochastic load from EV. The lifetime of a battery varies significantly as a result of factors such as different operating conditions, the level of renewable energy sources (RES) penetration, cyclic operation, temperature, discharge/charge rate, and depth of discharge [26]. Lithium iron phosphate batteries, which are used mainly with solar panels, have a lifespan between 17-24 years [27].

2.5.3 Hydrogen Electrical Storage System

Usage of hydrogen in terms of ESS has gained attention in research. It could potentially become essential in transition to low carbon energy systems due to its high energy density and broad sectoral applicability. Furthermore, it can be extracted using low-carbon methods such as water electrolysis. Production of ”green hydrogen”, is done via electrolysis, and then the hydrogen is converted into electricity, using fuel cells. Fuel Cell (FC) is an electrochemical device that converts chemical energy, from electrochemical reactions, into electrical energy [28]. A hydrogen energy system contains a fuel cell in order to generate electricity from hydrogen[29]. The excess hydrogen is stored in hydrogen tanks. Compared to conventional batteries, hydrogen can be stored for extended periods of time, since it has zero self-discharge[29].

Still, hydrogen-based ESS come with certain disadvantages connected to low volumetric energy density in the tanks, significant energy consumption for high-pressure compression, and safety risks related to leaks and potential explosions[23]. The disadvantages are connected to the properties of hydrogen, such as its small molecular size, high diffusivity, reactivity and flammability and its tendency to embrittle certain materials[23]. Furthermore, liquid hydrogen systems which provide superior volumetric density come with energy-intensive cooling requirements. For the time being, there have been efforts in order to increase safety in terms of hydrogen usage and storage. Those are for instance Algorithms and AI integrated monitoring which provide anomaly detention and automated safety protocols [30]. One of the key challenges in hydrogen storage system design is selecting suitable materials. Hydrogen embrittlement depends on both temperature and pressure and can, under certain conditions, reduce the service life of pressure vessel materials by as much as 90%, making careful material selection and design adaptations essential [30].

A hydrogen tank has a lifespan of 30 years and electrolysis has a lifespan of 15 years [4].

3 Method

For this project, the methodological approach combines a literature study with quantitative calculations performed in Microsoft Excel. The simulations are performed with Python for Power System Analysis (PyPSA) software. Figure 3.1 below shows the overall methodology and workflow of the study.

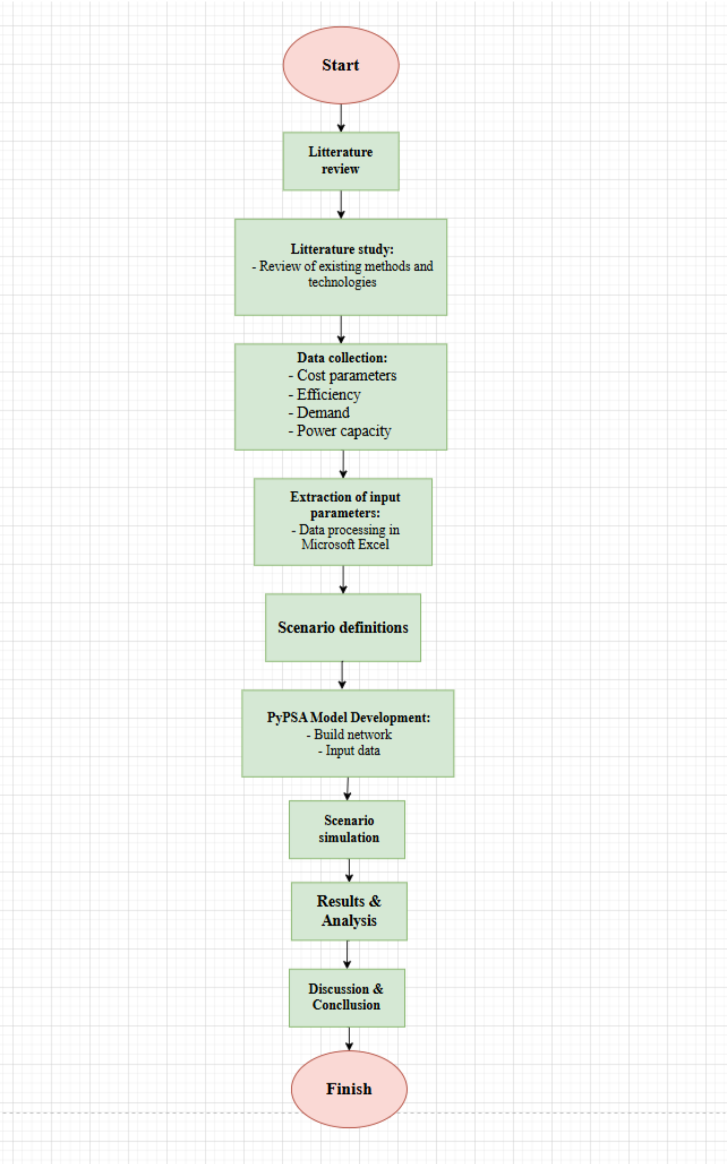


Figure 3.1: Flowchart of the overall methodology.

3.1 Literature study

A literature study is conducted to determine the theoretical framework and support technical solutions, assumptions, and evaluation criteria. The literature consists of scientific articles, research reports, publications from authorities and industry organizations, and documents available from Bengt Dahlgren AB.

This study is focused on power reduction and power balancing in buildings, energy flexibility and sector coupling, thermal energy storage and battery storage, economic and environmental impacts and incentives available for property developers. The literature study defines the input parameters that are cost assumptions for this project. Figure 3.2 shows the approach when performing the literature study and source collection.

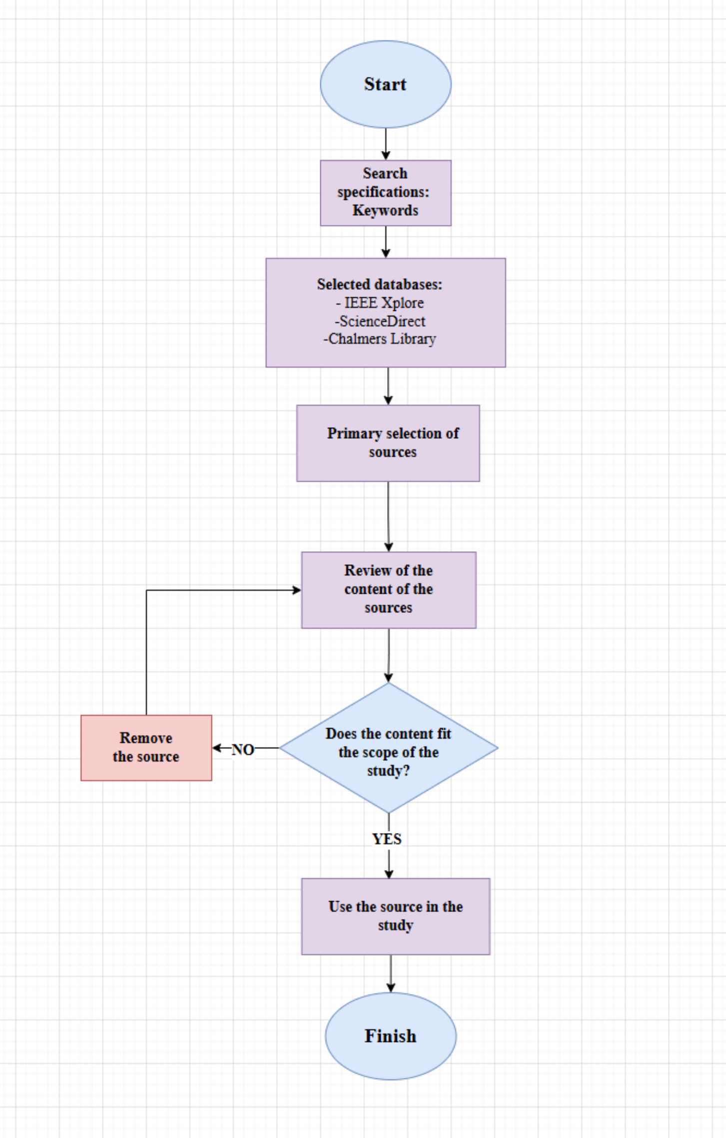


Figure 3.2: Flowchart of review methodology.

3.2 Data collection

The analysis of the scenarios is based on data for electricity and thermal demand with daily resolution, heat pumps, thermal storage tanks, battery systems, electricity prices, energy-based and power-based taxes and emission factors for electricity.

If data is unavailable from Bengt Dahlgren AB, estimations and typical load profiles acquired from literature are used. The environmental impacts are obtained from the literature study. All assumptions are documented and consistently applied across the project.

3.2.1 Data processing

The data processing and compilation is performed in Microsoft Excel where data is collected in order to later formulate the scenarios. It is used for data compilation where following data is systematically collected and organized:

- Electricity load profiles
- Peak power demand
- Estimation of power reduction potential through load shifting
- Calculation of shifted or stored energy
- Comparison of maximum power demand between scenarios
- Economic calculations include investment costs

3.3 Software

The modeling and optimization of solutions suggested in this study will be performed in PyPSA software. It is an open source Python framework used for optimizing and simulating power and energy systems[31]. In this project, PyPSA is used as a sector-coupled energy system optimization model. This software utilizes basic coding and incorporates coding with pre-defined built-in functions. Figure 3.3 below depicts a flowchart that shows input- and output data in the PyPSA software.

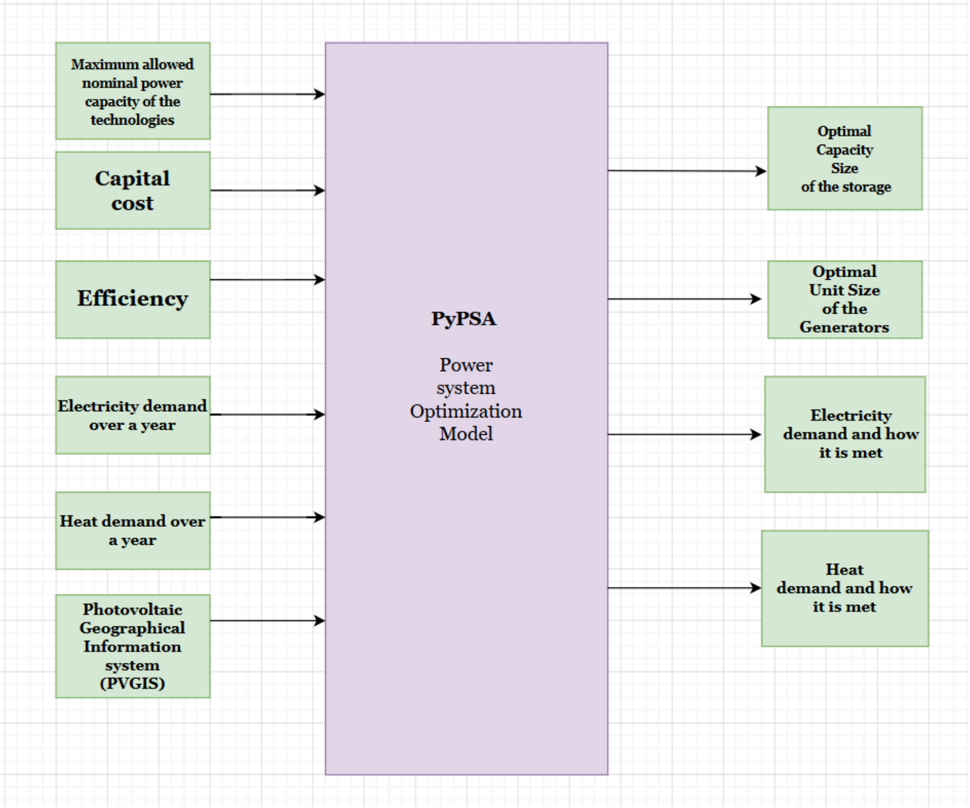


Figure 3.3: Flowchart presenting the input data and output data in the study when using the software.

The input parameters considered in the study and the output parameters obtained using the software are presented in Figure 3.3 . The energy system is modeled by defining components such as generators, loads and storage. PyPSA converts an energy system to a linear optimization problem and solves the problem, using Linopy framework which is PyPSA, an optimization backend that prepares and solves optimization problems. It also uses HiGHS which is an open-source linear programming solver [31]. This is done in order to determine the most optimal option and to be able to compare the different solutions.

Energy buses are fundamental components in the PyPSA network. They represent connection points in the designed energy system - where energy is produced, stored, consumed and converted in the different sectors. The buses can also model other energy carriers such as heat, hydrogen or gas. In this project separate buses are used for electricity, heat, hydrogen and gas which enables usage of technologies such as heat pumps, electrolyzer, fuel cells to exchange energy between the sectors while maintaining the energy balance in the system.

Furthermore, there are generators such as solar PV and grid import in order to provide the system with information on power generators. The system is also provided with an Photovoltaic geographical information (PVGIS) and Comma Separated Values (CVS) time series through which information on solar radiation as well as photovoltaic system performance is obtained for the area in which the project is aimed to be located. Hourly heat and electricity demand data for the area for the full year are used as inputs to the model.

As seen in Figure 3.3 the model takes as input the maximum allowed nominal power for each technology, expressed in MW. This input parameter is adjusted based on the selected scenario and the technology used in the scenario. Constraint parameters such as capacity (MWh) are also set for storage methods, such as the thermal tank, the hydrogen tank, and the energy storage of EV´s. Capital costs (SEK/MW) as well as efficiency are specified for each technology.

The results obtained from the program is the optimal generation capacity (MW), optimal storage unit size as well as demand profiles and dispatch schedules visualizing how the electricity- and heat demand is met over a certain time period. The output data is later be analyzed and the simulation results of the scenarios are compared. It is thereby possible to determine the most optimal solution alternative.

4 Case Study

This chapter provides an overview of the investigation process, data collection and definition of scenarios used in the study as well as key assumptions made.

4.1 Data collection

To define scenarios to be tested and evaluated, data obtained from Bengt Dahlgren AB is used for PV roof area, electricity demand, heat demand, car parking opportunities, and the maximum power that can be installed for AC and DC chargers for the area. The heat demand contains the demand for Heating, Ventilation, and Air Conditioning (HVAC), which is calculated by Bengt Dahlgren AB. The PV roof area is calculated as it is possible to install solar PV on 75% of the roof area. In Table 4.1 and Table 4.2 the different buildings are meant for:

- S1: Offices, retail and restaurant
- S2: Restaurant
- S3: Gas station, car wash with AC and DC vehicle chargers
- B1: Rock cave for storage
- N1-N9 and O1-O10: Business activities/logistics

HVAC demand, roof area, PV roof area, power factor and maximum solar PV power that can be installed is shown in Table 4.1. The electricity demand is estimated for every hour per year, and the calculations were performed by Bengt Dahlgren AB. The annual electricity demand were estimated to be 65132 MWh for the year 2035.

Table 4.1: Summary of building PV and HVAC data

Building	Roof Area (m^2)	PV Area (m^2)	Installed PV Power (kW)	HVAC (kVA)	HVAC (kW)	Power Factor
S1	2560	1920	422	52.4	47.16	0.9
S2	500	375	83	12.2	10.98	0.9
S3	1270	953	210	23.3	20.97	0.9
B1	0	0	0	178.2	160.38	0.9
N1	4350	3263	718	79.8	71.82	0.9
N2	9690	7268	1599	177.7	159.93	0.9
N3	3080	2310	508	56.5	50.85	0.9
N4	3610	2708	596	66.2	59.58	0.9
N5	5110	3833	843	93.7	84.33	0.9
N6	3750	2813	619	68.8	61.92	0.9
N7	4540	3405	749	83.2	74.88	0.9
N8	5280	3960	871	96.8	87.12	0.9
N9	4410	3308	728	80.9	72.81	0.9
O1	68950	51713	11377	1264.1	1137.69	0.9
O2	17310	12983	2856	317.4	285.66	0.9
O3	18700	14025	3086	342.8	308.52	0.9
O4	3610	2708	596	66.2	59.58	0.9
O5	12050	9038	1988	220.9	198.81	0.9
O6	15590	11693	2572	285.8	257.22	0.9
O7	8760	6570	1445	160.6	144.54	0.9
O8	31990	23993	5278	586.5	527.85	0.9
O9	12740	9555	2102	233.6	210.24	0.9
O10	9720	7290	1604	178.2	160.38	0.9
Maximum Installed PV Power (MW)			40.85			
Efficiency of solar PV			23%			
Total HVAC demand Power (MW)			4.25322			

The maximum installed PV power was calculated to 40.85 with an efficiency of 23%, as seen in Table 4.1. Since an installed solar PV capacity of 40.85 MW is likely to overestimate the practical solar energy potential in the Hogstorp area, lower capacities were chosen for simulation corresponding to 23%, 5.75%, and 2.3% of the maximum installed PV power. This approach enables an assessment of how different levels of PV deployment affect the simulation results and provides a more realistic range of possible outcomes.

Table 4.2 contains the values used for the maximum parking lots, charging spots and charging power that can be installed for AC and DC chargers. The calculations in 4.2 are performed by Bengt Dahlgren AB.

Table 4.2: Summary of EV charging infrastructure

Building	Parking Spaces	Charging Spots	AC Power (kVA)	Fast Charging Power (kVA)	Total Power (kW)
S1	20	8	32	222.2	282.44
S2	10	4	16	0	17.78
S3	150	60	240	3555.6	4217.33
B1	0	0	0	0	0
N1	40	8	32	0	35.56
N2	90	18	72	222.2	326.89
N3	200	40	24	0	26.67
N4	35	7	28	0	31.11
N5	50	10	40	0	44.44
N6	35	7	28	0	31.11
N7	45	9	36	0	40.00
N8	50	10	40	0	44.44
N9	40	8	32	0	35.56
O1	660	132	528	1333.3	2068.11
O2	165	33	132	666.6	887.33
O3	180	36	144	666.6	900.67
O4	35	7	28	0	31.11
O5	115	23	92	444.4	596.00
O6	150	30	120	444.4	627.11
O7	85	17	68	222.2	322.44
O8	305	61	244	666.6	1011.78
O9	120	24	96	444.4	600.44
O10	95	19	76	222.2	331.33
Total Charging Spots		571			
Total Power (MW)					12.51

The total power in kW, seen in Table 4.2 is calculated by adding AC power with fast charging power and then dividing it with the effect factor of 0.9 that is used by Bengt Dahlgren AB.

The total power of 12.51 MW, seen in Table 4.2 it is what is possible to install in the area, however the goal is to not exceed 10 MW. The value for the power needed for charging spots was instead calculated by multiplying the total charging spots by 10 kW, which resulted in 5.71 MW, if every car parked was an EV with a charging need of 10 kW.

4.1.1 Economic data

To investigate and analyze the different scenarios, the optimization model needs Capital Expenditure (CapEx). The total CapEx is calculated by multiplying the CapEx for every technology by the simulated optimal storage/capacity units. Data for CapEx, is shown in Table 4.3. The data in the table are derived from comparing prices of different companies, other written projects, pilot projects, and with the help of data from Bengt Dahlgren AB.

Table 4.3: Cost parameters and references

Element	Cost	Unit	Reference
PV system	5 000 000	SEK/MW	[32]
Hydrogen storage tank	2 520 000	SEK/MWh	[33]
Electrolyzer	3 000 000	SEK/MW	[4]
Fuel cell	10 000 000	SEK/MW	[4]
Heat Pump	10 000 000	SEK/MW	[34]
V2G charging	2 000 000	SEK/MW	[35]
Battery	4 000 000	SEK/MW	[32]
Electricity	1000	SEK/MWh	[36]
Accumulator storage tank	500 000	SEK/MWh	Bengt Dahlgren AB
Electric boiler	2 000 000	SEK/MW	[37]

4.2 Scenario definition

In order to analyze the results from PyPSA, different scenarios have been defined, where a reference scenario has been made by Bengt Dahlgren AB, which will be compared with alternative scenarios, to find profitable methods, both economically and environmentally.

Reference scenario: All buildings are heated by using heat pumps, where the grid is the only electricity provider.

Battery scenario: Solar panels are installed on several buildings, and the generated energy is stored using batteries as storage. Heat pumps are used in all buildings. This scenario will be tested with 23%, 5.75% and 2.3% solar PV, where 100% is defined in Table 4.1 as 40.85 MW.

Thermal tank scenario: For energy storage, accumulator tanks will be used and simulated with 23%, 5.75%, 2.3% and 0% solar PV. All buildings are heated with heat pumps.

Hydrogen tank scenario: Hydrogen tank used for energy storage, where the hydrogen is produced by the electrolyzer and then changed to electricity with the help of fuel cells. This will be simulated with 23%, 5.75%, 2.3% and 0% solar PV.

Electric boiler scenario: Heat pumps will be replaced by electric boilers, and this will be simulated with battery and thermal tank as energy storage methods.

V2G scenario: Assuming that all cars are electric vehicles, with most parking spaces equipped with chargers. A simplified V2G profile is used: the EV's are connected to the grid at work time 7AM to 4PM, since there are mostly officies and industries. At worktime the discharge was expected and after that period the cars where assumed to be charged. The maximum charging and discharging power was calculated, under the chapter Data collection, to 5.71 MW assuming that every vehicle is an EV.

5 Results

Following section discloses results of obtained through simulation, in PyPSA, of the defined scenarios. Data processing and data assembly was done in Microsoft Excel. Calculations of CapEx in Microsoft Excel is based on data collection from the relevant sources. The analysis focuses on how EES and SC affect system flexibility as well as the ability of a system to reduce power peaks and strain of the electricity grid.

5.1 Reference scenario

The graph on electricity demand and supply fulfillment obtained when simulating the reference scenario can be seen in Figure 5.1 below.

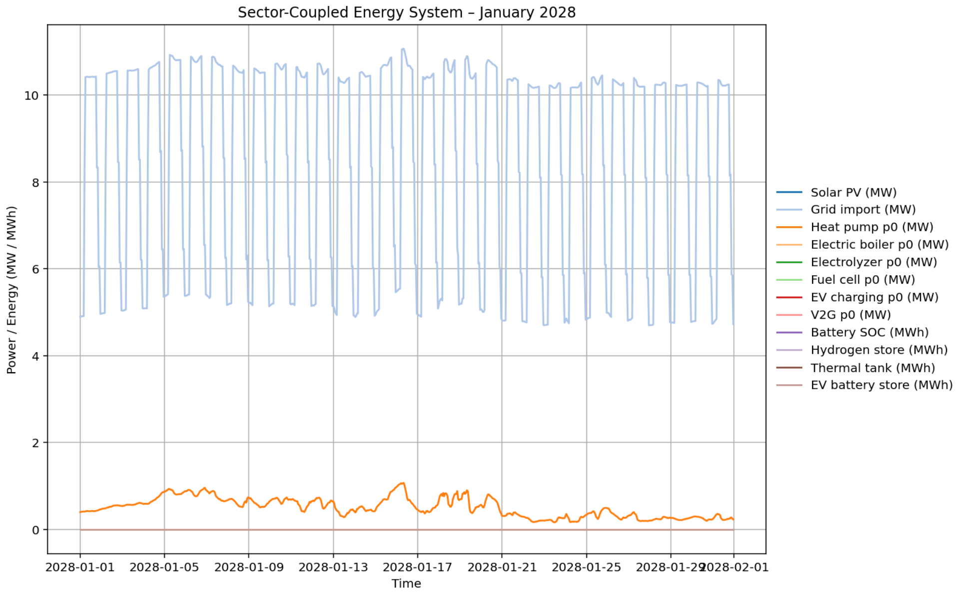


Figure 5.1: Sector coupled energy system behavior in January in reference scenario

In Figure 5.1 light blue peaks can be observed in January during the colder and more demanding times of the year. Meanwhile, the orange line shows the behavior of the heat pump during January, where the heat pumps draw power from the grid. The presence of the light blue peaks imply that the amount of power drawn from the grid, as the light blue color shows supply from the grid, exceed 10MW. As the system lacks EES and there is nothing that can compensate or reduce the power peaks.

In the Figure 5.1 , it also can be noticed that in the reference scenario, all the power is obtained from the grid, all power supply seen is light blue which represents the grid import, as there is no local power production. No storage methods are implemented and hence there is no system with the purpose to reduce power peaks.

Figure 5.2 below represents the behavior of sector coupled energy for the reference scenario in July.

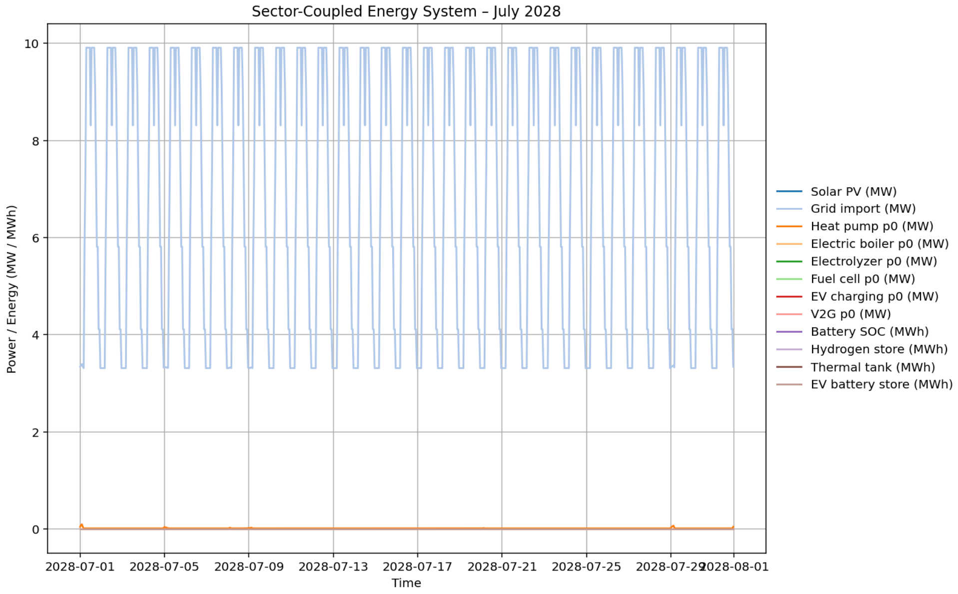


Figure 5.2: Sector coupled energy system behavior in July in reference scenario

Figure 5.2 shows that the grid import is less than 10MW since the demand is lower in the summer, due to less need for heating.

It can be determined that the system is not flexible as it does not seem to be able to adjust to demand variations, as the climate and weather, changes over a year.

Table 5.1 shows the simulation results for this scenario.

Table 5.1: Scenario: Reference

Parameter	Test 1
Grid import (MW)	11.07
Solar PV	0%
Heat pump (MW)	1.07
Total CapEx (SEK)	10 724 631

The grid import was 11.07 MW which exceeds the goal of keeping the usage at 10 MW with 0% solar PV in this scenario and the total Capital Expenditure (CapEx) was 10.72 million SEK.

5.2 Battery scenario

The graph on sector coupled energy system behavior in January obtained when simulating the reference scenario can be seen in Figure 5.3 below.

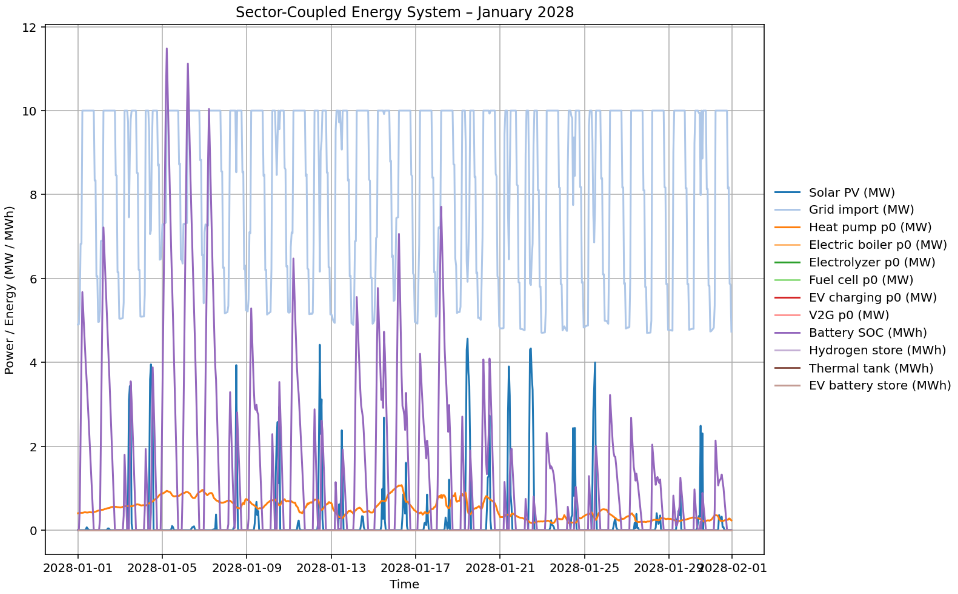


Figure 5.3: Sector coupled energy system behavior in January when BESS is used with 23% solar PV

It can be noticed in Figure 5.3 in January, as the climate is the coldest and the demand seems to be greater, the peaks are compensated with energy discharged from the battery, as indicated by the purple peaks that indicate the battery state of charge (SOC). In other words, the BESS seem to be able to reduce power peaks from the grid and the battery discharges instead resulting in a more stable system. The peak power is reduced by 1.07 MW during the day and the SOC in the battery goes up to almost 12 MWh. The energy in the battery needs to be more than 1.9 MWh. According to the simulation results, the nominal power of the battery should be at least 1.9 MWh, as seen in Table 5.2 and remains the same in all scenarios where battery has been used.

Figure 5.4 shows sector coupled energy system behavior in July when BESS is used with 23% solar PV.

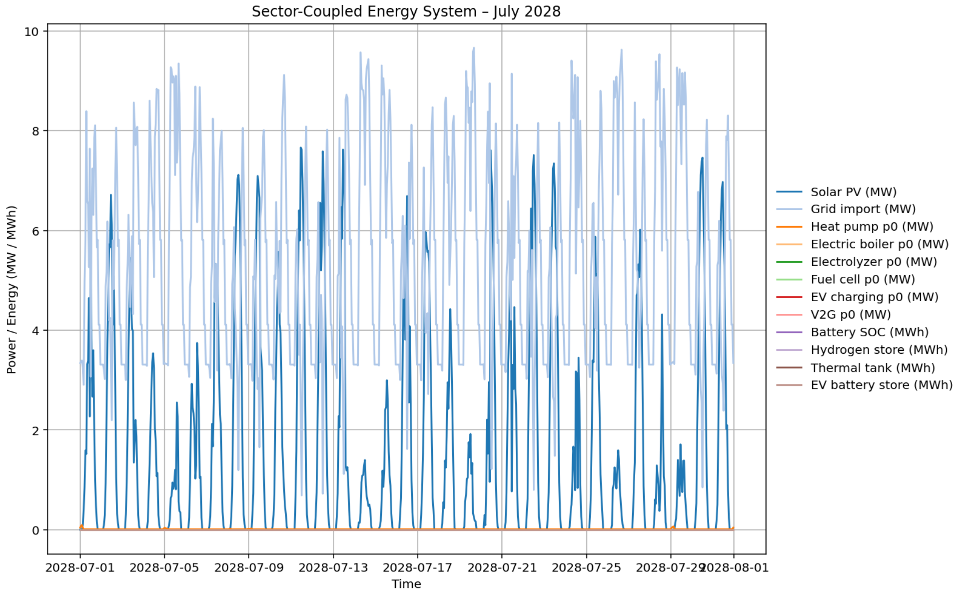


Figure 5.4: Sector coupled energy system behavior in July when BESS is used with 23% solar PV

It can be observed in 5.4 that in July, as the climate is warmer and the energy demand also is lower, there is also increase in production of solar power is greater due to sunlight, as indicated by the dark blue color. The solar PV seems to act as support to the grid and there are no peaks exceeding 10 MW. In addition, the power production obtained from the grid is lower than 10 MW at some periods of the month which can be observed in the light blue color. Due to the solar production, there is no need for the support from the BESS and thereby no purple peaks from the battery can be observed in the month of July.

Figure 5.5 sector coupled energy system behavior in January when BESS is used with 5.75% of solar PV instead of 23%.

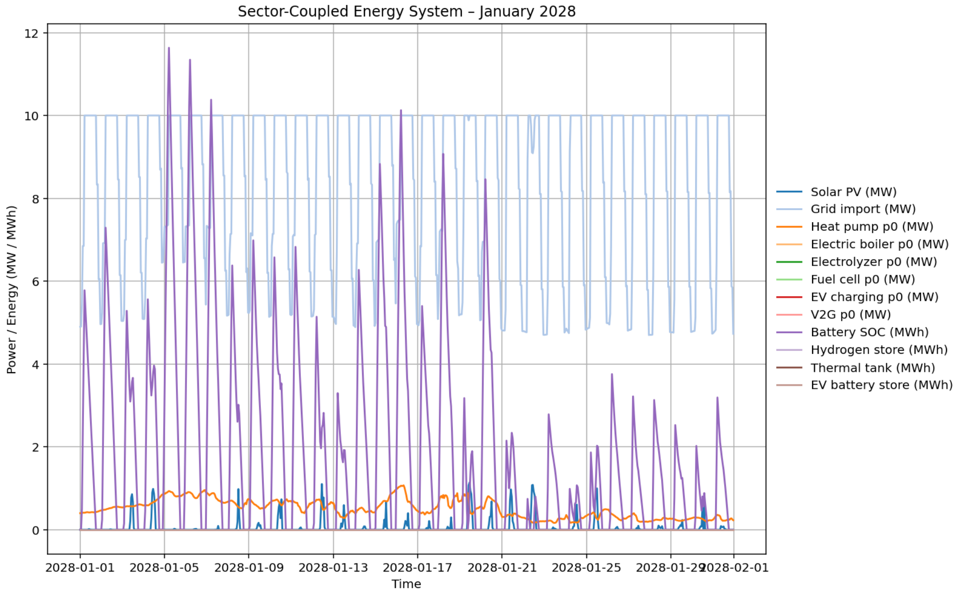


Figure 5.5: Sector coupled energy system behavior in January when BESS is used with 5.75% solar PV

As seen in Figure 5.5, reducing the solar PV to 5.75%, leads to less minimizing of power peaks. It is evident that the solar PV support the grid and reduce both peaks and the grid usage, but not as much as 23% solar PV. Similar results are obtained when 2.3% of solar PV is used.

Figure 5.6 below shows sector coupled energy system behavior in January when BESS is used with 5.75% of solar PV.

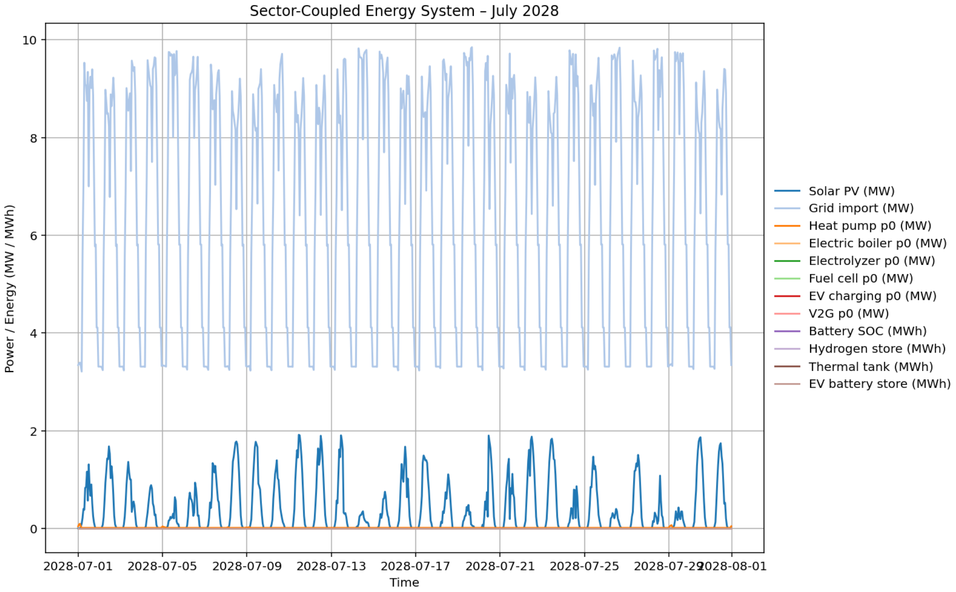


Figure 5.6: Sector coupled energy system behavior in July when BESS is used with 5.75% solar PV

According to the graph seen in Figure 5.6, in the battery scenario with the high solar buildup, the power is still mostly obtained from the grid, as seen by the light blue color, and the photovoltaic cells act as a complement, as indicated by the dark blue color. In comparison with Figure 5.4 23% solar PV in July, the peaks are larger with 5.75% solar PV.

It can be determined that a system with PV as well as BESS contributes to an increased flexibility of the system.

Table 5.2 shows the simulation outputs for this scenario, where tests were carried out for; battery with 23%, 5.75% and 2.3% solar PV.

Table 5.2: Scenario: Battery

Parameter	Test 1	Test 2	Test 3
Grid import (MW)	10	10	10
Battery storage capacity (MWh)	1.91	1.94	1.94
Solar PV	23%	5.75%	2.3%
Heat pump (MW)	1.07	1.07	1.07
Total CapEx (SEK)	222 627 636	69 529 364	38 999 648

The results for the nominal energy of the battery were very close to each other. The simulation does not choose larger batteries, if more solar PV is integrated. The CapEx differs a lot, since the battery is almost the same for all tests, it is mostly dependent on how much solar PV is wanted. For reference, Test 1 with 23% solar PV has a CapEx of 222.63 million SEK and Test 3 with 2.3% solar PV has a CapEx of 39 million SEK, which is a difference by 183.63 million SEK.

5.3 Thermal tank scenario

Figure 5.7 below, shows Sector coupled energy system behavior in January in the thermal tank scenario with 23% solar PV.

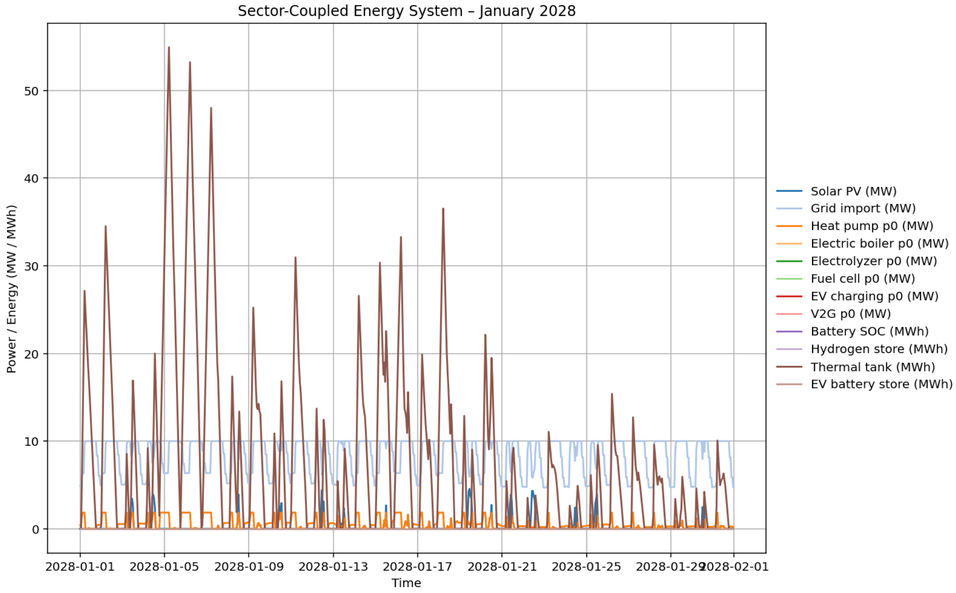


Figure 5.7: Sector coupled energy system behavior in January when a thermal tank is used as EES with 23% solar PV

As seen in Figure 5.7 and Table 5.3, the optimized solution for the 23% solar PV scenario includes a thermal storage tank with a capacity of 54.91 MWh and a heat pump capacity of 1.85 MW, compared with 1.07 MW in the reference scenario. The optimization favors this combination because the larger heat pump can generate excess heat during periods of lower demand, which is then stored in the thermal storage tank and discharged during periods of higher demand. This operational strategy reduces the need for electricity imported from the grid in January and enables the system to maintain grid power at or below the imposed 10 MW limit. The reduced grid imports are reflected by the smaller light-blue contribution in Figure 5.7, while the brown peaks illustrate periods when the thermal storage is discharged to meet demand.

Figure 5.8 below, shows Sector coupled energy system behavior in January in the thermal tank scenario with 0% solar PV.

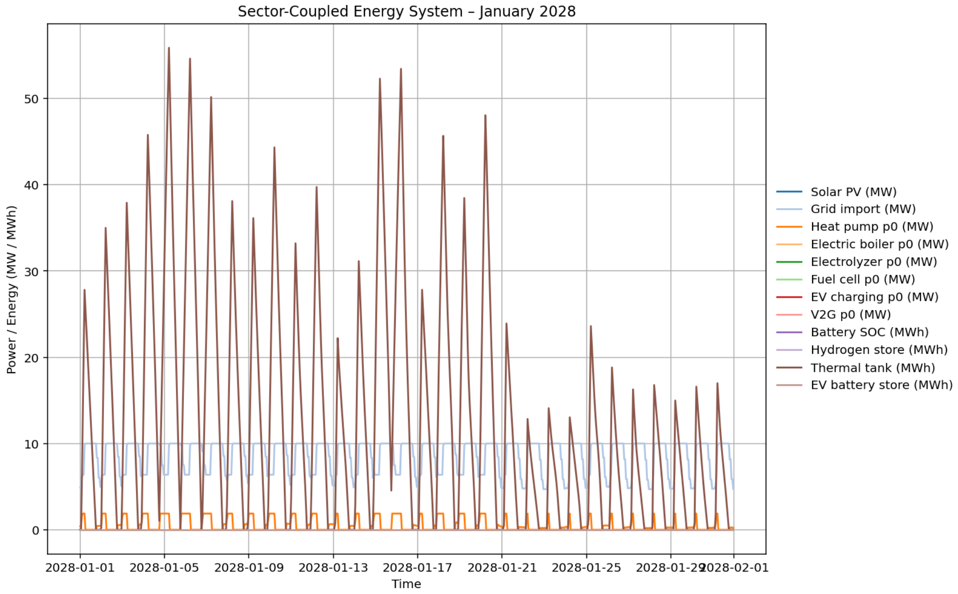


Figure 5.8: Sector coupled energy system behavior in January when a thermal tank is used as EES and 0% solar PV

When comparing Figures 5.7 and 5.8 it can be seen that the absence of the solar PV leads to an increased use of energy discharged from the thermal tank. This is due to the fact that there is no support from the solar PV.

Figure 5.9 below, shows Sector coupled energy system behavior in July in the thermal tank scenario with 0% solar PV.

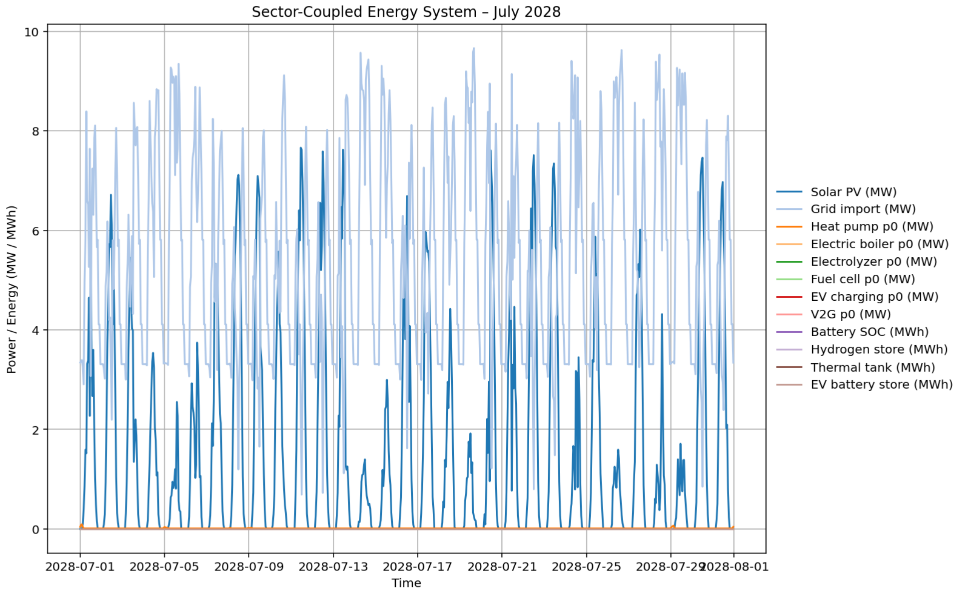


Figure 5.9: Sector coupled energy system in July when a thermal tank is used as EES and 23% solar PV

As seen in Figure 5.9, solar PV electricity generation, represented by a dark blue color, is highest during daytime hours when solar availability is high, allowing it to meet a significant share of the system demand. Consequently, less electricity needs to be imported from the grid, as indicated by the reduced light-blue contribution. Increased solar PV generation substantially offsets grid electricity consumption, reducing both the magnitude and variability of the grid import. This operating pattern improves the system's ability to rely on locally generated RES while maintaining grid power below the 10 MW limit.

Table 5.3 shows the simulation outputs for this scenario, where tests were carried out for; thermal tank in combination with 23%, 5.75% and 2.3% solar PV.

Table 5.3: Scenario: Thermal tank

Parameter	Test 1	Test 2	Test 3	Test 4
Grid import (MW)	10	10	10	10
Thermal storage capacity (MWh)	54.91	55.64	55.79	55.88
Solar PV	23%	5.75%	2.3%	0%
Heat pump (MW)	1.85	1.87	1.88	1.88
Total CapEx (SEK)	250 233 362	97 593 958	67 155 739	46 730 753

According to Table 5.3 the optimal size, for the thermal tank resulted in 55-56 MWh is scenarios when 23%, 5.75% and 2.3% have been used. The grid import was then kept at the intended 10MW. Furthermore it can be observed that when heat pumps are combined with a thermal tank they are optimized to a larger capacity than in the reference scenario, since the energy obtained from them can be stored in the tank. This is not the case in the other methods.

5.3.1 Hydrogen tank scenario

Figure 5.10 below, shows Sector coupled energy system behavior in January in the hydrogen tank scenario.

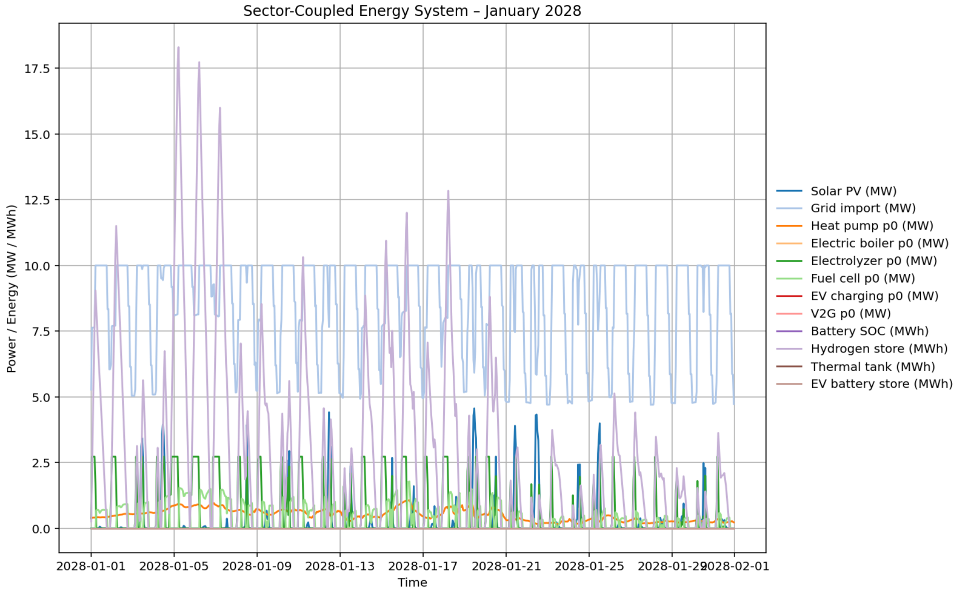


Figure 5.10: Sector coupled energy system behavior in January when a hydrogen tank is used as EES and 23% solar PV

As seen in Figure 5.10, optimization under the 10 MW grid import limit results in the selection of hydrogen storage as one of the viable options to reduce peak demand during high-load periods, particularly in January. This is reflected by the light purple discharge peaks, whereas grid imports represented by a light blue color, remain strictly at or below the 10 MW limit throughout the period. The model minimizes the total cost of the system by investing in the available technologies: solar PV, electrolysis, fuel cells, and hydrogen storage—to meet the demand within this constraint.

Grid electricity is complemented by locally produced solar PV and hydrogen-based conversion via electrolysis and fuel cells, represented by a dark green color, which reduces reliance on imported electricity. Although the hydrogen storage system is relatively small in size, it provides sufficient flexibility to shift energy from periods of low demand to peak periods, thereby ensuring that the grid constraint is respected while maintaining system balance.

Overall, the results indicate that hydrogen storage contributes to improved operational flexibility and effective peak shaving within the modeled cost-optimal system design.

Figure 5.11 below, shows Sector coupled energy system behavior in July in the hydrogen tank scenario.

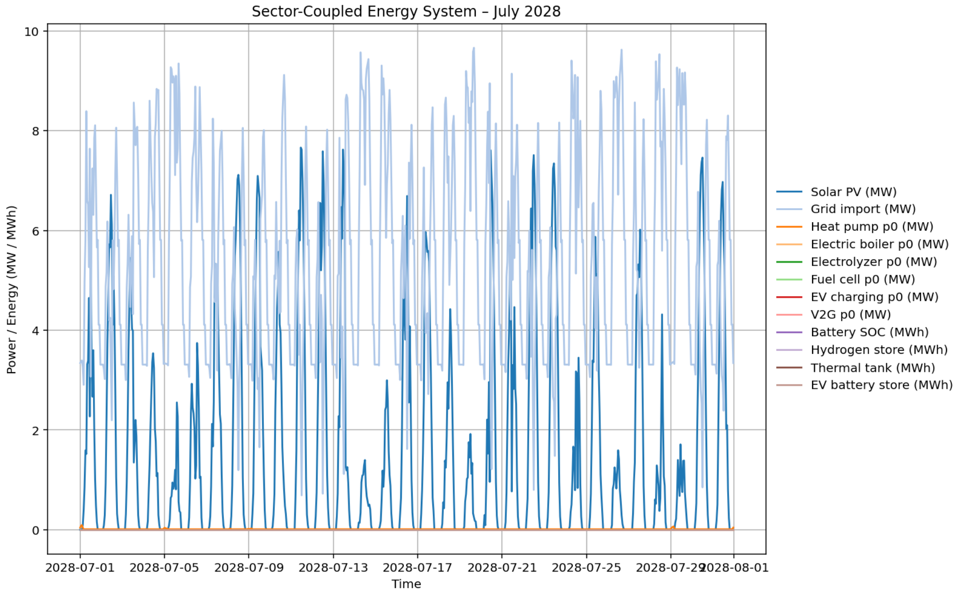


Figure 5.11: Sector coupled energy system behavior in July when a hydrogen tank is used as EES and 23% solar PV

As seen in 5.11 there does not seem to be a need for discharging the thermal tank as there is a lot of solar PV electricity production during July. Thereby the solar power seems to act as support for the grid holding it as a stable level.

Table 5.4 below shows the simulation results for the hydrogen tank scenario.

Table 5.4: Scenario: Hydrogen tank

Parameter	Test 1	Test 2	Test 3	Test 4	Test 5
Grid import (MW)	10	10	10	10	9.5
Hydrogen tank storage capacity (MWh)	18.30	18.55	18.59	18.63	42.623677
Solar PV	23%	5.75%	2.3%	0%	0%
Heat pump (MW)	1.07	1.07	1.07	1.07	1.07
Electrolyzer (MW)	2.73	2.79	2.81	2.81	4.33
Fuel cell (MW)	1.79	1.79	1.79	1.79	2.62
Total CapEx (SEK)	250 168 367	97 282 116	104 356 862	83 964 569	157 306 180

The simulation output shows that for every case with a 10 MW grid import, the nominal energy of the hydrogen tank is kept at almost the same level, although the value of solar PV is changed.

In Test 5 the grid import was reduced to 9.5 MW, where the nominal power of the hydrogen tank was 42.62 MWh with a total CapEx of 157.31 million SEK.

5.4 Electric boiler scenario

Figure 5.12 below, shows sector coupled energy system behavior in January in the electric boiler scenario.

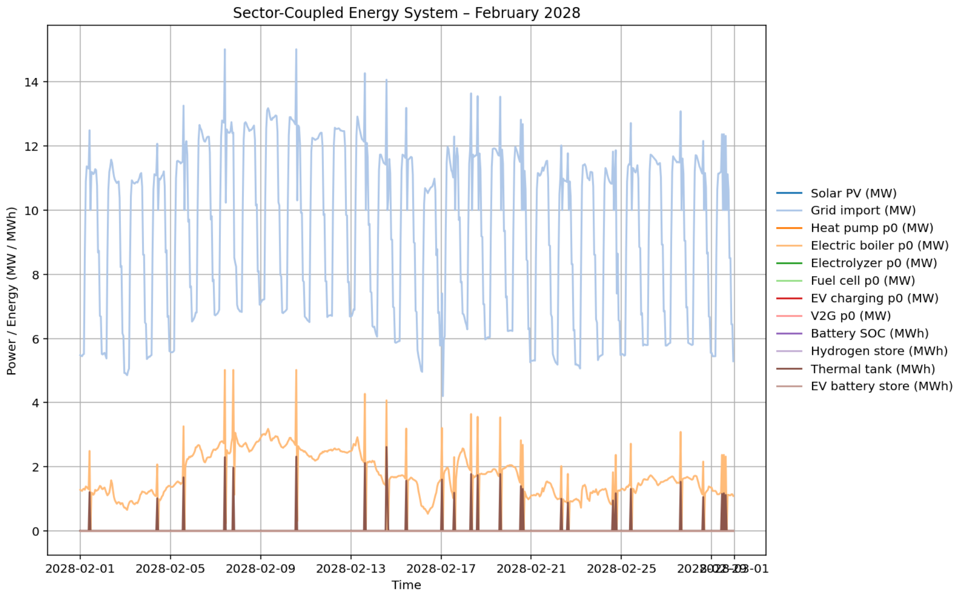


Figure 5.12: Sector coupled energy system behavior in January when heat pumps are replaced with electric boilers with 0% solar PV

When the heat pumps are replaced with electric boilers with 0% solar PV the peaks in power provided by the grid represented with the light blue color, seem to be significantly higher than when heat pumps are used, as seen in Figure 5.12. This scenario also lacks ESS which means that there is no other method that can reduce the peaks. When electric boiler scenario is implemented, the peaks exceed 10 MW. The thermal tank does not seem to contribute with peak reduction.

The simulation results for the thermal tank scenario can be seen in Table 5.5.

Table 5.5: Scenario: Electric boiler

Parameter	Test 1	Test 2
Grid import (MW)	15.02	11.90
Electric boiler (MW)	5.02	4.10
Thermal tank capacity (MWh)	2.61	20.41
Solar PV	0%	115%
Total CapEx (SEK)	11 358 060	1 058 400 027

The grid import limit of 10 MW resulted in an infeasible optimization problem in the electric boiler scenario. This indicates that the system, under the imposed configuration, could not meet the demand and operational requirements within the 10 MW restriction. Therefore, the grid capacity constraint was relaxed in order to obtain a feasible and solvable optimization problem. The updated constraint allows for a higher grid import capacity, ensuring that the model can identify a valid optimal solution while still minimizing total system cost and utilizing local generation and storage where possible. The grid import in both tests exceed 10 MW, but with more integration of solar PV the accumulator tank was larger, and therefore the grid import could be reduced, closer to 10 MW, but never reaching the limit of 10 MW.

5.5 V2G scenario

Figure 5.13 below, shows sector coupled energy system behavior in January in the V2G scenario with battery.

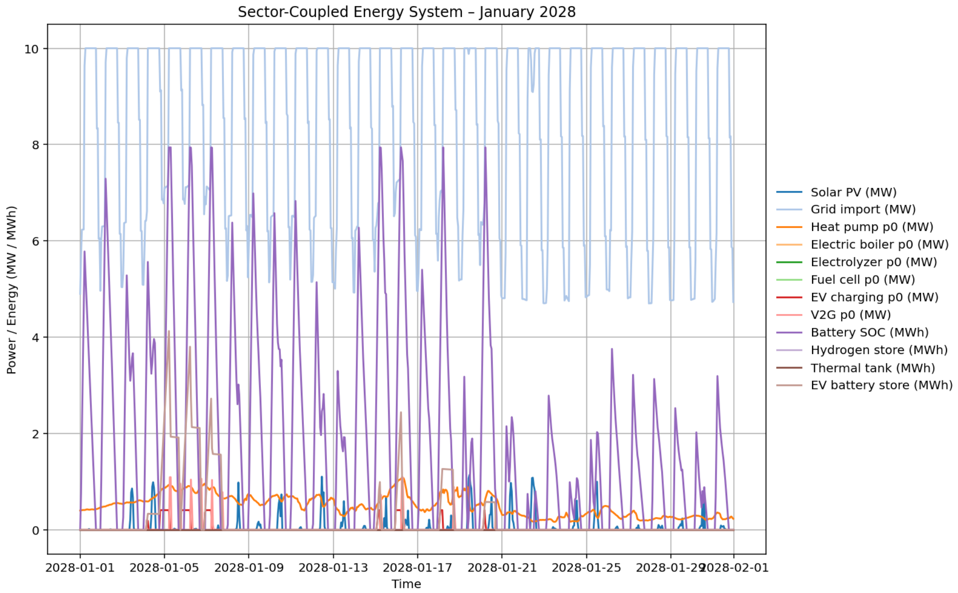


Figure 5.13: Sector coupled energy system behavior in January when using V2G with batteries

As seen in Figure 5.13, when BES is used in combination with V2G, both technologies contribute to supporting the grid, where V2G indicated by the light brown color and BES by the purple color. However, the results show that energy is predominantly supplied by the BES, while V2G is used less frequently and contributes only marginally to peak reduction.

This behavior can be explained by differences in system efficiency and cost assumptions between the two storage options. BES have higher efficiency and lower operational losses compared to V2G, where additional constraints such as battery degradation in electric vehicles and lower availability reduce its attractiveness in the optimization. As a result, the model prioritizes

BES over V2G when minimizing total system cost and losses. V2G provides supplementary flexibility, but its limited utilization suggests that it is less cost-effective under the current assumptions compared to dedicated BESS.

Figure 5.14 shows sector coupled energy system behavior in January when simulating the V2G scenario with 5.75% solar PV and thermal tank as a storage method.

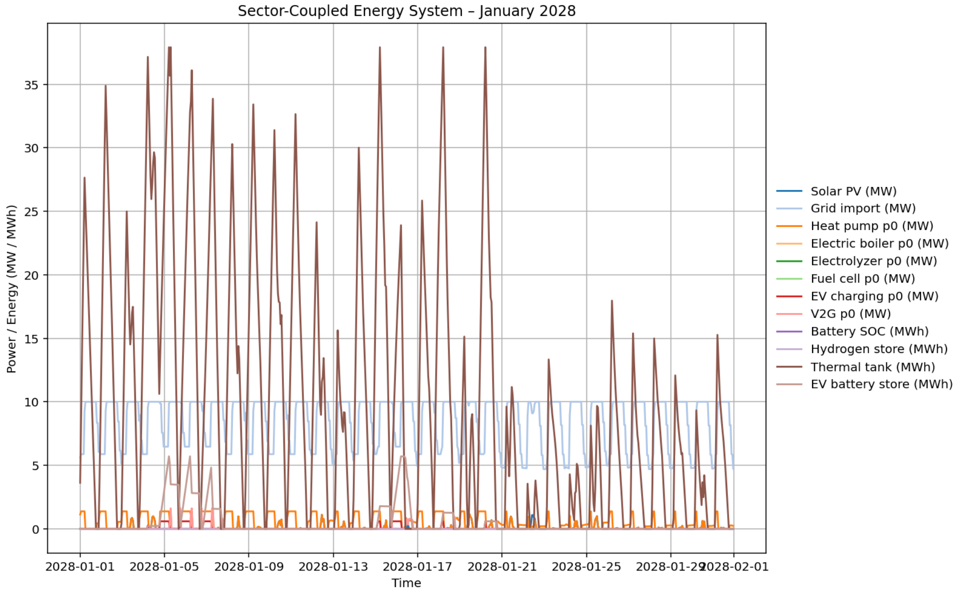


Figure 5.14: Sector coupled energy system behavior in January when V2G is used with 5.75% solar PV and thermal tank as a storage method.

As seen in Figure 5.14 the system can reduce the peaks through discharging of the thermal tank and EV battery storage. The EV battery store is used more with thermal storage than in the scenario with batteries.

The simulation output for V2G can be seen in Table 5.6.

Table 5.6: Scenario: V2G

Parameter	Test 1	Test 2	Test 3	Test 4
Grid import (MW)	10.91	10	10	10
EV charger in (MW)	0.018	0.41	0.59	0.59
EV charger out (MW)	0.19	1.09	1.62	1.63
EV battery store (MWh)	0.56	4.13	5.71	5.71
Solar PV	5.75%	5.75%	5.75%	0%
Heat pump (MW)	1.07	1.07	1.37	1.38
Thermal tank (MWh)	0	0	37.91	38.15
Battery (MWh)	0	1.32	0	0
Total CapEx (SEK)	32 566 450	86 581 818	111 030 357	60 191 655

In Table 5.6 ”EV charger out” is how much power the EV can give back to the grid, and ”EV charger in” is the power the vehicle charges with.

The results in Table 5.6 show that in Test 1, V2G is rarely utilized. This indicates that, under the given cost and system assumptions, V2G is not the least-cost option to balance demand compared to other available technologies such as BESS and grid import. One key reason is that V2G is subject to additional limitations, including efficiency losses and potential degradation costs, which makes it less economically attractive in optimization.

In Test 2, additional BES is introduced together with V2G, increasing the overall flexibility of the system and leading to a higher but still limited utilization of V2G. In Tests 3 and 4, the inclusion of a thermal accumulator enables better temporal shifting of energy demand, allowing the system to make full use of the available EV battery capacity of 5.71 MWh.

The fact that the 10 MW grid limit is not consistently binding in all cases indicates that the combination of local generation and storage technologies is, in some periods, sufficient to meet demand without fully saturating the grid constraint. Therefore, optimization uses only V2G when it is cost-effective relative to alternative flexibility options.

5.6 Economical analysis

The reference scenario has the lowest total CapEx of all scenarios since it contains only the grid and heat pumps, but flexibility is limited, as the grid must meet the electricity demand on its own. The investment cost for this scenario is 10.72 million SEK as shown in Table 5.1.

Hydrogen tanks are very expensive compared to other technologies, the price of such a tank ends up at 83.96 million SEK with a capacity of 18.63 MWh, as shown in Table 5.4 in Test 4. However, smaller hydrogen tanks are needed to supply the electrical system compared to accumulator tanks, but the price is significantly lower for accumulator tanks. Table 5.3 in Test 4, shows that an accumulator tank with a capacity of 55.88 MWh has an investment cost of 46.73 million SEK, which make accumulator tanks cheaper than hydrogen tanks.

In Table 5.5, the grid import for electric boiler scenario is more than 10 MW in both tests, and in test 2 an attempt was made to reduce the grid import, but then an unreasonable amount of solar PV was needed, where the total CapEx were 1058.4 million SEK. Test 1 is more reasonable in reality and in price, electric boilers are not that expensive in CapEx, but more expensive in OpEx compared to heat pumps.

For the V2G scenario, when maximum capacity for EV chargers with 0% solar PV and a thermal tank, the total CapEx landed at 60.19 million SEK as shown in Table 5.6 in Test 4. The simulation of the tests for this scenario did not want to use V2G fully without a battery or accumulator tank as a storage method. Test 4 was the cheapest alternative, but with 5.75% solar PV it was cheaper to use a battery than an accumulator tank.

In every scenario using 23% solar PV, led to a very large CapEx, it is more profitable to use 5.75% or 2.3% solar PV. Using batteries as a storage method is the cheapest CapEx scenario.

6 Discussion

In this section, results obtained in the study are discussed.

6.1 Flexibility in Energy Systems

The results indicate that, there are various potential methods to increase flexibility of energy systems. All scenarios in which a form of EES and TES was integrated, the system could reduce the power peaks and the strain on the grid by discharging either a battery or a tank resulting in a more balanced energy system. This is most useful during the most demanding, cold months, of the year.

While hydrogen- and thermal tanks provide a high storage capacity and reduce power peaks, BESS also provide support for the grid and contributed to a more flexible energy system as the stored energy provided necessary support during periods of high load through discharging. However, the fact that BESS have short storage time makes it unsuitable for seasonal storage in contrast to thermal tank. Furthermore, the storage capacity in BESS was not as high as it was for the methods in which a form of tank was used. Still BEES provided the support that reduced power peaks and thereby not all power had to be obtained from the grid.

Systems that lacked any form of EES did not provide the necessary support for the grid. The results show that when a system lacked EES there were power peaks present and there was no power balancing also meaning that more than the intended 10MW were used from the grid.

6.2 Economic Perspectives on Flexible Energy Systems

The different technologies differ greatly in CapEx, and for some it is still quite difficult to find the exact CapEx as some technologies are not standardized and the amount of research on them is limited for the time being. For instance, the high cost for hydrogen tanks comes from the fact that there are no actual projects, other than pilot projects, for large hydrogen tanks and the materials to build them, the production of hydrogen, and later the conversion to electricity may become cheaper and more efficient over time. Hydrogen has a high energy density and hydrogen tanks could be a key component in the future for the transition of industries and heavy vehicles to fossil-free.

As for V2G, in order to use V2G with the goal to increase grid flexibility, the technology needs to be further developed and standardized. To make it worth the investment, better charging structure is needed, more EV´s in society and adaptation of when EV´s are charged, i.e. charging at night when power peaks are low and discharging when power peaks are high during the day. V2G needs special charging boxes for bidirectional charging, which also comes with great expenses and is not standardized for the time being. Private individuals with solar panel installations can benefit from this by storing solar energy in the car battery. Electricity prices can also be lower by avoiding expensive power peaks with V2G. However, in the area used in this study, it is difficult to regulate car discharge and charging, as there are no homes, but only service areas and industries. Assuming that users would like to have a fully charged car when they drive home from work and to work, adapting discharge and charging is needed. It is difficult to rely on how much power can be obtained from V2G every day, as it is difficult to predict how much the electric vehicles will give to the grid during power peaks. Integration of V2G does not seem like a viable op as it does not provide the desirable flexibility.

When it comes to electric boilers, they have lower efficiency than heat pumps, which makes this scenario less suitable for our area. The reference scenario by Bengt Dahlgren AB is designed for heat pumps, which is why it was difficult to maintain the limit for imports from the grid at 10 MW for the scenario with an electric boiler.

BESS is more expensive to store energy for a long time compared to accumulator tanks, accumulator tanks are a better investment over time, and they can store significantly more. For solar panels, the most expensive part is the investment cost, but the maintenance cost of the installation and inverter, which usually needs to be replaced before the panel itself needs to, leads to an additional cost.

6.3 Environmental Perspectives on Flexible Energy Systems

6.3.1 Solar panels

Solar panels have a lifespan of between 20-30 years, whereas the inverter has a lifespan of approximately 10-15 years, making this component the one that needs to be replaced most frequently. Solar panels have an efficiency of around 21.13%, which is very low compared to other technologies investigated in this study. However, solar PV are a method that provides renewable electricity production, which means that this technology has a great potential to facilitate transition to a fossil-free environment in accordance with the Paris Agreement.

However, this technology is relatively expensive and in the studied location, where winter months are characterized by limited sunlight hours and low solar availability, it becomes less economically attractive to install large amounts of solar PV. As a result, optimization limits solar PV capacity, as additional installed panels would contribute little additional energy production during critical winter periods, leading to poor utilization and higher system costs. Thus, it is difficult to predict and rely on the amount of annual electricity production. A positive aspect is that individuals who own a solar panel system have the possibility sell the excess electricity produced to the grid, or store it in a storage method such as an accumulator tank or battery, to later use the electricity when needed and to avoid expensive electricity prices during power peaks.

When it comes to materials used to manufacture solar panels, silicon is the most common material used in solar panels, where majority silicon currently manufactured being not fossil-free. However, there is interest in Sweden to produce ”green silicon”, which is technically possible and under development, but is not yet standardized. For stability and durability, the frame is made of aluminum in solar panels. Aluminum production is also energy-intensive, where it is usually made with fossil fuels. However, there is an ongoing transition in the industry with the goal to make this production fossil-free by using RES. The greatest environmental impact of solar panels occurs during the production of the panels, but in the long run, solar panels produce more energy during their lifetime than the energy used to manufacture them.

6.3.2 Batteries

Batteries used with solar panels can increase the self-use of solar energy. The battery’s capacity gradually decreases over time and its lifespan can furthermore decrease by extreme temperatures, deep discharges, and charges. Lithium iron phosphate batteries, which are used mainly with solar panels, have less impact on the environment than many other lithium-ion batteries, because they do not contain cobalt and nickel.

However, while batteries can technically store electricity over long periods with relatively low self-discharge, using them for seasonal storage is not economically viable. This is primarily because the cost per stored kWh is high, making large-scale or long-duration storage prohibitively expensive compared to other solutions. As a result, batteries are better suited for short-term balancing and peak shaving rather than inter-seasonal energy shifting. The desirable use of batteries is the storage of solar electricity in the summer and the use of excess in the winter, though this is not optimal with batteries. It is more efficient to sell the surplus in the summer and buy back the electricity from the grid in the winter. As seen in the simulation outputs for this scenario, the program did not choose larger batteries, although more solar PV was integrated.

6.3.3 Accumulator tanks

In the accumulator tank scenario, compared to other technologies, the simulation chose to use more heat pumps. That is, because what heat pumps can produce can be stored in the accumulator tank and then used when needed. From a sustainability perspective, it is very good to use heat pumps to their full potential and store the electricity they produce, then use it during peak power demand. The lifespan of an accumulator tank can be as long as 40 years, but oxygen-rich water or an incorrect pH value can accelerate corrosion and shorten the lifespan. However, the lifespan can vary greatly depending on materials, water quality, large temperature fluctuations, and maintenance, with some tanks lasting significantly longer, while others may experience problems sooner due to corrosion. Tanks made of stainless steel last longer than tanks made of untreated black steel, and tanks made of black steel need to have high-quality corrosion protection to reduce the chance of rust. If a tank has rusted, it is difficult to repair, so they usually need to be replaced when this happens. However, for tanks that have a water heater, this is usually the one that rusts first, after about 10-20 years, even if the mantle itself lasts longer than that.

6.3.4 Hydrogen tanks

In hydrogen tanks, the hydrogen must be produced in an environmentally friendly way, i.e. ”green hydrogen” to be sustainable. The emission product for converting hydrogen to electricity is water vapor via fuel cells, and there is a fossil-free potential for producing hydrogen via electrolysis. However, if natural gas is used to produce hydrogen, it becomes ”gray hydrogen”, and the climate benefit is then limited. Converting electricity to hydrogen, compressing it, storing it, and then converting it to electricity in a fuel cell is less energy efficient than direct electrification (batteries). In general, more renewable electricity is required overall to move a vehicle the same distance. Hydrogen becomes an indirect greenhouse gas in the event of a leak; such a tank can become very dangerous because hydrogen is a flammable gas, and if it leaks and mixes with air, it can form an explosive mixture. A larger proportion of hydrogen produced today is produced by steam reforming, as this method is significantly more industrially well-established. However, steam reforming cannot be used to store renewable energy as a result of its requirement for fossil gas; hence the electrolysis method is better suited to store renewable energy. In properly designed tanks, hydrogen can be stored for a very long time, making it a promising method for long-term storage of renewable energy, and such tanks have a lifespan of approximately 25 years.

6.3.5 Electric boilers

Electric boilers have a lifespan between 15–25 years, sometimes up to 50 years. They are inexpensive to install and maintain. To increase durability and reduce costs, it is often recommended to have an electric boiler in conjunction with a heat pump or stove. Often, only the water heater needs to be repaired (not the entire boiler), which is quite profitable and more environmentally friendly. However, electric heaters are a consumable item that may need to be replaced. An electric boiler is a sustainable choice if electricity is renewable, but it is an inefficient method of using electrical energy, in which case a heat pump is more energy efficient and cheaper to operate.

6.3.6 Vehicle to Grid

V2G has the potential to be very sustainable, as cars can not only be charged but also send electricity back to the grid when needed, it can relieve the grid during high demand and make the grid more stable. This technology can increase the share of renewable energy in the system by storing energy during the high production of solar and wind power. This can reduce the production of fossil-fueled power plants and thereby reduce carbon dioxide emissions. There may be some risk with V2G that car batteries will have a shorter lifespan due to frequent charging and discharging. The results showed that the storage of the EV battery could be used at its maximum capacity of 5.71 MWh only with the accumulator tank, since batteries cannot store energy for a long time. When V2G was simulated in the software without any extern energy storage it gave infeasible results, which means the heat and electricity demand was not successfully met. In other words it was not possible to successfully implement this method without using external energy storage.

6.4 Most optimal scenario

When evaluating the scenarios from an economical, environmental and technical perspective, the scenario that seems to be most optimal and technically possible for this area is thermal tank with heat pumps complemented by PV cells, the thermal tank scenario.

While the lifetime of a thermal tank is long compared to the other methods tested, the method is also simple, the cost is fairly low, and this method is environmentally friendly in terms of material and maintenance. The only method that had a comparable lifespan, 25 years, was a hydrogen tank but this method is not yet standardized nor implemented in modern energy systems of similar nature. Furthermore, hydrogen tank comes with safety hazards which is not the case for a thermal tank. The other methods such battery storage also seemed to contribute to reducing of power peaks, but do not have such a long lifespan nor are they suitable for long time storage.

A thermal tank also provides a large storage capacity and is, as seen in the results, effective in terms of reducing power peaks by discharging, thereby providing support to the grid - especially when solar PV is used as a complement to the grid. It is also an effective method as it, according to results in the study, uses the heat pumps to their fullest capacity and stores the excess heat produced to later discharge when needed. This was not observed in the other scenarios. Thereby, the thermal tank wall well suited when implementing heat pumps, which was the case in this property project.

6.5 Future Perspectives on Energy System Flexibility

Technologies such as V2G and hydrogen tanks are in theory effective methods in terms of better energy flexibility and potential support of the grid. This is also a conclusion that could be drawn based on the results obtained in this study. When technologies are improved and implemented on a bigger scale, it is possible that they will be incorporated into future energy systems. However, considering that these technologies are relatively new and for the time being, only pilot projects have been conducted, those may not be the most reliable options when applying them, on an actual residential area on a bigger scale.

7 Conclusion

The purpose of this project was to investigate, evaluate, identify and analyze possible measures for power reduction and power balancing through sector coupling. Scenarios that were designed in this project were BESS, hydrogen tanks, thermal tanks, V2G and electric boiler. All of the scenarios were simulated in PyPSA with 23%, 5.75% and 2.3% solar PV possible for this property area. The reference scenario was designed by Bengt Dahlgren AB and was later compared with the named scenarios.

The results of the investigation showed that there are indeed many possible measures to reduce power peaks and create a flexible energy system. After comparison of the scenarios, the scenario that was the most optimal option for this the property area was the thermal tank scenario due to, when compared with the other methods, its long lifespan. Furthermore, this method also works well when combined with heat pumps which are intended to be used in the property area. The pumps were used to their full potential, which was not the case in the other scenarios. The excess heat energy could then be stored in a thermal tank in order to be used when the need arises.

Solar PV, when used as a complement to the grid, also contributed to reducing of power peaks and acted as a support to the grid. This was the case in all the simulated scenarios.

Hydrogen tanks reduced power peaks and contributed to a more flexible energy system, but the large cost and safety difficulties made this scenario not as reliable as the thermal tank scenario. Because electrolysis requires electricity to produce hydrogen and then fuel cells are used to produce electricity again from stored hydrogen, there are a many losses in the process. A thermal tank that stores excess heat without any excessive processes, is more efficient compared to a hydrogen tank.

BESS contributed to an increased flexibility in the energy system but it is an expensive method to store SEK/kWh in a long term compared to the thermal tank scenario. Thereby the thermal tank scenario was a more suitable option. Furthermore, in contrast to the thermal tank scenario, it was not suitable for seasonal storage. This method was suitable for handling short time variations in demand and production. There is also degradation as a result of the charge and discharge of a BESS, where the lifespan of a BESS decreases faster than a thermal tank.

The V2G scenario could contribute to a more flexible energy system if it was configured in a suitable way in the simulation software. Since the property area is not yet real, many assumptions were made in order to make the V2G scenario a feasible solution. This method has a potential to be a suitable method to increase flexibility in energy systems though it needs to be further developed and standardized. For the time being there are only a few pilot projects where this method is implemented. On the other hand, this method contributes to a lot of stress on the vehicle's battery which can be problematic in the future.

The replacement of heat pumps with electric boilers was not a feasible solution in this property project. This is because heat pumps are a more efficient.

Due to time constraints and difficulty in finding reliable information on the newer technologies such as V2G and hydrogen tanks, it was not possible to investigate further regarding operational costs. Furthermore, it is considered that there may be more scenarios that could be suitable but it was not possible to formulate more, also due to time constraints. However, there is a possibility to investigate these aspects further in future work.

In conclusion, the purpose of this study has been fulfilled as the research questions were answered. The investigation has fulfilled the objectives formulated.

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