Hydrogen and battery storage for local power generation and supply: A feasibility study for Forsåker

Thesis in the Master's Programme Design and Construction Project Management

Marcus Wademyr

Department of *Chemistry and Chemical Engineering*
Division of *Applied Chemistry*
CHALMERS UNIVERSITY OF TECHNOLOGY
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DEPARTMENT OF *Chemistry and Chemical Engineering* CHALMERS UNIVERSITY OF TECHNOLOGY

Marcus Wademyr

Examensarbete ACEX30
Institutionen för arkitektur och samhällsbyggnadsteknik
Chalmers Tekniska Högskola, 2023

Department of *Chemistry and Chemical Engineering*
Chalmers University of Technology
SE-412 96 Göteborg
Sweden
Telephone: + 46 (0)31-772 1000

Department of *Chemistry and Chemical Engineering*
Göteborg, Sweden, 2023

Abstract

Society faces a large transition of the energy system where the fossil fuels need to be phased out and replaced by renewable energy production, to enable electrification of mobility services, building sites as well as of heavy vehicles. Requirements on new builds of real estate regarding energy efficiency is getting stricter as well as increased interest from property developer to be more sustainable both in the building phase as well as the operation. Adding local power production of heat and electricity as well as interim storage of such becomes more important for the property developer. Adding these new technologies to the real estate gives new opportunities but also some challenges. This thesis is about investigating a production and storage of renewable energy in batteries and hydrogen at the real estate development district Forsåker. The thesis aims to increase the knowledge and competence regarding energy management of energy systems consisting of local hydrogen and battery storage, combined with local electricity production and consumption, as well as sector coupling for vehicles in the districts.

The pre-study uses an on-going development project in Västra Götalandsregionen, “Forsåker” in Mölndal. The project has an energy consumption demand for 245,000 m^2 of planned properties and battery electric vehicle charging and will include local electricity production consisting of a hydropower plant, wind power, facade solar panels, roof solar panels and a solar park close by the district. The thesis has been performed side by side with another pre-study named ScALES, done by a consortium of companies. ScALES has evaluated the energy usage and production balance on a system level in the “Forsåker” district, from start of construction to a fully developed district. The thesis methodology approach is therefore largely based on collaboration and discussions with industry representatives as well as previous reports.

Results indicate that “Forsåker” has got a possibility to reach a high degree of self-sufficiency and resilience (and to become an energy positive district) regarding electricity. This requires large investments in solar parks, local hydro power, and energy storage components. Due to the uncertainty of many parameters for 2031, the study has investigated different scenarios to enable guidance for property owners, policy makers and other stakeholders involved in decision making regarding energy storage in urban development projects.

It is important that policymakers allow energy sharing for large areas, like Forsåker, in order to increase the willingness to invest in renewable energy generation and storage components. This would increase Sweden's chances of achieving its climate goals. Another important parameter for the economic sustainability of the examined scenarios is to maintain the tax exemption for electricity imports used in green hydrogen production through electrolysis.

Equally important is the dimensioning of a robust system balance concerning energy system storage components and the required control parameters for decisions such as buying or selling electricity versus storing or not storing. To optimize ROI while simultaneously meeting the area's needs most effectively. In further optimization of the energy system its crucial to strike a balance in determining when the various storage components shall start and stop operation, as well as when to buy and sell electricity to the regional grid. The balance in the examined system is functional but yet to be optimised.

Sammanfattning

Samhället står inför en stor omställning av energisystemet där fossila bränslen behöver fasas ut och ersättas av förnybar energiproduktion, vilket ställer nya krav på mobilitetstjänster, byggarbetsplatser och tunga fordon. Kraven på energieffektivitet i nya byggnader blir därmed strängare, intresset för fastighetsutvecklare att vara mer hållbara både i förvaltningsskede och under byggfasen ökar. Lokal produktion av värme och elektricitet samt mellanlagring blir viktigare för fastighetsutvecklaren. Att införa dessa nya tekniker i fastigheter ger nya möjligheter men också utmaningar.

Arbetet handlar om att undersöka produktion och lagring av förnybar energi i fastighetsutvecklingsområdet Forsåker. Arbetet syftar till att öka kompetensen inom energihantering av energisystem bestående av lokal vätgas- och batterilagring, kombinerat med lokal produktion och konsumtion av elektricitet, samt sektorsintegration för fordon. Uppsatsen har genomförts parallellt med förstudien ScALES, ett konsortium av företag.

Förstudien grundar sig på ett pågående utvecklingsprojekt i Västra Götalandsregionen, Forsåker i Mölndal. Projektet omfattar energibehovet för 245 000 m^2 fastigheter, laddning av batteridrivna fordon samt lokal elproduktion bestående av vattenkraftverk, vindkraft, solpaneler på fasader och på tak, samt en solcellspark intill stadsdelen.

Resultaten tyder på att Forsåker har möjlighet att uppnå en hög grad av självförsörjning. Vid en kris kan energilagringssystemet täcka stadsdelens energibehov och hålla den fungerande i timmar till veckor, beroende på omständigheter som tillgången till lokal produktion och årstiden. Detta kräver stora investeringar i solcellsparker, lokal vattenkraft och energilagringskomponenter utöver elproduktion på byggnader. På grund av osäkerhet kring många parametrar för 2031 då alla byggnader är färdigbyggda har studien undersökt olika scenarier för att ge vägledning för fastighetsägare, politiska beslutsfattare och andra intressenter som är involverade i beslutsfattandet kring stadsutvecklingsprojekt.

Fler gröna investeringar skulle öka Sveriges möjligheter att nå sina klimatmål. För att öka attraktiviteten och viljan att investera i förnybar energiproduktion och lagringskomponenter för stadsdelar har studien identifierat två betydande parametrar. Det ena är att beslutsfattare bör tillåta energidelning för stadsdelar likt Forsåker, och det andra är att den ekonomiska hållbarheten i de undersökta scenarierna får behålla skattebefrielsen för elimporten som används i produktionen av grön vätgas genom elektrolys. Dessa två parametrar skulle inte bara öka investeringsviljan i området utan också underlätta övergången inom transportsektorn, eftersom energisystemet också kan tillhandahålla elektricitet och/eller vätgas för att driva framtida fordon.

Att hitta en bra balans mellan de olika lagringskomponenterna är viktigt för att minimera kapitalkostnaderna (CAPEX). Ytterligare optimering av energisystemet är avgörande för att hitta en balans när och med vilken effekt de olika lagringskomponenterna ska starta och stoppa, när systemet ska köpa och sälja el till det regionala elnätet. Balansen i det undersökta systemet är fungerande men inte ännu optimerat.

Acknowledgements

The work has been carried out at Powercell AB and Skanska AB in Gothenburg and is the final part of my Master's degree "Design and construction project management", MSc in civil engineering at Chalmers University of Technology. The case-study in the thesis followed the pre-study ScALES, which involved several other companies. The high involvement of the industry as well as academia provided valuable insights. I would like to express my sincere gratitude to my supervisors Anders Palmqvist, Andreas Bodén, and Peter Fredriksson, as well as all my colleagues at Powercell and Skanska who have supported and guided me throughout this project. I would also like to thank the participants of ScALES, including Bengt Dahlgren AB, Johanneberg Science Park, and Mölndal Energi AB, for their involvement in this interesting pre-study.

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Marcus Wademyr

Gothenburg, Sweden 2024
www.chalmers.se

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1. Introduction

Society is facing a significant transition in its energy system, where the electrical system is phasing out fossil fuels and increasing the share of renewable energy, all while experiencing growing electricity needs. Mobility services and the electrification of construction sites and heavy vehicles require a new frame of mind regarding knowledge, skills, and tools to integrate sector coupling when constructing new buildings. For decades, society has relied on fossil fuels to achieve higher living standards, but the effects of the emissions from fossil fuels have resulted in deteriorated living standards in some locations and the destruction of ecosystems. There is therefore a need for a transition to different energy sources, but historically this has only occurred because the new technologies were more efficient, cheaper, better, or easier to use.

Several major urban development projects are currently under way in the Västra Götaland region in Sweden, with plans to produce up to 100,000 housing units and tens of thousands of jobs, commercial areas, and facilities by 2030. The question of electrical energy is a crucial aspect of these projects, considering both climate issues, energy supply infrastructure, living environments, and mobility. The needs in an electrified society must be included and considered in the early stages and incorporated into the planning phase of a new urban district.

Individual property owners cite difficulties in setting early goals for energy, mobility, climate impact, etc due to the electrification. These factors often lead to deferring the issues addressed in this study to later phases, such as the program or even system planning stage. The problem is that by then, it may be too late, and it may no longer be possible to achieve goals such as energy-positive districts, climate neutrality, or finding optimal solutions for integrating mobility as part of the energy system in combination with sector integrated energy storage.

Questions then arise regarding the requirements of mobility for electrical supply, how the needs align with the electricity demands of buildings, how local electricity production and storage can be best utilized. As in term of energy management, and how the district interacts with the electrical grid. These are examples of questions that can have significant consequences for an urban development project, and currently, there is a lack of methodology and tools, making planning and decision-making more challenging. The result can be suboptimal solutions or inadequate information to set goals regarding climate impact, self-sufficiency, or potential system services.

As a consequence, requirements on new builds of real estate regarding energy efficiency is getting stricter and there is an increased interest from property developer to be more sustainable both in the building phase as well as the operation. Adding local power production of heat and electricity as well as interim storage of such becomes more important for the property developer. Adding these new technologies to the real estate gives new opportunities but also some challenges. This thesis is about investigating some aspects for production and storage of renewable energy at a real estate development district Forsåker.

1.1 Introduction of Forsåker and ScALES

Forsåker is emerging as a brand-new neighbourhood between 2021 and 2035, a 24-hectare area located close to Mölndal's city centre and approximately 10 minutes from Gothenburg Central Station. The new district of Forsåker will accommodate up to 3,000 residential units, thousands of job opportunities, as well as spaces for commerce, education, and culture. The area is being developed by the municipal real estate development company, MölnDala Fastighets AB, along with Aspelin Ramm, ByggVesta, Peab, Nordr, Trollängen, and Wallenstam.

The site's 300-year-old history as a paper mill, along with the river flowing through the area, gives Forsåker its unique character. The historical buildings will be complemented by modern architecture and filled with restaurants, commerce, culture, education, and even its own hydropower plant, all working together to create exciting environments and restore the area's vitality.

Shaping new urban environments presents challenges for both social and ecological sustainability. However, development also brings significant opportunities to create collective solutions for multiple problems and harness potential synergies. The area where Forsåker is growing will become a densely populated urban setting for thousands of people. One sustainable initiative is the goal of constructing mobility hubs instead of traditional underground parking facilities in each block. This initiative aims to promote sustainable transportation options but, with an increased concentration of cars, including electric vehicles, it also poses additional demands on electricity supply and capacity.

The Forsåker area with 6,000 new residents and 4,000 new workplaces, will consist of even more buildings than the pre study ScALES project includes. Since completed, calculations of potential surfaces were only finished for the detail development plan DP1A [1] when starting the pre study ScALES. Figure 1.1.1 below is an illustration over Mölndal where Forsåker is located on the right side of the road.

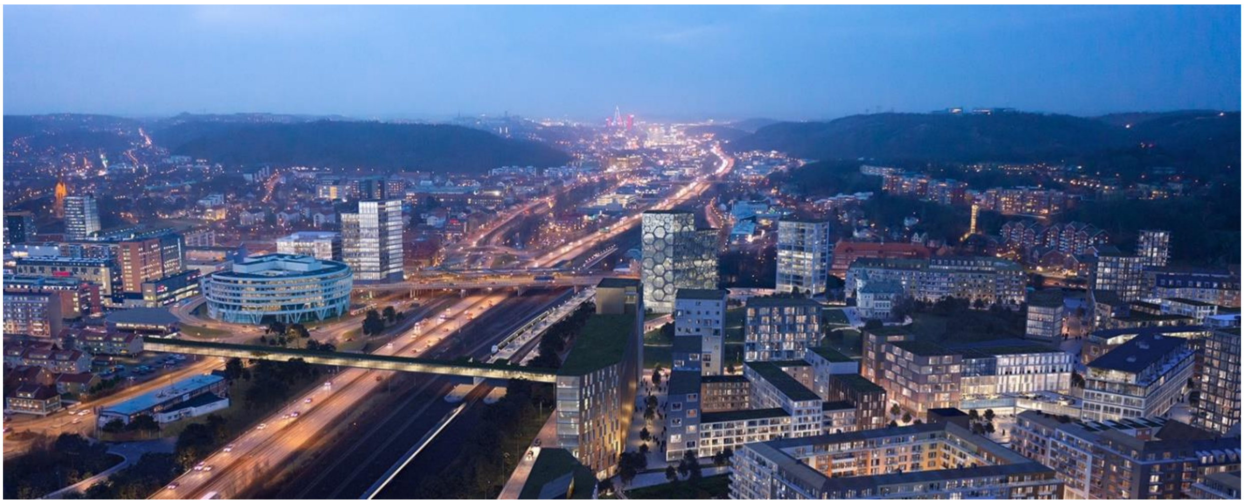


Figure1.1.1 Illustration of future Forsåker on the right side of the road [1].

Forsåker will be developed in several stages over a period of approximately 10 to 15 years. The first stage, known as detail development plan 1A (DP1A), has defined the building commencement, occupancy, building heights, construction rights sizes, and other parameters for the specific blocks. The remaining stages are currently rough estimations in terms of the building commencement, volumes, and other details for the blocks seen in Figure 1.1.2 divided into property categories.

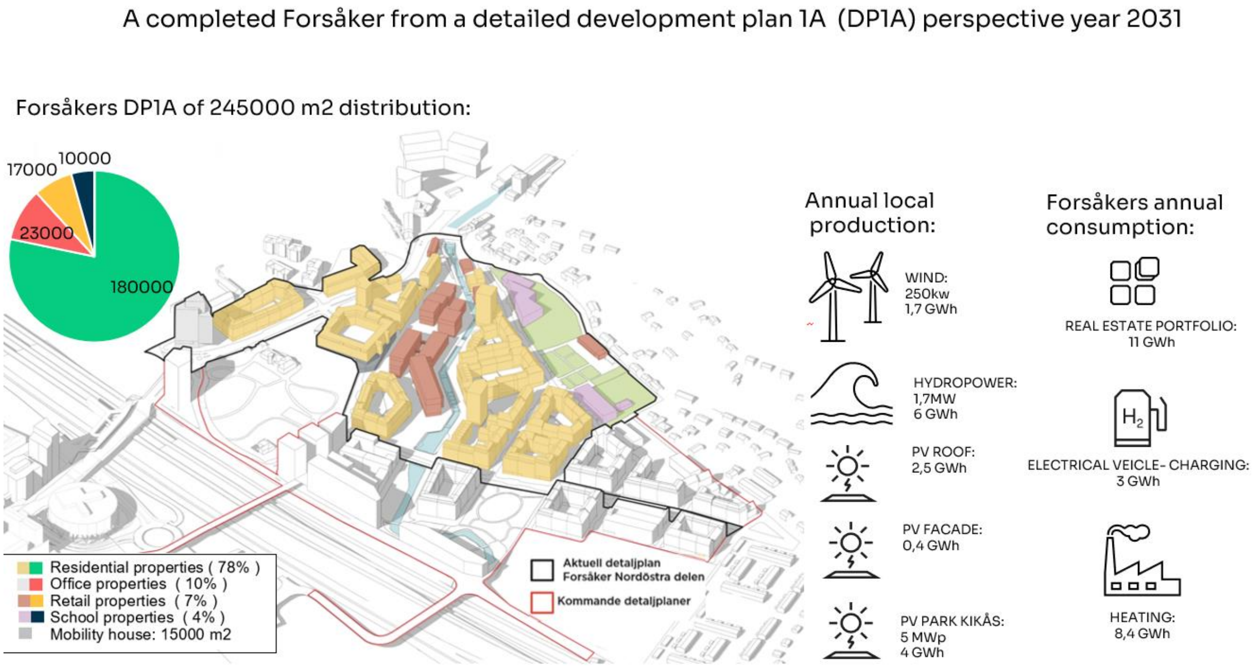


Figure 1.1.2. DP1A, Stage 1A in the Detailed Plan, indicated by a black boundary line. Combined with Forsåkers annual planned local electricity production and consumption demands. [1].

Illustrations of DP1A in the finished stage year 2031 represent area inside of the black marking, which will consist of 245000 m2 of residential properties, office properties, retail properties, and school properties distributed as in Figure 1.1.2. The red area includes other detailed development plans which will not be taken into consideration for either the ScALES or this thesis study.

For new urban development projects, the question of electricity energy is an important aspect with connections to climate issues, energy supply infrastructure, residential environment, and mobility. Society is facing a major transition of the energy system, where the electricity system is phasing out fossil fuels and increasing the amount of renewable energy while also facing increased electricity demand.

In Sweden, a large portion of electricity is produced in the northern part of the country due to the abundant supply of hydropower. Regions with nuclear power plants also contribute significantly to electricity production. Western Sweden, with its many industries and large population, is the region that consumes the most electricity.

Ensuring and introducing local electricity production close to where it is consumed is part of the solution to this challenge, as it reduces the need for external capacity through regional and main grids. At the same time, there are many other measures required to address future electricity supply, including increased capacity in the electricity grids, increased flexibility in electricity usage, energy efficiency, and energy storage to store excess electricity for use during shortages.

Figure 1.1.3. To the left an illustration of Forsåker's future hydropower, to the right an illustration of Kikås solar power plant which is close to Forsåker (picture from the ScALES report [2]).

In Forsåker local hydro-power plants have produced electricity since the end of the 19th century. Due to the favourable conditions for hydropower, it is planned to reconstruct the old hydro-power plant in Forsåker with new turbines, without capability to dam water. The hydropower plant is dependent on an approval of the detailed development plan as well as permission from the land and environmental court in Vänersborg.

Mölndal Energi AB currently constructs a 5-Megawatt solar park in Kikås seen in Figure 1.1.3 above, that will be ready for local electricity production in autumn 2023 [2]. Solar on roofs and facades has increased recent years for real estate owners, the technology and price development for solar panels has enabled real estates to produce their own electricity. A new EU directive that has recently been voted through in the European Parliament stipulates that from 2028, all new buildings, with technical and economic feasibility is required to be equipped with solar panels. Starting from 2032, the same requirement applies to residential buildings undergoing major renovations [3]. Wind power in urban environments is not a common sight, but small wind turbines do exist and will be investigated in Forsåker.

Total energy flow in Forsåker's grid from local electricity production annually exceed Forsåker's consumption. Electricity is a perishable commodity, the same amount of electricity produced must be consumed continuously. In Forsåker production and consumption never align in terms of timing and quantity. Annually there will be incoherent hours of excess electricity from Forsåkers electricity production during 50% of the year and lack of electricity during the other 50%. Therefore, imports and exports via Mölndal's regional grid are vital to manage Forsåker's consumption demands as well as surplus electricity from local production which is not consumed within Forsåker. These external energy transactions ensure that Forsåker's electricity consumption demands are met, and any excess energy is efficiently distributed to the local grid.

An overview illustrating the traditional situation when managing the excess electricity and electricity deficits between electricity consumption and production are illustrated in Figure 1.1.4. The specific profile shows a 24-hour period in August, but the principle will remain the same regardless of the day of the year, even though the difference between production and consumption may change due to various factors but will never align.

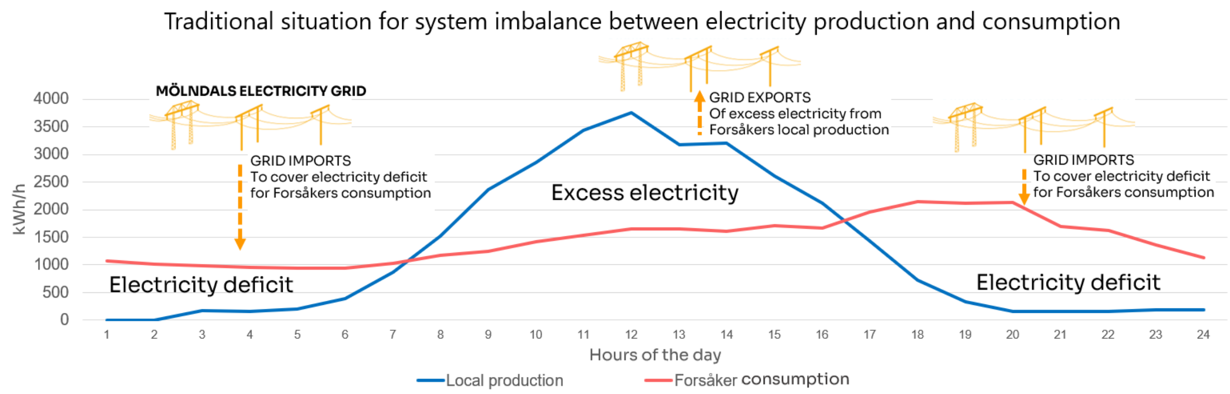


Figure 1.1.4. Example of one daily production and consumption profile in Forsåker to illustrate how grid imports and exports needs to be managed to handle the imbalance between Forsåker's local electricity production and consumption demands.

To reduce grid dependency, technologies for electricity storage can be introduced to match electricity consumption with production. Some hydropower plants possess storage capability to regulate flow of dammed water according to electricity demand, Forsåker's Hydropower plant will not have this capability. Hydrogen and batteries are storage mediums that will be investigated in this thesis, since technology developments are currently advancing rapidly and could maybe become crucial puzzle pieces in aligning Forsåker's consumption and production curve, helping alleviate stress on Mölndal's regional power grid and enhancing redundancy in Forsåker during potential energy crises.

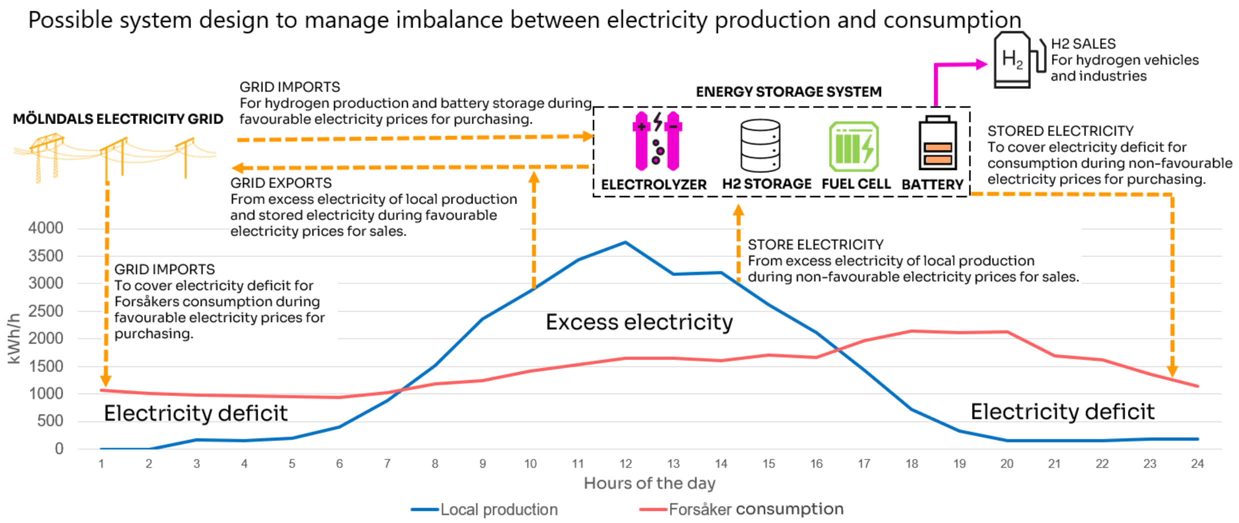


Figure 1.1.5. Example of one daily production and consumption profile in Forsåker to illustrate how hydrogen and battery storage combined with grid imports and exports, can manage Forsåkers local production and consumption demands.

As seen in Figure 1.1.5 the energy storage system become an additional tool together with Möndal's regional grid to manage Forsåker's local production as well as consumption. Energy storage enables an increased possibility of matching between consumption and production gaps, instead of export excess of local electricity during non-favourable day ahead electricity prices as in Figure 1.1.4 and later purchase electricity to cover electricity deficits during high day-ahead electricity prices, the storage system moves electricity to match. In terms of delta between the input and output electricity, battery and hydrogen storage will always generate less kWh out compared to input electricity due to storage losses. In terms of amount of kWh electricity storage will always be a less profitable method compared to electricity imports and exports from Mölndal's grid. In terms of right amount at the right time combined with costs, hydrogen and battery storage may be a good choice and will therefore be investigated in this thesis. The day-ahead electricity prices fluctuate depending on supply and demand. Simply, when electricity demand is high and electricity supply is low, prices will increase and visa verse.

A hydrogen and battery storage system can reduce strain on the electrical grid by purchasing large amounts of electricity during times with high supply and low prices, to avoid purchasing and instead sell electricity during times with high demand and high prices. This could in theory be beneficial both for society in general since more wind and solar are implemented in the electricity system as well as the economy for the powerplant and real estate owner. To further enhance societal benefits, sector coupling will occur, hydrogen produced in Forsåker will also be sold at a hydrogen refuelling station for vehicles and to industries.

Construction sites and finalized buildings where people live, and work will co-exist for many years until Forsåker has grown to its planned potential. Between 2021 and 2035 the consumption and production of energy will change on a day-to-day basis depending on the active amount of construction sites, amount of finished real estates, and amount of people that live and work in the area. Transportation within the area will change and affect, both in the form of charging needs for trucks, charging needs in the form of living and working, as well as charging needs for electric construction tools and machines on construction sites.

1.2 Aims of the thesis

This thesis report aims to investigate energy management of Forsåker's energy system consisting of local hydrogen and battery electric storage, local electricity production and consumption, as well as sector coupling for vehicles in Forsåker, in relation to the ongoing electrification in society.

1.2.1 Questions to address:

1. How will future energy flows look like in the urban development project Forsåker?

    - During the construction phases
    - In a completed phase

2. Which parameters are important for energy management regarding energy storage consisting of hydrogen and batteries to contribute to the Forsåker district, looking at:

    - Financial values
    - Self-sufficient values
    - Environmental values

1.2.2 Scope of the thesis

The thesis has been carried out together with Powercell, Skanska and Chalmers University of Technology. It was performed in parallel to the pre-study ScALES. Its focus has specifically been energy management with addition of a local energy storage consisting of hydrogen and battery integration with Forsåker’s local electricity production and energy consumption, based on the scenario “a fully developed Forsåker from a detailed development plan DP1A perspective” in the ScALES pre-study [1].

Investigations of storage component sizes was carried out to understand how to manage Forsåker's local production together with electricity imports from the regional grid to cover Forsåker's annual consumption demands on hourly basis in order to find the vital control parameters and system dimensioning, rather than to find the optimal energy system dimensions and control parameters.

2. Theory

In this Chapter the theoretical background is presented, starting with hydrogen and its usage, followed by the Swedish electricity market, as well as the fundamental laws and regulations that affect hydrogen and electricity usage in energy systems. Finally, a comprehensive overview of the energy system's storage components is provided.

2.1 Hydrogen gas – sources and usage

Sweden's industries have used hydrogen for various processes for many years. In Sweden, approximately 180,000 tons of hydrogen were annually used in 2020. Most of the hydrogen used comes from non-renewable and fossil sources. Industrial processes are often enclosed and run with qualified personnel with knowledge of safe hydrogen handling. As hydrogen becomes a more sought-after energy carrier, the presence of stored hydrogen will become a fact in people's everyday lives. This leads to increased safety requirements as individuals exposed to hydrogen probably will not have the same knowledge as industries with continuous safety and risk management practices [4].

Hydrogen can be extracted from different sources, but the most environmentally friendly production method is using electrolyzers that split water into hydrogen and oxygen [7]. This is the least used method today, but as 70 percent of the Earth's surface is covered by water, out of which 35 million cubic kilometres are freshwater, the availability of water in comparison to other sources makes hydrogen a good alternative to use as energy storage medium.

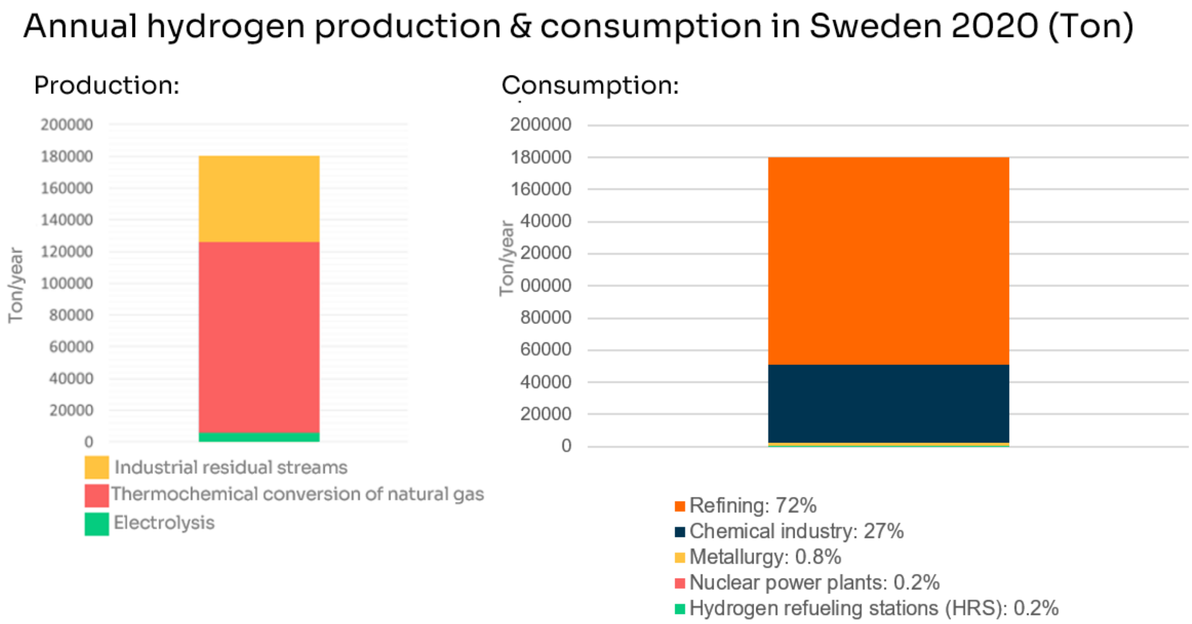


Figure 2.1.1. Annual hydrogen production and consumption in Sweden 2020 [7].

Hydrogen is regulatory marked with a colour depending on the climate impact caused by the production method, and there is a whole spectrum of hydrogen colours. The actual hydrogen gas is of course the same regardless of colour, the difference lies only in the environmental impact of the way the hydrogen gas has been produced. Green hydrogen is the most environmentally friendly. However, the global production of green hydrogen accounts for only 2 % of the total production, whereas 3 % of Sweden's hydrogen production in 2020 was green hydrogen.

The three most common hydrogen classification colours from the spectrum are:

- **Green hydrogen** – hydrogen where the total carbon footprint in the production chain is less than 1 kg CO_2e per kg of H_2. If the process used to produce hydrogen is electrolysis, and the consumed electricity comes from renewable sources such as solar or wind, the hydrogen is referred to as green [5].

- **Gray hydrogen –** hydrogen produced by reforming crude oil. Hydrogen is classed as grey if its carbon footprint during production is 10-14 kg CO_2e per kg of H_2 [5].

- **Blue hydrogen –** hydrogen produced by reforming natural gas. Gray hydrogen is classified as blue if the carbon footprint can be reduced by 50-95 %, with CCS (Carbon Capture and Storage) [5].

Hydrogen is classified as a flammable gas and can self-ignite at concentrations between 4-75 %, requiring only 0.002mJ, compared to 0.33 mJ for methane [6]. Hydrogen is invisible, odourless and burns with a transparent flame. It has a low density but a high diffusivity, allowing it to rapidly rise in the air, mix with other gases, and leak through materials classified as tight for other materials than hydrogen.

The lightness of hydrogen results in low energy content per unit volume but high energy content per unit weight. The gas requires pressurized or liquid storage forms to achieve reasonable energy concentration compared to other fuels. Hydrogen is typically stored at around 300 bars in buildings, 700 bar in vehicles, and 950 bar at refuelling stations. Hydrogen transitions into a liquid state at -253°C, which may be suitable for transporting hydrogen via bulk ships at sea [6].

2.2 Sweden's electricity market

The Swedish Energy Agency estimates that Sweden's electricity production will increase, even though it was almost no change in the overall production in 2015 to 2020. In 2015 Sweden had a total production of 159.4 TWh, and in 2020, it was a total of 159.9 TWh. However, the agency provides projections for 2030 and 2050 where a larger difference can be seen in increased electricity production [7].

Differences between the current energy market and how it is expected to evolve in the future can change depending on the rate of implementation of renewable and nuclear power.

In Sweden's electricity market today, the percentages in distribution by different power sources and their geographical localization vary. A large share of hydroelectric production is in the northern half of Sweden, while significant portions of the population and industries are situated in the southern half. As a result, Sweden's territory was divided into four electricity areas in 2011 (SE1, SE2, SE3, and SE4) to facilitate the management of transmission capacity limitations between northern and southern Sweden [7].

This has often led to higher electricity prices in southern Sweden compared to the north, as there is an electricity surplus in the north and a deficit in the south. The southern region has a significant wind power capacity, resulting in lower electricity prices during favourable wind conditions. The electricity demand in northern Sweden will increase dramatically due to the growing demand from major industrial initiatives in the north, such as HYBRIT, Northvolt and H_2GreenSteel. Additionally, existing operations are increasingly requiring more electricity due to the transition toward electrification in society. Historically, southern Sweden has been able to rely on electricity transfers from the north to the south. Figure 2.2.1 gives an overview of Sweden's annual electricity production among different power sources. Figure 2.2.2 gives an overview of Sweden's installed capacity per electricity area first of January 2022 (MW).

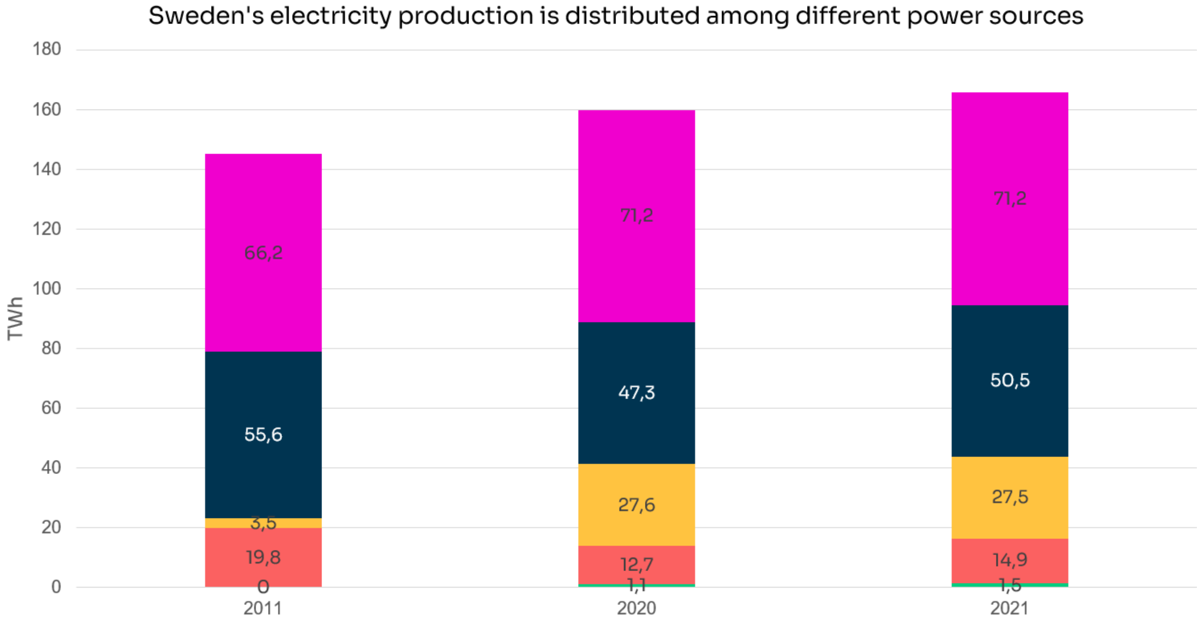


Figure 2.2.1. Overview of Sweden's annual electricity production among different power sources [7].

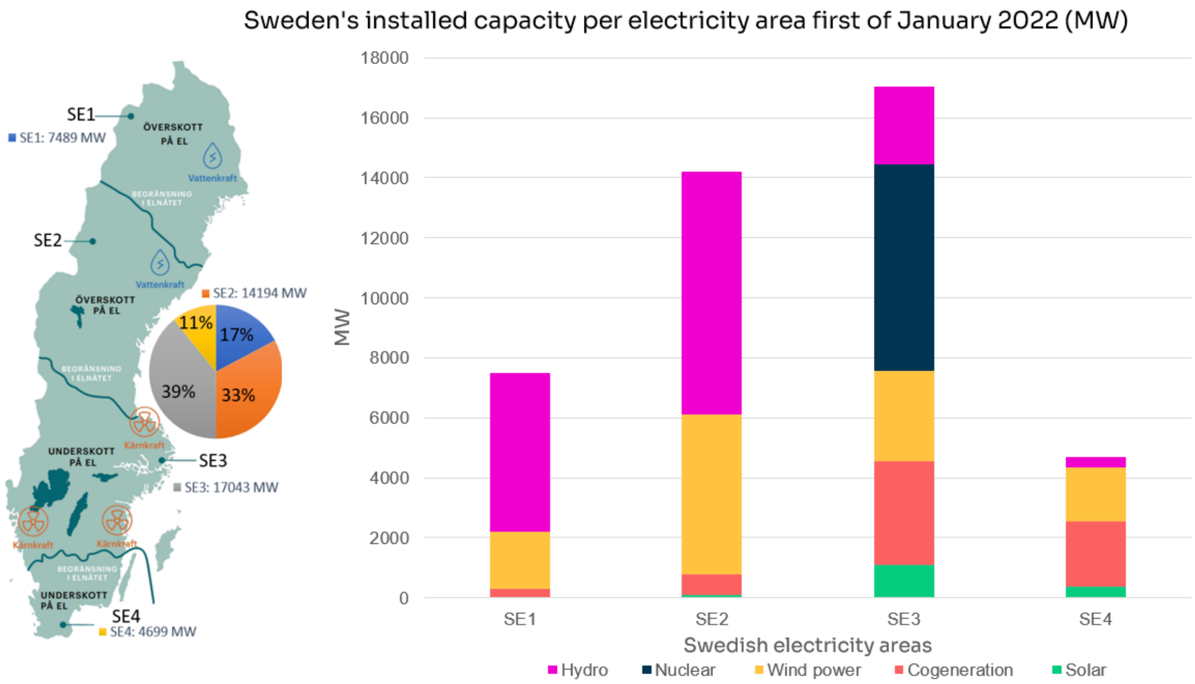


Figure 2.2.2. Sweden's installed capacity per electricity area first of January 2022 (MW) [7].

Southern Sweden is also more affected by electricity prices on the continent. Sweden's electricity market is interconnected with the EU, allowing for the import and export of electricity across national borders. Sweden has interconnections with Norway, Finland, Denmark, Germany, Poland, and Lithuania in the form of power cables. As a result, there is some correlation between electricity prices in Sweden and the rest of Europe, as was evident during the sharp increase in gas prices following Russia's invasion of Ukraine.

Future scenarios according to the Swedish Energy Agency

Predicting the future is difficult, but the Swedish Energy Agency estimates that Sweden's electricity production will increase. The projections can be seen in Figure 2.2.3 for 2030 and 2050, where a larger difference can be seen between the two 2050 scenarios compared to the two 2030 scenarios in increased electricity production [7].

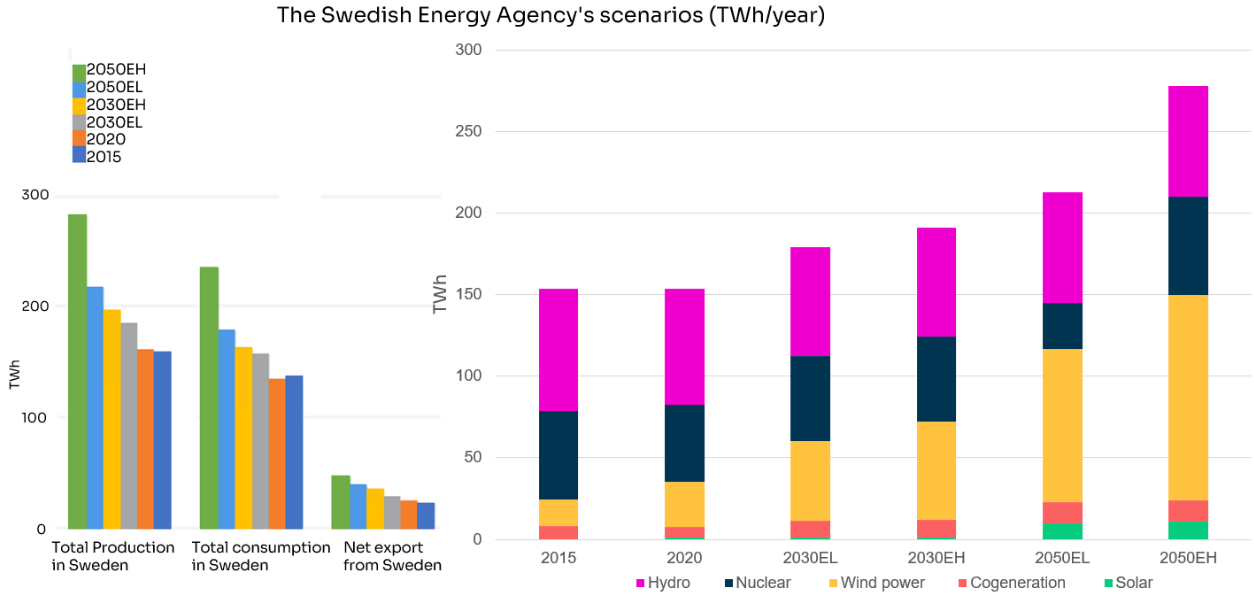


Figure 2.2.3. The Swedish Energy Agency's scenarios (TWh/year) [7].

Power sources can be categorized into weather-dependent sources such as utility-scale solar power, small-scale solar power, onshore wind power, and offshore wind power as well as hydropower. Some hydropower plants face the challenge of being unable to dam water, hydropower plants that can leverage water damming offer increased flexibility. The ability to control and regulate water flow through damming provides these plants with greater adaptability in responding to varying energy demands. Conventional power sources include nuclear power, combined heat and power from waste, and combined heat and power from wood fuels. The Swedish Energy Agency has compiled the Levelized Cost of Energy (LCOE) for each power source. LCOE is based on all expected costs, including start-up, operation, and decommissioning, spread over the expected production during the power plant's lifetime, like an economic Life Cycle Assessment (LCA). However, for weather-dependent power sources, the need for higher capacity margins for grid connection may make these Figures misleading as they do not include storage and regulation costs. For planned power sources, the grid connection capacity can be more accurately dimensioned [7].

As seen in Figure 2.2.3 the increase in wind production 2030 and 2050 compared to today will lead to higher fluctuations of the electricity price on a national level. This is something that Forsåker's grid will be affected by and may take advantage of if energy storage is used. It is important to consider the new 2022 government proposal for increased nuclear power, which could potentially increase electricity production more quickly or in a different mix than predicted in these scenarios.

2.3 Laws and regulations

To design different scenarios for Forsåker to study, and to set the steering system parameters, it is important to know the current laws and regulations, and how they may change in the future. Therefore, background information on the laws and regulations that impacted the assumptions in the chosen simulated scenarios are described in this Chapter.

2.3.1 Hydrogen storage

In Sweden, hydrogen storage is covered by the Act on Flammable and Explosive Substances which requires specific competence of the storage facility and equipment requirements due to safety. There is no specific law that hinders hydrogen storage of over five tons at one site. The legislation and regulations for the handling and storage of hydrogen in Sweden are primarily governed by various safety regulations and standards aimed at ensuring safe and secure handling of gases, including hydrogen. This regulatory situation affects the thesis' later assumption of a five-ton hydrogen storage and the subsequent simulation with energy storage. Ongoing discussions for a national hydrogen regulation may affect the five-ton assumption, but no prediction has been made in the thesis. Hydrogen storages of more than five ton are still possible to implement, one option is to spread out multiple storages with a five-ton limit.

In Sweden, the handling and storage of hydrogen are primarily regulated by The Swedish Civil Contingencies Agency (MSB) safety regulations and standards [19]. Since there is not yet a specific law or clear general regulation in Sweden, requirements may vary depending on factors such as location, intended use, and specific safety regulations applicable to the area.

2.3.2 Grid concessions and energy sharing

In a future with energy sharing as in the Forsåker scenarios, it is vital that society has the ability of flexibility regarding power grid usage due to the larger implementation of renewable energy production. This ability would be greatly limited if there were no possibility of exemptions from the main rule on grid concession since the investment attractiveness in renewable energy production then would decrease.

Despite the amendment to the regulation entered into force on first of January 2022, the outcome is still unclear, and many cases are currently being tested individually. Since no precedents have been issued yet, one may refer to the Regulation (2007:215) on Exemptions from the Requirement for Grid Concessions under the Electricity Act (IKN Regulation), which specifies the exemptions that exist.

The explanatory memoranda of the regulation outline three basic criteria that have guided the determination of when power lines should be exempted from the concession requirement as

- Internally:
  A powerline or a line network must be internal, an internal network is used for the transmission of electricity for the holder's own account.

- Not too widespread:
  The powerline or network must not be too widespread.

- Well defined:
  The area within which the powerline or network is laid must be well defined. [8].

Each of the three criteria regarding amendments to the Regulation (2007:215) on exceptions from the requirement of network concession according to the Electricity Act (1997:857) includes more details [9]. The outcome of how the government chooses to interpret the exemptions will determine whether the principle can be applied in Forsåker or not, thereby affecting Forsåker's ownership structure and economy regarding energy storage and production. If the government decides to limit the exemptions from the main rule on grid concession of districts like Forsåker, energy sharing scenarios investigated in Forsåker would be jeopardized. If instead, the government decides to allow areas of the size of Forsåker, all investigated scenarios in this study are possible to become a reality.

2.3.3 Hydrogen taxation

According to the Gas Market Council, the Swedish government has pushed for a revised Energy Tax Directive ETD to accelerate the energy transition, because the current directive hinders technological development and the transition to renewables.

The revised ETD may change future circumstances for hydrogen, but while waiting for a new Energy Tax Directive, hydrogen is taxed based on current regulations. The regulations that affect Forsåker are:

- Electricity mainly consumed for chemical reduction or electrolytic processes is exempt from tax.
- Renewable hydrogen and fossil hydrogen are taxed equally [10].
- Hydrogen is not taxed when used in fuel cells in vehicles. Hydrogen is taxed as natural gas when used in internal combustion engines.
- Hydrogen is not taxed when used for heating. The concept of heating includes not only building heating but also process heating within industries, etc [10].

2.3.4 Electricity taxation

Forsåker’s energy system will be dependent on the regional grid tax, and regulations have a large impact on how to manage the electricity flows. All local production in Forsåker is renewable. However, renewable electricity is taxed the same as fossil electricity, but there are some exceptions in the Energy Tax Act (LSE), the exceptions is primarily related to the size of the installed generator capacity. Examples where electrical power is not subject to taxation are when it is:

- Produced in a facility with a total installed generator capacity of less than 50 kW, and the electrical power is not transferred to a concessionary network.
- Produced from wind or waves with a maximum installed generator capacity of 125 kW.
- Produced from solar with a maximum installed peak power of 500 kW.
- Produced from another energy source without a generator with a maximum installed capacity of 50 kW.
- There are a few more exceptions, but there is no distinction between renewable and fossil electricity in terms of taxation for larger facilities [11].

In Forsåker there will be many housing cooperatives. If all facade and roof solar installations are divided so that the 500 kW limit is not exceeded per housing cooperative, electricity generated from facades and rooftops will not be subject to taxation. Before the 1st of July 2021 solar installations over 255 kW were subject to taxation, therefore this regulation may change until

2031 as well. Forsåker's wind production will consist of several 5 kW wind turbines, and therefore, this exception may affect the wind production as well.

There are different types of costs related to the electricity grid: electricity tax, power, transmission fee, and VAT are costs that will affect Forsåker's energy system and the system control parameters that will be implemented, depend on them.

2.4 Hydrogen and battery storage components

There are a few available technologies for energy storage, the ones relevant in Forsåker are hydrogen and battery storage. To store hydrogen, different components are necessary, background information of relevant components in Forsåker's storage system simulations are presented below.

Electrolyzer
There are a few different types of electrolyzer technologies available. The technology used in this thesis is a Proton Exchange Membrane Electrolyzer abbreviated PEM EL. The PEM EL splits water to hydrogen and oxygen with electricity and is thus a way of storing electricity in a chemical state. The PEM EL is a device that utilizes a polymer electrolyte membrane to split water into hydrogen and oxygen gases through an electrochemical process. It utilizes electricity to facilitate two electrochemical reactions, the hydrogen evolution reaction and the oxygen evolution reaction, that occur on catalysts placed on each side of a proton exchange membrane. PEM electrolyzers are an important technology for hydrogen production, as they enable the generation of clean hydrogen fuel from renewable energy sources. They are primarily used in applications such as hydrogen production for fuel cell vehicles, energy storage, and industrial processes. Electrolyzers are key to green hydrogen production [14].

Energy storage
Hydrogen storage is a vital function for the implementation of electrolyzers and fuel cells. Hydrogen can be stored in three different ways: as a gas, in a liquid phase, or by absorption or reaction with metals in solid form, typically as metal hydrides. This thesis will only focus on pressurized hydrogen storage. When stored as a gas, hydrogen is typically compressed and stored in high-pressure tanks with pressures between 300 and 700 bar (no cooling). At 100 bar and 20 °C, the density of hydrogen is approximately 7.8 kg/m^3, which is relatively low and results in the need for large storage volumes and relatively high investment costs. However, lower storage pressures require less compression work and therefore lower operational costs. For pressures above 700 bar, safety issues become more severe and storage is thus typically limited to lower pressures than that. Compressed gas storage is currently the most commercially common method to store hydrogen, and it is the technology assumed in this work, where hydrogen is compressed and stored in high-pressure tanks at 300 bars. One kilogram of hydrogen contains 33 kWh of energy. To compare the energy storage capacity, a 20 feet container supplied with hexagon purus pressure tanks can store 395 kg of hydrogen at 300 bar pressure [20] which equals 13035 kWh. H_2 containers can store hydrogen up to 900 bars of pressure wich would increase the energy amount even more. Volvo Energy's portable BESS Battery Energy Storage System which is a battery container stacked with lithium-ion battery cells supplied from Volvos heavy-duty applications up to 600 kWh [30] [31].

The previous prototype used consisted of 6x66 kWh battery packs from Volvo cars which equals 396 kWh (Sales manager at Volvo Energy, personal communication, 2022-12-11). Despite the difference regarding the amount of energy for hydrogen and battery containers, progress is being made in both areas. To make a fair assessment, it is necessary to include other components such as a fuel cell and electrolyzer in the distribution to produce and use hydrogen, while the battery can receive and release electricity in its existing state. Hence, a fair comparison is hard to make since the energy ratio is only comparable for the energy content and not comprehensive.

Fuel cell system

As for electrolyzers, there are a few different types of fuel cells available, for example:

- Direct methanol fuel cell (DMFC)
- Solid oxide fuel cell (SOFC)
- Alkaline fuel cells

The fuel cell system considered in this thesis converts hydrogen to electricity with the only byproducts being water and heat. The thesis thus only includes low temperature Proton Exchange Membrane Fuel Cells referred to as PEM FC, which is the core of Powercell's technology. A PEM FC operates in the reverse mode of a PEM EL and is a type of fuel cell that uses a polymer electrolyte membrane to convert the chemical energy of hydrogen fuel and oxygen into electrical energy through two electrochemical reactions, *i.e.* the hydrogen oxidation reaction and the oxygen reduction reaction. Even if heat losses occur in the chemical reaction, it is a highly efficient and clean energy technology that produces electricity with water as the only byproduct. PEM fuel cells are the most researched as well as the dominating fuel cell technology. The PEM fuel cells are primarily developed for portable, transportation and stationary power generation purposes. This type of fuel cell uses hydrogen gas with high purity as fuel [13].

The stack is dependent on a system that supplies control signals, hydrogen, cooling, pressure regulation, water management, and other necessary components. Oxygen is extracted from the air inside the FC system. The FC system is then integrated in an application with other components, as exemplified in the thesis, *e.g.* stationary fuel cell system applications or mobile applications as vehicles.

Stationary battery- BESS

Stationary batteries refer to energy storage systems designed for stationary applications. Battery developments are primarily driven by the automotive industry where the lithium-ion battery is the most common type. Volvo Energy used new 66 kWh battery packs from Volvo cars to stack both in containers and real estates as well as second life batteries of 60 kWh but has now made their own with a 90 kWh storage capacity for each pack provided by their own heavy-duty applications [30] [31]. Other common types of stationary batteries are:

- NMC: Lithium Nickel Manganese Cobalt Oxide ($LiNiMnCoO_2$)
- LFP: Lithium Iron Phosphate ($LiFePO_4$)
- NCA: Lithium Nickel Cobalt Aluminium Oxide ($LiNiCoAlO_2$) [21].

Batteries are used to store electricity during periods of low demand and release it when demand is high. Batteries play a crucial role in grid stabilization, renewable energy integration, and peak power shaving. Stationary batteries provide benefits such as load levelling, backup power supply, frequency regulation, and grid reliability. They are increasingly being deployed in various settings, including residential, commercial, and utility-scale installations, contributing to a more efficient and sustainable energy ecosystem. Information of the battery that calculations that this thesis are based on, are provided from the Swedish solar company SolTech from 2022 [22].

3. Method

This Chapter describes the methodology used in the study. It provides an overview of how the study was conducted and the methods that were employed to gather data and analyse the results. The study is a combination of methodological research to understand the important parameters in order to make relevant assumptions for Forsåker's energy system simulations, and scenario comparison in the form of a case study.

Before the case study ScALES started, background information from reports were collected to get better understanding regarding energy systems with hydrogen storage and their boundary conditions. One of the main contributors for knowledge and inspiration was Kungliga IngenjörsVetenskapsAkademins report "Om vätgas och dess roll i elsystemet" [7]. Another report is Karlsson, A [24] thesis report, which is a previous thesis report written at Powercell with a problem formulation that is in many ways like my addressed research questions.

When information collection of previous project reports was performed, discussion with supervisors, industry partners, colleagues from Powercell and Skanska mostly formed the approach method. The research questions of the thesis changed during work, and so did the thesis scope. A short history background to understand the process is as follows. Initially, the purpose was to develop a template for the suitability of hydrogen implementation in hospitals, office buildings, multi-family residences, and logistics halls. Construction sites were also included which they continued to be in the ScALES study even though time limitation restricted investigations for construction sites. The goal was to provide an overarching guide for stakeholders involved in these types of constructions, offering an understanding of challenges, safety risks, advantages, disadvantages, economic considerations in the systems, and hydrogen storage from an environmental perspective.

Interviews with Skanska colleagues indicated that hydrogen storage in form of material and economical resources would most likely have a larger impact as a part of an energy system for a larger area of a group of properties or a district with different kind of property types. Ljusekulla in Helsingborg [28] is one example where investigations show that hydrogen storage as part in a larger energy system could be beneficial for the district.

Valuable lessons from the bachelor thesis [29] indicated that hydrogen and battery storage for one property in form of off-grid operation would require much economical resources compared to a smaller storage system with higher implementation of grid flexibility.

When awareness of ScALES emerged, the realization dawned that it was a perfect example of a case study to future investigate in the thesis based on the previous conclusions from interviews and knowledge. ScALES scenarios in form of electricity production and consumption profiles were performed and decided together with the industry participants' further explained in Chapter 4. Energy storage dimensions and control parameters were decided by me in collaboration with the participants and supervisors. At first, most components of the energy system were very large to accommodate extreme scenarios, after future adoption of higher interaction between components in later versions of the simulations which resulted in decreasing component sizes for most components. Finding the control parameters selected involved a lot of trial and error as some control parameters seemed to work well until there were issues in certain operating conditions which lead to errors and rethinking. More details of the process will be explained in coming chapters.

3.1 Assumptions of investigated scenarios

There are many scenarios and combinations which are of high interest to investigate regarding energy storage in Forsåker. Due to time constraints, some of those scenarios had to be deprioritized. The choice for deeper investigation of the 2031 high production high consumption scenario was made with the following assumptions.

- Forsåker's grid infrastructure will already 2026 be dimensioned for the capacity needs for 2031 and beyond to manage a completed district, including the DP1A area as well as phases of the detailed development plans that the ScALES study did not include. Therefore, it will be feasible to cover Forsåker's consumption demands with the regional grid in combination with the local production for the 2026-2029 scenarios. Hence the decision was made to select the 2031 - High production and High consumption scenario, since that would contribute the most to the district planning. The study mostly focused on a helicopter perspective of the district, and less on specific streets. Problems with capacity limitations in specific streets may occur under the 2026-2029 construction phases even though the grid capacity is good enough at a district level.
- Since the total consumption demand of the future Forsåker district were not included in the DP1A, most likely an even larger energy storage system will be required to cover consumption demands for the future Forsåker. By selecting the High consumption scenario and not the Low Consumption scenario as dimensioning, the scenario becomes closer to reality where consumption demands for properties of the other detailed development plans are included.

3.2 Investigated scenarios

Time periods of the years 2026, 2029 and 2031 have been investigated in the ScALES study. For each of the time periods all possible consumption has been divided into one high and one low consumption scenario. All possible local production has also been divided into one high and one low production scenario. More information about the Low scenarios can be found in the ScALES report. The thesis has focused on scenarios with hydrogen and battery storage based on the 2031 high consumption high production scenario.

Electricity consumption

- Mobility consumption includes personal travel, specifically focusing on electric vehicles (EVs) for residents and workers in Forsåker. The low scenario assumes a development of EVs based on estimated trends in Sweden, calculated using the

Sustainability Tool developed by the Gothenburg Region and the Swedish Environmental Research Institute (IVL) together with Volvo cars. It is assumed that residents charge their EVs in Forsåker, and an additional 10% of visitors traveling to Forsåker in their own EVs will charge on-site. In the high scenario, an EV pool is introduced, increasing the proportion of EVs used by residents. Additionally, it is assumed that 30% of visitors traveling to Forsåker in their own EVs will charge within the area.
- The energy consumption of real estates was estimated based on modern buildings as consumption per square meter times the total BTA (Gross floor area is the sum of all floor areas within a building, bounded by the outer surfaces of the enclosing building elements [23]) for each building category in Forsåker. The calculations were carried out by Bengt Dahlgren AB.

Electricity production

For electricity production, the focus has been on the ScALES 2031 High production scenario considered to utilize all available roof space that is not shaded or facing the wrong direction for solar panels. Approximately 30% of suitable facades have facade-integrated solar panels. We also include a small hydropower plant starting from 2026, a larger one from 2029, and a few wind turbines from 2029, with additional turbines added from 2031. More specifically the following aspects are considered.

- Photovoltaics (PV) Roof 80% corresponds to 100% of the available area for PV, which equals 80% of the total roof area. Some roof area will consist of roof terraces and installations, which results in inaccessible space for solar panel installations.
- PV Facade 30% consists of a PV band of 1m width. Facade PV installations will most likely be a common sight in the future, even though some building blocks will shadow others.
- Solar Park Kikås 5 MWp is under construction during summer of 2023.
- The hydropower production of 8 GWh are expected from end of Q4 2028. Depends on when the building permit will win legal force. The water has a drop height of 37 meters and an annual production of 8 GWh. The drops consist of a 13 meter drop as a first step in the permit and 37 meters drop as a second step in the permit.
- The establishment of wind turbines consisting of small 5kW turbines on roofs are planned as follows:
    - Year 2026 - 0 turbines
    - Year 2029 - 18 turbines
    - Year 2031 - 34 turbines

The difference between different energy storage scenarios is how the energy storage system manages local production and consumption demands, the energy flow in the area will change a lot but the total production and consumption profiles will remain unchanged compared to the non-storage scenarios. The installations and properties planned in ScALES scenarios will happen in some form, since they are recommendations. The energy storage scenarios are an additional track for which no decision has been made yet.

Day ahead electricity prices
Three different scenarios were considered to assess the sensitivity of the results on the variable day-ahead electricity prices according to the following.

- "LOW Day-ahead electricity price scenario" based on day-ahead electricity prices from 2016 on an hourly basis. Transmission fee, power fees and tax expenses, based on the 2022 values.
- "MEDIUM Day-ahead electricity price scenario" based on day-ahead electricity prices from 2021 on an hourly basis. Transmission fee, power fees and tax expenses, based on the 2022 values.
- "HIGH Day-ahead electricity price scenario" based on day-ahead electricity prices from 2022 on an hourly basis. Transmission fees, power fees and tax expenses, based on the 2022 values.

Implementation of day-ahead electricity prices from historical years in the simulations is to get an understanding of how the energy system will respond to the fluctuations and prices like that specific historical year and not to get a historical perspective. In the future the historical day-ahead electricity price patterns will never be the same, but future patterns may be like one or another and that's the reason for implementation of these different simulations.

Day-ahead electricity price assumptions of running simulations based on the price from 2022, 2021 and 2016 were made related to the specific year 2022. When Russia invaded Ukraine energy prices increased more than usual, since the future is unpredictable it is of interest to include a high average price year to see the system result if the electricity prices for 2031 and beyond develops in the same direction. 2016 years electricity prices had the lowest average price as well as low fluctuations of the years with available data. 2021 was the closest completed year when the thesis project started.

Important to point out is that no adjustment for inflation has been made between the 2016-2022 day a head electricity price. In the cost comparison for each scenarios the power fee, tax, and transmission fees for 2022 was used for 2016 and 2021 as well. For all investigated scenarios, the energy tax is based on the 2022 values for both 2022, 2021 and 2016, which is 0.36 SEK/kWh and 0.45 SEK/kWh including VAT [11]. In Forsåker, Mölndal Energi AB is the grid owner. For all investigated scenarios the transmission fee is based on the 2022 values for both 2022, 2021 and 2016, which is 0.058 SEK/kWh [12]. The day-ahead electricity prices are typically published and made available to market participants before the start of the trading day at Nord Pool's website. The assumption was made that the fixed costs in SEK/ kWh will most likely increase during the years, maybe as the inflation does. Day-ahead electricity prices on the other hand are not connected to the inflation in the same way, day-ahead electricity prices depend on the supply and demand of electricity, which fluctuates frequently.

The larger the implementation of renewable energy is, the larger fluctuations there will be. When the sun is shining and the wind is blowing there will be price drops, sometimes even negative electricity prices, meaning exporters need to pay to get rid of the produced electricity. During negative electricity prices some producers disconnect production facilities from the grid. Not being able to utilize the generated electricity during peak production periods results in multiple losses from various perspectives. It leads to financial losses for power plant owners and has broader implications for society, since hours later lack of electricity will occur leading to price hikes. The disparities between peak and off-peak periods are already significant in terms of electricity supply and demand, which affect the day-ahead electricity prices. However, society is just at the initial stages of transitioning to renewable energy, which could potentially establish these fluctuations as the new norm. Hence, energy storage can play an even greater role in the future, especially if energy sharing principles are put in place to encourage energy storage.

Owner structure

Two different ownership structures were considered to assess the sensitivity of the results on this variable, the details of which are described below.

- Traditional structure. The real estate owners own solar cells on the roof and facade, which is assumed be under the 500 kWp limit for each housing cooperative to avoid tax. Energy companies or others own the remaining power plants. Tax and transmission fees occur for import and export of electricity, both to and from Forsåker's local grid, and the regional grid outside Forsåker.
- Energy sharing principle. The property owner and the energy companies jointly own both the properties and energy plants based in Forsåker under the IKN (Non-concessionary grids [8]) regulation. Tax and transmission fees occur for import and export of electricity from the regional grid outside Forsåker. For all energy that is produced and consumed inside of Forsåker, tax and transmission fees and power fees do not occur, due to the energy sharing principle. Electricity imports for hydrogen production is tax free.

This study has not investigated the details of how many solar installations that are under 500 kW at each housing cooperative. In 2021, the limit was raised to 500 kW from the previous 255 kW limit indicating that future regulations may be more favourable. The wind powerplants could also be tax free for all scenarios but in the scenarios of traditional ownership, tax on wind production has been included.

Storage components

The technical specifications of the storage components included in the study and used in the simulations are summarised below.

- Battery energy storage capacity: 4 MWh
- Electrolyzer power capacity: 6 MW using one large electrolyzer stack
- Hydrogen storage capacity: 5 tons H_2, consisting of 300 bar pressurized gas. Pressurized carbon fibre or glass fibre cylinders have been assumed in the calculations. Underground storage of hydrogen may be possible but has not been investigated.
- Hydrogen refuelling stations enable fuelling of hydrogen vehicles both passenger cars and heavy-duty vehicles at up to 700 bars.
- Fuel cell system capacity: 1.5 MW consisting of 15 modular stacks of 100 kW each.
- Heat pump capacity: 2 MW consisting of heat pump modules of 90 kW stacked together as alternative to heat from Riskulla.

The component CAPEX numbers used in the calculations are from a combination of sources of today's price as well as future estimations. The reason for this is that some components are installed in the close future. As the Kikås solar park is scheduled to be installed in the summer of 2023, it provides a more accurate basis for estimation compared to components that will be installed 2031. The further in the future the installation is planned, the more uncertain the assumptions become. Unexpected events are likely to occur that can alter the reality from future estimates, some for the better and some for the worse. This is particularly true in the rapidly developing market of battery and hydrogen components. No consideration has been given to future increased performance in the simulations, only to future CAPEX.

Estimations of the electrolyzer and fuel cell system is selected from the DOE targets where price has decreased, and lifetime increased. In the simulations, an 80% FC- system performance is assumed as beneficial operational load. Performance of the 15 stacks of 1.5 MW combined with operational performance thus reduce power to 1.2 MW during beneficial operational conditions. If the future performance would allow 100% operational as beneficial operational conditions, 20% less stack capacity would be required, as well as 20% less CAPEX. In the thesis investigation focus on fuel cell system components has not been investigated, but the technology performance continues to improve.

Real estate and construction-related expenses have not been included in the thesis. The construction of the buildings will not be significantly altered depending on the outcomes of the different scenarios, hence the construction expenses will most likely be the same for all the scenarios. However, construction site energy storage will impact the economy, a deeper investigation of this was not performed due to the choice of 2031. Rent income for the property portfolio will be set in relation to the energy related incomes and expenses.

Early in the study, a choice was made, to primarily prioritize Forsåker's consumption demands in the simulations. The energy system must be able to meet Forsåker's consumption demands every hour of the year, regardless of circumstances. Sometimes this choice aligns with the economically beneficial decisions, while other times it goes in the opposite direction. The following trade-offs are necessary to find a good balance for and depending on the importance of different parameters they can be weighted differently in the control system.

- The initial setup was chosen for the energy sharing ownership structure, where all self-produced energy is considered free regarding energy purchases. However, there are additional fees for capital expenditures (CAPEX) instead.
- The market value of the self-produced electricity will not be prioritized primarily, as the degree of self-sufficiency is considered more valuable.
- Electricity purchases during hours with favourable prices have been prioritized, while electricity sales during hours with high prices have not been prioritized. This is because the primary focus on achieving operation reliability of the area's consumption demand.
- Hydrogen production and battery storage of accessible electricity is greater than the economical focus of exports during high prices. The prioritization to avoid selling electricity during periods of high electricity prices is compensated by the H_2 sales for vehicles in the area, in addition to its use for increased sector coupling.

There is indeed significant potential for further optimization to achieve the right balance between parameters in this context. Most likely a mix of electricity sales and hydrogen production is the best alternative, but such an optimisation is beyond the scope of this study.

4. Case study - the urban development project Forsåker

This Chapter will delve directly into the energy-related aspects of Forsåker, which include local production, consumption needs, and energy systems with and without energy storage.

Chapter 4 shares many similarities with the ScALES report, as it was originally written for the report in collaboration with the ScALES participants. This Chapter offers unique insights into the 2031-High production- High consumption scenarios involving energy storage and provides a more in-depth analysis of its implications. Regarding economical comparisons of day-ahead electricity prices and the ownership structures (Traditional ownership and Energy Sharing owner structure) as seen in Figure 4.1:

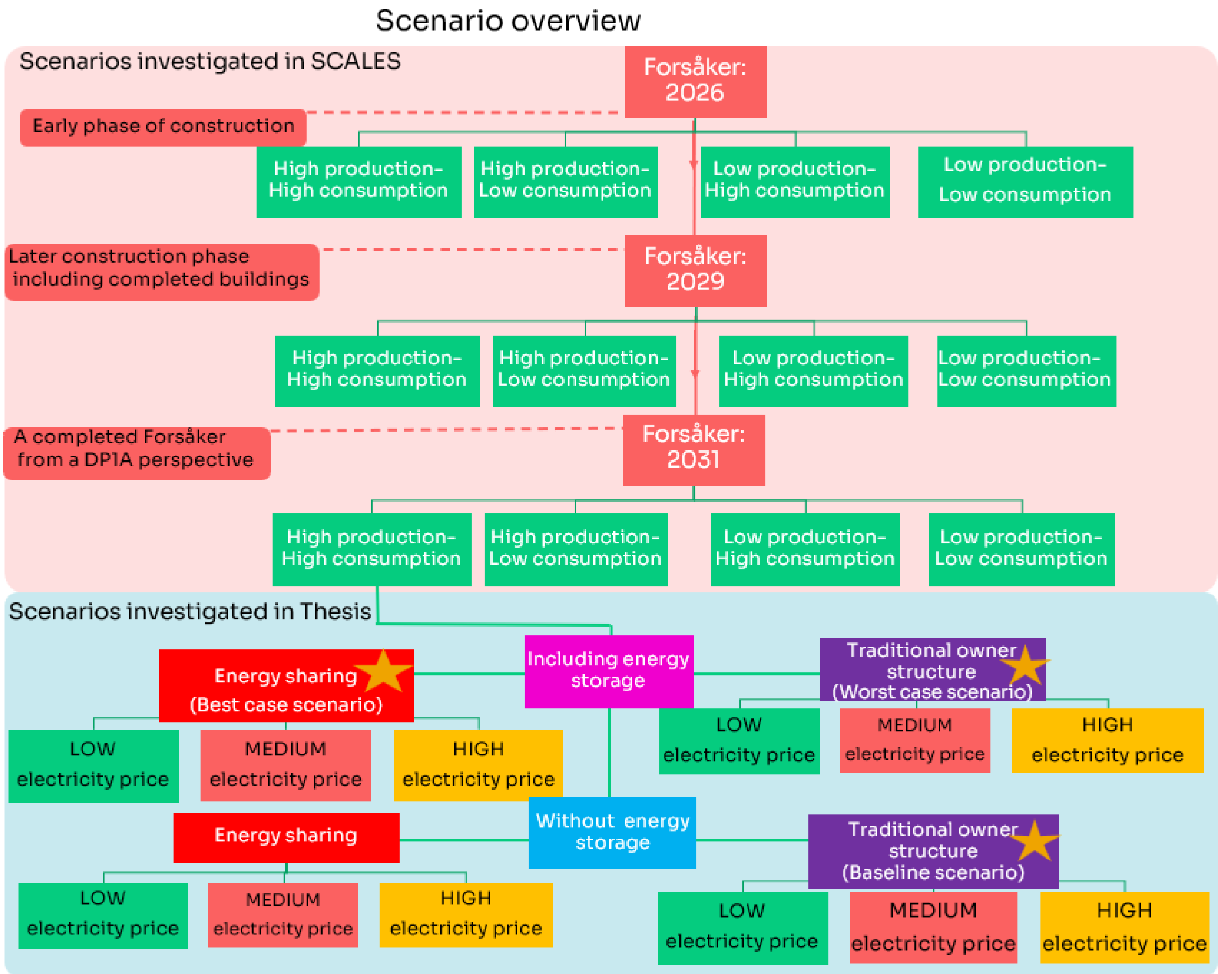


Figure 4.1. Overview of the combinations of time periods and scenarios of high and low production and consumption in Forsåker. The 2031-High Production-High consumption scenario includes storage scenarios and non-energy storage scenarios based on day ahead price data for 2016 as LOW, 2021 as MEDIUM and 2022 as HIGH divided into Scenarios with traditional ownership structure as well as energy sharing.

From the detail plan of the development project, time periods of the years 2026, 2029 and 2031 have been investigated in the pre-study ScALES, during those time periods ongoing construction occurred, whereas Forsåker 2031 is completed from a DP1A perspective illustrated in Figure above. For each of the time periods all possible consumption has been divided into one high and one low consumption scenario. All possible local production has also been divided into one high and one low production scenario illustrated in the upper part of Figure 4.1.

In Figure 4.1, the scenario labelled "2031-High Production-High Consumption-Energy Storage-Energy Sharing" is marked with a star, indicating that it is assumed to be the best-case scenario. Conversely, the scenario labelled "2031-High Production-High Consumption-Energy Storage-Traditional Ownership Structure" is assumed to be the worst-case scenario. The assumed hydrogen prices and hydrogen taxation regulations also play a significant role in both the best-case and worst-case scenarios.

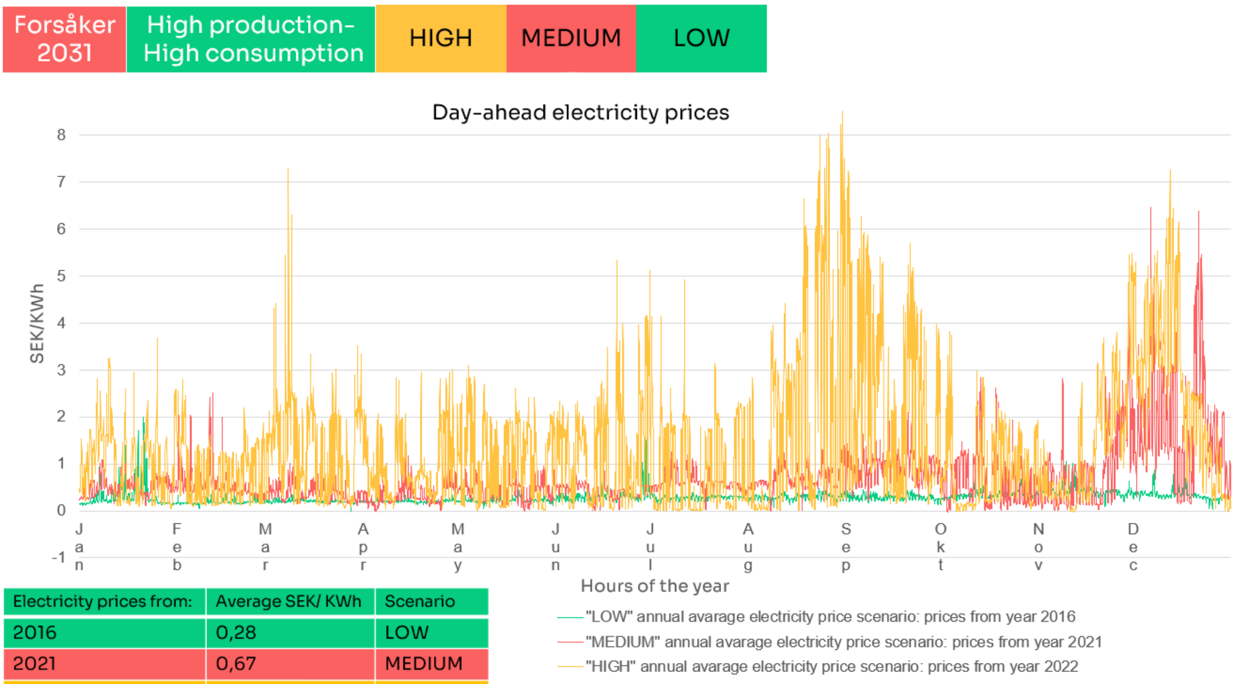
Furthermore, the scenario labelled "2031-High Production-High Consumption-Without Energy Storage-Traditional Ownership Structure" is also marked with a star, representing the baseline scenario. This scenario assumes that no investment is made by real estate owners in local energy production facilities or energy storage systems, and that the traditional ownership structure remains unchanged.

The best-case and worst-case scenarios represent the endpoints on the scenario scale. The best-case scenario assumes that future laws and regulations are favourable and result in the most economically beneficial outcomes and visa verse with the worst-case scenario, while in the baseline scenario no investment in renewable energy production, energy storage (hydrogen and batteries), and no changes in ownership structure.
In all Traditional Ownership scenarios, the roof and facade solar installations are owned by the real estate owners themselves. In the Energy Sharing scenarios, however, they are co-owned by the consortium.

The range of scenarios between the best-case and worst-case scenarios highlights the various factors that should be considered when evaluating investments in energy storage and renewable electricity production in Forsåker. It is important to note that future outcomes are unlikely to align exactly with any specific scenario examined. However, these scenarios provide valuable insights into the factors that have varying degrees of influence on the outcomes.

Historical electricity prices on an hourly basis were collected from the Nord Pool electricity exchange for the years 2016, 2021, and 2022. 2016 had a low average electricity price, while 2021 and 2022 had higher average prices. Future electricity price profiles will never be exactly like those of 2016, 2021, or 2022. The purpose of testing the system with historical electricity prices is to understand how energy storage contributes to Forsåker's energy system during years with both high and low average electricity prices.

Simulations with the storage scenarios have been performed based on the day a head electricity prices for 2022, 2021 and 2016, which are named LOW, MEDIUM and HIGH day-ahead electricity price scenarios, respectively. An economic comparison was made between traditional ownership structure and the relatively new principle of energy sharing, for all the 2031 high production-High consumption scenarios with and without energy storage.



Electricity prices from:	Average SEK/ KWh	Scenario
2016	0,28	LOW
2021	0,67	MEDIUM
2022	1,37	HIGH

Figure 4.2. Day-ahead electricity prices from year 2016, 2021 and 2022 which are input data for LOW, MEDIUM and HIGH day ahead electricity price scenarios [17].

The mindset regarding energy storage is to import electricity during low day-ahead electricity prices and export it during high day-ahead electricity prices. This mindset is beneficial for both producers and consumers. Consumers can use energy storage to import electricity at lower prices, thereby avoiding the need for imports when day-ahead electricity prices are high. On the other hand, producers can utilize electricity storage to avoid exporting electricity during low prices, waiting instead for the price to rise, and increase their profits. This mindset does not only provide economic advantages for both producers and consumers but also contributes to increased stability in society. This is particularly relevant now as the category of "prosumers" becomes more common, where property owners both produce and consume their own electricity.

In addition to energy flows, ownership structure is crucial for the outcome of energy-related costs. Therefore, the energy flows, both with and without energy storage, will be categorized into traditional ownership structure and the relatively new exception from the exemption from the requirement for grid concession (IKN) regulation that enables energy sharing will be investigated.

4.1 Forsåker's local electricity production plants and storage components

Data in Chapter 4.1 & 4.2 has been provided and calculated by the ScALES participants, hence more information can be found in the ScALES report. Forsåkers energy system 2031 in the high production scenario will consists of a variety of renewable electricity powerplants in forms of hydropower, windmills and solar panels on the facade and roof as well as Kikås solar park. All the powerplants are weather dependent and non-steerable.

Figure 4.1.1 shows prognosed annual hourly production profile divided on production categories.

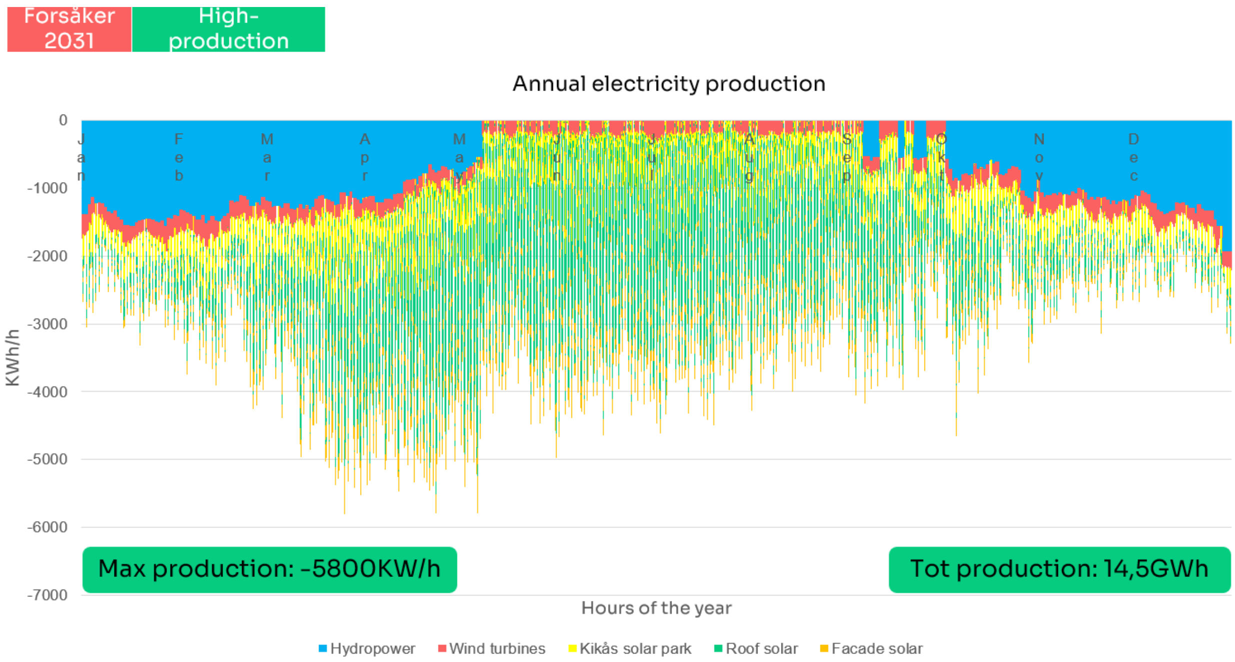


Figure 4.1.1. prognosed annual electricity production in Forsåker from all plants combined hourly in a 2031 High production scenario. Datapoints of simulated production has been provided by Mölndals Energi ABs simulation tool as well as from Bengt Dahlgren AB.

Roof solar electricity production on top of the buildings
The annual hourly roof solar production profile is marked as green in Figure 4.1.1. Assumptions made in the high scenario regarding Roof solar were made by the following process, based on the maximum capacity of solar production decided by blueprints of Forsåker. Roofs were divided into 9 categories, 3 directions, 3 roof slopes. Shading has been considered by adjusting available solar area by reducing shaded area as if a taller building constantly creates shade on nearby roofs.

Facade solar electricity production on the buildings
The annual hourly facade solar production profile is marked as orange in Figure 4.1.1. From a Revit 3D model potential for solar was selected. The same directions as for roof solar Southeast, South and Southwest where selected excluding facades shaded by nearby buildings that were higher or located too close for the sun to penetrate sufficiently. Existing buildings that are K-marked were extracted as facade solar candidates directly. The potential facade assumption that a 1meter wide facade band of solar cells will cover each floor at the facade. Exception for one office building where the solar panel band will be 2 meters wide per floor. All the data of available facade area for solar panels were processed by Mölndal Energis simulation tools that created the hourly production curves based on historical solar radiation data in Forsåker.

Solar Park Kikås
The annual hourly solar production profile from the park in Kikås is marked as yellow in Figure 4.1.1. Mölndal Energi AB currently constructs a 5-Megawatt solar park in Kikås that will be ready for local electricity production in autumn 2023, the park area equals 10 football fields. The solar park will be built on areas that during 1930-1990 were used for

landfills but are closed for landfills since a few years back, therefore construction of real estates on this area is not allowed. The park will contribute with green electricity to areas that are unusable for many other purposes. Building the park here utilizes the land in an efficient manner, rather than constructing the park on areas with potential for real estate or agriculture.

Hydropower Forsåker

The annual hourly hydropower production profile is marked as blue in Figure 4.1.1. Construction of Forsåker's hydropower plant is expected to be divided into two steps. The first stage consists of a 450-kW turbine at a drop height of 14 meters, planned in Q4 2026. In the second stage utilization of the entire drop height of 37 meters will be possible, then with an even more powerful turbine of 1700 kW or combinations of two smaller ones. In both cases a minimum flow of water is necessary to enable a profitable start of production.

A continuous bypass flow around the hydropower plant is required to create a pleasant atmosphere. This means that the hydropower plant most likely will be unable to operate and produce electricity during June, July and August due to the weather conditions. Because of the indications of weather conditions and circumstances within the area, electricity production input data was set to zero between 15th of June to the first of September in the simulations by Mölndal Energi AB. Forsåker's hydropower plant will not have the ability to dam water like some other hydropower plants, thus there is no possibility to utilize water as an energy storage or to balance production and consumption curves in Forsåker through the hydropower plant. If the 450 kW turbine is changed to the 1700 kW turbine higher minimum flows are required, which in turn will affect availability of turbine operation.

Wind turbines

The annual hourly wind turbine electricity production profile marked as red in Figure 4.1.1. In the urban environments of today wind turbines are not a common sight, the complexity of wind loads and problems related to noise are two factors that hinder implementation. For local production in urban areas like Forsåker wind power is of interest as a complement to solar due to weather-depending production variations for production sources both on daily and yearly basis.

Development of small-scale wind power has been taken into consideration in the ScALES study regarding vertical wind turbines with integrated generators. Assumptions were made to implement wind power to some extent within the high production scenarios. Primarily to illustrate how wind power complement other local production in the area. The amount of implemented wind power capacity requires further investigations. In the high production scenarios 0, 18 and 24 plants of 5 kW turbines were selected to be spread out over the area's property roofs. The simplified production profile used was developed by averaging historical wind data for several years, with a yearly average speed of 3.5 m/s to calculate the hourly production.

4.2 Forsåker's energy consumption

As in Chapter 4.1, electricity consumption data in Forsåker in Chapter 4.2 has been provided and calculated by the ScALES participants as well. Electricity demand for buildings and transportation in the area has been compiled, both on a daily and annual basis. In this study, the electricity demand within the area has been separated from the electricity demand caused by properties in the area and mobility consumption caused by battery electric vehicles and plug in hybrids. Assumptions are made that truck transportations to Forsåker are charged at a depot outside Forsåker and mostly even outside Mölndal. The additional electricity demand required by these trucks, which does not burden the local grid, is accounted for separately and is not included in the overall compilation of the area's electricity demand.

Figure 4.2.1. Annual electricity consumption profile in Forsåker 2031-High consumption scenario categorized by Operational electricity, Property electricity and EV-charging electricity.

4.2.1 Forsåker's real estate electricity consumption

Electricity consumption for the real estates has been categorized, with key Figures for operational electricity and property electricity for the properties schools, offices, residential and commercial properties. Daily distribution curves of household electricity, operational electricity and property electricity are estimated from statistics in combination with experience of typical values collected from a variety of reference projects by Bengt Dahlgren AB.

In combination with the time schedule of finalized constructed real estate areas sorted by categories for each chosen time, calculations of the total energy consumption for each period have been estimated. Shares of both finalised constructions as well as the shares of ongoing construction phase activities, in 2031 no construction activities occur related to DP1A.

Electricity consumption in the buildings is categorized as household electricity/ operational electricity and property electricity. Within the category household electricity/ operational electricity, kitchen, and laundry appliances as well as other electronics used by the resident are included. Within the category property electricity appliances used by the building are included such as elevators, ventilation, pumps, fans and lighting for shared areas etc. Key Figures for energy consumption in kWh/m² in combination with experience values and statistics of variations on daily basis for the different categories of properties were provided by Bengt Dahlgren AB.

The Gross Area of Forsåker's building categories mentioned above serves as the fundamental basis for summarizing the total electricity consumption for Forsåker's property portfolio. By expressing energy consumption in kWh/m2, also called Gross Area. It becomes easier to compare Forsåker's electricity consumption with other districts, considering that no other district is likely to have an identical property portfolio as Forsåker. This unit of measurement allows for a more meaningful comparison and provides a perspective on energy efficiency and consumption patterns relative to the size of the buildings. An example of variations on daily basis of household electricity consumption for residential properties are showed in Figure 4.2.1.1:

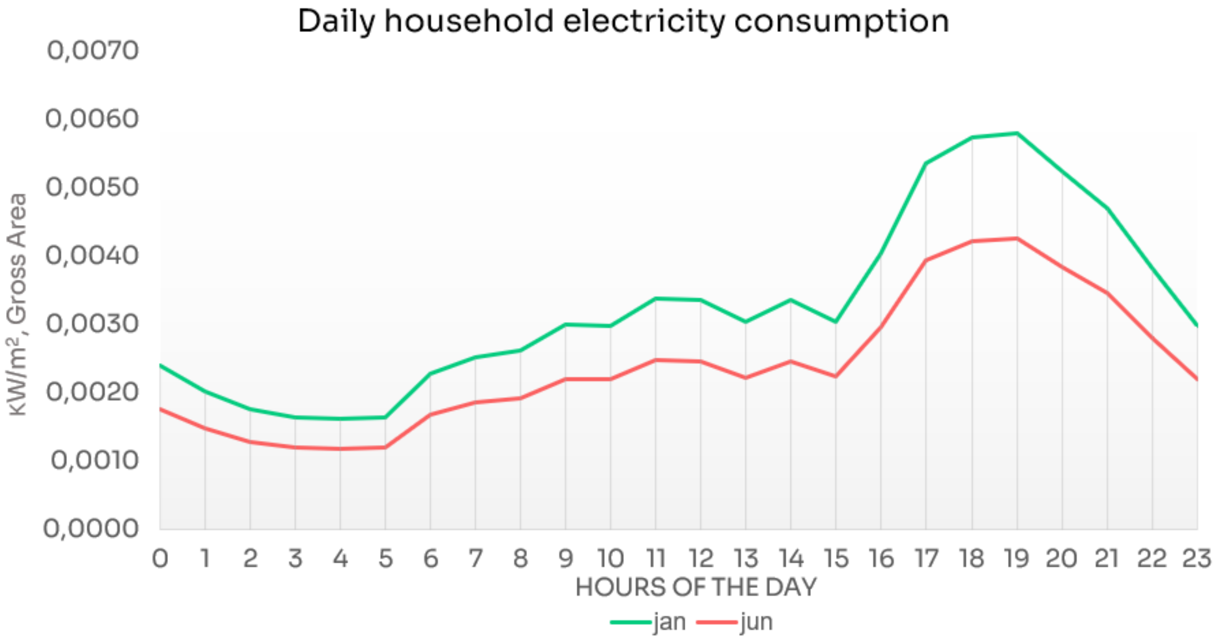


Figure 4.2.1.1. Variation of household electricity consumption on daily basis in January and June.

Daily and annual variation profiles have been created by Bengt Dahlgren AB for each category of property that will be constructed in Forsåker during the period. That data has been provided to a simulation tool by Mölndal Energi AB to generate total electricity consumption curves for all properties combined in Forsåker, which are included in Figure 4.2.1. More details can be found in the ScALES report [1].

4.2.2 Mobility and transportation

An increased share of electric vehicles (EVs) in the area demands a local EV charging infrastructure. MölnDala Fastighets AB has provided the share of parking spots in relation to the planned amount of inhabitants in Forsåker. Göteborgsregionen has together with IVL (Institutet för vatten- och luftvårdsforskning) also called Svenska Miljöinstitutet developed a sustainability tool. Some parameters that the sustainability tool considers are the possibility for public transportation within Forsåker, proximity to the city centre, as well as the rate of development of electric vehicles. It has resulted in the transportation and travel requirements for the inhabitants and workers in Forsåker as well as their future travel partners including car, bike, public transportation etc. Based on these results, forecasts of the increased electricity consumption for EV charging, in relation to the amount of people living in Forsåker at each period have been calculated. The sustainability Tool can be used for other urban development projects as well but this was the first time the tool was used for a real case. An electric car pool is planned in Forsåker which will affect the share of EV trips in the area for the 2031 High consumption scenario.

Results shows that until 2031 the share of EVs has increased to 58%. IVL has estimated the number of cars in relation to residents, number of trips per resident and distance for each trip. Those parameters have been converted to an electricity consumption of kWh per year. IVL has estimated that 100% of the charges occur within the area for all residents. Electricity consumption for cars generated by the sustainability tool is shown in Table 4.2.2.1:

Electricity consumption for cars generated by IVL:s sustainability tool

Vehicle type	2026 (kWh)	2029(kWh)	2031(kWh)	2035(kWh)	2040(kWh)	2050(kWh)
Electric passenger cars, residents (EVs)	75,700	772,400	1,566,400	1,994,600	2,693,300	3,687,000
Plug-in Hybrid Electric passenger Vehicle, residents (PHEV)	12,400	92,500	158,600	152,700	108,800	26300
Electric passenger cars, business (EVs)	925,900	2,283,300	2,777,600	3,430,700	4,411,900	5,467,000
Plug-in Hybrid Electric passanger Vehicle, businesses (PHEV)	152,200	273,400	281,300	262,700	178,200	39000
Passenger cars residential per total area (kWh/m2)	2.1	5.6	7.5			
Passenger cars business per total area (kWh/m2)	25.7	16.6	13.3			
All cars per total area (kWh/m2)	27.8	22.2	20.8			

Table 4.2.2.1 Electricity consumption based on vehicle-kilometres (EV pool included) estimates from IVL.

In the High scenario with the EV pool 30% of the charges for business trips are estimated to appear in Forsåker, the remaining 70% charging is estimated to appear elsewhere.

The company Charge Node has contributed with statistics from 84 housing cooperatives with a total of 1200 chargeable vehicles in general, the data has been collected over 2.5 years period from real cases. The results from the collected data showed that no difference in the charging pattern can be distinguished depending on the day of the week. Hence the hourly charging pattern daily as people plug in and start charging is shown below.

The majority starts to charge at the afternoon 16:00 seen in Figure 4.2.2.2 and stop charging at 07:30 in the morning, resulting in a 15.5-hour continuous charge repeated every second or third day.

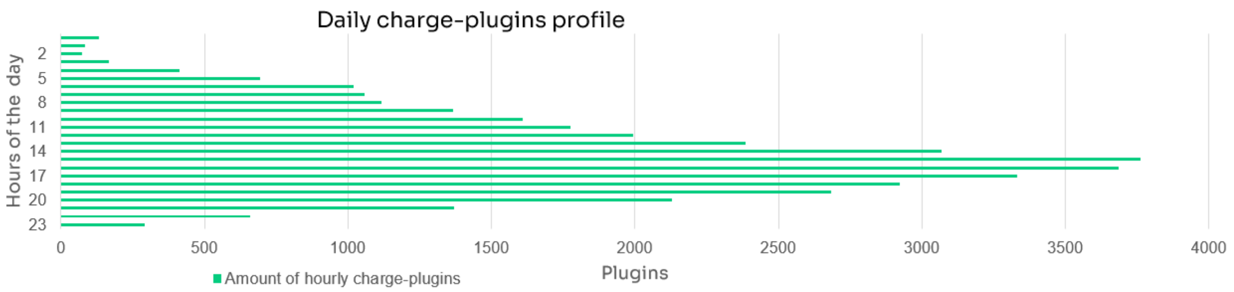


Figure 4.2.2.2. Statistics from Charge Node showing various housing cooperatives on starting times for EV charging for residents.

4.2.3 Forsåker's energy consumption and production without energy storage.

Forsåker's "2031-High production scenario" has investigated local production compilations of total energy production and power capacity from Forsåker's local hydro-power plant, electricity production from the solar park Kikås close to Forsåker, electricity production from roof and facade solar integrated at the properties in Forsåker, and wind turbines in Forsåker. Annual production from Forsåker's local production estimates is illustrated in Figure 4.2.3.1 below:

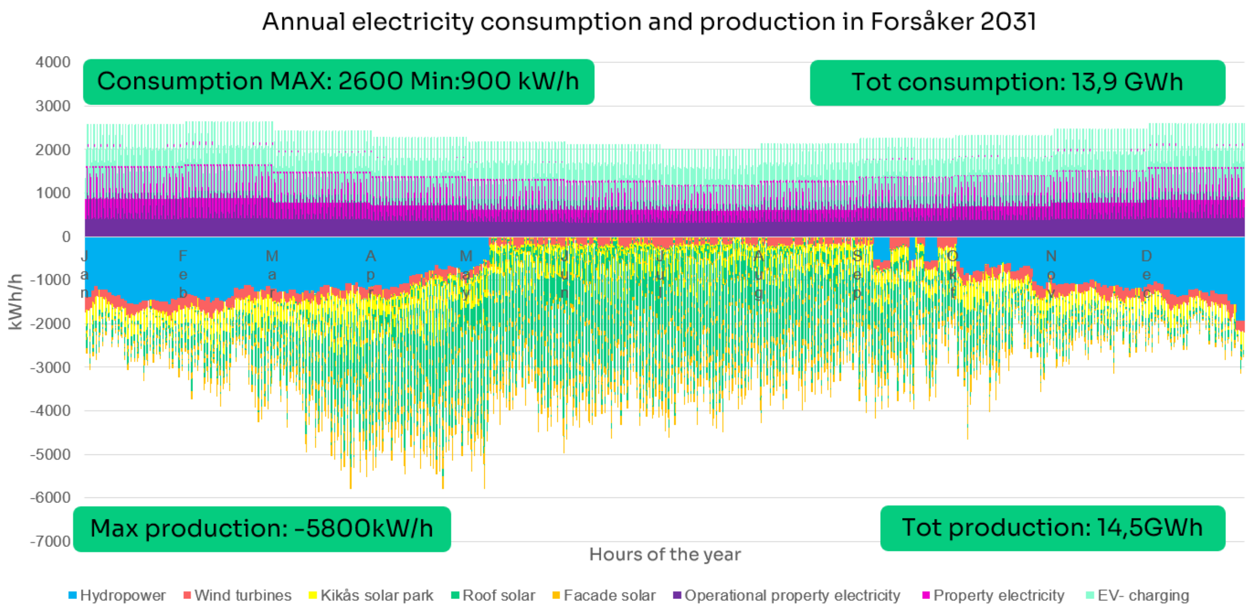


Figure 4.2.3.1. Annual electricity production and consumption on hourly basis 2031-High Production-High consumption without energy storage. Input data from Mölndal Energi AB from the ScALES report[1].

Total annual electricity consumption for Forsåker 2031-High Consumption-High production is 13 900 MWh/year with a production of 14 500 MWh, hence the completed area will still be a net exporter to the regional electricity grid on annual basis due to larger production than consumption during the year. Annual net exporter indicates that the Positive Energy District (PED) has achieved meaning that Forsåker local production, surpassing its own energy consumption and exporting the surplus energy to external grids or consumers. Figure 4.2.3.2 below shows hourly difference between production and consumption in Forsåker 2031:

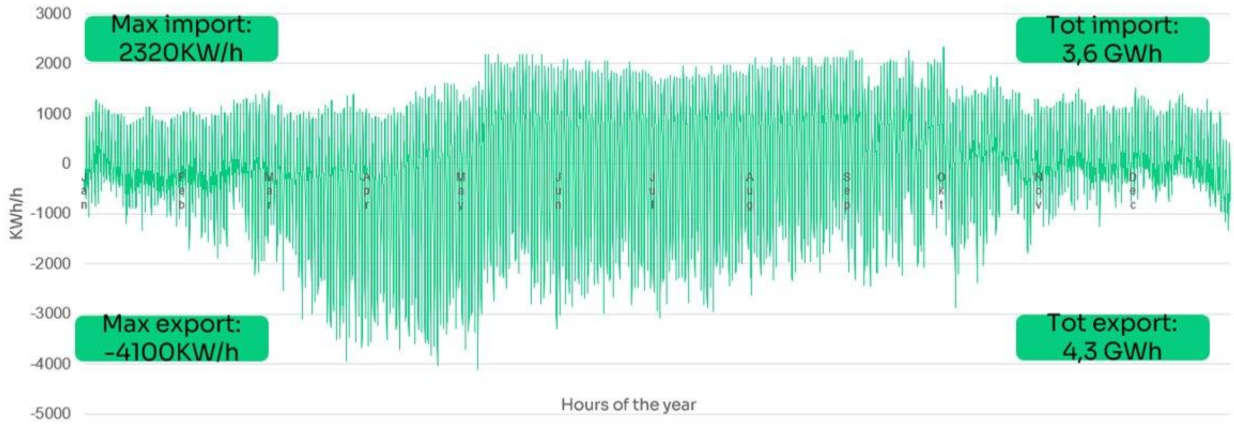


Figure 4.2.3.2. Delta power difference between consumption and production on hourly basis in Forsåker 2031, in a high production high consumption scenario.

To maintain a balance between electricity demand and supply, grid trades or energy storage solutions are necessary since Forsåker's local production never equals consumption. Therefore the energy system relies on grid export or import during all hours of the year. Annual excess electricity occurs 50.2% of the hours and annual electricity lack occurs 49.8% of the rest hours of the year.

From May to September, local electricity production in Forsåker is unable to match with peak consumption, even when considering maximum imports from the regional power grid. This pattern continues in October with some milder gaps. Consequently, during peak consumption periods, there is a shortage of local production, requiring reliance on regional grid imports to bridge the gap.

By strategically placing energy storage within Forsåker's local energy system, excess production can be shifted to times when there is a shortage of electricity. This not only relieves the strain on the power grid during critical periods but also contributes to a more efficient dimensioning of the grid and distribution infrastructure.

Electricity consumption in the fully developed phase of Forsåker 2031 is distributed as:

- Property portfolio 80%
- Mobility regarding electric cars 20%

Total maximum peak capacity for consumption for Forsåker is 2 600 kWh/h, consisting of 530 kWh/h distributed for EV-charging. Resulting in that around 20% of the peak capacity will consist of EV charging, an increase of EV adoption results in higher capacity demands as well as increased electricity consumption in average. Those 20% of capacity demand is an uncertainty since the charging pattern of the public can vary from the assumptions in this study. Another parameter that is not considered in this assumption is how the charging fluctuates depending on the electricity price.

Conclusions made are reasonable relative systems that are built today regarding combinations and steering systems of capacity limitations for charging systems. Scenarios that include a large share of fast chargers are also likely to occur, if EV-pools becomes common in combination with a higher share of electrical company cars that cannot wait for a long time to reach a 100% charge level due to more frequent trips compared to a typical private person that drives to work, stays there for 8 hours, then drives home.

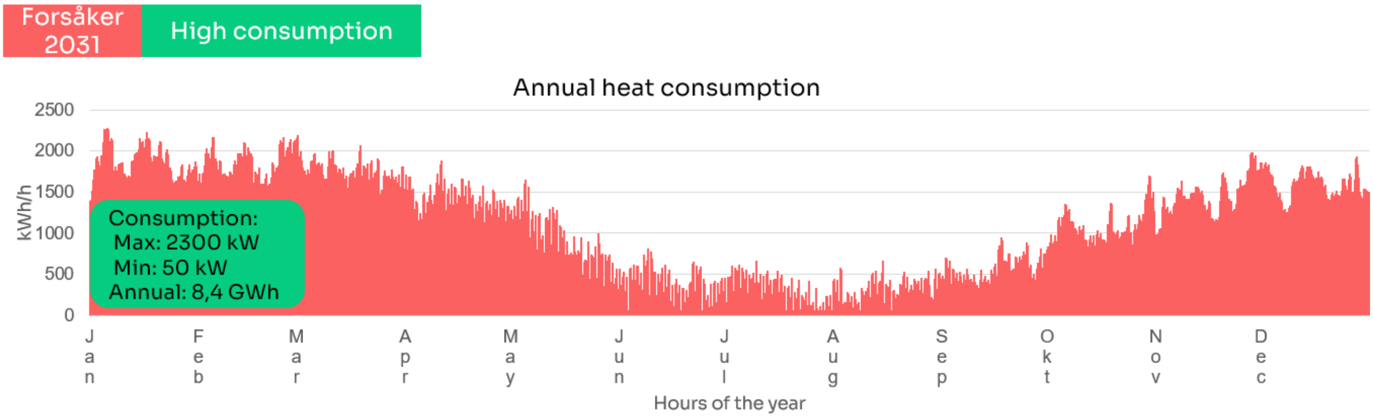


Figure 4.2.3.3. Annual heat consumption profile in Forsåker 2031-High consumption scenario (Heat consumption in Forsåker are equal in all 2031 scenarios).

Forsåker's annual heat consumption illustrated in Figure 4.2.3.3 is planned to be covered by district heating from the combined heat and power plant Riskulla in Mölndal, both construction sites as well as properties in the completed property portfolio for the scenarios without energy storage. The aim of Riskulla plant is to produce heat, but electricity is created as well. For every kWh of energy converted, roughly 75% becomes heat and 25% electricity. For the 8.4 GWh of heat demand in Forsåker, 2,8 GWh electricity is produced which is distributed directly to Mölndal's regional grid. Since heat production appears outside of Forsåker in scenarios without energy storage, heat consumption will not affect Forsåker's electricity consumption.

4.3 Storage component's purpose and choice of size

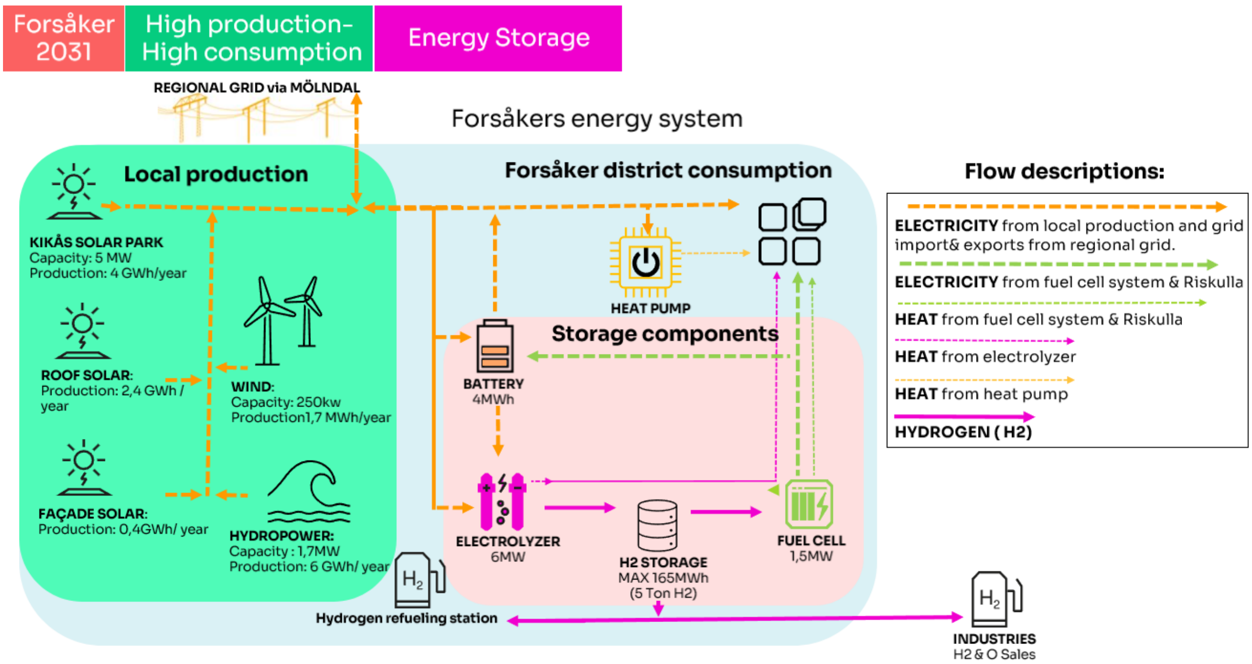


Figure 4,3,1, Component sizes of Forsåkers energy system including energy storage in the 2031- High production-High consumption- Energy storage scenario, as well as energy flow descriptions.

Figure 4.3.1 gives an overview of Forsåkers energy system including energy storage in batteries and hydrogen, all production profiles from the local renewable energy sources will remain the same as without storage, as will all consumption from buildings and mobility. The purpose with hydrogen and battery energy storage in Forsåker is to cover Forsåker's consumption demands as well as production flows in a better way than without an energy storage. The exact meaning of a better way is hard to define, hence it depends on the prioritization by the energy system dimension and control parameters, hence they are described in the method Chapters. Another important additional implementation is the H_2 refuelling station which enables sector coupling.

None of the battery, fuel cell and electrolyzer contribute with any new electricity to Forsåker as the local production does. The storage system only moves electricity from time to time depending on the control parameters. Every conversion between hydrogen and electricity, as well as the storage of electricity in the battery, contributes to conversion and transmission losses. Therefore, energy storage must be used wisely. Sometimes, it is worthwhile to store energy despite the losses, and sometimes it is not. Finding this balance is crucial. The parameters of the energy system have been examined for Forsåker-High production-High consumption scenarios, and the components that enable this are described in the following Chapter. The areal energy flows to Forsåker's energy system will be affected since simulations with energy storage will import larger amounts of electricity based on the electricity price. The larger share of Forsåker's consumption that is covered by the fuel cell system, the larger the quantity of storage is required compared with directly consumed electricity imported from the regional grid. The larger quantity of hydrogen production the larger quantity of electricity consumption for the energy system, even if Forsåker's property portfolio and EV-charging electricity consumption demands remains.

4.3.1 Battery storage

Batteries can quickly absorb or emit electricity or store for hours with low storage and transmission losses. Storing locally produced electricity in the battery can be beneficial in situations like Figure 4.3.1.1 illustrates, the battery can move local electricity production by storage during excess hours with local production or during low electricity prices to cover local electricity demand during electricity deficit or high electricity prices.

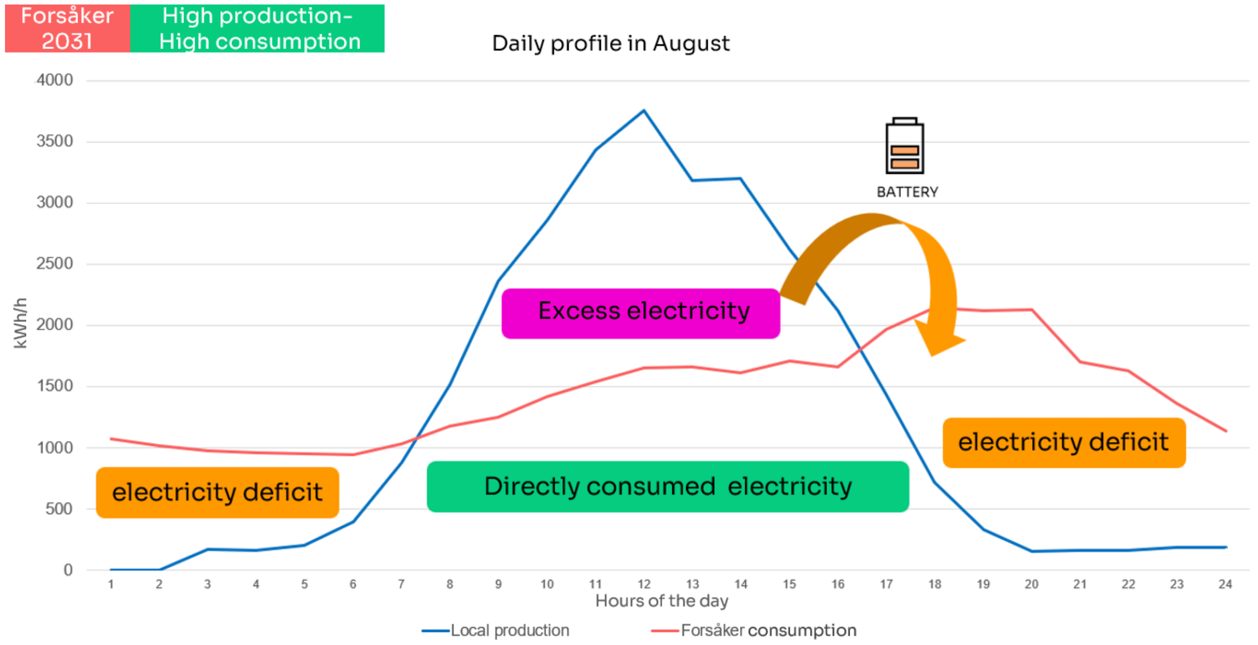


Figure 4.3.1.1. Illustration of electricity moved by battery for a daily profile in august. Local production: 30 MWh, Forsåker consumption: 35 MWh. Consumption filled with grid import or fuel cell production: 5MWh.

During most hours the battery works together with the other storage components, this particular 24-hour period in Figure 4.3.1.2 does not represent a decisive peak or trough in the production profile. It is merely presented to illustrate the frame of mind regarding energy storage to match consumption with production in Forsåker. With the right dimensions a battery can manage to cover this 24-hour period by itself by store production together with grid imports to cover consumption demands. For that a 6.3 MWh battery would be needed and 5 MWh additional electricity from grid imports is required. Simulations with only battery storage has not been performed, in such a case system dimensioning would most likely differ.

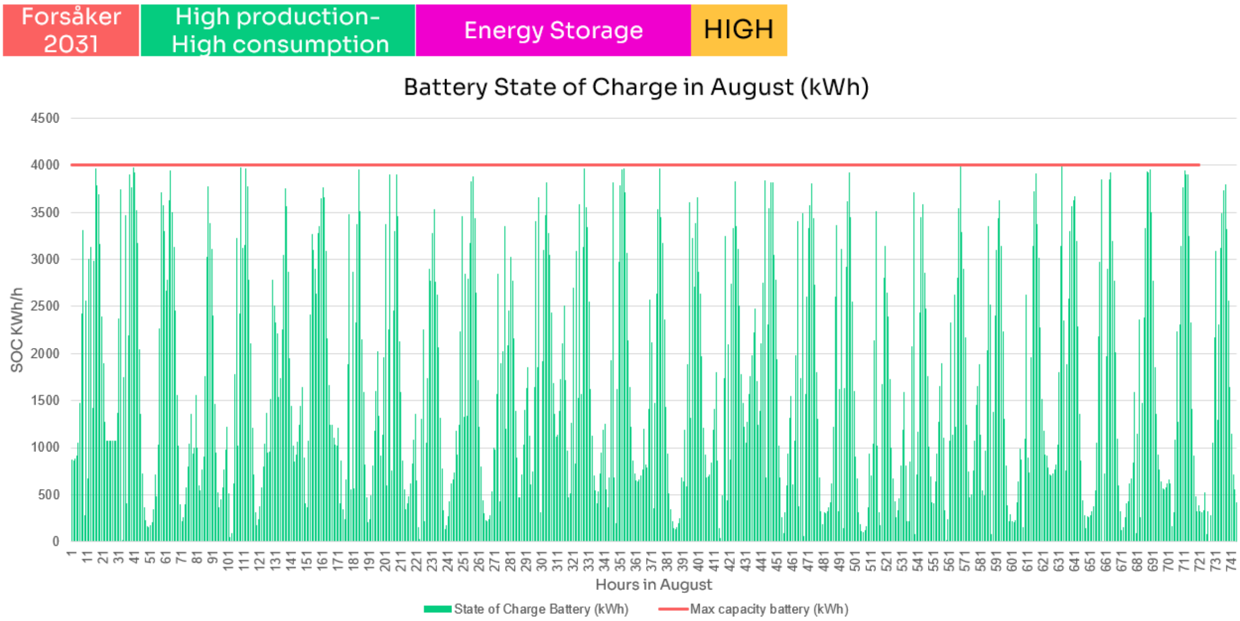


Figure 4.3.1.2. August SOC variations of the battery based on local production and consumption in combination with the day a head electricity prices for 2022.

Figure 4.3.1.2 illustrates the influx of electricity into the battery from local production, which is not immediately consumed in Forsåker as well as grid purchases during occurrence of favourable electricity prices. The electricity is then directed from the battery to meet the consumption needs in Forsåker or to the electrolyzer for hydrogen production. On a few occasions, electricity is sold to Mölndal's power grid. The energy flow through the battery is large, not only due to the storage of local production, but also to an import from the regional electricity grid on hours with a favourable electricity price. Due to the component combination of electrolyzer, fuel cell and battery working together, in combination with managing electricity flows with a smart control system where components cooperate, all the components can be decreased in size compared to the initial simulations. A 4 MWh battery was sufficient for the system.

4.3.2 Electrolyzer

The electrolyzer converts electricity into hydrogen gas at those times decided by the control parameters described in Chapter 5, both the fundamental and deviations from them. Figure 4.3.2.1 shows annual electrolyzer operation from the simulation based on High day-ahead electricity prices from 2022. Operational hours are divided into electricity imports (Green) from regional grid as well as Electricity from battery and local production (Red) below:

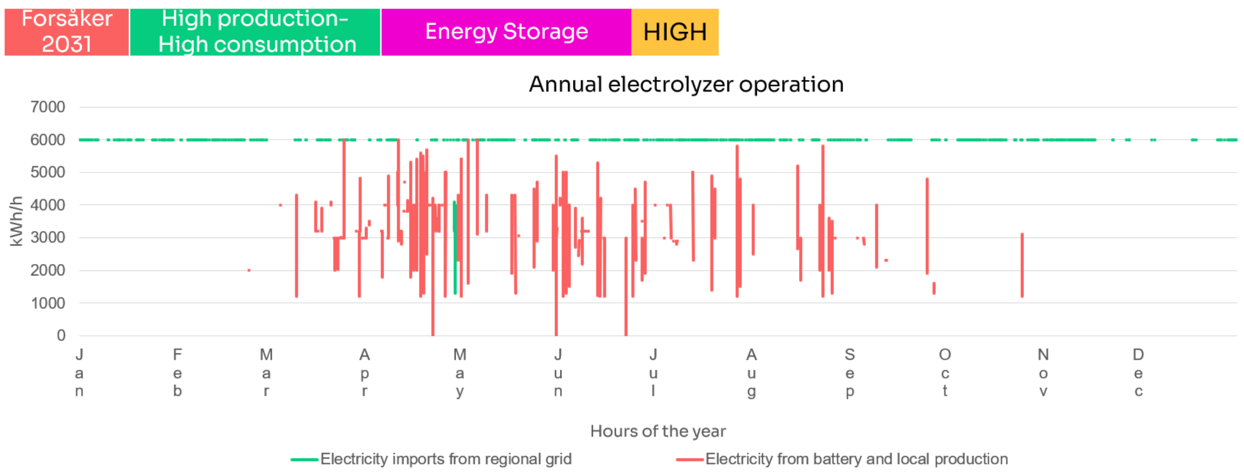


Figure 4.3.2.1. Annual electrolyzer operation from the investigated simulation based on day ahead electricity prices from 2022.

As seen in Figure 4.3.2.1 during most operation at maximum capacity the electrolyzer imports consumed electricity from regional grid marked green in Figure 4.3.2.1. During lower and mixed load capacity operational hours, most electricity consumption transfers from the battery or local production marked red in Figure 4.3.2.1. If only utilization of excess electricity on an hourly basis was necessary, a 4 MW electrolyzer would be sufficient to accommodate the maximum load. The 6 MW electrolyzer can produce more hydrogen for one hour and therefore fill up the storage in fewer operational hours. A 4 MW electrolyzer would require more regional grid import hours, to produce the same quantity of hydrogen compared to the 6 MW electrolyzer. The more operational hours of grid import for the electrolyzer, the higher average electricity price in SEK/kWh, resulting in increased expenses for electricity purchases.

For the investigated years 2022, 2021 and 2016 there is only a limited number of hours where the electricity price is below a certain amount in SEK/kWh. The more hydrogen the electrolyzer produce during those hours, the lower average price is required for electricity purchases. If the electrolyzer cannot produce the required amount of hydrogen during the cheap electricity price hours, hydrogen needs to be produced during hours with higher day ahead electricity prices, or the overall quantity of hydrogen production decreases.

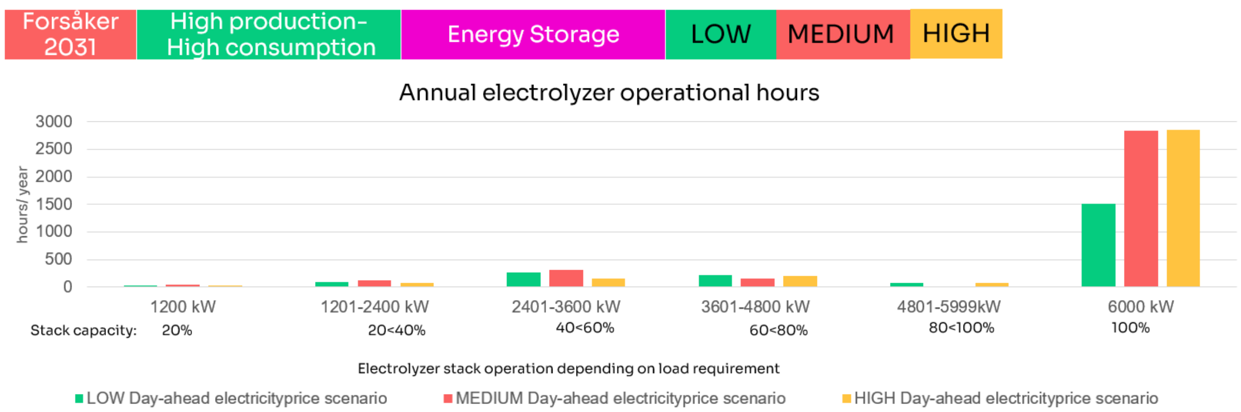


Figure 4.3.2.2. Overview of operational hours for the electrolyzer divided into share of the maximum capacity, based on the LOW, MEDIUM and HIGH day a head electricity prices from 2022, 2021 and 2016.

The electrolyzer consists of one large 6 MW stack in the used simulations, the load of the electrolyzer varies depending on excess electricity from battery transfers, Forsåkers local production combined with electricity purchases from Mölndal's local electricity grid during favourable prices. The estimated lifetime of the electrolyzer is 90000 hours, the CAPEX/kW is less than the fuel cell system, resulting in a lower average cost of H_2 production in SEK/kg or SEK/kWh. Electrolyzers are dimensioned by the net input power and fuel cells by their output power, meaning the SEK/kW of electrolyzer is not comparable with the SEK/kW of fuel cell power.

The electrolyzer is operational in 3500 hours in the MEDIUM scenario, whereas the electrolyzer only operates around 2200 hours in the LOW scenario, at a mixed capacity. Seen in Figure 4.3.2.2 a majority of all operational hours occur at maximal capacity mostly from purchased electricity from Mölndal's electricity grid during favourable electricity prices.

A stable electricity price throughout the year, regardless HIGH, MEDIUM, or LOW, would decrease electrolyzer operation, as the difference between the maximum and minimum electricity prices decreases and rarely occurs. On the other hand, greater variation in the difference between the maximum and minimum electricity prices, occurring frequently, would increase electrolyzer operation. If electricity prices in Sweden 2031 and beyond will be stable a 4 MW electrolyzer to cover local excess electricity is good enough, if future electricity prices fluctuate more, an even larger electrolyzer may be interesting.

Another critical factor is the hydrogen price and demand. The electricity price for hydrogen production depends on costumers' willingness to purchase hydrogen at the refuelling station. The higher demand the greater feasibility of hydrogen production at a higher electricity price and vice versa, which affect operation hours of the electrolyzer.

The minimum capacity for operation is 20% of the stack capacity resulting in a minimum load of 1.2 MW electricity allocated to the electrolyzer. These 20% could be reduced when divided into several smaller electrolyzer stacks, like the approach used with fuel cell stacks. With such a solution, more electricity could be retained in the battery, as there would be no need to discharge a minimum of 1200 kWh each time. The sensitivity regarding operation of dividing the electrolyzer stack into many smaller ones would elevate the complexity of simulations, but concurrently, it would enhance the overall efficiency of the system since hydrogen production would be possible with even smaller amounts of electricity than 1200 kWh.

4.3.3 Fuel cell system

The FC-system produces electricity from stored hydrogen at times dictated by the control parameters. Like the electrolyzer, the fuel cell system experiences conversion and transmission losses during electricity production. Out of the total energy quantity in kWh contained in hydrogen gas, typically around 50% can be converted into electricity, while 40% is lost as heat, and 10% accounts for system losses. The efficiency of the FC-system varies depending on the operational load percentage, during optimal operation, the efficiency can be 60% to electricity whereas during bad conditions only 40% or less is feasible. Other influential parameters include factors such as access to hydrogen gas supply, cooling, and more. For the sake of simplicity, a uniform efficiency of 50% has been assumed for all operations in the simulations.

The FC-system used in the simulations is a simplified variant comprising 15 units of Powercell's PS-100 stacks. The optimal operation mode for the fuel cell stack is to maintain usage below 80% and above 40% of its capacity to minimize degradation and hydrogen consumption. Therefore, the FC-system will typically operate with 15 units of 80 kW during most operational hours. However, there may be certain hours where the demand exceeds the combined capacity of the battery and fuel cell system operating at 15x80 kW. In such cases, each of the 15 stacks will proportionately share the additional load contribution, allowing for a combined power output of up to 1500 kW from the fuel cell system, if required, during hours where more than 1200 kW of fuel cell electricity is needed.

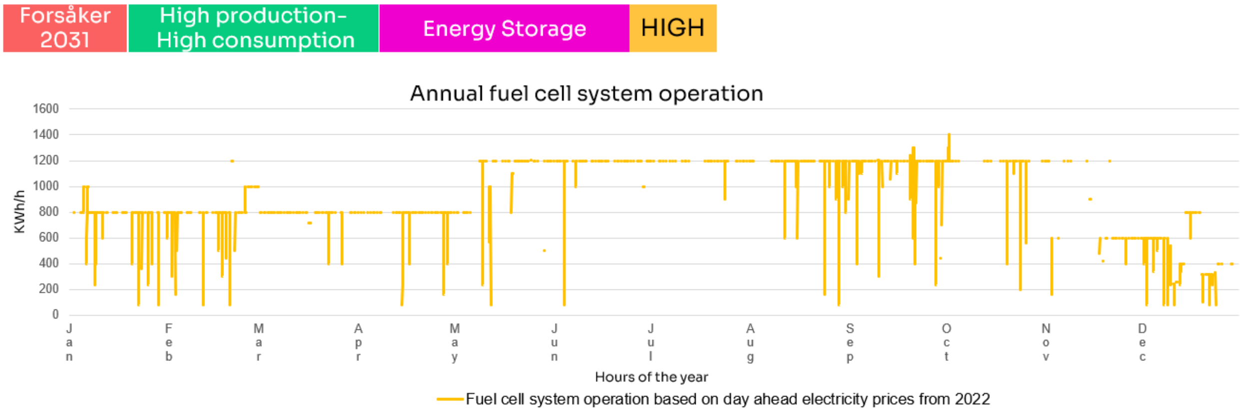


Figure 4.3.3.1. Annual FC-system load of electricity production during the HIGH investigated day ahead electricity price scenario based on prices from year 2022.

As depicted in Figures 4.3.3.1 the annual load profiles for the FC-system exhibit consistent patterns across all three years electricity prices hence only HIGH electricity price scenario is showed above. This consistency is attributed to the underlying consumption and production profiles in Forsåker throughout the years. The only variation is in the annual heat pump consumption demand, which constitutes a relatively small portion of Forsåker's total electricity consumption. However, this fluctuation can have a significant impact on power requirements during specific hours. The FC-system load profile exhibits significant variations from hour to hour, primarily influenced by the fluctuating electricity prices observed between the different years.

The lifetime of the fuel cell system is a balance between CAPEX and OPEX as well as hydrogen supply. Lifetime also depends on the amounts of starts and stops as well as the ramp ups/downs. All those parameters will not be analysed in detail in this report, hence the lifetime of 40000 hours for stationary FCs are taken from the DOE targets for 2029-2035 [15]. Figure 4.3.3.2 shows the operational hours depending on the load requirement from the fuel cell systems. Seen in Figure 4.3.3.2, all stacks are not always operated simultaneously, the total lifespan of the fuel cell system can therefore exceed 40,000 hours without accounting for stack replacements depending on the required operation load, although no precise investigation has been conducted in the study.

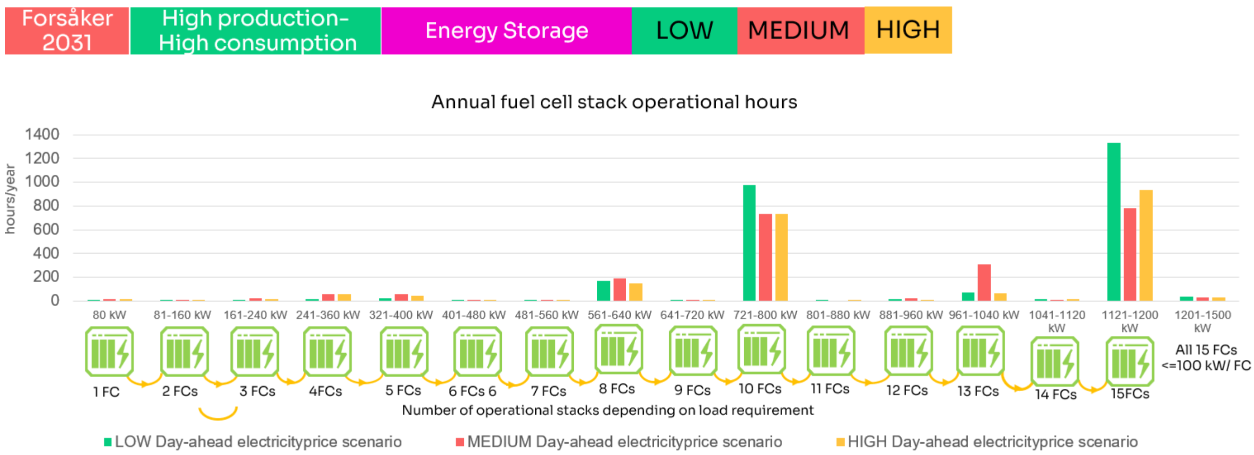


Figure 4.3.3.2. Fuel cell system operation hours based on the LOW, MEDIUM and HIGH day-ahead electricity prices for the years 2016, 2021 and 2022 in 2031-High Consumption-High production-Energy sharing scenarios.

As illustrated in Figure 4.3.3.2, the fuel cell system will not exceed 1200 kW for more than 30-35 hours, depending on the year. Therefore, the lifetime cost of the solution with 15 stacks is lower compared to adding only 3 more stacks to cover those specific hours each year. If the number of operational hours exceeding 1200 kW was to increase in the future, it may be worth considering adding more stacks. In the simulations operation of 8 stacks at 561-640 kW whereas 7 stacks are idling. Operation of 10 stacks at 721-800 kW range whereas 5 stacks are idling. Operation of all 15 stacks is the most frequent load requirement illustrated in Figure 4.3.3.2. Additionally, the potential development of fuel cell technology has not been considered. If future stacks in 2030 could operate at maximum efficiency under full load, eliminating the need for 15 stacks down to 12, a lower CAPEX would be the result.

In the simulations, the FC load per stack varies between 40-80 kW based on the hourly load requirements. Each stack has a minimum power of 10 kW, with favourable operating conditions falling between 40-80 kW. Consequently, the stacks primarily operate in blocks of 80 kW steps. During the few hours that require over 1200 kW of FC power, each of the 15 stacks will share the load equally. FC1 in the Figure does not represent a specific stack. Instead, it indicates the first stack to start operation. When only 80 kW FC power is needed, one of the 15 stacks will not consistently start first. Instead, the stacks rotate or circulate to ensure an even average degradation across all the stacks. If the stacks were designated as specific entities, if a specific stack always would start as the first stack degradation will differ drastically between the 15 stacks.

The simplification of 50% efficiency in the fuel cell stack is based on an average efficiency, meaning that instances of 40% efficiency are offset by those with 60% efficiency. This assumption is highly simplified compared to real operating hours, as the time efficiency varies more than that, during starts more hydrogen is required compared to continuous operation. The overall efficiency is depending on the amounts of stops and starts which as well has not been taken into consideration. Powercell and other fuel cell manufacturers invest significant resources in developing more efficient systems, hence the 2031 versions of a fuel cell system are likely to be more efficient than today's 40-60% efficiency span. Despite technological advancements, no weight has been given to this during the simulation, since transmission losses for compressors and hydrogen storage are not considered in the simulation. To implement all details of the fuel cell stack and other components in the simulation was deemed to be too complicated in this early state of investigation.

4.3.4 Hydrogen storage

The hydrogen storage stores hydrogen from the electrolyzer, to primarily be consumed by the fuel cell system in Forsåker. The 300-bar hydrogen storage has been set at a maximum storage amount of five-tons of hydrogen due to regulations broadly mentioned in Chapter 2.3.1, but which may change in future regulations. To set the amount of hydrogen in a perspective, five tons of hydrogen at 300 bar equals 165 MWh of energy and is 41.25 times the energy stored in the 4 MWh battery. When the realization that Forsåker's local electricity production would not be sufficient for off-grid operation of the area, the decision was made to focus on storage with a capacity of five tons. If more time had been available, it would have been interesting to investigate the optimal storage amount for Forsåker. Exceeding 5 tons of storage would incur increased costs in terms of components and additional adjustments as higher safety standards would be required. Instead, the choice was made to focus on more flexible electricity trading. In a future electricity price scenario with long periods of low prices followed by extended periods of high prices, larger storage volumes would become more interesting to explore.

To justify increased storage volumes, it is necessary to reduce the costs associated with them in other parts of the storage system. One example is that the average price of purchased electricity for hydrogen production could decrease with larger storage volumes, as the system could retain more of the produced hydrogen during even more favourable electricity prices than what a limitation of storage volumes would otherwise prevent. Many trade-offs were necessary to adjust the system profitability and regulations to create an economically justifiable system.

Hydrogen production and consumption occur throughout the year, leading to an exchange of hydrogen within the tank. To increase the degree of self-sufficiency, an even larger storage size can be installed. 5 tons has been chosen in the simulation due to economic and regulatory reasons. The value to add an additional five tons of hydrogen storage would not outweigh the cost relative to the benefit, the money resources would create greater value elsewhere. If multiple five-ton storage units would be included, it would be challenging to determine the exact minimum distance between the storage units without further investigation. For example, a safety distance for the maximum distance from the tank to a building could be 100 meters, but the distance could be reduced with a potential protective barrier in between.

Seasonal storage systems as the [29] Bergman, R and Wademyr, are designed to produce hydrogen during summer from solar panels and store until winter due to limited hours of sunlight during the winter. In seasonal storage systems the hydrogen is stored for long periods from summer to winter which gives an exchange rate close to one time a year. Forsåkers system is designed to annually produce several times more H_2 than the storage capacity, as well as to consume several times more H_2 than the storage capacity. The annual H_2 production in Forsåker varies from 356 to 584 tons of H_2 as showed in Figure 4.3.4.1. that’s 70-120 times the storage capacity. When the hydrogen storage reaches its maximum capacity, any excess hydrogen is directed to a smaller storage facility at the filling station for sale or further transportation.

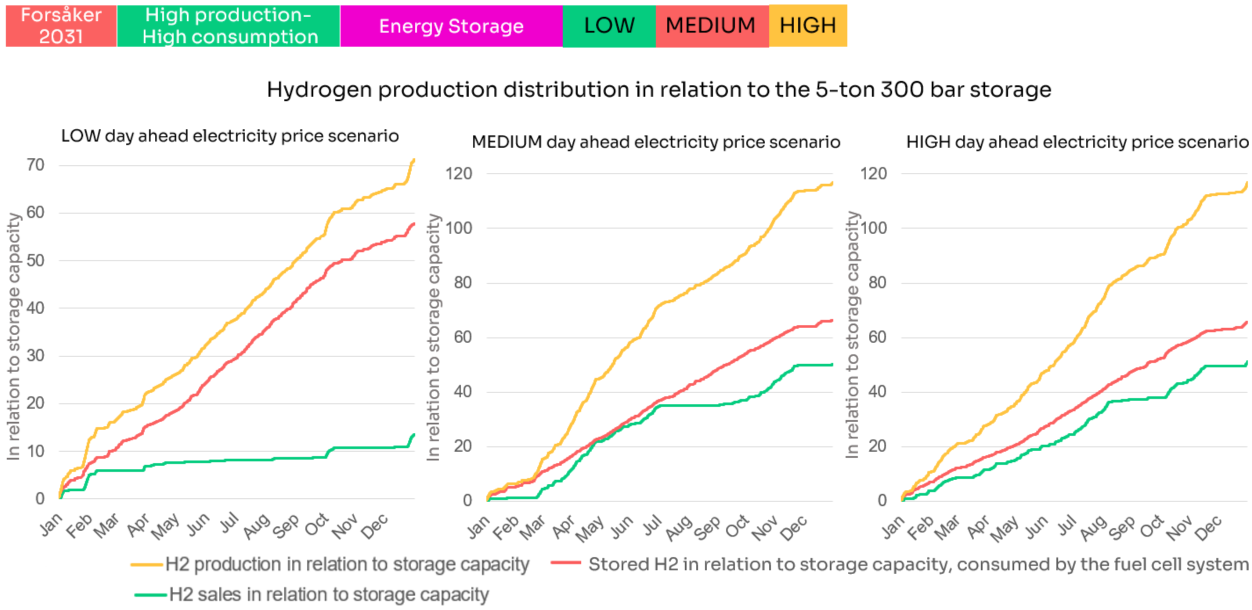


Figure 4.3.4.1. Annual hydrogen production and distribution in relation to storage capacity of 5 Tons for the years 2016, 2021, 2022 which represents the LOW, HIGH and MEDIUM scenarios.

To get a better perspective of the amounts of H_2 produced, stored and sold annually in Forsåker Figure 4.3.4.1 illustrates the H_2 production amount and distribution in relation to the storage capacity. Storage costs are calculated based on 300 bar pressure tanks [24]. If future regulations allow an increased storage capacity over five tones the 300 bar pressure tanks can manage an increased pressure for shorter time periods. However, if underground hydrogen storage is feasible in relation to Forsåker, the storage costs may further decrease. It has been indicated by IVA (Royal Swedish Academy of Engineering Sciences) that underground or cave storage options can be more cost-efficient. However, such options have not been explored in the context of Forsåker in this investigation [4].

Further investigation is necessary to determine the optimal location for the hydrogen storage in Forsåker. Several potential locations, marked with the "HYDROGEN GAS" sign in the Figure 4.3.4.2, need to be evaluated. Considering safety aspects, open areas are likely the most suitable locations to avoid the need for reinforcement. One promising option is to place the storage in the Kikås solar park area, benefiting from its lower population density. A low-pressure hydrogen pipeline can then be used to connect the storage facility to the Forsåker site. Another interesting possibility is locating the storage near the mountain side, utilizing the natural rock wall as a protective barrier surrounded by uninhabited territory. Underground or cave storage options may be an interesting topic for future investigations. If a larger storage capacity is desired while staying within the 5-ton limit, multiple 5-ton layers could be considered at each designated sign. Alternatively, a combination of several smaller tanks can be used to achieve the desired capacity. However, it should be noted that exceeding the 5-ton capacity in a single location would require stricter supervision and compliance with additional regulations.

Figure 4.3.4.2. Potential locations for hydrogen storage in Forsåker and Kikås.

4.3.5 Hydrogen Refuelling Station (HRS)

Fuel cell cars and trucks, although still in their infancy, are already being driven on public roads in various shapes and sizes. Figure 4.3.5.1 depicts examples of fuel cell vehicles undergoing testing as well as those in daily operations. The growing number of vehicle developers incorporating fuel cell technology in their current and future planning, highlights the need to explore the advantages of establishing a hydrogen refuelling station in Forsåker.

Figure 4.3.5.1. examples of fuel cell vehicles that are in test phase and in daily operations.

Figure 4.3.5.1 provides a visual representation of potential fuel cell vehicles that may be operating in or around Forsåker by 2031.

The NIKOLA 3-FCEV truck requires 72 kg of H_2 to fill its onboard tanks [25], while the Mirai passenger car requires 5 kg [26]. These vehicles are designed to handle hydrogen at a pressure of 700 bar, which differs from Forsåker's current H_2 storage pressure of 300 bar.

While 700 bar storage would require less space, in a district where space-saving is not financially justifiable, it becomes more practical to prioritize vehicle space over storage space. Therefore, 700 bar storage for vehicles is financially justifiable, as it allows for larger hydrogen storage capacity without compromising valuable payload space.

A smaller storage capacity is required in relation to the hydrogen refuelling station, due to the uneven flow of hydrogen from the larger 5-ton hydrogen storage. It is expected that the arrival times and hydrogen demand of vehicles may not always align with the excess hydrogen available from Forsåker's larger 5-ton storage. While direct H_2 fillings from the 5-ton H_2 storage are technically feasible, they have not been factored into the simulations. This poses a potential risk to the consumption of Forsåker district during periods of low SOF in the H_2 storage.

To understand the potential impact of the available quantity of hydrogen for sales, Table 4.3.5.1 showcases the estimated number of Class 8 heavy-duty fuel cell trucks and Toyota Mirai passenger cars that can be filled on average each year and day by the hydrogen quantities for H_2 sales depending on the electricity price.

Number of times hydrogen vehicles can be refueled by H2 sales in Forsåker

Electricity price from	H2 sales (Ton)	Annual NIKOLA 3 FCEV H2 fillings	Daily NIKOLA 3 FCEV H2 fillings	Annual Toyota Mirai H2 fillings	Daily Toyota Mirai H2 fillings
HIGH	255,4	3550	10	51080	140
MEDIUM	251,7	3500	10	50340	138
LOW	68	940	3	13600	37

Table 4.3.5.1. Shows an example of what the amounts of H_2 sales can be used for illustrated in NIKOLA 3 FCEVs and Toyota Mirai FCEVs.

IVL numbers in Table 4.2.2.1 only include estimates for Electric Vehicles (EVs) and Plug in Hybrid Electric Vehicles (PHEVs) and do not include Fuel Cell Electric Vehicles (FCEVs). To provide a perspective Table 4.3.5.1 shows the amount of possible annual as well as daily truck and personal vehicle fillings from the hydrogen produced in Forsåker if all hydrogen sales is allocated to the refuelling station. Since vehicle manufactures are releasing FCEVs to the market is highly likely that there will be FCEV cars and trucks operating in the area between 2031 and 2050, no specific FCEV number estimates have been studied. Hydrogen sales will also be targeted towards other industries such as construction vehicles and various industrial applications. As a result, the only assumption made is that there will be a demand for locally produced green hydrogen, regardless of the specific application in which it is consumed.

4.3.6 Heat management

In the storage scenarios Forsåkers heat demand will be covered by heat created via the fuel cell and the electrolyzer combined with heat pump modules. For the LOW-day ahead electricity price simulation the electrolyzer had less operational hours which results in more operational hours by the heat pump system pump system. Given that the 6 MW electrolyzer capacity exceeds the 1.5 MW FC-system due to larger size, its showed that the electrolyzer contributes to a greater quantity of heat production in kWh heat, even if the FC system has a proportion of 50% heat production in terms of stack capacity whereas the electrolyzer has 30%.

The heat consumption scenarios covered by heat pump modules, FC-system and electrolyzer are showed in Table 4.3.6.1 below:

Heat consumption and production in Forsåker

Based on day-ahead electricity prices from	Forsåkers heat consumtion (MWh)	Heat consumtion Covered by EL & FC (MWh)	Heat consumtion Covered by heat pump (MWh)	Electricity consumtion heat pump (MWh)
HIGH	8250	5950 (73%)	2230 (27%)	765
MEDIUM	8250	6310 (76%)	1938 (24%)	646
LOW	8250	5450 (66%)	2800 (34%)	933

Table 4.3.6.1. Coverage of Forsåker's heat consumption based on day-ahead electricity prices 2031-High consumption- Energy storage scenarios.

The electrolyzer and FC-system cover 66-76% of Forsåker's heat consumption depending on the yearly electricity prices together with storage in the accumulator tank. The rest 24-34% are covered by heat-pump modules.

5. Energy management

The objective of energy storage is to generate value and contribute positively to the district. Implementing storage introduces additional complexity and costs, so it is crucial that the overall value with storage surpasses that without storage. The value of energy storage can be measured in terms of enhanced security through increased self-sufficiency, financial benefits, peak shaving capabilities, and enabling a greater integration of renewable energy into the electricity grid. To fulfil these requirements, it is essential to have a well-defined energy management framework. The control system should adhere to specific parameters to determine the optimal starting and stopping points for various components.

5.1 Energy system control parameters

Dimensioning scenario in the simulations is the 2031-High Production-High Consumption-Energy Storage-Energy Sharing scenario. Meaning that the control parameters are adapted in favour of that scenario. The three simulations for LOW, MEDIUM and HIGH are different based on the same control parameter settings adapted to each day-ahead electricity price scenario in combination with the local production and Forsåker consumption profile. For each scenario within LOW, within MEDIUM and within HIGH, the control parameter settings are the same regardless of the energy sharing or traditional ownership structure, regardless of if electricity purchasing for hydrogen production is subject to taxation or not. A fairer comparison could be made if one specific simulation would be performed in favour of each specific scenario. That would require 30 specific simulations instead of 3 which is excluded due to time constraints.

The fundamental control parameter principle is to prioritize and adjust the parameters based on the overall production, consumption, and electricity prices. If a better pattern emerges over multiple hours, the parameters can be re-prioritized accordingly. Figure 5.1.1 gives an overview of how the fundamental control parameters for the energy flows in Forsåker are managed. The figure illustrates the hourly control parameters, however deviations from the fundamental control parameters often occur when a more favourable pattern is discovered for a series of hours.

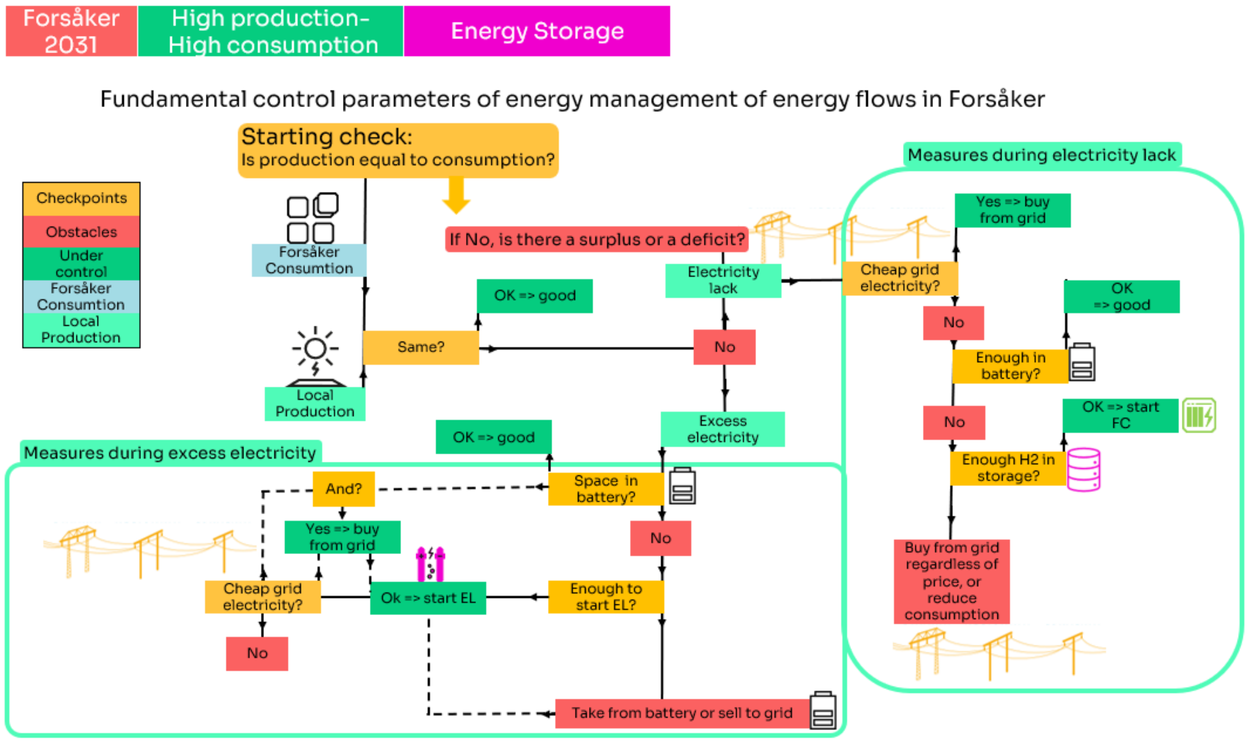


Figure 5.1.1. Fundamental control parameter management for the energy flows in Forsåker.

The "orange checkpoints" in Figure 5.1.1 verifies if and which action needs to be taken. The "green under control boxes" indicate that it is the final action in the branch that needs to be taken for the system to achieve harmony. In some cases, multiple branches are executed simultaneously. The "red obstacles boxes" indicate that further action needs to be taken at a later stage. Control parameters for different scenarios will be listed below.

- As seen in Figure 5.1.1 the first check in the steering system is if the local production and consumption is equal. If that is the case the energy flows are in harmony, and nothing else needs to be done. But if the electricity prices are low the electrolyzer will produce hydrogen at maximum capacity by electricity imports from the regional grid.

- Most likely the consumption demand will not equal the production supply, hence there will be excess electricity or lack of electricity in Forsåker. When electricity lacks from local production, the first check the system will do is to see if the electricity prices are cheap. If so, electricity will be imported from the regional grid and nothing else needs to be done. Hence the electrolyzer may import extra electricity depending on the electricity prices. If so the electrolyzer will aim to ramp up to 6 MW, while direct grid imports to Forsåker area consumption or use of battery storage is less than 1 MW. If the lack of area consumption is larger than 1 MW and the electricity prices are favourable, grid imports will primarily be allocated to fill the area consumption needs and the electrolyzer prioritization is secondary.

No shift in area consumption has been applied in the simulations, despite it would be interesting to investigate in future studies.

System priorities to cover Forsåker's consumption during electricity lack of local production:

- If the electricity price is high when electricity lacks arise, the second check the system will do is to see if the battery have enough stored electricity to cover the lack. If so, nothing else needs to be done.

- If the battery does not have enough stored electricity to cover the electricity lack, a third check will be done to see if the hydrogen storage has enough hydrogen to cover the electricity lack via FC electricity production, then most time nothing else needs to be done, except if the hours of higher consumption demands more than the FC system can provide.

- If the hydrogen storage is empty the system will purchase electricity via grid imports from the regional grid. Forsåker's consumption could also be reduced or moved forward, but this is not something that has been tested in the simulations.

- Throughout all the simulations, the electrolyzer has always ensured the availability of hydrogen by prioritizing the price parameters for electricity import to the electrolyzer over an extended period in case the hydrogen storage becomes nearly depleted. This approach has been successful in the simulations, with the only difference being a slight increase in the average price of purchased electricity for hydrogen production. However, it is important to note that the possibility of panic purchasing of direct-acting electricity exists if an extended period of high electricity prices and high electricity under-supply occurs in the coming years.

  System priorities during excess electricity from local production:

- The primary check the system will do if excess electricity appears, is if there is space to store it in the battery for later future consumption. If so, nothing else needs to be done. Battery storage is good for short term electricity storage due to less electricity storage losses compared to the conversion of electricity to hydrogen to electricity.

- The secondary check the system will do if excess electricity appears, and the battery is full is to allocate the electricity to the electrolyzer if there is enough power for the electrolyzer to start. Otherwise, the electrolyzer will take the excess electricity as well as drain the battery to reach 1.2 MW which is the minimum operation power for the electrolyzer.

5.2 Deviations from fundamental control parameters due to multiple hour patterns

It is important to mention that the fundamental control parameters are the desired targets to strive for, but these priorities are adjusted at times if a better approach pattern is observed in relation to production, consumption, and electricity prices over a series of hours. Examples are listed below:

- When the components interact with each other, the fuel cell system can provide electricity to the battery even if the battery is not completely depleted. This approach aims to achieve a smoother operating cycle. To prevent the FC repeatedly starting and stopping over a series of hours, the FC system then operates at a lower power level for an extended period. This reduces degradation in the fuel cell and results in a more harmonious performance curve, as opposed to a sporadic operating cycle.

- By allowing the FC system to start earlier, as in the example above, the FC system in combination with the battery can handle higher peak power demands than they could if only the fundamental parameters were followed. If the system knows that a significant electricity under-supply will occur in Forsåker in a few hours, but no surplus electricity will be supplied to the battery before that, the FC system covers those hours with a minor electricity under-supply, ensuring that the battery remains fully charged until the hours when the under-supply is significant enough that the FC system alone cannot handle it, but it can be managed with a fully charged battery working together with the FC system. Without this type of principles, hours with a 2.3 MW electricity lack and an empty battery would require grid imports to prevent a power outage, or a 2.3 MW fuel cell system, which would increase CAPEX.

- The electrolyzer also applies the principle of depleting the battery and utilizing surplus energy even when the battery is not fully charged at times when the system detects that the battery will not manage surplus electricity multiple times over a series of hours. Such cases, enables the electrolyzer to operate at a lower power level for several consecutive hours, instead of starting & stopping which would result in running at higher power levels during the operating hours. This reduces degradation in both the electrolyzer and the battery, extending their lifespan. Because of that, the battery avoids certain charge cycles, while the electrolyzer avoids frequent ramping up and down.

- If Forsåker's consumption demand are covered by electricity import from the regional grid during a series of hours with low electricity prices, followed by a series of hours without electricity surplus and high prices, the system can wait until the hour or sometimes hours when the electricity price is at its lowest and charge the battery during these hours.

- In situations where the battery becomes fully charged and some extra excess electricity is available, the excess electricity will be exported to the regional grid instead of draining the battery of 1.2 MWh if the following hours requires electricity from the battery. With this exception from the fundamental principles the fuel cell and electrolyzer save operational hours since they otherwise would run more frequently, which would result in greater energy losses.

5.3 Influencing factors on the selection of component sizes

Series of simulations were conducted to reach the selected method of managing energy flows, choosing component sizes based on technical specifications, economics, and environmental considerations. Below some points will be presented on the journey to the component setup that was selected.

The first setup was conducted with an infinite hydrogen storage, to evaluate whether an energy system with infinite storage capacity could be self-sufficient without electricity import from the regional grid. Such an off-grid scenario was examined to investigate what amount of stored hydrogen would be necessary. For this a 4 MW electrolyzer was used in the simulations since the maximum excess of local electricity production is around 4 MW/h. The battery size was 8 MWh. Results showed that the hydrogen storage would be in the range of 25-30 tons to cover the hydrogen storage needed. Grid imports would still be necessary, due to longer periods without hydrogen in the storage.

12 MW electrolyzer simulations were performed as well to shorten the hydrogen storage filling time, which would decrease by 66% during maximum operation compared to the 4 MW electrolyzer. In event of a crisis perspective the electrolyzer with 12 MW capacity would be the best option, but the dimension of power grid cables and CAPEX would increase. Selection of the 6 MW electrolyzer choice was made as a trade-off between CAPEX, filling times and grid line dimensions. Scenarios without energy storage will manage 7 MW grid import and export. Hence, the 6 MW electrolyzer would still allow grid imports to battery and direct usage of 1 MW during times when the electrolyzer operates at maximum capacity without changing the original plan for grid dimensions of 7 MW.

The maximum lack of electric power is 2.3 MW, which simulations with the 8 MWh battery suggest would be capable of covering for 3.5 hours in a row without grid imports from the regional grid. Those 3.5 hours would increase the self-sufficiency and operation reliability, as well as lower costs for grid purchases. Self-sufficiency would not increase that much to make the CAPEX economically justifiable, since the system will still contain a fuel cell system. Therefore the 4 MWh battery was selected for all scenarios.

Upgrading to a 7 MW electrolyzer can be advantageous, since the electrolyzer mostly operates at the maximum capacity of 6 MW, a 7 MW electrolyzer would reduce the load profile from 100% with the 6 MW electrolyzer to 86% with a 7 MW electrolyzer. This would increase electrolyzer CAPEX with approximately 17% in relation to the expansion of the stack alone, without considering the decrease in SEK/kW with increased stack capacity in these ranges. It is likely that the lifespan of the electrolyzer will increase with the implementation of a 7 MW electrolyzer. A deeper investigation to see if its beneficial with a 7 MW electrolyzer has not been conducted.

A fuel cell system with 2.3 MW capacity would be necessary if the FC system alone would be required to cover the maximum lack of electricity during peak hours. This would increase CAPEX, and the FC system would not use its full capacity for that many hours annually. By having the battery and fuel cell work together the sizes of both can be reduced. The 1.5 MW FC system combined with the 4 MWh battery manage to cover Forsåker's consumption demands all hours, with the right control parameters. This reduces component CAPEX at the same time as the components' capacity is utilized more. There is a balance between CAPEXs and degradation. If, for example, a 2.3 MW FC system had been used, each stack would not operate that often, which would lead to increased lifetime. The FC-system CAPEX is high while technological development is progressing. Therefore, it is advantageous to use as small system as possible to manage the energy flows, this may be different in the future or during prioritization of grid exports.

The compressor is one of the main components in the energy storage system since the hydrogen is stored at a pressure of 300 bar, whereas the fuel cell system operates with 1.2 bar and even below that. The higher pressure the higher electricity consumption is needed to obtain the pressure. Compressor investigation is not included in the scope. Easier assumptions of the compressor operation could have been made, to compensate this 50% FC efficiency, and 65% electrolyzer capacity is used for the whole load profile. The efficiency varies during operation depending on factors such as current, voltage, percentage of load capacity, etc. If a more advanced program or more time would be available, it would be beneficial to implement variations in the efficiency of fuel cells and electrolyzer.

Optimization improvements can be done in future investigations, since the method now was much trial and error to find a low average import price from the regional grid, with the chosen components and then see the outcome. Running a new simulation based on the previous results when changing some parameters of improvement. The steering system works and can manage Forsåker's energy flows in a way that prevents power outages for the district and prevents disconnection of the production facilities to the regional grid at low or negative electricity prices.

An improved way to manage the electricity flows would increase the efficiency and the economy of the system. The simulations were performed using historical electricity prices and future estimations of production and consumption curves. However, despite this, smart control system could anticipate overarching patterns based on all the available data. Production curves for wind, water, and solar can be supplemented with weather data obtained from sources such as SMHI. Consumption patterns can be based on statistics and day-ahead prices always based on previous bidding, enabling the steering system to get the future electricity prices and predictions of future weather data. The difference between reality and estimations will probably differ but the more improved steering system the less difference it would be between reality outcome and predictions. One interesting development is that of AI, which is likely to be able to help improve the operation of the steering system.

5.4 Energy flows & electricity price parameters in the storage energy system

As previously mentioned, the capacity of the electrolyzer plays a significant role in determining the amount of hydrogen that can be produced within a given timeframe. A larger capacity electrolyzer, such as a 6 MW electrolyzer, has the advantage of producing a greater quantity of hydrogen in fewer hours. For instance, with the 6 MW electrolyzer and a 5-ton hydrogen storage, it would take approximately 42 hours of maximum operation to produce 5 tons of hydrogen. On the other hand, a 4 MW electrolyzer would require 64 hours to produce the same amount.

Electrolyzer and Fuel cell system balance

The capacity of the fuel cell systems in relation to the electrolyzer is also crucial. In this Chapter, we will discuss the importance of this balance using an example from the day-ahead electricity prices in 2022.

Figure 5.4.1 shows the annual SOF variations in the hydrogen storage as well as hydrogen sales based on year 2021 day ahead electricity prices.

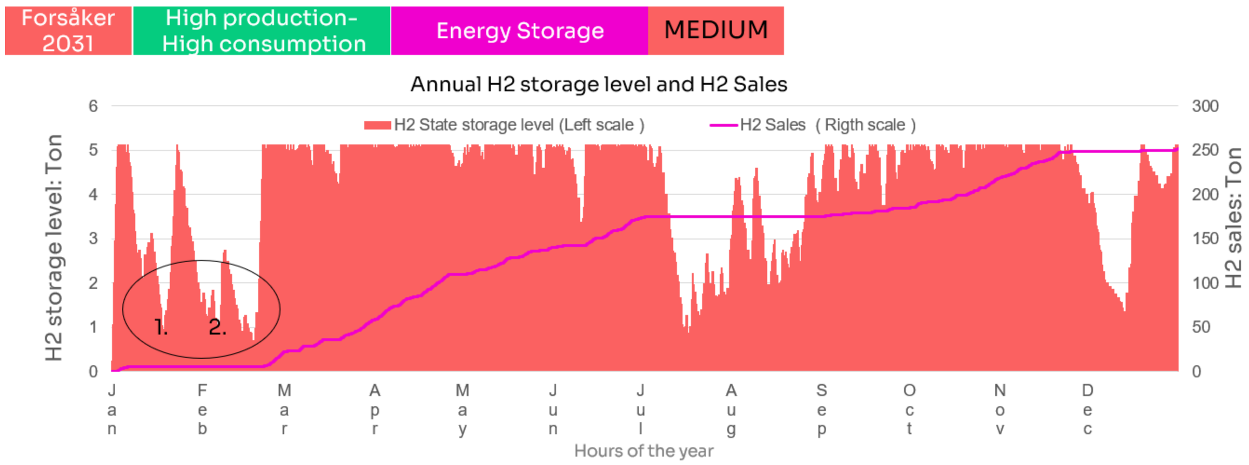


Figure 5.4.1. SOF in the hydrogen storage as well as hydrogen sales based on the MEDIUM day ahead electricity price scenario in the 2031-High Consumption-High production- Energy storage scenario.

The events in the black circle in Figure 5.4.1 illustrate the importance of having a larger electrolyzer compared to fuel cell system. During periods when most hours consist of high electricity prices, it is crucial for the electrolyzer to have a higher hydrogen production rate per hour compared to the fuel cell system's consumption rate per hour. Otherwise, the limited number of hours with lower electricity prices would result in a zero-sum game, where the electrolyzer produces just enough hydrogen for one hour of fuel cell system operation, leading to an empty storage. Then direct consumption of grid imports would be more beneficial due to transmission losses. However, if the electrolyzer can produce enough hydrogen within one hour to sustain the fuel cell system for more than one hour, the storage capacity will continuously generate more hours of fuel cell system operation than electricity operation, creating a positive trend.

This approach ensures that during rare hours with lower electricity prices, the electrolyzer can produce surplus hydrogen, which can be stored for later use when electricity prices are high and create more value than directly consumed electricity. By maintaining a surplus in hydrogen production, the system becomes more resilient and capable of capitalizing on favourable price periods. It optimizes the utilization of resources and improves the overall efficiency of the system, resulting in cost savings and a more sustainable energy management strategy.

If the selected electrolyzer capacity had been limited to 4 MW, the peak circle in Figure 5.4.1 above, events 1 and 2 in the H_2 storage would not have reached the same height, leading to a deeper valley for event 2. In this scenario, there is a higher likelihood that the storage would have been depleted, potentially resulting in higher average electricity import prices.

By choosing a larger electrolyzer capacity, such as the 6 MW used, the hydrogen storage peak between events 1 and 2 can be better maintained, ensuring a more stable supply of hydrogen since the 6 MW electrolyzer produce 3.9 MWh H_2/h at max operation whereas the 1.5 MW FC-system consumes 3 MWh of H_2/h at max operation. This combination faster allows a greater buffer of stored hydrogen, which can be utilized during periods of higher demand or lower local production. As a result, the average electricity import prices can be kept lower, providing financial benefits, and reducing reliance on external energy sources.

Electricity imports and exports balance

Each time the hydrogen storage reaches its maximum capacity of five tons and additional hydrogen is produced, hydrogen is transferred to the storage in the refuelling station and the quantity for hydrogen sales to hydrogen vehicles or industries increases. If no immediate demand or intention to sell the excess hydrogen occurs, simply stopping the operation of the electrolyzer would not be the most favourable business decision. This approach would force excess electricity exports to the regional electricity grid with low or even negative compensation, while additional taxes and transmission fees are incurred. It would also mean missing out on the opportunity to take advantage of those favourable electricity prices. By carefully monitoring these variations, it becomes possible to identify advantageous price periods for exporting excess hydrogen and generating additional revenue.

By actively managing the system and capitalizing on favourable price differentials, it is possible to maximize the economic benefits and overall efficiency of the energy storage and production setup. This strategic approach ensures that excess energy is not wasted and can be effectively utilized to generate additional income and optimize the system's financial performance. Resulting in the conclusion that producing hydrogen with imported electricity during hours with low electricity prices is a good business idea, both for Forsåker's consumption and for hydrogen sales.

As seen in Figure 5.4.2 storage results in a lower average price SEK/kWh, since the 14 GWh of local production has a market value of 20 MSEK resulting in an average of 1.4 SEK/kWh, meanwhile the 17 GWh of imported electricity has a value of 4 MSEK with an average of 0,2 SEK/kWh.

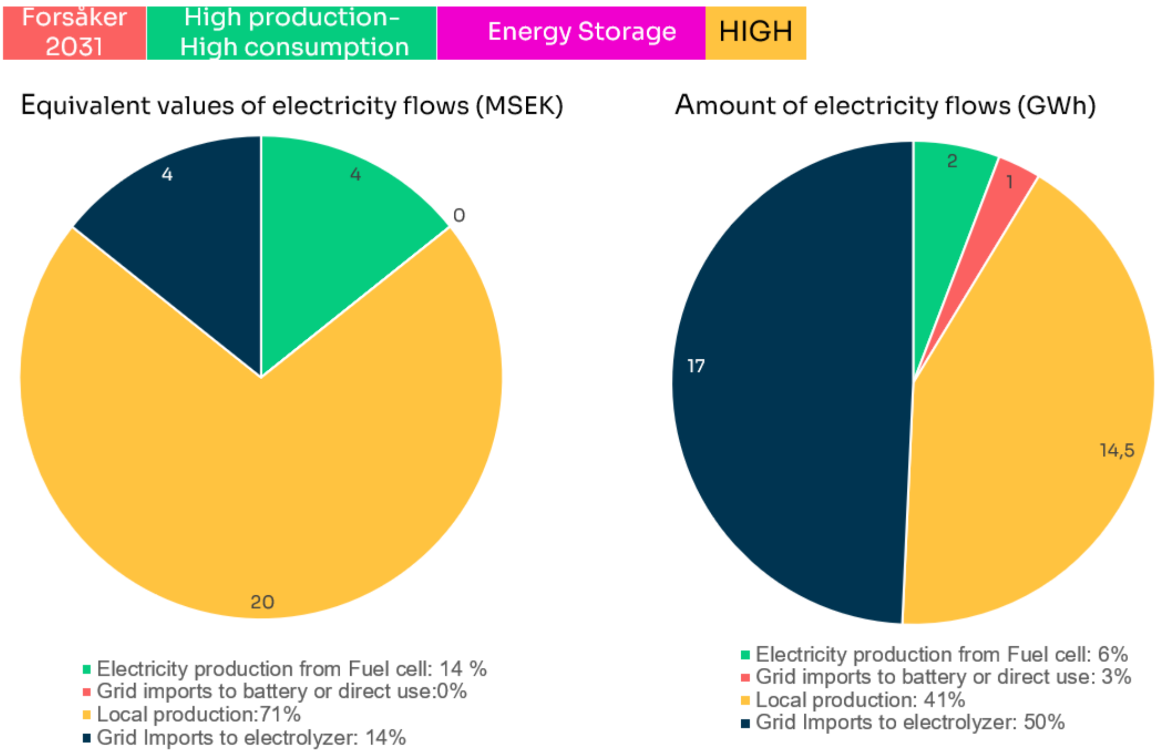


Figure 5.4.2. "HIGH" electricity flow scenario based on 2022 years day-ahead electricity prices of an average 1.37 SEK/kWh measured in GWh and MSEK sorted in categories.

Energy storage results in a larger quantity of kWh compared to direct consumption from grid imports or local production due to conversion and transmission losses. Depending on the cost and regulations of these energy quantities, the stored amount of kWh can be purchased for a more favourable price. A lover variable electricity cost in SEK/kWh can be in favour even though larger amounts of energy are required, depending on tax, transmission fees and OPEX & CAPEX for the energy storage structures. To illustrate the significance of keeping the imported electricity for hydrogen production tax-free, the effect of introducing tax on the price of electricity from the fuel cell was evaluated. Introducing a tax surcharge on imported electricity for hydrogen production would increase the average price from 0.23 SEK/kWh to 0.69 SEK/kWh, approximately a 190% increase, resulting in an additional 12 MSEK cost.

In Figure 5.4.2 above, the value of the 2 GWh of electricity produced by the fuel cell system is equivalent to 4 MSEK. This value is calculated based on the assumption that the same electricity quantities would be purchased from the regional grid during the times when the fuel cell system is producing electricity. Only the day-ahead electricity prices are considered in this calculation, without considering taxes or other fees which will be demonstrated in Chapter 7.

Forsåker's 14.5 GWh of local production in the 2022 day ahead electricity price simulations accounts for approximately 71% of the total value. Depending on how the system is optimized, this share of local production can be utilized for sales via grid exports during periods of high electricity prices. Instead, the fuel cell system and battery can be utilized to cover the consumption demand within Forsåker. It should be noted that a scenario involving grid sales optimization has not been investigated due to the self-sufficiency requirement.

If local production is sold during times of high electricity prices while the area's consumption is covered by energy storage, the degree of self-sufficiency would decrease significantly. This is because local production would primarily be used locally during periods of low prices and exported during high-price periods. However, this does not necessarily have to be seen as negative. It is possible that in such a scenario, energy storage contributes the most to both society and the financial aspect. Therefore, an energy management approach that considers this economic perspective would be interesting. Electricity prices depend on supply and demand, in a scenario which more areas, similar to Forsåker and other smaller systems, import electricity during periods of low prices and sell during high-price periods, utilizing their total capacity, could contribute to a stabilization mechanism for the power grid.

In terms of efficiency, a combination of grid import and export would likely be the most optimal solution. However, implementing such a mix would introduce additional complexities to the steering system responsible for managing the flow of electricity.

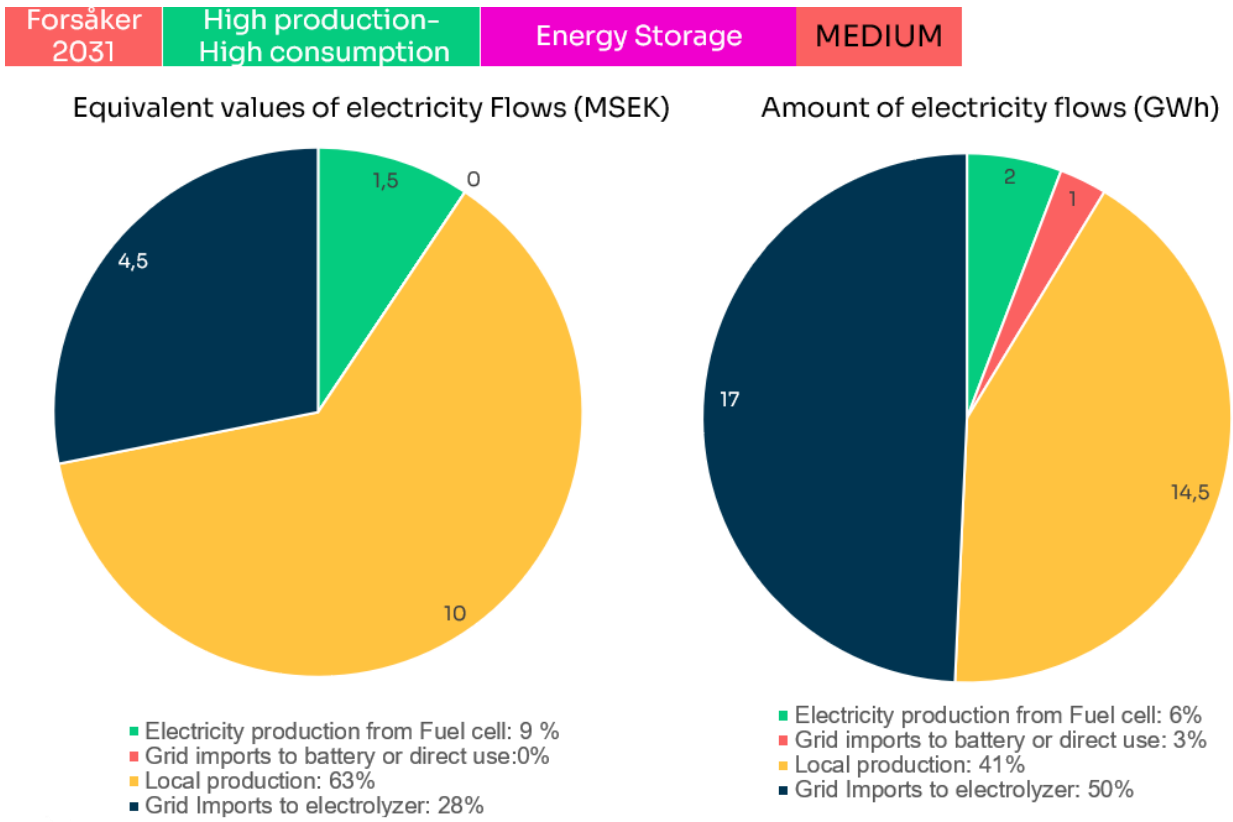


Figure 5.4.3. "MEDIUM" electricity flow scenario based on 2021 years day-ahead electricity prices of an average 0.67 SEK/kWh measured in GWh and MSEK sorted in categories.

Seen in Figure 5.4.3 the 2021 day-ahead electricity price simulation surprisingly resulting in almost the same quantities of electricity flows in all categories in Forsåker's energy system compared to the 2022 day ahead electricity prices simulation with decimal differences. Even though the quantity of electricity imports to the electrolyzer depends on the day ahead electricity prices that fluctuates on an hourly basis and differs between the two years.

The 2021 market value of Forsåker's 14.5 GWh of local production is 10 MSEK results in an average of 0.7 SEK/kWh. The value of local production 2021 is 50% of 2022. Less variations occurs for the value of FC production which has an average of 1.3 SEK/kWh. Grid imports for electrolysis has an average of 0.26 SEK/kWh. For both 2022 and 2021 Grid imports to battery or direct use get an average of 0.3 SEK/kWh. The results of less variations of electricity imports for electrolyzer consumption, battery storage and direct usage, is due to the occurrence of electricity import during favourable prices.

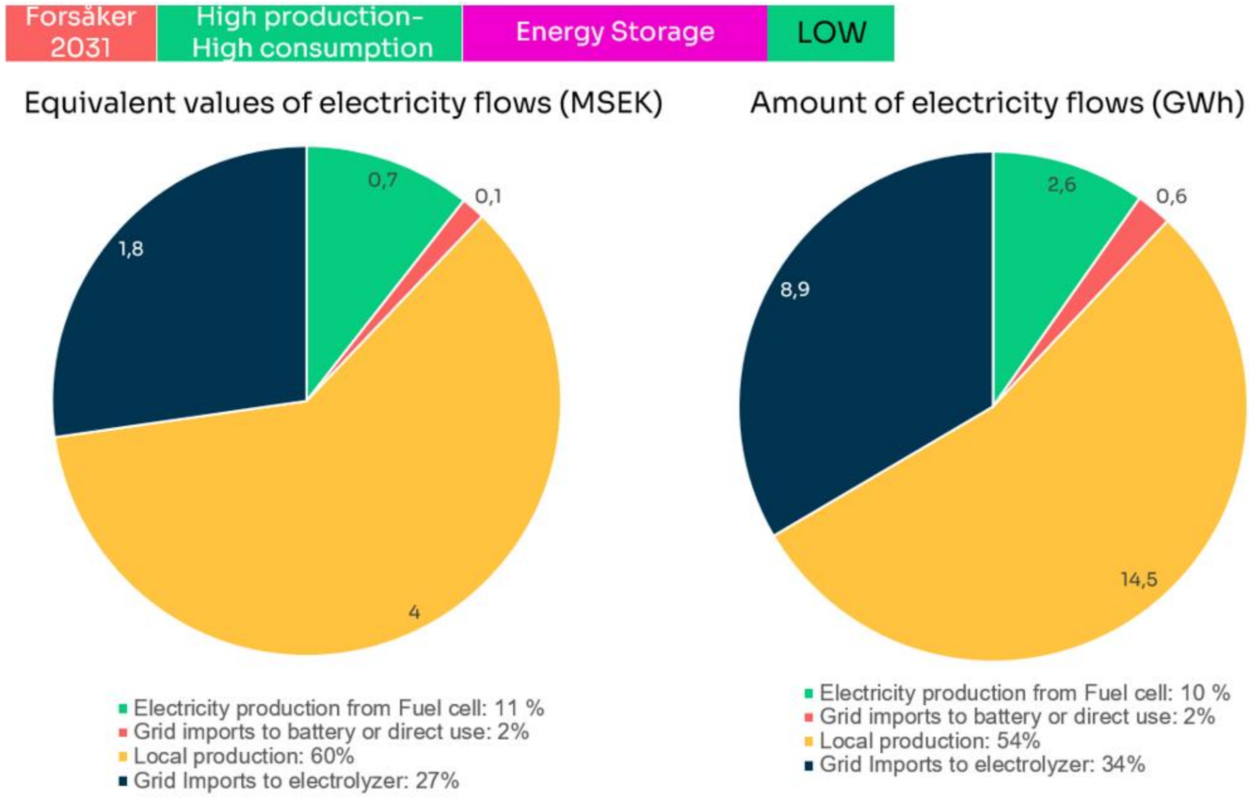


Figure 5.4.4. "LOW" electricity flow scenario based on 2016 years day-ahead electricity prices of an average 0.28 SEK/kWh measured in GWh and MSEK sorted in categories.

Day-ahead electricity prices for 2016 on the other hand differs a lot compared to 2022 and 2021, both in value and amounts of kWh, the amount of local production is still the same as for 2022 and 2021.

In all three years, the average cost of purchasing electricity for storage is cheaper compared to the value of local production. Regardless of whether it is a year with higher average prices like 2022 and 2021 or a year with lower average prices like 2016, stored electricity proves to be more cost-effective on average compared to purchasing electricity on an hourly basis. In an overall level, it is important to consider various factors such as CAPEX and OPEX for the energy storage system, electricity taxes, transmission fees, and other political decisions that may impact the overall cost which will be further discussed in the following Chapters and especially in Chapter 9.3. Consequently, it is not possible to draw a definitive conclusion that energy storage is always the cheaper option. The cost-effectiveness of energy storage will depend on these variables and the specific circumstances of each situation.

Figures 5.4.5 to 5.4.7 below provides a visual representation of the hydrogen flow in the storage system and the corresponding hydrogen sales based on the day ahead electricity prices for the investigated year. While the amount of electricity imported from the regional grid to the electrolyzer remains relatively consistent throughout the year in 2021 and 2022, variations are observed in the storage profiles.

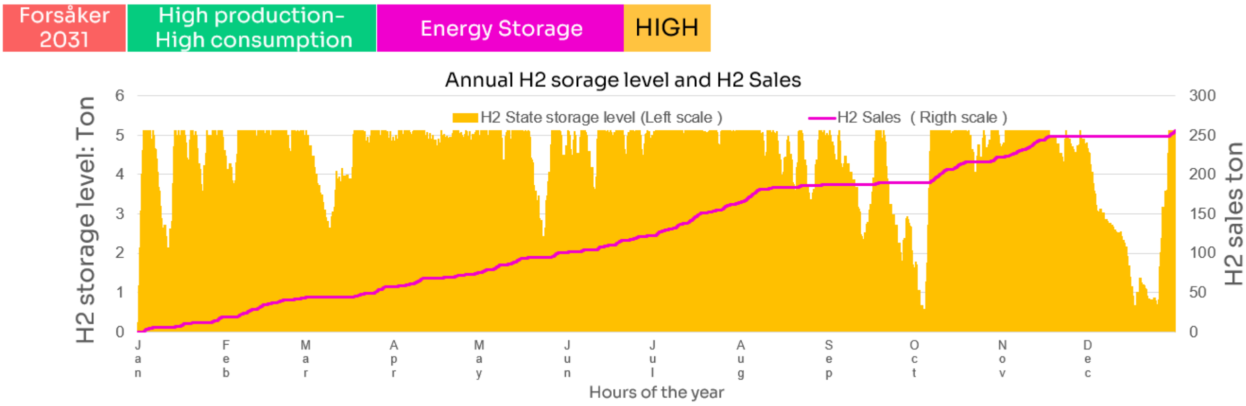


Figure 5.4.5. Illustration of Forsåker's annual H_2 storage level and H_2 sales in a HIGH day-ahead electricity price scenario based on day-ahead electricity prices from 2022.

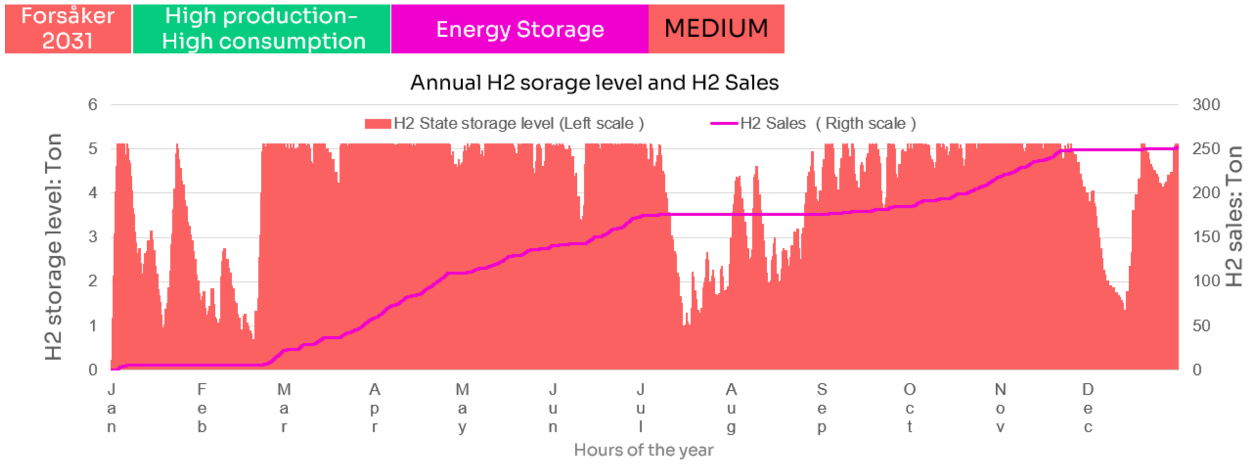


Figure 5.4.6. Illustration of Forsåker's annual H_2 storage level and H_2 sales in a MEDIUM day-ahead electricity price scenario based on day-ahead electricity prices from 2021.

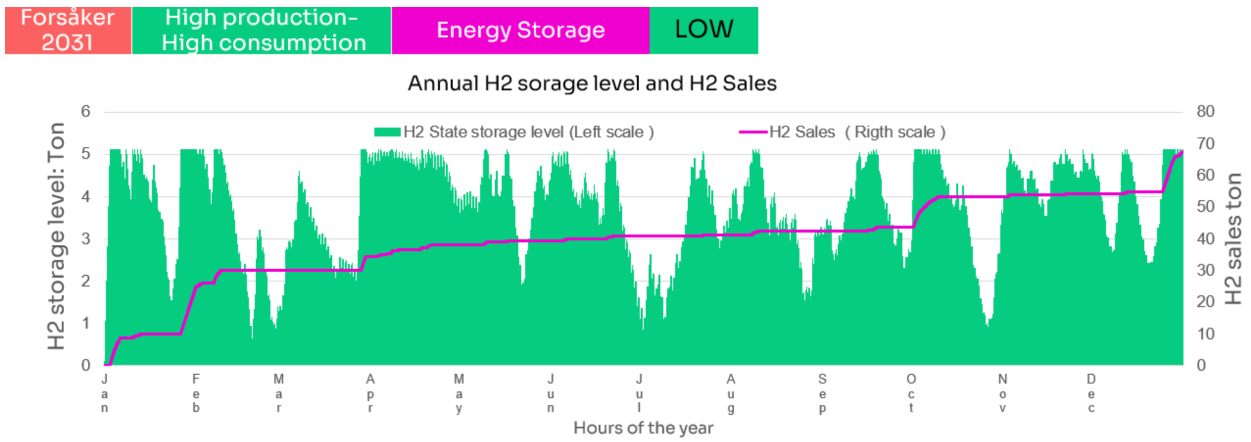


Figure 5.4.7. Illustration of Forsåker's annual H_2 storage level and H_2 sales in a LOW day-ahead electricity price scenario based on day-ahead electricity prices from 2016.

As seen in Figure 5.4.5 to 5.4.7 a relation between the H_2 SOF and day ahead electricity prices can be seen in Figures, during electricity price peaks the H_2 SOF decreases due to FC operation. During low electricity prices the electrolyzer operates and begin filling the storage with hydrogen. The electricity price is not always correlated with the hydrogen storage level since the hydrogen storage level also depends on Forsåker's' local production and consumption.

However, electricity prices are often the controlling parameter as the quantity of imported electricity for H_2 production during low-price periods often exceeds the surplus of locally generated electricity. If there is an electricity deficit in Forsåker during low-price periods, the consumption demand is often covered by imported electricity for immediate consumption and electricity import for electrolyzer operation.

5.5 Overview of energy storage system operation

This Chapter provides an overview of the energy system's operation during periods ranging from 2 days up to one week at various times of the year. Detailed Figures depicting the component operation and the functioning of the steering system will be presented to enhance understanding.

All the sequences presented in this Chapter are derived from the 2031-High Consumption-High production- Energy sharing: 2022 day-ahead electricity prices simulation. These sequences provide insights into the behaviour and performance of the system under these conditions.

5.5.1 Short term operation overview and explanation of 48 hours

Below is a detailed description of the various components and their hourly behaviour, depicted in the Figures:

Figure 5.5.1.A illustrates a 48-hour timeframe, showcasing the local production and consumption in Forsåker. Both production and consumption are categorized and segmented. The start of a new day is marked at hour 1 and hour 25.

The Figure provides insights into the hourly fluctuations of local production, highlighting the periods of peak and low production. It also showcases the consumption patterns of Forsåker, revealing the varying demand throughout the 48-hour period. By categorizing the production and consumption data, it becomes easier to identify trends and patterns.

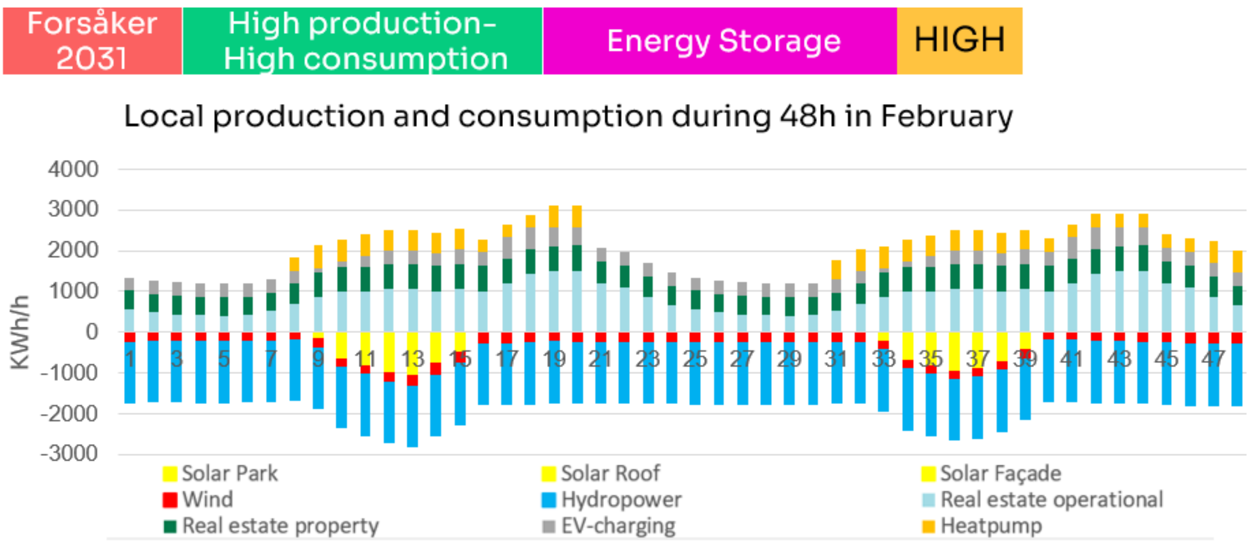


Figure 5.5.1.A. 48 hours selection of the local production and Forsåker's consumption. (2031-High Consumption-High production- Energy sharing: 2022 day-ahead electricity prices from 2022 simulation)

The energy system in Forsåker relies on hydro power and wind power as base load sources, providing a consistent supply of electricity. Solar power, on the other hand, contributes predominantly during daytime hours. This combination ensures a stable base load and utilizes the available renewable energy sources efficiently.

Figure 5.5.1.A depicts the consumption and production patterns in Forsåker, highlighting the fluctuations throughout the day. The peak consumption occurs during the afternoon and early evenings when energy demand is at its highest.

To manage the energy consumption and production, the energy storage components play a crucial role. They are responsible for optimizing the utilization of local production and coordinating electricity imports from the regional grid, considering the prevailing electricity prices. The aim is to cover Forsåker's energy consumption in the most cost-effective and efficient manner.

In Figure 5.5.1.B, the brown line represents the "Delta consumption and production Forsåker." This line illustrates the difference between the production and consumption levels shown in Figure 5.5.1.A. When the brown line is above 0, it indicates that consumption exceeds production, and vice versa.

Monitoring the Delta consumption and production allows for real-time assessment of the energy balance in Forsåker. It helps determine whether the local production is sufficient to meet the consumption demands or if additional electricity needs to be provided by grid imports, battery, or FC-system production.

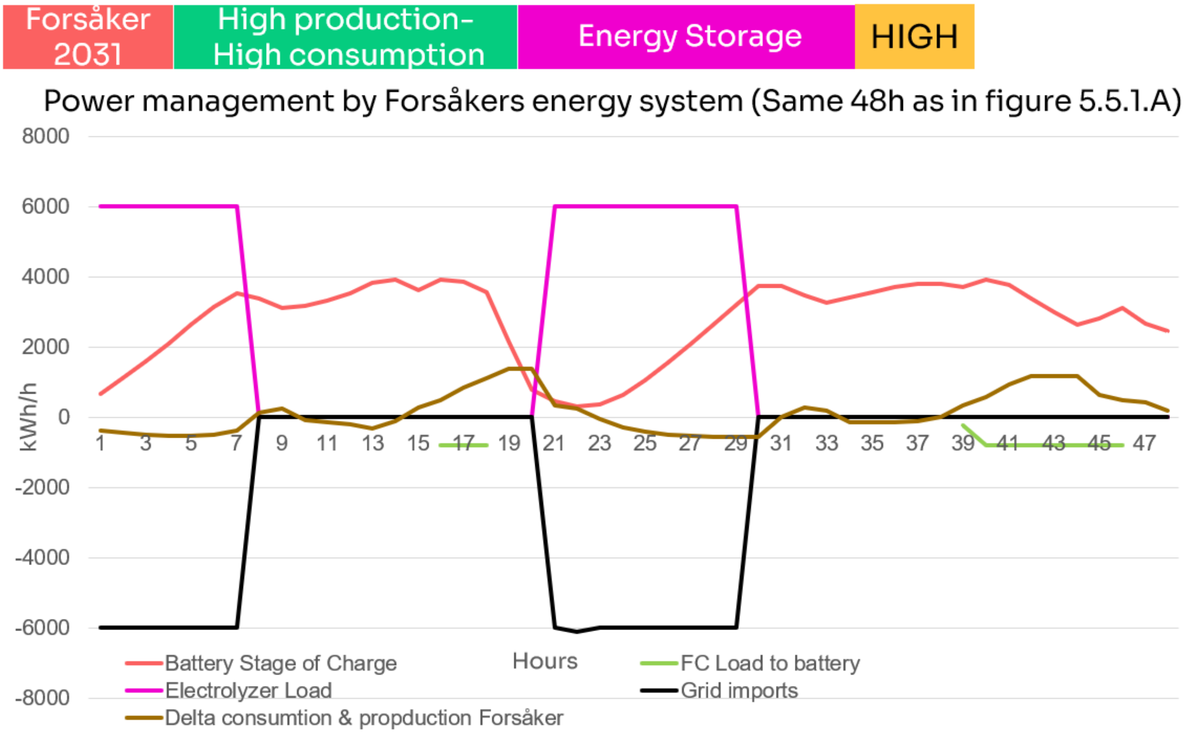


Figure 5.5.1.B. Power management activities by components in Forsåker during the same 48 hours as Figure 5.5.1.A. (2031-High Consumption-High production- Energy sharing: 2022 day-ahead electricity prices from 2022 simulation)

In Figure 5.5.1.B, an electricity surplus is observed in Forsåker until hour 7. During this period, the surplus electricity is stored in the battery, resulting in an increase in the storage volume, as indicated by the rising red line. Simultaneously, Figure 5.5.1.C displays that the electricity prices remain low until hour 7. Consequently, the electrolyzer operates at maximum capacity to produce hydrogen, utilizing the surplus electricity. It is worth noting that during this time, the electrolyzer relies solely on imported electricity for hydrogen production, as shown by the alignment of the purple and black lines in a mirrored pattern in Figure 5.5.1.B.

From hour 7, Forsåker's consumption surpasses the local production, triggering the discharge of electricity from the battery (red line). To avoid high electricity prices, the system avoids electricity imports from the regional grid. The battery and the interplay between local production and consumption influence each other throughout the 48-hour period, ensuring optimal energy management.

During hours 16-18 and 39-46, the FC- system contributes to the electricity production in Forsåker. This can be observed in the Figures as an additional source of electricity. The FC-system plays a crucial role in addressing the electricity deficit, which is most prominent at hour 20. To mitigate the shortfall, the fuel cell system proactively charges the battery in advance, a deviation from the fundamental control parameters described in Chapter 5.2 to avoid the need for grid imports before the electricity prices decrease at hour 21.

It is worth noting that at hour 21, there is a slight increase in electricity imports for both the electrolyzer and direct consumption in Forsåker, as depicted by the small bump in the black "Grid imports" curve. This coincides with the fluctuations in electricity prices during that hour.

The Figures demonstrate the intricate coordination among the battery, local production, consumption, and external electricity sources to optimize energy management and minimize reliance on grid imports, particularly during periods of high electricity prices.

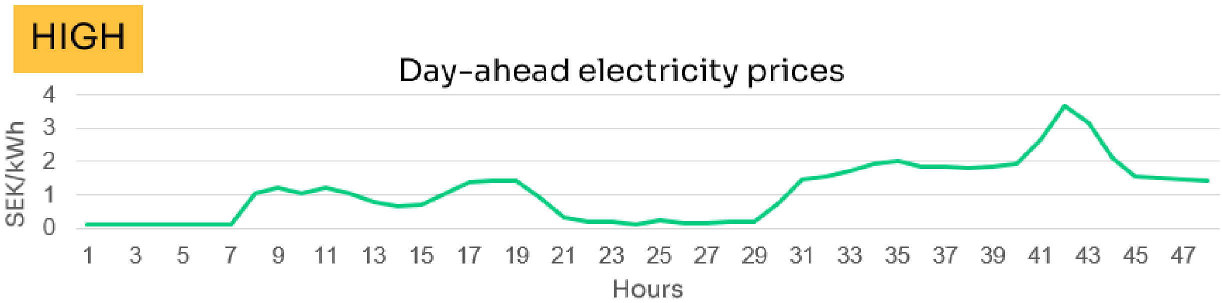


Figure 5.5.1.C. Day ahead electricity prices for the same 48 hours as in Figure 5.2.1.A-B. (2031-High Consumption-High production- Energy sharing-HIGH day-ahead electricity price scenario from 2022 years prices)

During the same 48 hours as in Figure 5.5.1.A-C heat management is shown in Figure 5.5.1.D. When the electrolyzer operates at maximum capacity heat production is greater than consumption as the purple staples for electrolyzer heat production are greater than the black line of heat consumption for properties. The reason is that the primary electrolyzer focus is hydrogen production and secondary heat production. Meaning the electrolyzer prioritises hydrogen production during advantageous hours and heat production is just a side effect, which in this case is used to cover the Forsåker consumption needs. The excess heat from the electrolyzer is stored in an accumulator tank seen in the light blue line. During hour 8 the electrolyzer stopped operation due to increased electricity price, the accumulator tank then releases the heat and covers a share of the heat consumption for hour 8. When the accumulator tank is empty combined with or not enough heat from the fuel cell system and electrolyzer, the heat pump covers the remaining heat consumption.

The combination of the accumulator tank, fuel cell system, electrolyzer, and heat pump ensures efficient heat management, allowing for the utilization of excess heat generated during hydrogen production and providing alternative heat sources when needed. This integrated heat management system helps optimize energy utilization and reduces reliance on external heat sources, contributing to improved energy efficiency in the overall system.

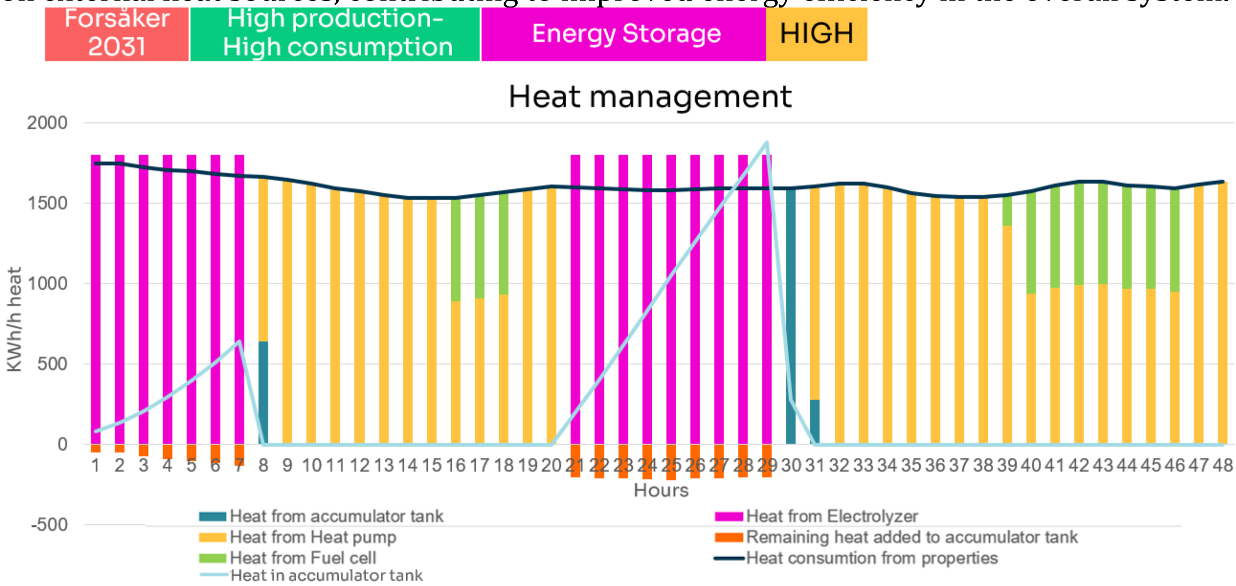


Figure 5.5.1.D. Heat management during the same 48 hours as in Figure 5.5.1.A-C by Forsåker's energy storage system. (2031-High Consumption-High production- Energy sharing-HIGH day-ahead electricity price scenario from 2022 years prices)

Electricity consumption for the operation of the heat pump is allocated based on control parameters described in Chapter 5.1 and 5.2. It is likely that a portion of the electricity produced by the FC-system is allocated to the heat pump during fuel cell operation hours, as shown in Figure 5.5.1.D.

In Figure 5.5.1.E, the variation of hydrogen flow during the same 48-hour period is depicted. During electrolyzer operation hours (hour 1-7 and 21-29), the hydrogen storage level increases as hydrogen is produced and stored. At hour 28, the storage reaches its maximum state of fill (SOF), and therefore, during hour 29, the hydrogen produced by the electrolyzer is directed towards the hydrogen filling station for sale or is directly sold as hydrogen sales.

During fuel cell system operation hours (hour 16-18 and 39-46), the hydrogen storage level decreases as hydrogen is consumed for electricity production. This illustrates the dynamic nature of hydrogen flow in response to the operation of the electrolyzer and fuel cell system. The hydrogen storage acts as a buffer, allowing for the storage of excess hydrogen during periods of high production and the utilization of stored hydrogen during periods of high demand or fuel cell system operation.

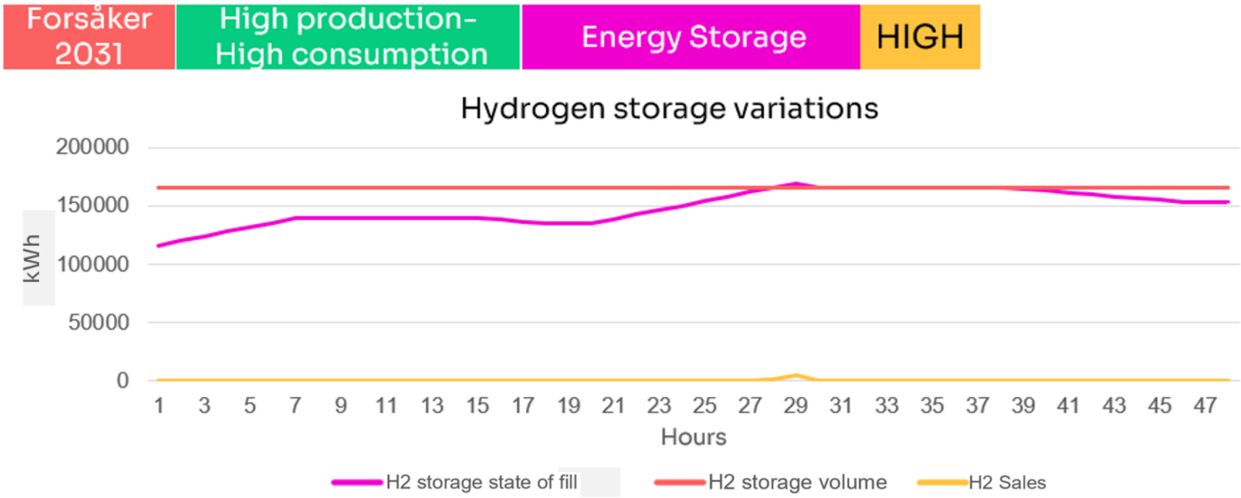


Figure 5.5.1.E. Same 48 hours as in Figure 5.5.1.A-D.Hydrogen flow variations in the hydrogen storage, during the same hours as in Figure 5.5.1.A-D. (2031-High Consumption-High production-Energy sharing: 2022 day-ahead electricity prices from 2022 simulation)

5.5.2 Long term operation overview and explanation of week periods

Figure 5.5.2.A provides an overview of component activity during a week in July, based on the 2022 day ahead electricity prices. The colour codes used in Figure 5.5.1.B are maintained for consistency. It is evident that the electrolyzer operates at maximum capacity for most hours at the beginning of the week, requiring only a few stops and starts. During these hours, electricity is imported from the regional grid due to the low electricity prices. Imported electricity is used for both hydrogen production, battery charging and direct consumption which is clearly seen when electricity import feeds from the regional grid is 7 MW.

As a result, when there is a surplus of electricity from local production, the need for grid imports decreases. However, when there is a deficit in local production, the battery levels decline rapidly, and Forsåker's consumption is supplemented with grid imports due to the low electricity prices.

Towards the end of the week, specifically after hour 126, there is a predominance of high electricity prices. Consequently, the fuel cell system is observed to cover the consumption demand during most of the deficit hours after hour 126. The electrolyzer operates at a lower capacity during this time, primarily focused on draining the battery before it reaches its maximum state of fill (SOF). Beyond hour 126, the electrolyzer exhibits frequent starts and stops.

This sequence of events demonstrates that the interplay between the different components of the system can manage Forsåker's electricity consumption demands. In the event of a crisis where the regional grid becomes inaccessible, Forsåker's energy system would manage consumption demands quite well during a July week.

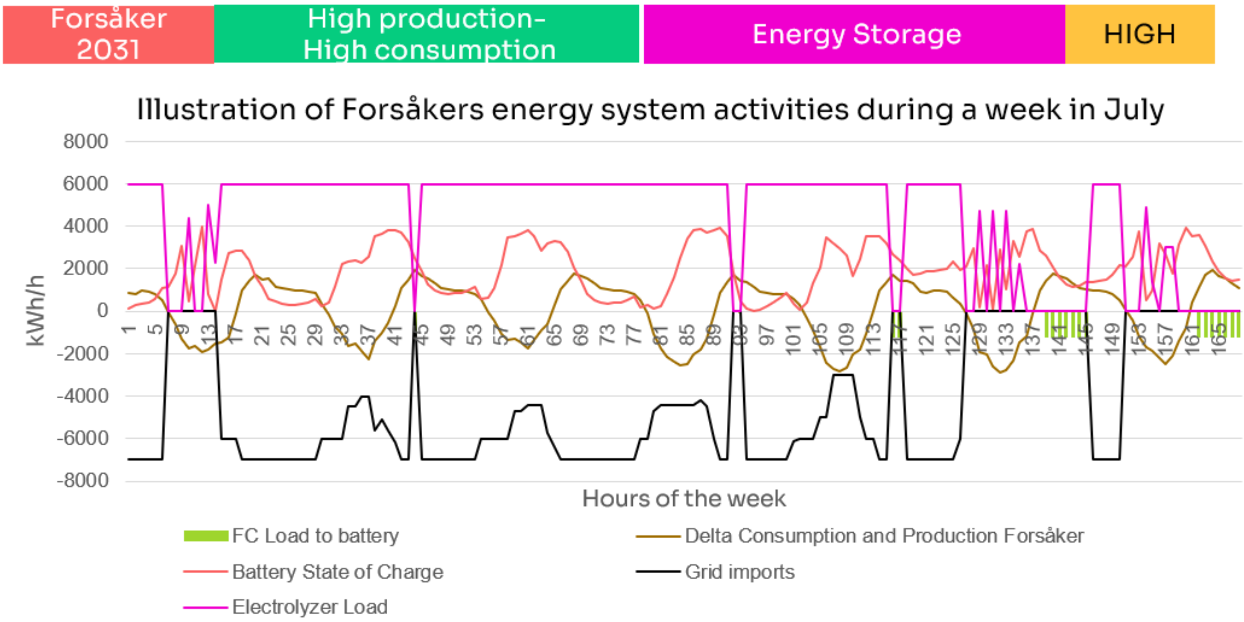


Figure 5.5.2.A. Energy storage component activity during circumstances in one July week based on day ahead electricity prices from 2022.

To enable operation, Forsåker's energy system relies heavily on the battery storage, which is more frequently used than the hydrogen storage. While simulations focusing solely on battery storage have not been conducted, Figure 5.5.2.B illustrates the function of the battery more clearly by depicting the July week scenario from Figure 5.5.2.A. with only battery storage. Day ahead electricity prices for this period are not shown in any figure but the behaviour of the energy system relies on them in the same way as in Figure 5.5.1 A-E. In Figure 5.5.2.A electricity prices are favourable during grid imports, when the electrolyzer operates at 6000 kW electricity purchasing occur with compensation for excess electricity from local production.

It is important to note that no optimization of control parameters has been performed specifically for the "battery storage only" scenario in Figure 5.5.2.B. Some modifications have been made, including the removal of grid imports to the electrolyzer. Instead, excess electricity is exported to the regional grid to prevent the battery from reaching its maximum state of charge (max SOC). Additionally, the electricity production of the fuel cell system is replaced with grid imports.

This scenario highlights the significant role of the battery in managing energy storage and grid interactions within the energy storage system.

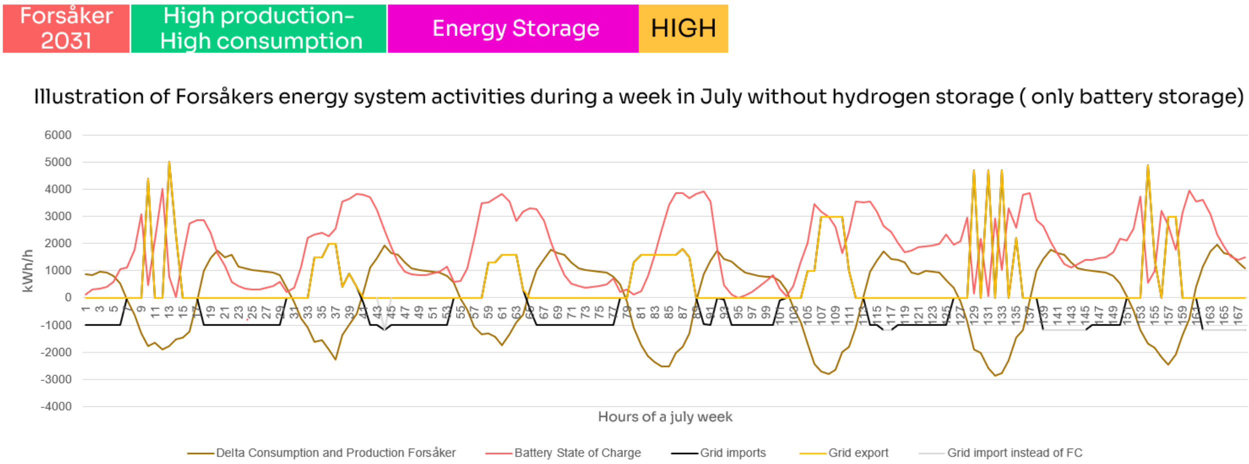


Figure 5.5.2.B. Energy storage component activity during circumstances in one July week based on the HIGH day ahead electricity prices from 2022 years electricity prices. If only battery storage would be included.

If the simulation were to be conducted solely for battery storage, certain adjustments could be made to optimize its suitability and mitigate any potential degradation risks. The import and export peaks of electricity in Figure 5.5.2.B could be modified to minimize sharp peaks that could potentially accelerate battery degradation. Electricity import would be necessary even during high electricity cost periods and 100% heat production from the heat pump would contribute to larger grid imports even during high electricity prices. District heating from Riskulla would be one option as well. Battery storage alone is entirely possible but would then only cover parts of the function's hydrogen storage entails.

Figure 5.5.2.C shows the same July week as 5.5.2.A. the extensive operation of the electrolyzer results in the hydrogen storage level reaching its maximum state of fill (SOF) for most of the hours. The H_2 storage SOF decreases during fuel cell operation hours. As seen the amount of hydrogen produced for hydrogen sales during this week is around 14 tons, which corresponds to 280% of the hydrogen storage capacity.

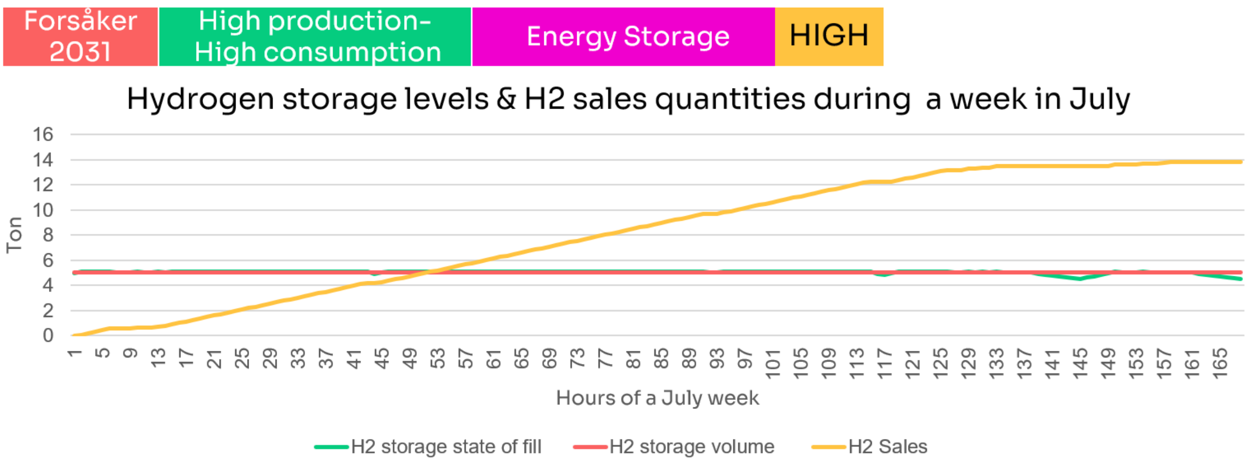


Figure 5.5.2.C. Hydrogen flow variations in hydrogen storage. Same July week as in Figure 5.5.2.A.

Figure 5.5.2.D presents a week in September, based on the day ahead electricity prices from 2022. The prevailing conditions during this period result in high activity of the fuel cell system, which is utilized to meet Forsåker's electricity consumption demands. The

electrolyzer, on the other hand, primarily consumes excess self-produced electricity to prevent the battery from reaching its maximum state of charge (SOC). The electricity imports during this week are minimal due to the high electricity prices. Small quantities of electricity sales of exports to the regional grid occur.

For the September week conditions of high electricity prices and limited excess electricity from local production, there are instances where the system exports small quantities of electricity, aiming to avoid operating the electrolyzer. This is due to the minimum operation load of the electrolyzer, which is 1.2 MW. Exporting a few hundred kWh to the regional grid would keep the battery fully charged for later use during high demand hours with electricity lacks and high electricity prices. Hence, a minimum start of the electrolyzer followed by immediate grid imports to the battery is now avoided.

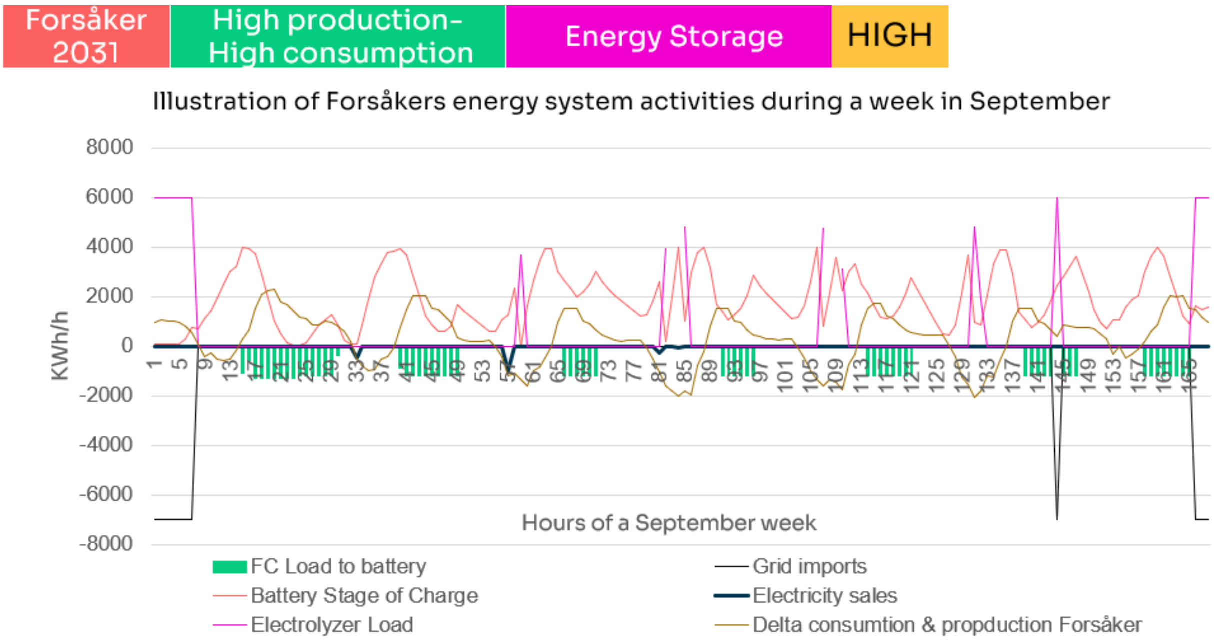


Figure 5.5.2.D. Energy storage component activity during circumstances in one September week based on HIGH day ahead electricity prices from 2022.

An interesting system dimensioning to investigate if an energy storage system would be integrated in Forsåker, would be a combination of smaller electrolyzer stacks like the fuel cell system combination of 15 fuel cell stacks, or alternatively, one large electrolyzer as in the simulations combined with a small one to avoid small grid exports. Smaller electrolyzer stacks would most likely enable a better flow in the battery due to smaller more frequent discharges, at the same time their combined capacity works as the presence of a 6 MW electrolyzer that enables the system to handle larger electricity demands and fluctuations as well. The exact sizing of the electrolyzer in such case needs to be investigated more closely. If the simulation would go down to shorter measuring points than hours, less extraction than 1.2 MW would be possible even with a large electrolyzer of 6 MW, hence the electrolyzer degradation would increase of short starts and stops like that, it may not even be possible due to the necessary ramp up time required.

Figure 5.5.2.E shows the hydrogen storage level during the same September week as in Figure 5.5.2.D. The high fuel cell system consumption of hydrogen combined with low hydrogen production results in a storage level from full to under 2 ton during the week.

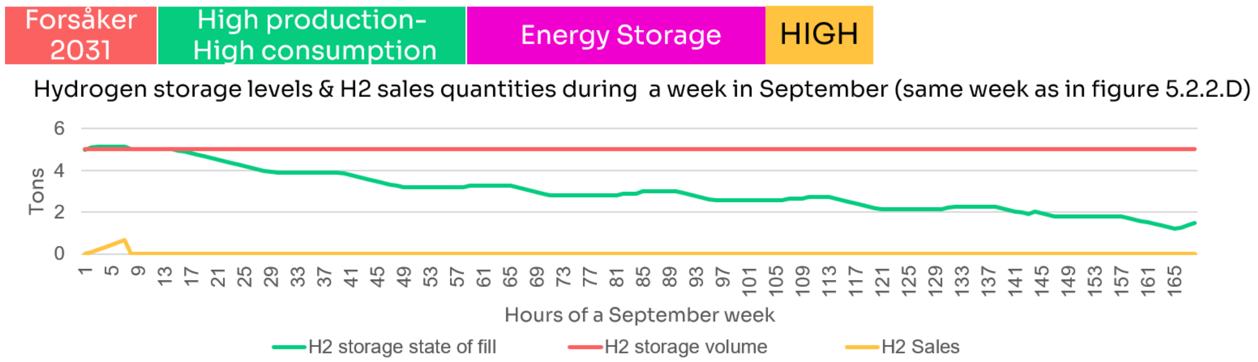


Figure 5.5.2.E. Hydrogen flow variations in the hydrogen storage during a week in September based on the HIGH day-ahead electricity price scenario from 2022. Same September week as in Figure 5.5.2.D.

6. Financial evaluation of energy flows without storage in Forsåker 2031

This Chapter will present costs for scenarios without energy storage in Forsåker. Based on LOW, MEDIUM and HIGH day ahead electricity price scenarios, for traditional owner structure as well as energy sharing showed in Figure 6.1 below:

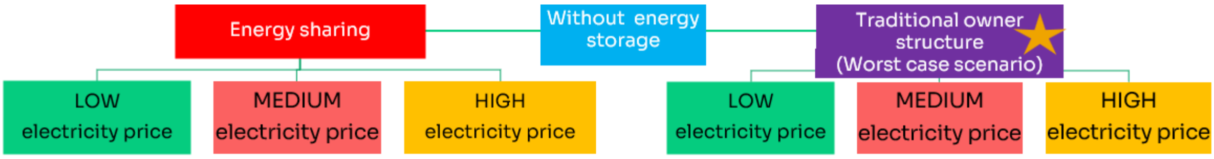


Figure 6.1. Overview of scenarios without energy storage in Forsåker.

The star in Figure 6.1 Traditional Owner structure indicates that is the baseline scenario, which represents the energy system without any investment in either electricity production or energy storage and will therefore serve as the baseline for future comparisons, since electricity traditionally has been purchased from electricity companies. In all Energy sharing scenarios additional investments in energy storage and local production facilities are required. If any additional investments are made compared to the standard scenario, these new investments must also contribute to improvements in terms of economics, environment, self-sufficiency, and operational reliability. In all scenarios both Traditional Ownership and Energy Sharing scenarios, the roof and facade solar installations are owned by the real estate owners themselves. All roof and façade solar installations will be assumed to be at maximum 500 kW installations each to avoid being a subject of taxation. Scenarios with small batteries for all 500 kW would be one possible solution as well but has not been investigated in the thesis.

6.1. Annual heat consumption expenses

The total cost for district heating purchases in Forsåker amounts to 5.2 million SEK. Figure 6.1.1 provides an overview of the cost distribution for each month and cost category. The power fee remains consistent throughout the year, while the monthly energy cost varies. In June, the power fee accounts for 90% of the total cost, while in January, it is less than 17%. The period from December to March represents nearly 60% of the total cost for the year.

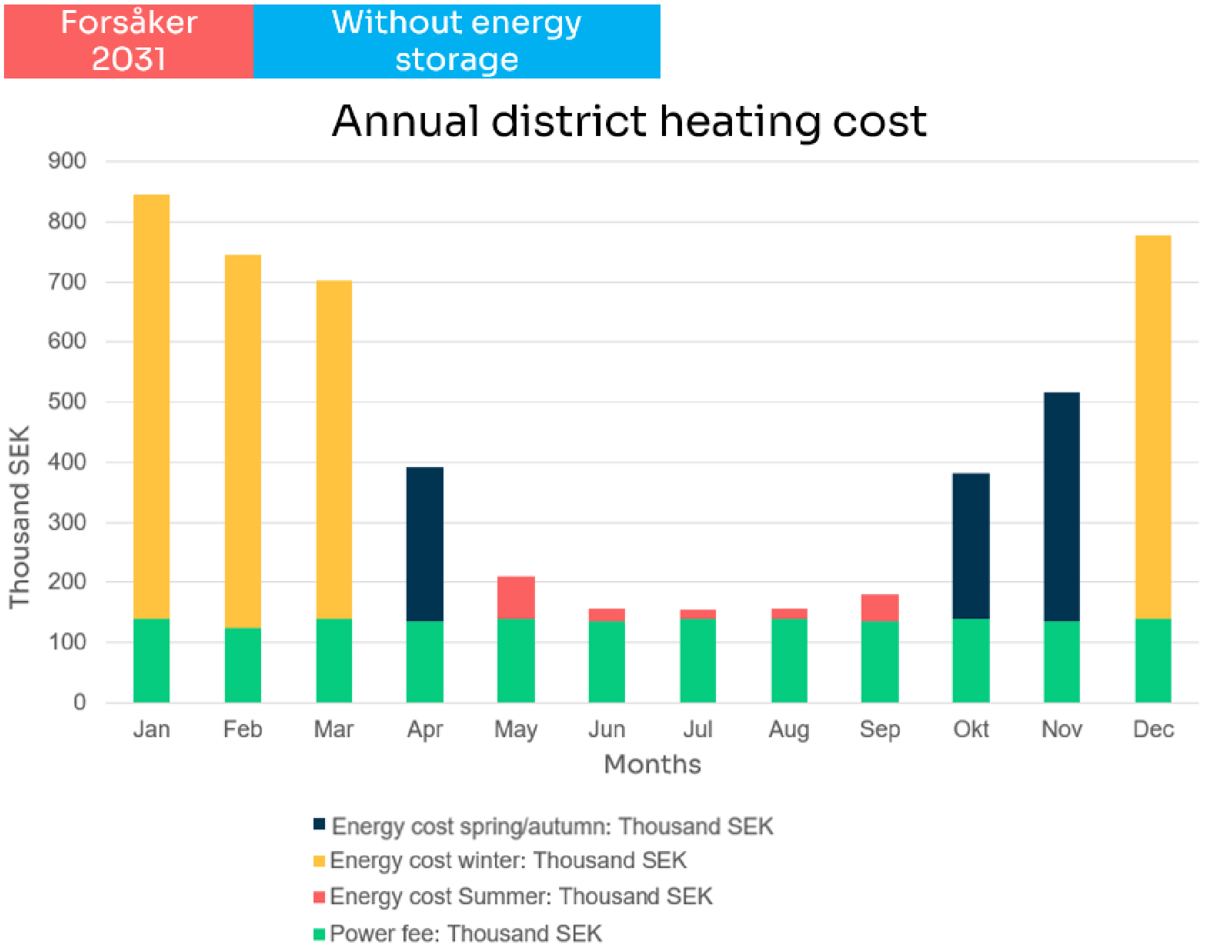


Figure 6.1.1. Annual costs for district heating in Forsåker distributed on Months divided by cost categories.

The district heating price consists of a fixed power fee and a variable energy cost. The variable price varies between 100 to 520 SEK/MWh depending on the month. The fixed cost is based on the peak power demand over the year, which is 2340 kW in Forsåker 2031, resulting in a fixed price divided over the months between 126 kSEK to 140 kSEK. The power fee in SEK/MWh is higher during the summer months when the energy cost in SEK/MWh and total purchases per month are at their lowest. This is because the amount of kWh used during the summer is lower, resulting in the power fee being distributed over a smaller quantity of kWh. Conversely, during the winter months, when a larger amount of kWh is consumed, the power fee measured in SEK/MWh is lower.

6.2 Annual electricity consumption coverage for traditional owner structure

Figure 6.2.1 provides an overview of the amount and percentage of electricity from each source that contributes to covering Forsåker's consumption. The solar installations on the roofs and facades of the properties have been distributed under 500 kW per housing cooperative to avoid energy tax implications. However, further study is required to confirm this assumption. This distribution was made to demonstrate the potential contribution of available areas on the properties in relation to the annual electricity needs. It is important to note that not all urban development projects have easy access to nearby hydro power and solar panels within the district.

Any excess electricity production that is not directly consumed by the properties is exported to the regional grid. In this case, approximately 15.2 MWh of electricity is exported annually.

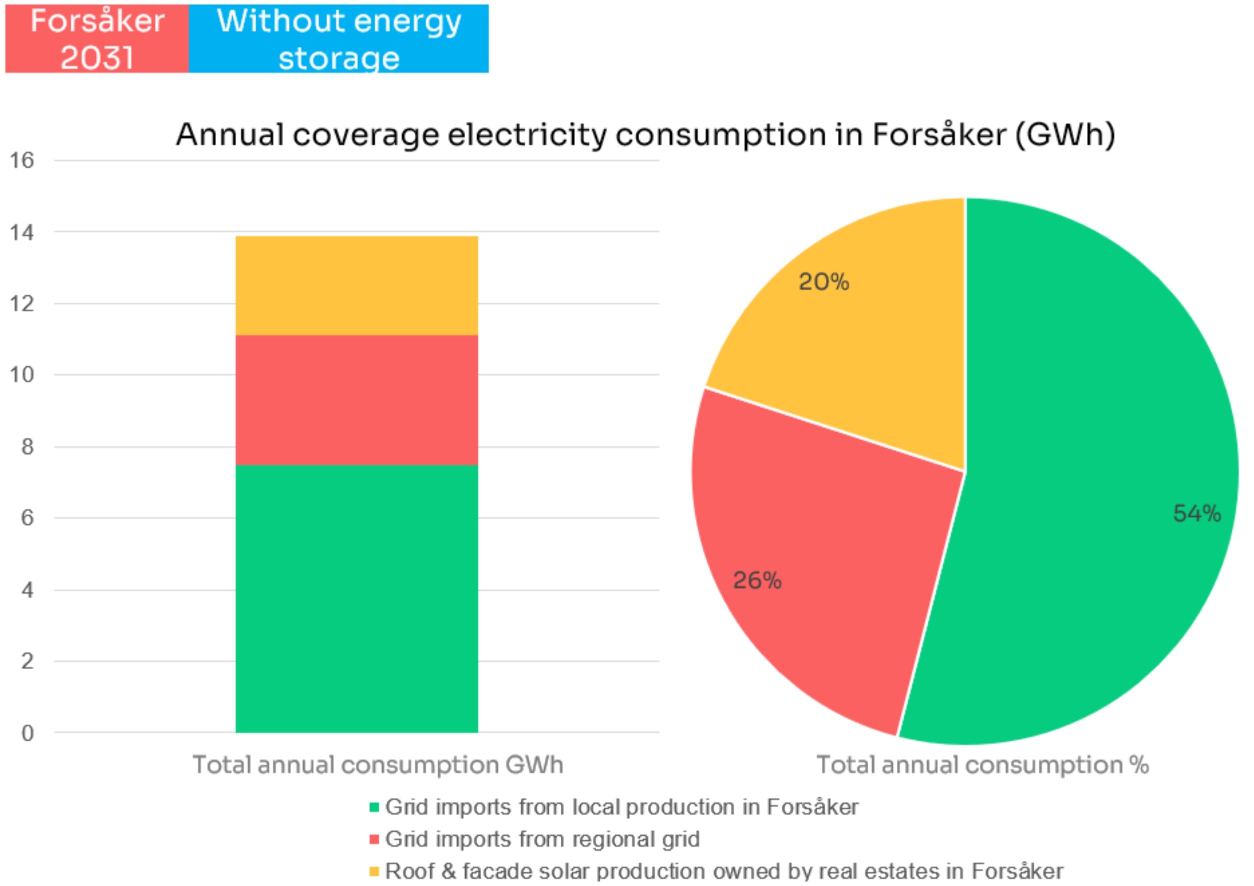


Figure 6.2.1. Annual coverage of electricity consumption in Forsåker divided into categories.

6.3 Financial overview - traditional ownership structure

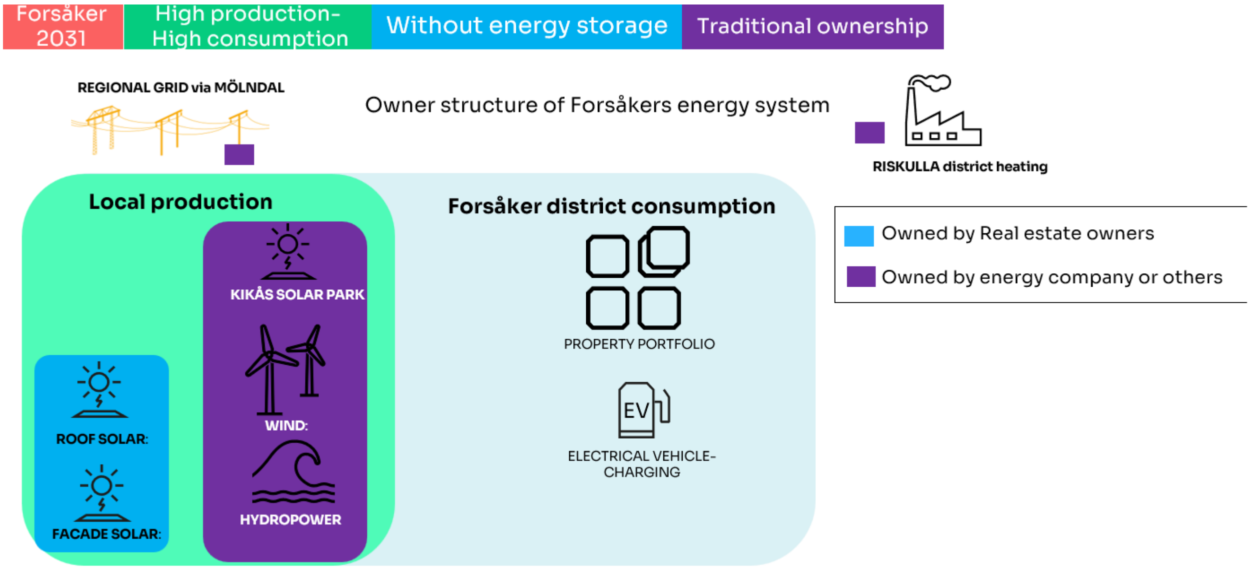


Figure 6.3.1 Overview of Forsåker's energy system and the traditional owner structure without energy storage 2031-High Production-High consumption.

In a traditional ownership structure visualised in Figure 6.3.1, annual costs related to electricity purchases, transmission fees, power fees, energy taxes, and district heating can be unpredictable and beyond the control of the property owners. However, by investing in facade and roof solar panels, the expenses become more predictable and provide a value for each operational year. This value has been determined by comparing the electricity purchase costs from the regional grid with the amount of kWh produced by the solar panels on an hourly basis.

By distributing the solar installations under 500 kW, their electricity production is considered as not being subject to taxation resulting in cost savings. Additionally, transmission fees are saved since the solar production comes from self-owned panels. Instead, CAPEX for roof and facade solar installations is added, which will be included in the property section loan and therefore not reported as a cost in the examined scenarios. Figure 6.3.2 provides an overview of all the costs and values associated with energy flows in Forsåker, the top boxes offer a scenario-oriented perspective on the costs and values:

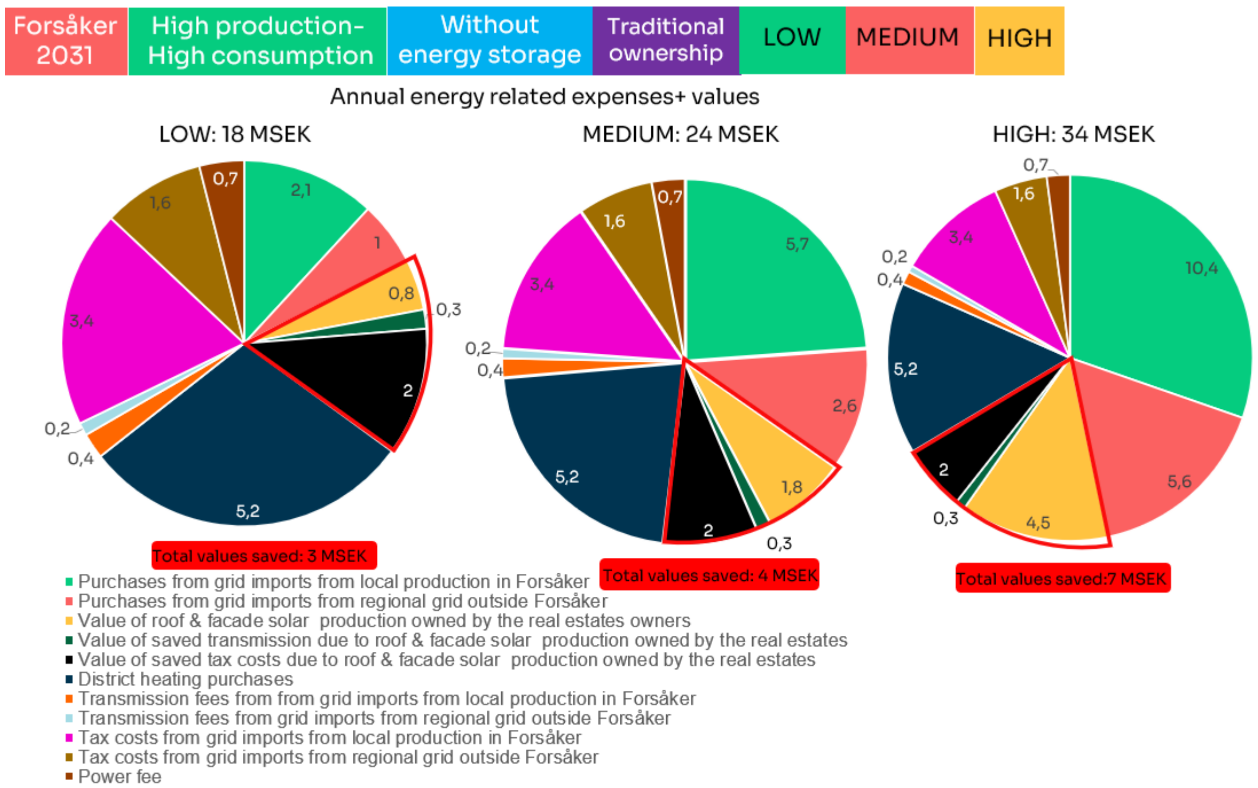


Figure 6.3.2. Annual value distribution of energy related values in Forsåker 2031 based on LOW, MEDIUM and HIGH day ahead electricity price scenarios based on input data from 2016, 2021 and 2022 day-ahead electricity prices.

For all scenarios facade and roof solar panels costs are decided to be showed at the real estate budget instead of adding them to each scenario when they are the same in each investigated scenario. Red marks in Figure 6.3.2 show equal annual values saved by the roof and facade installations, as purchases of its equivalent electricity production profile from the grid would be. Annual values nearly doubling from LOW to HIGH day-ahead electricity prices. By investing in solar panels on roofs and facades, Forsåker's property owners would annually save 3 MSEK to 7 MSEK marked as red in Figure 6.3.2, the remaining categories are actual costs.

Depending on fluctuations like the LOW, MEDIUM or HIGH day-ahead electricity price scenarios become the new normal 2031 and forward. Since savings do not include the CAPEX and OPEX for roof and facade solar installations, so those expenses must be deducted from the savings of 3 MSEK to 7 MSEK. Depending on the interest rate the solar installation CAPEX and OPEX not only gains more predictability in terms of costs but also experiences significant cost savings and increased value in relation to energy consumption. The reason why CAPEX and OPEX for facade and roof solar cells have not been investigated but instead assumed in the property budget is that the cost will remain the same in all examined scenarios in the thesis. Therefore, those costs will not affect the comparison between the different scenarios.

The assumption was made that the real estate owners own the roof and facade solar panels, and each installation has a capacity of less than 500 kW. As a result, the real estate owners are exempt from paying for electricity purchases, taxation, and transmission fees related to the solar panels showed in Figure 6.3.2. Instead, they will need to repay bank loans for the solar cell investments and cover the costs of operation and maintenance for the panels mentioned above. These costs were assumed to be included in the real estate bank loans and were not accounted for as a separate yearly fee.

Figure 6.3.3 provides an overview of the actual annual energy related expenses for the property owners. If the roof and facade solar panels are not owned by the real estate owners, the associated solar values in Figure 6.3.2 these solar installations will be considered as expenses in Figure 6.3.3 which also depicts a scenario orientation in the bottom right corner of the Figures.

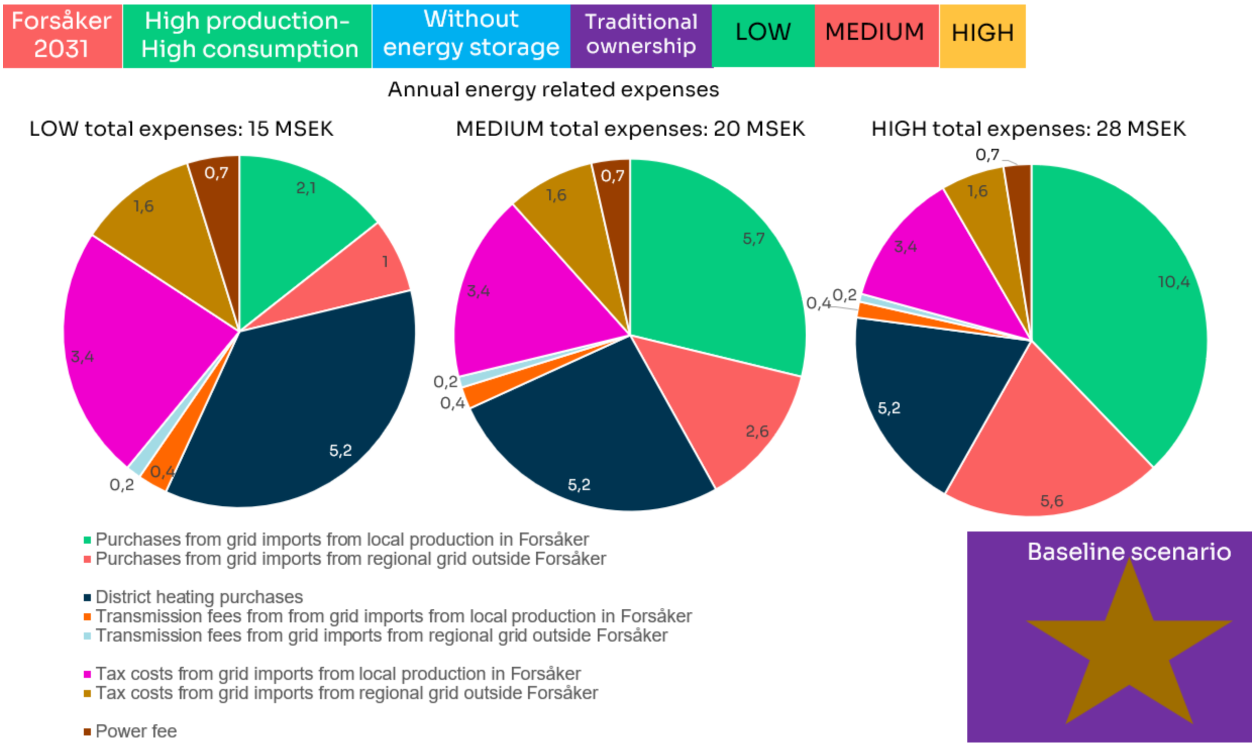


Figure 6.3.3. Annual expenses distribution of energy related expenses in Forsåker 2031 based on LOW, MEDIUM and HIGH day ahead electricity price scenarios based on input data from 2016, 2021 and 2022 day-ahead electricity prices.

The annual expenses depicted in Figure 6.3.3. above represent the Baseline scenario where no investments in energy production facilities or storage components are required, since the traditional approach of purchasing energy are followed. This is the most common setup for energy-related expenses among property owners in Sweden traditionally. Between the LOW and HIGH day-ahead electricity price scenarios, there is an increase from 15 to 28 million SEK, which represents almost a doubling of annual energy related expenses.

The “Without Energy Storage-Traditional ownership structure scenario” serves as the baseline for comparison with the other scenarios. To justify making additional investments in energy production facilities and storage components, the other scenarios need to offer greater advantages than the Without Storage-Traditional ownership structure scenario, since in this scenario, no additional investments are required neither any technology risks.

6.4 Financial overview - Energy sharing principle

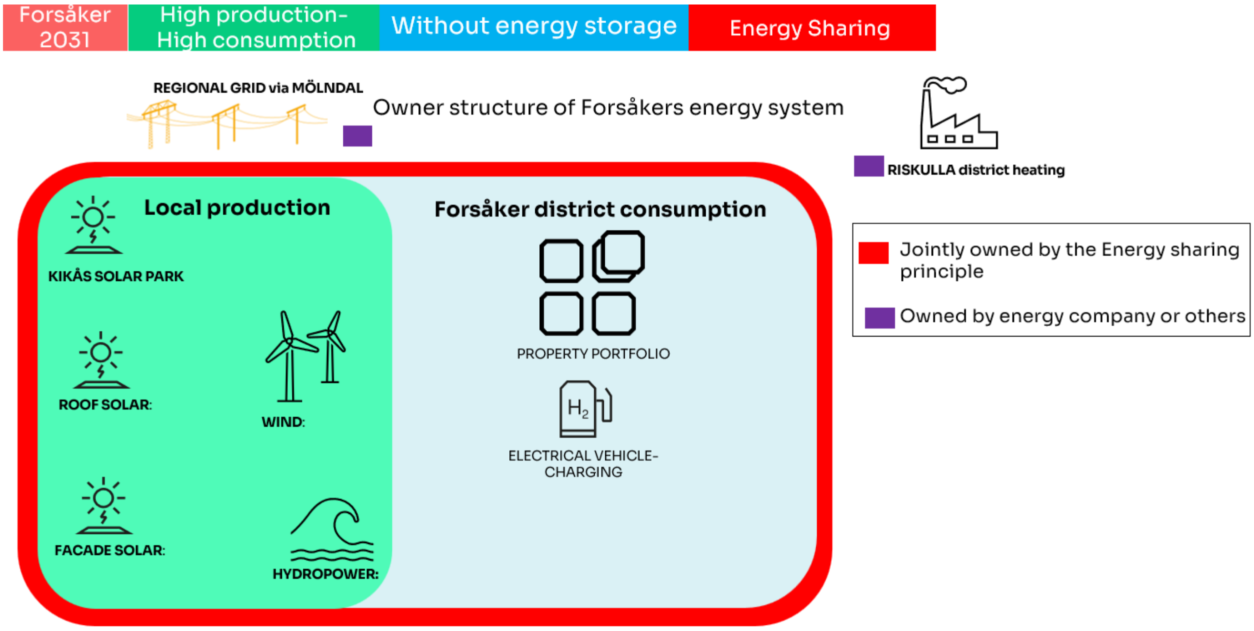


Figure 6.4.1. Overview of Forsåker's energy system and the energy sharing principal owner structure without energy storage 2031-High production-High consumption.

The energy sharing scenario illustrated in Figure 6.4.1 means that all production plants and properties are jointly owned by different stakeholders in the Forsåker consortium. Energy costs as transmission fees, and taxes will disappear for all electricity produced and consumed inside of Forsåker. Only grid exports and imports from Forsåker to the regional grid will be assumed a subject of taxation. Transmission fees and power fees are purchased for exports and imports between Forsåker and the regional grid.

Before January 2022 direct sharing of energy between neighbouring properties was not permitted. The new decision Ordinance (2007:215) on exemptions from the requirement for network concessions according to the Electricity Act (1997:857) provides exceptions and allows energy sharing between neighbouring properties and local production as described in more detail in theoretical Chapter 2.3. Since this exception is quite new negotiations are ongoing, the future is still uncertain whether these types of energy communities will be allowed on a larger scale as a district of Forsåker's scale or not in the future. This Chapter will show the costs for energy sharing structure.

6.4.1 CAPEX for energy sharing principle.

In the energy sharing principle, investments in jointly owned energy production, such as the hydro-power plant, Kikås solar park, and wind turbines, need to be considered. These investments are financed through bank loans. Instead of monthly energy expenses being paid directly from the owner's bank account, the bank loan will be repaid from the owner's bank account. The capital expenditure (CAPEX) for the Kikås solar plant is estimated to be 42 MSEK, based on other similar investments made in 2022 since the Kikås solar park will be installed summer 2023. 30% of the CAPEX will be covered by equity capital, and the remaining amount will be financed by the bank. The calculations are based on a 2.5% as well as 5% interest rate in the discussion Chapter 9.3 and a 30-year payment plan, as shown in Table 6.4.1.1 below.

Investment plan for KIKÅS solar park (For all Energy sharing scenarios)

Solar park Kikås (MSEK) CAPEX investment	Lifetime (years)	Annual expenses 5% interest rate (MSEK)	Annual expenses 2,5% interest rate (MSEK)	Owner's equity (MSEK) 30 %
42	30	1,9	1,4	12,6

Table 6.4.1.1. Payment plan based on a similar 5 MWp solar park installation as in Kikås. The Kikås solar plant will be built during the summer of 2023, hence the price is assumed to be like Softech's example of a 5 MWp park installation 2022 of 42 MSEK [22]

Annual payments for the solar park bank loan are 1.9 MSEK with a 5% interest rate or 1.4 MSEK with a 2.5% interest rate which are based on the 42 MSEK required investment of the solar park. Additionally, equity of 12.6 MSEK is required by the consortium owners of the energy sharing principle in Forsåker since 70% of the investment are covered by the bank loan and 30% owners' equity. These payments are added to the expenses for the energy sharing principle. In the cost comparisons between the energy sharing and traditional ownership structure, the interest rate of 2.5% is used. However, it is important to note that the real interest rate can vary over time. Factors such as inflation, green loans and political decisions can influence the availability and terms of loans for renewable energy investments. Therefore, it is difficult to predict the exact expenses for 2031.

Since hydro-power plant and wind turbines investment are unknown, a conclusive comparison of the traditional ownership structure and energy sharing principle cannot be drawn. Similar loan payment plans would need to be calculated for the hydro power and wind power investments so that the yearly expenses for the loans can be included in the overall cost comparison. Energy sharing principal scenarios can be compared to each other because the expenses for the hydro-power plant and wind turbines will remain constant across those scenarios.

Even without the knowledge of the CAPEX for hydro and wind, a comprehensive analysis of their costs has been conducted in Chapter 9.3. Based on the known investment costs for Kikås solar park in terms of cost per installed kW of production capacity. These costs will not provide an accurate picture of wind and hydro power plant prices but enables a reflection of how CAPEX and OPEX impact profitability depending on interest rate as well as providing a meaningful comparison between traditional and energy sharing scenarios.

6.4.2 Annual electricity flows in Forsåker 2031 - Energy sharing principle

As seen in Figure 6.4.2.1 the quantity of GWh that will flow in or out in Forsåker's grid is local production from solar, wind and water. Even though the local production is greater than Forsåker's consumption annually, the consumption and production do not appear at the same time in the same quantity. Hence imports and exports via the regional grid are vital to fulfil the consumption demands and get rid of the production that is not consumed in Forsåker.

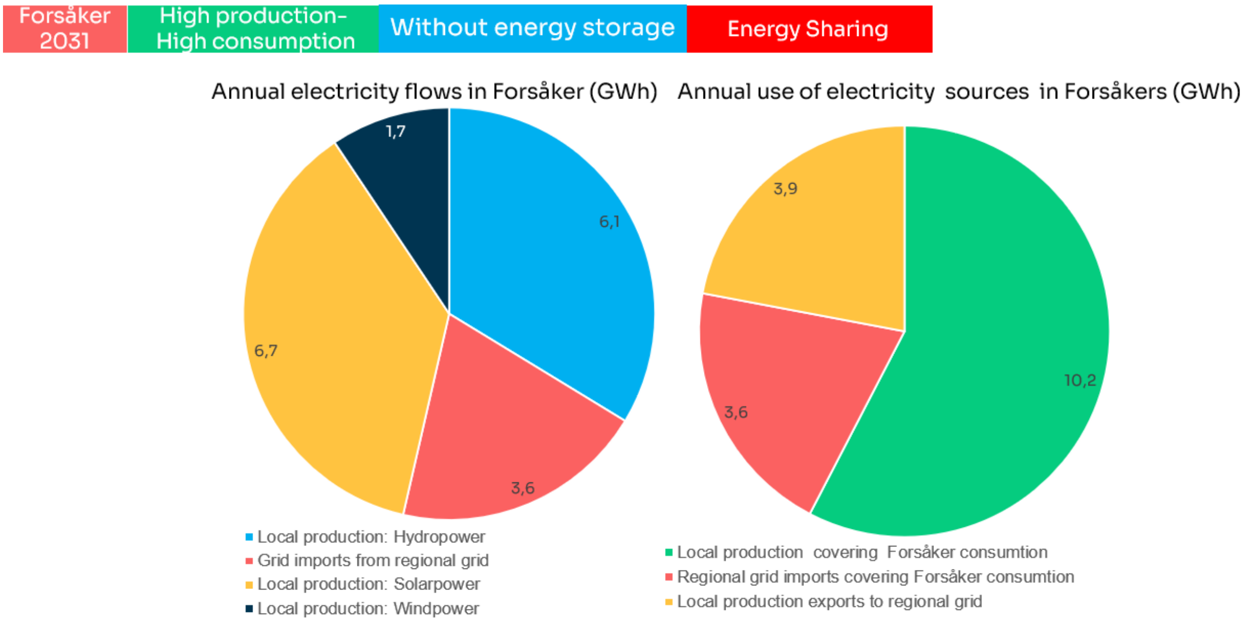
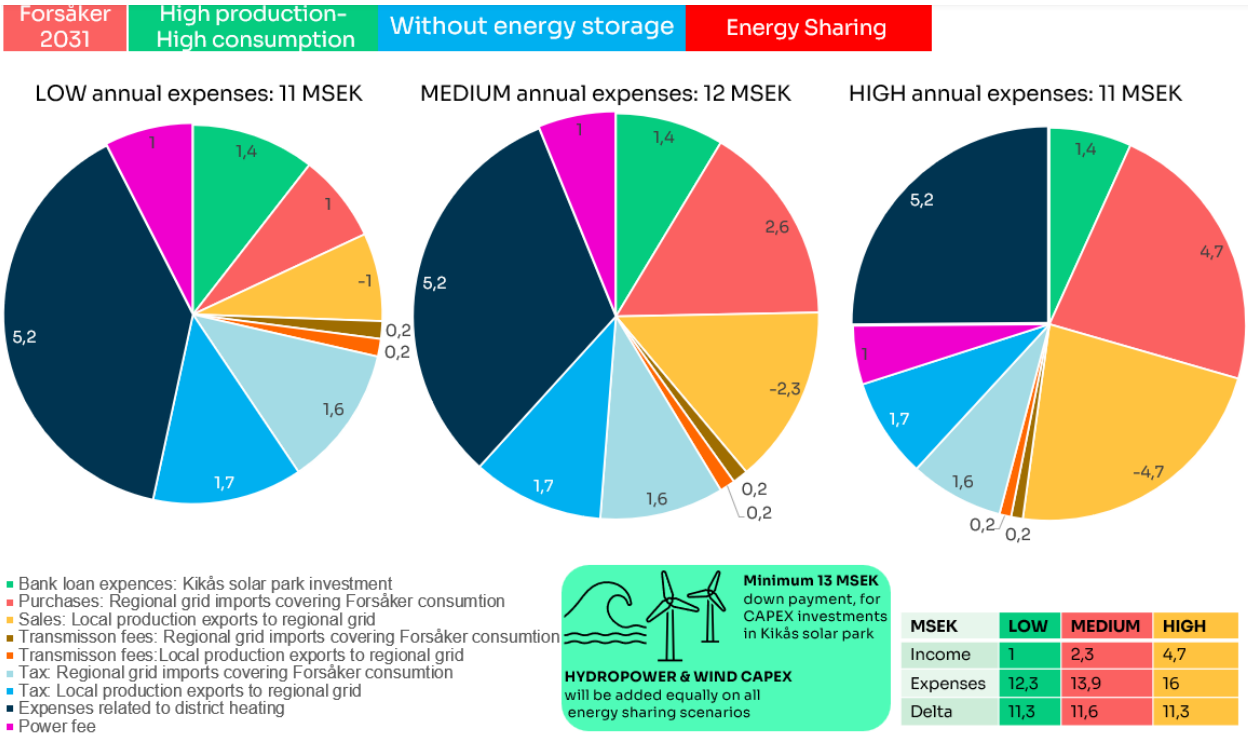


Figure 6.4.2.1. Annual electricity flows in Forsåker as well as the annual electricity use for Forsåker consumption divided in categories of electricity sources.

Figure 6.4.2.1. shows sources and receivers of annual electricity flows in Forsåker. Figure 6.4.2.2. shows annual costs of electricity flows as well as revenue from sales based on the electricity flows from Figure 6.4.2.1. The overall value of 1 kWh of electricity varies continuously on an hourly basis, total amount of kWh produced or consumed for each hour multiplied the hourly price repeated for all hours of the year gives the annual price sum for each category. It is important to note that the expenses associated with the Kikås solar park investment remain constant regardless of the electricity price or the amount of kWh produced. These expenses will be the same every year, determined by the interest rate. Consequently, in 2022, the earning potential from the solar park was higher than 2016.



MSEK	LOW	MEDIUM	HIGH
Income	1	2,3	4,7
Expenses	12,3	13,9	16
Delta	11,3	11,6	11,3

Figure 6.4.2.2. Annual expenses distribution of energy costs in Forsåker based on day ahead electricity prices from 2016, 2021 and 2022.

As depicted in Figure 6.4.2.2, the costs of transmission fees and taxes which are fixed per kWh are included in the calculation of grid imports and exports. The power fee remains the same as in the traditional scenario, as the peak exports are unchanged. It's important to note that electricity consumed within Forsåker's grid is not subject to taxes or transmission fees. Therefore, the produced electricity that is consumed within Forsåker does not have a monetary value within the local grid of Forsåker. Only grid exports and imports outside of Forsåker's local electricity grid are subject to taxation.

During numerous hours when electricity is exported from Forsåker's local grid to the regional grid, the hourly day-ahead electricity prices are lower than the combined costs of taxes and transmission fees. To export electricity from local production to the regional grid during those hours leads to a negative profit, as the expenses incurred for tax and transmission fees outweigh the revenue generated from the excess electricity production.

Despite this, on an overall level, as Forsåker's energy system both purchases and sells electricity during high and low electricity prices, it can be observed in Figure 6.4.2.2 that when the annual total cost for day-ahead electricity prices increases, the revenues from electricity exports also increase. Additionally, a 13 MSEK down payment for the Kikås solar park is required together with the unknown costs for wind and solar plants.

As depicted in Figure 6.4.2.2, the delta costs for both LOW, MEDIUM and HIGH day-ahead electricity price scenarios became similar to each other. This because the energy system both purchase regional grid imports as well as export electricity sales during both high and low day ahead electricity prices. A lower average annual day ahead electricity price results in lower income for exports as well as lower expenses for imports, a higher average annual day ahead electricity price results in higher income for exports as well as higher expenses for imports. Since the energy system cannot store any electricity both exports and imports are made regardless of the day a head electricity price.

This results in a stable expenditure regardless of the annual average electricity price for the examined day-ahead electricity price scenarios. In the Without Storage-Traditional ownership structure scenario, where no additional investments are made in energy production or storage, the expenses in a HIGH scenario resulted in annual expenses that was nearly double the LOW scenario expenses. The annual expenses stability in the energy sharing scenario can be beneficial for property owners as it provides a predictable cost structure irrespective of fluctuations in electricity prices.

Here, a similar mindset applies as with fixed or variable interest rates. The variable interest rate can decrease, resulting in lower expenses compared to a fixed interest rate. However, if one is unlucky, the interest rate may increase, making a fixed interest rate more favourable. Investors in Sweden typically prefer fixed interest rates for larger amounts over long periods, as it provides increased predictability. Regardless of whether the interest rate increases or decreases, investors with fixed interest rates can plan.

Depending on future scenarios regarding day-ahead electricity prices in Forsåker 2031 and beyond, the advantage of the investment will vary, thus affecting the interest in investing as it entails risks. The results of this analysis demonstrate that the higher the average price of the day-ahead electricity price set, the greater the annual savings obtained from investing in own power plants and implementing energy-sharing principles. Conversely, when the average price is lower, the potential savings from such investments are reduced. This suggests that the economic benefits of investing in renewable energy generation and energy-sharing strategies are directly influenced by the prevailing day-ahead electricity prices.

7. Financial evaluation of energy flows with storage in Forsåker 2031

As depicted in Figure 7.1 this Chapter will showcase the expenses for scenarios that incorporate energy storage in Forsåker. These scenarios will compare the day-ahead electricity price scenarios LOW, MEDIUM and HIGH based on day-ahead electricity price 2016, 2021, and 2022 for both traditional owner structures and energy sharing setups, *i.e.* the same scenarios as used for Chapter 6, but which did not include energy storage.

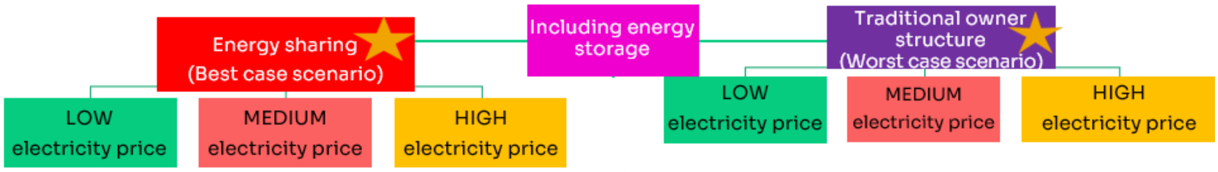


Figure 7.1. Scenarios including energy storage that will be investigated in Chapter 7.

To assess the economic value contribution of the storage system in 2031, a prediction of the two scenarios: the BEST-CASE scenario and the WORST-CASE scenario were made. The WORST-CASE scenario was assumed as the "Energy Storage-Traditional ownership structure" where separate actors produce and consume electricity.

The BEST-CASE scenario envisions an "Energy Storage-Energy sharing" scenario where all stakeholders in Forsåker jointly own properties and power plants as well as hydrogen and battery storage related components. This is combined with the current hydrogen regulations of 2023, which state that electricity imports for hydrogen production through electrolysis are not subject to taxation. In the BEST-CASE scenario, the hydrogen price is assumed to be 90 SEK/kg H_2, which was the 2023 price at hydrogen refuelling stations in Sweden.

The WORST-CASE scenario, "Energy Storage-Traditional ownership structure" results in additional costs in form of energy taxes and transmission fees. Energy production plant investments are not needed for property owners since the energy company or other stakeholders owns the production plants. Investments in battery and hydrogen storage related components are made by the real estate owners. The assumed price for hydrogen in the hydrogen refuelling stations is the target price for 2030, which is 4 EUR/kg H_2. In addition, is assumed that the current hydrogen regulations of 2023, which state that electricity imports for hydrogen production through electrolysis are not subject to taxation, will be changed and these electricity imports will be subject to taxation. This will result in decreased incomes for hydrogen sales combined with higher tax related expenses on electricity imports for hydrogen production.

Important to acknowledge is that the actual outcome in Forsåker 2031 and beyond most likely will not be as either the BEST-CASE scenario or the WORST-CASE scenario, due to many uncertain factors. It is impossible to predict the precise outcome of all the parameters that affect the result. The best-case and worst-case scenarios establish a range within which the actual outcome is anticipated to lie. The intermediate scenarios will shed light on the parameters that hold significance in the decision-making process, as well as those that may have a lesser impact. This analysis aims to help identify the key factors to consider and prioritize when evaluating the potential outcomes and making informed decisions.

In all energy storage scenarios, Forsåker's heat consumption will be met by the heat generated from the fuel cell system, electrolyzer, and heat pump. The primary function of the fuel cell system is to produce electricity, while the electrolyzer's main purpose is to generate hydrogen. Consequently, the heat produced as a by-product in the system will be considered as an additional benefit but not be control parameters for operation.

To ensure sufficient heat supply for Forsåker's consumption, either a heat pump or district heating from Riskulla would need to be utilized. The specific combinations of heat sources involving the fuel cell system, electrolyzer, and Riskulla have not been studied in this analysis but are entirely feasible options to explore.

7.1 Traditional ownership structure including energy storage

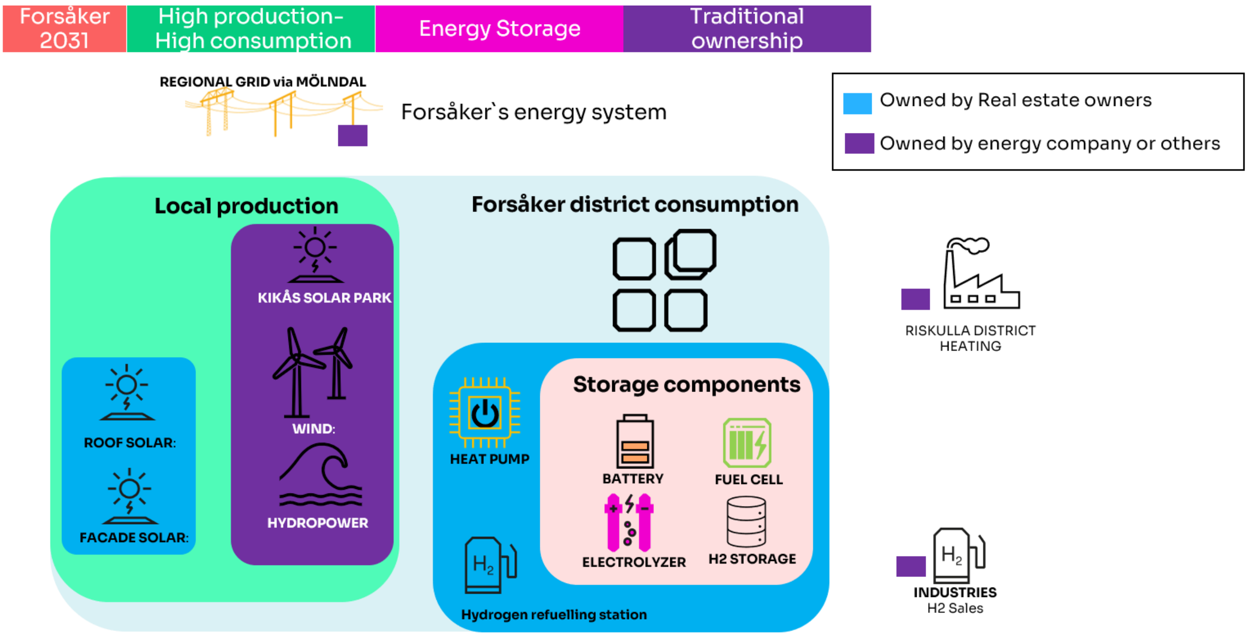


Figure 7.1.1. Overview of Forsåker's energy system and its owners in a traditional owner structure including energy storage. Large amounts of O_2 are produced from the electrolyzer, no investigation of demand or how to manage O_2 quantities has been made in this study.

As depicted in Figure 7.1.1 the storage components and solar installations on facades and roofs are owned by the real estate owner. On the other hand, larger production plants such as Riskulla, Kikås solar park, and wind turbines are owned by an energy company such as Mölndal Energi AB.

Traditionally, energy production has been the domain of energy companies, with real estate companies primarily serving as consumers. However, advancements in technology have now empowered real estate owners to generate small-scale green electricity from sources like solar and wind. The future scenario in Forsåker could involve the traditional structure where Mölndal Energi AB owns the Kikås solar park, wind power, and hydro power plants. Meanwhile, the condominium associations in Forsåker would own the facade and roof solar panels, each being below 500 kW to avoid taxation.

In this scenario, energy tax would be applicable to grid imports for the electricity consumed by the electrolyzer. However, in 2023, grid imports for electrolyzer consumption are not subject to energy tax. The assumption made was to include the tax on grid imports for electrolyzer consumption in a worst-case scenario from an economic perspective for the real estate owner.

7.1.1 CAPEX for energy storage components.

Energy storage plays a significant role in reducing the average price of electricity purchases through electricity purchases during hours of low electricity prices, leading to a decreased average price of SEK/kWh. This section will delve into the investment costs associated with the storage components. Table 7.1.1.1 summaries the total and annual CAPEX below.

Investment plan for storage components

Component	Capacity	CAPEX (MSEK)	Lifetime (Years)	Annual OPEX 5% inrest rate(MSEK)	Annual OPEX 2,5% inrest rate (MSEK)
Battery	4 (MWh)	21,8	15	1,5	1,2
Fuel cell system	1,5 (MW)	14	20	0,8	0,6
Electrolyzer	6 (MW)	31	30	1,4	1
H2 storage	5 (Ton)	20,5	15	1,4	1,2
H2 Station	700 bar	20	15	1,3	1,1
(Heat pump)	2 (MW)	17	15	1,1	1
Total		125		7,5	6,2

Table 7.1.1.1 Overview of CAPEX cost for storage components. As well as the payment plan for the CAPEX investment [14], [15], [18], [22] and [27].

Storage components contribute to CAPEX that is 70% (87.5 MSEK) covered by bank loans and 30% (37.5 MSEK) equity capital. CAPEX for storage components is the same for both traditional and energy sharing ownership structure. Since the scenarios include a heat pump system, storage components will contribute with annual bank loan expenses of 6.2-7.5 MSEK annually depending on the interest rate, for calculations below the 6.2 MSEK from a 2.5% interest rate will be used. At the beginning of the thesis the interest rate was 2.5%, subsequently rising to 5% when the current calculations were made. The interest rate has been on historical low levels for some years even negative interest rates have been experienced. In the final stages of the project, the interest rate has increased. Therefore, the difference is illustrated between an interest rate of 2.5% and 5%. 5% would have been more likely to base the calculations on if the work had started at the time of its completion.

Storage components presented in Table 7.1.1.1 have a specific lifetime, this lifetime can change depending on the operational circumstances, hence it is vital for the energy system to use the components wisely to avoid risks of degradation in advance. The cost and lifetime of the storage components are not the price of 2023, depending on when the installation will be made the price will change. To estimate prices for 2031 articles like [14], [15], [18] and [27] and discussions with the industry participants have been used, therefore the price may differ from the estimations in the future.

In Figure 7.1.1.2, we present the annual expenses for Forsåker's energy system, including energy storage, for the year 2031. These expenses are categorized based on the annual day-ahead electricity prices from the years studied.

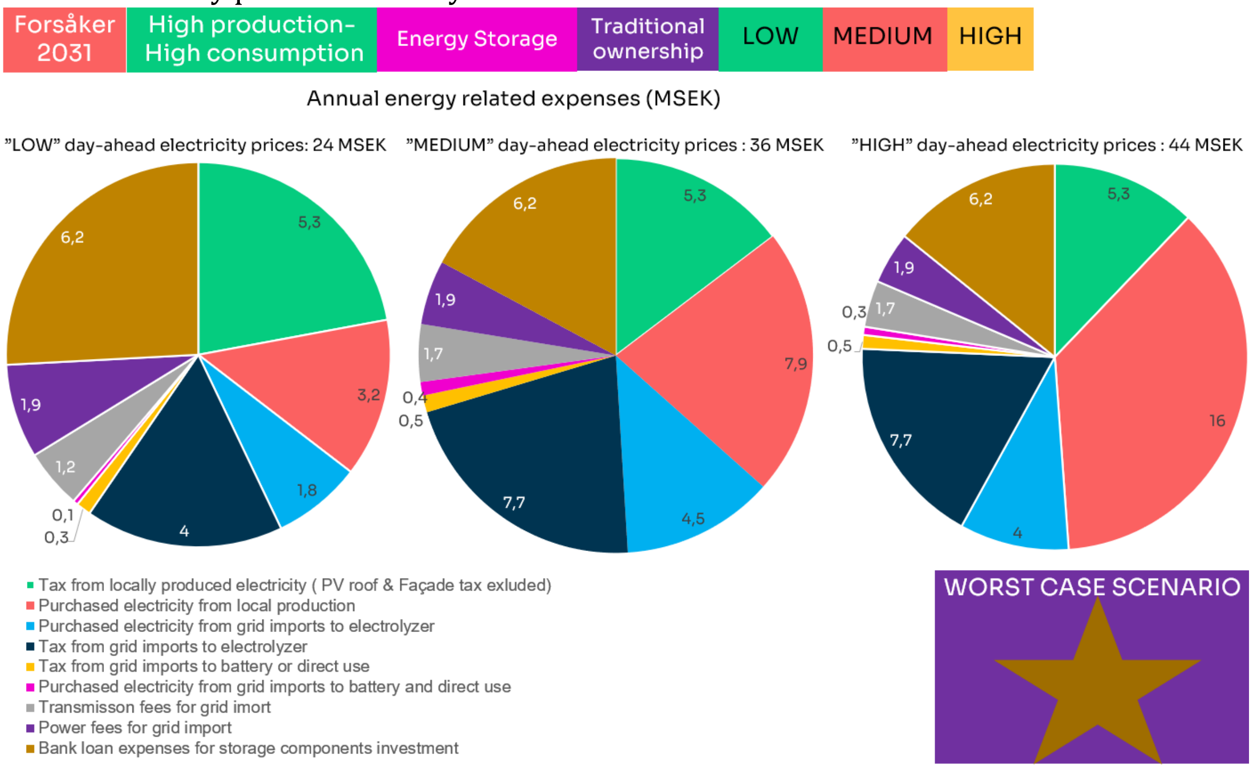


Figure 7.1.1.2 Annual OPEX purchases and taxes for the years 2016, 2021, and 2022.

The numbers in the pie charts in Figure 7.1.1.2 are the reason the Energy Storage - Traditional owner structure has been assumed the WORST-CASE scenario combined with the assumption of current hydrogen regulations of 2023, which state that electricity imports for hydrogen production through electrolysis are not subject to taxation will be changed so that electricity imports for hydrogen production will become subject of taxation 2031.

Depending on the hydrogen prices in 2031, a variable revenue from hydrogen sales will be generated for the Energy Storage - Traditional scenario. Apart from this, the expenses compared to the Baseline scenario are approximately between 20% to 60% higher across the examined day-ahead electricity price scenarios, which would result in a significant increase in energy-related expenditures. To make this scenario profitable compared to the Baseline scenario, very high hydrogen prices are required. However, a high emphasis on alternative values such as self-sufficiency and operational reliability could offset this cost increase for investments in storage-related components in an actual outcome in 2031, where Traditional ownership becomes a reality while electricity imports for hydrogen production via electrolysis are taxed. Otherwise, this would not be a favourable investment.

The numbers in Figure 7.1.1.2 indicate increased total expenses compared to the traditional ownership structure without energy storage, and to the Figure 7.1.1.2 expenses investment costs for Hydro power and Wind power will occur as well.

7.2 Energy sharing principle including energy storage

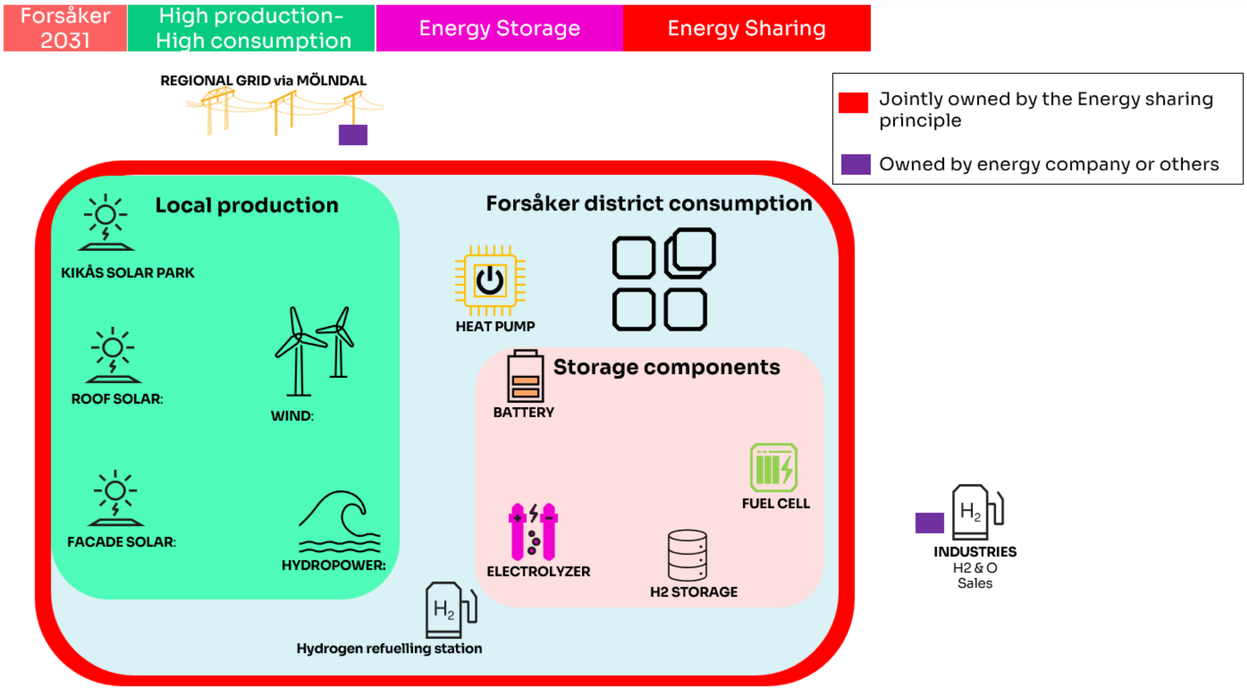


Figure 7.2.1. Overview of Forsåker's energy system and the energy sharing principal owner structure with energy storage 2031-High production-High consumption.

This Chapter presents annual expenses for Energy Storage - Energy sharing scenarios, as seen in Figure 7.2.1 all local production plants as well as storage components are jointly owned by the consortium in Forsåker illustrated by the red lines in the Figure. Inside the red line electricity taxes, transmission fees and power fees are not existent, since all electricity production and consumption are jointly owned, the produced electricity are assumed to not have market value and considered free. Instead, CAPEX and OPEX for electricity production plants and storage related components are added.

Electricity imports and exports between Forsåker and the regional grid is still required for electricity tax, transmission fees and power fees.

Expenses for electricity tax, transmission fees and power fees do still occur for electricity imports and exports between Forsåker and the regional grid. The exception is that the current regulation for 2023 states that electricity imports for hydrogen production are not taxed. In the BEST-CASE scenario, this current tax regulation also applies in 2031 and beyond. This means that all electricity imports from the regional grid would also be classified as non-taxable, even though the grid imports occur from the regional grid outside of Forsåker. However, transmission fees and power fees related to electricity imports for hydrogen production still need to be paid, despite not being subject to taxation, as Forsåker's consortium does not co-own the regional grid from which the electricity is imported.

If the current regulation for 2023, which exempts electricity imports for hydrogen production from taxation, is changed so that electricity imports for hydrogen production become taxable in 2031, it would result in increased costs for the Energy Storage - Energy

Sharing scenario. This means that the scenario would incur additional expenses due to the taxation of electricity imports for hydrogen production.

Figure 7.2.2 illustrates the BEST-CASE scenario for Energy Storage - Energy Sharing. The scenario includes LOW, MEDIUM, and HIGH day-ahead electricity price scenarios. Additionally, it assumes the current 2023 regulation, which exempts electricity imports for hydrogen production from taxation will be unchanged for 2031. This exemption plays a significant role in determining the annual expenses for the scenario.

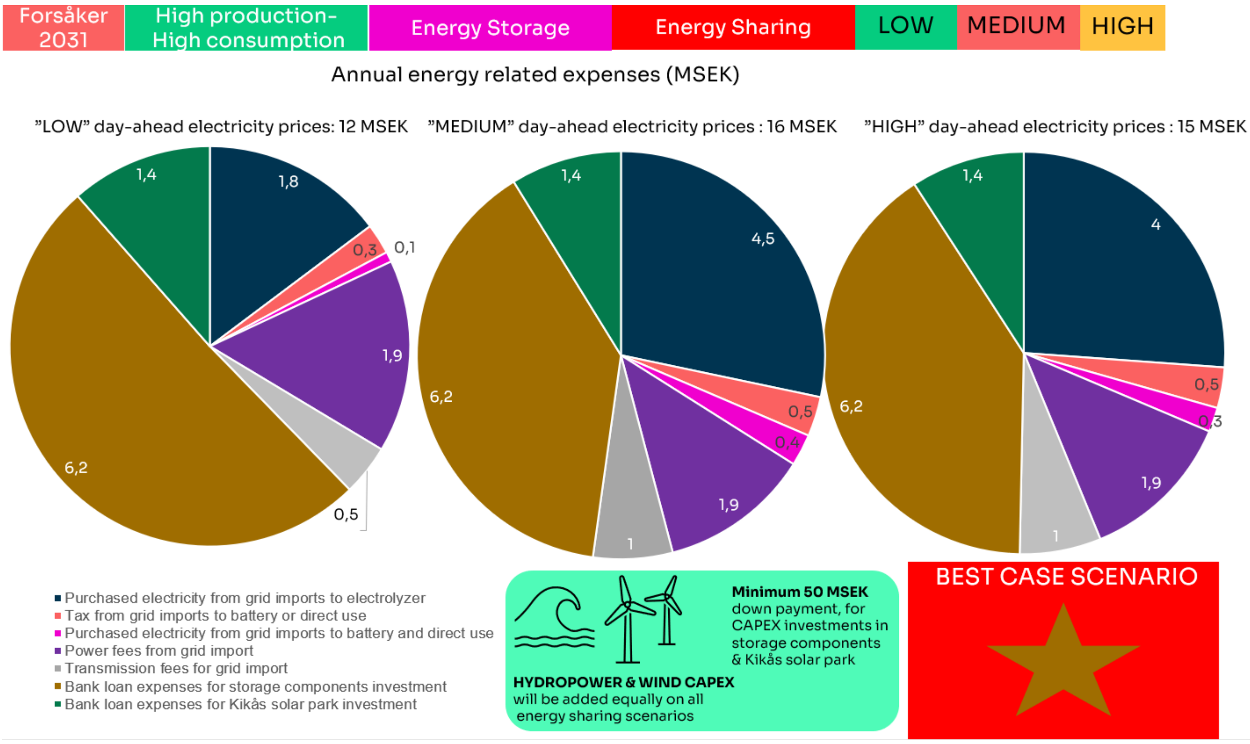


Figure 7.2.2 annual OPEX of electricity purchases, taxes, transmission, and power fees in an energy Sharing owner structure.

In the BEST-CASE scenario depicted in Figure 7.2.2 the annual expenses significantly decrease compared to all the Traditional ownership structure scenarios as well as the baseline scenario. Hydropower and Wind CAPEX and OPEX will need to be added equally to all Energy Sharing scenarios to make a fair comparison against all Traditional Ownership scenarios. Additionally, a minimum down payment of 50 million SEK is required for the investment in storage components and the Kikås solar cell park based on a 40% upfront payment for the investment. Regardless of the sum of hydropower and wind CAPEX and OPEX, the total annual expenses will increase. In discussion Chapter 9.3, costs for wind and hydro power plant estimations are based on the costs of Kikås solar park, to provide more relevant representation in the comparisons between traditional and energy sharing. Small differences between annual expenses for the LOW, MEDIUM and HIGH day-ahead electricity price scenarios occur in perspective to other scenarios, since fixed costs do not vary between LOW, MEDIUM, and HIGH scenarios. The market value of the local electricity production is not included because it is free, when local production and storage components are co-owned by the Forsåker consortium. Instead, fixed fees in the form of CAPEX and OPEX for the investments in local production and storage components are incurred.

The majority of the total electricity purchases related to day-ahead electricity prices consists of electricity imports from the regional grid for hydrogen production via the electrolyzer, which already occur at favourable day-ahead electricity prices in the LOW, MEDIUM, and HIGH scenarios. As a result, the fluctuation of electricity prices does not have a significant impact on the total expenses if there are many hours with low day-ahead electricity prices.

7.3 Specific value of component contribution

Each storage system component contributes with additional costs for every process the electricity is passing in the value chain of hydrogen production, which becomes a factor of consideration when designing the control parameters. As an example, when to purchase electricity for hydrogen production or battery storage instead of using stored energy and vice versa. To get an understanding of the total additional costs Figure 7.3.1. gives an overview of the frame of mind regarding cost by fuel cell produced electricity.

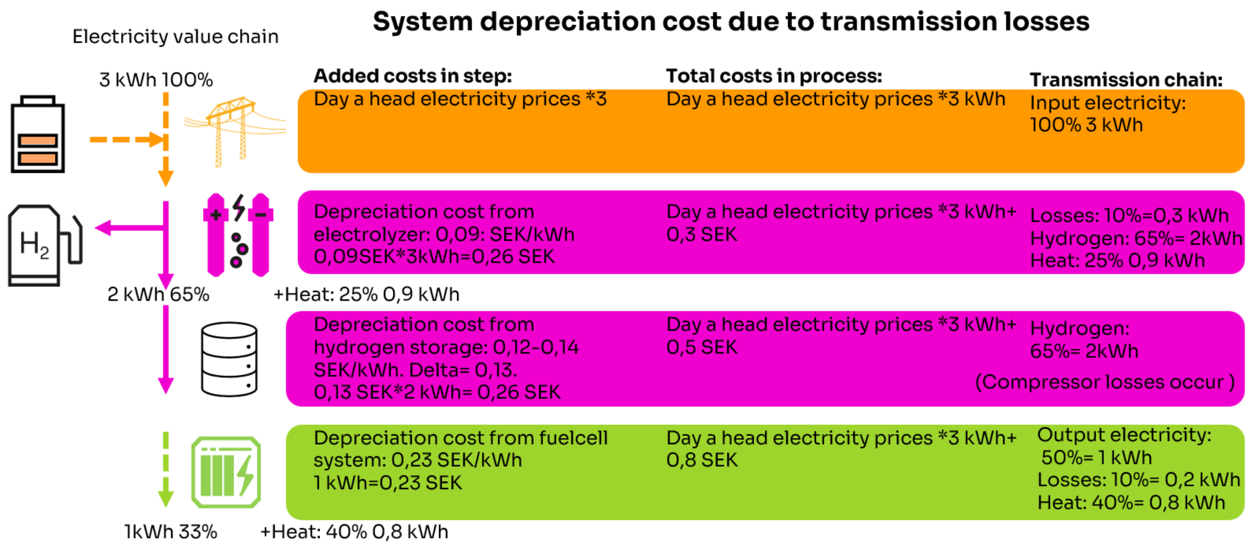


Figure 7.3.1. System overview of cost addition in the value chain of hydrogen and electricity production. Each added cost is based on component CAPEX converted into depreciation costs of 1 kWh produced by the fuel cell system.

Depreciation costs of 1 kWh of fuel cell output electricity through the value chain requires 3 kWh of input electricity, electricity allocated from local production can be considered as free but will still have a market value on the electricity grid. As seen in Figure 7.3.1 3 kWh of input electricity becomes 1 kWh of output electricity in the value chain, which is a huge loss in terms of electricity but if used during the right conditions can be beneficial in terms of system economy. Components in Figure 7.3.1 are primarily used for electricity or H_2 production, heat usage is secondary but important for increasing system efficiency.

The main task for the energy system is to hourly decide if the best option is to purchase those 3 kWh of electricity for direct consumption, from battery storage or hydrogen production. In comparison to produce 3 kWh of electricity from the fuel cell or from stored electricity in the battery. The best option depends on many factors, as a guidance it’s important to know additional depreciation costs for each process which will be explained below. As showed in previous chapters taxes, transmission fees and other costs will have an impact on the decisions as well.

Electrolyzer & Fuel cell system specifications based on 2031 targets.

Table 7.3.1 provides numbers related to the 6 MW electrolyzer and the 1.5 MW fuel cell system DOE target price of 2031 [15]. The electrolyzer lifetime is estimated to 90,000 hours. During its lifetime, it manages to process 540 GWh of electricity at maximum capacity for each hour, resulting in the production of 351 GWh of hydrogen. During real life operation the electrolyzer will not operate at maximum capacity for each hour which will lead to less than 351 GWh of hydrogen during its lifetime.

Hydrogen production cost estimation has been performed based on the electrolyzer CAPEX (capital expenditure) divided by its lifetime production at maximum capacity. Electrolyzer stack capacity is measured by its input capacity of consuming electricity, which add an additional cost of 0.06 SEK/kWh of input electricity which is 0.09 SEK per kWh measured in output energy when converted to hydrogen due to transmission losses. Fuel cells is measured by their stack output capacity of electricity production.

Estimated specifications of Forsåkers fuel cell system and electrolyzer 2031

	System size	Lifetime	End user cost	CAPEX	Hourly component depreciation cost	Hourly component depreciation cost per installed capacity
	kW	hours	USD/kW	MSEK	SEK/h	SEK/kWh
Fuel cell system	1500 (output)	40000 (20000)	900	14	350	0,23 (0,46)
Explanation of calculation	1500 KW system used in simulations	20000 of today 40000 DOE target	From DOE target	=1500kW*900USD/kW	=14000000 SEK/40000 hours	=350SEK/h /1500kw
Electrolyzer	6000 (input)	90000	500	31	344	0,06 electricity input 0,09 hydrogen output
Explanation of calculation	6000KW stack used in simulations	90000 DOE target	From DOE target	=6000kW*500USD/kW	=31000000 SEK/90000 hours	=(344SEK/h /6000kw =(344SEK/h /6000kw)/0,65

Table 7.3.1. Estimated fuel cell system and electrolyzer specifications.

Fuel cell system costs is distributed based on the same principle applies as with the electrolyzer, CAPEX divided into depreciation costs based on the total production of electricity during the system's lifetime until end of life. To get a real-life operation value additional cost for component maintenance must be included which they are not in the study. Examples are filter and cooling fluids exchange for the fuel cell and electrolyzer. Electrolyzer operations requires water purification that incurs costs but is not included in the study.

The fuel cell system, such as the one from Powercell, currently has a lifetime of 20,000 hours. Reaching the end of life (EOL) does not mean the system completely stops functioning. It indicates that the degradation of the fuel cell system has reached a specific level, which affects the amount of hydrogen needed for every kWh of electricity produced by the fuel cell.

For stationary use, this degradation does not necessarily have negative implications since Forsåker has a heat consumption demand. As the fuel cell system degrades further, more hydrogen will be consumed, resulting in a balance between hydrogen cost and the CAPEX cost for the fuel cell system.

The 20,000-hour lifetime of today compared to the 40,000 hours DOE target 2031[15] gives an 100% increased lifetime. The lifetime of today with the DOE 2031 CAPEX target gives an additional cost of 0.46 SEK per kWh produced by the fuel cell seen in Figure 7.3.1. Target prices are used since the fuel cell system and electrolyzer will be set to operation

2031 and therefore purchased a few years in advanced from 2031. Depending on the operation for each fuel cell stack, the overall system of 15 stacks may excess 40000 hours durability since all of them aren't always required to operate simultaneously. An increased fuel cell system lifetime would decrease the additional depreciation cost in terms of SEK/kWh but has not been considered.

If the 2031 DOE prices and lifetime target is not achieved the additional cost of hydrogen production via electrolysis and electricity production via fuel cell will become greater than the numbers showed in Table 7.3.1. If the actual prices 2031 are lower than DOE 2031 target prices, and actual lifetime 2031 are longer than the DOE target, the overall cost of hydrogen production via electrolysis and electricity production via fuel cell will less than numbers showed in Table 7.3.1. Therefore, it's important to note that these cost estimates and lifetime values may vary compared to actual costs and lifetimes depending on the specific fuel cell system and technological advancements in the future.

Hydrogen storage and sales

All hydrogen produced in Forsåker will not be used by the fuel cell system in Forsåker. H_2 sales enable hydrogen production during favourable day ahead electricity prices even if the hydrogen storage is full, as well as increased sector coupling. H_2 sales increase cashflow and higher costs as well as increased system complexity. Figure 7.3.2. illustrates and explains the depreciation cost of 1KG of hydrogen from electricity to storage, direct sales, or sales via the hydrogen refuelling station.

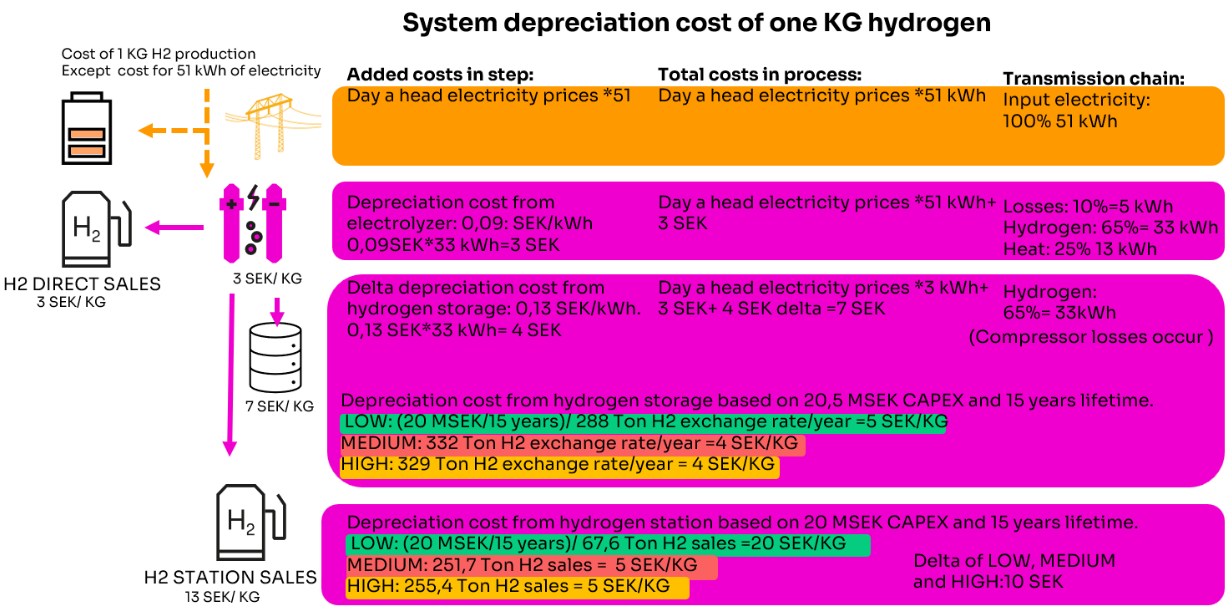


Figure 7.3.2. System overview of cost addition in the value chain of hydrogen production. Each added cost is based on the CAPEX converted into depreciation costs for one KG hydrogen.

To produce one kg of H_2 51 kWh of input electricity is needed, the cost of 51 kWh varies depending on local production or day ahead electricity prices. Added CAPEX cost per kg produced H_2 by the electrolyzer will be 3 SEK/kg.

The cost of the 5000kg hydrogen storage is 20,5 MSEK divided by 5000 which gives 4100 SEK/KG H_2 capacity. During the storage lifetime of 15 years much more than 5000 kg of H_2

will flow through the storage due to an exchange rate. To distribute the 20,5 MSEK storage CAPEX in a fair way, added costs for each kWh of hydrogen from the storage is depending on the annual exchange rate of hydrogen in the storage. Figure 7.3.2. illustrates how the 20 MSEK hydrogen storage CAPEX is distributed by the hydrogen passing by Forsåkers storage during the 15-year lifetime.

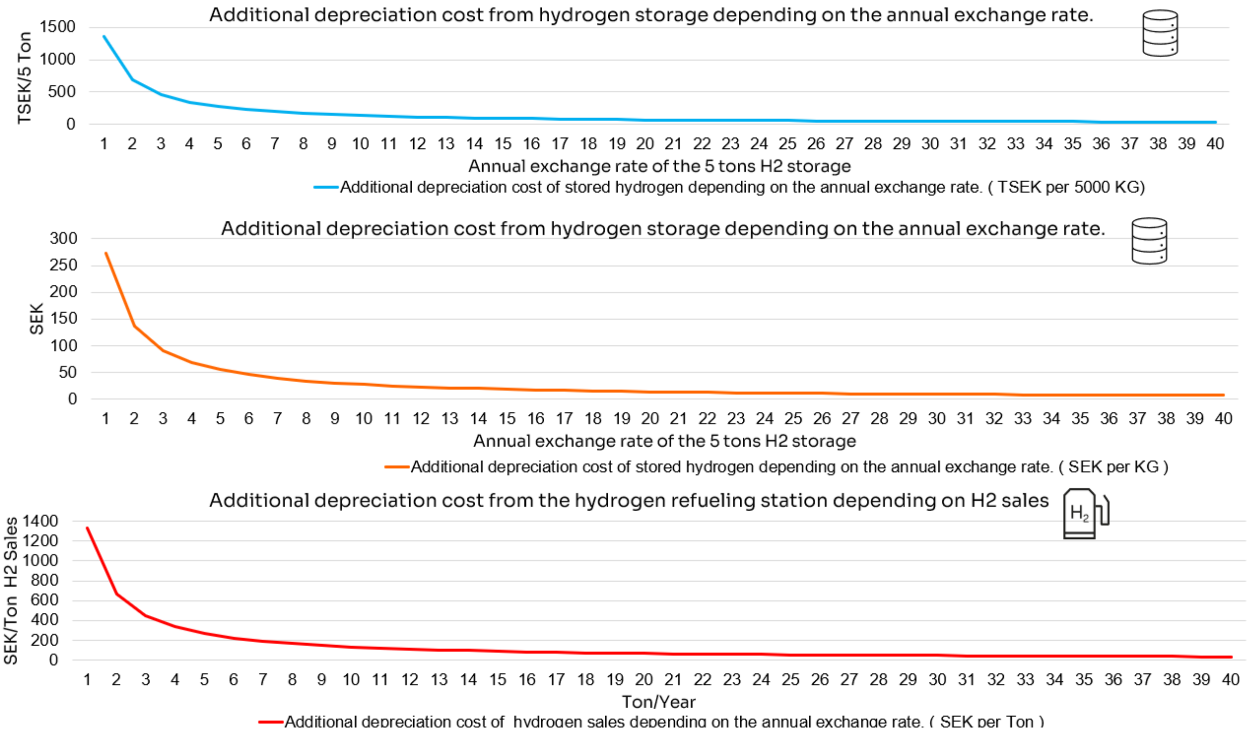


Figure 7.3.3. Illustration of addition depreciation costs as a function of the exchange rate of the 5000 kg H_2 storage. Illustration of addition depreciation costs as a function of the amount of stored hydrogen and hydrogen sales.

Each year the storage system costs 1,3 MSEK, Figure 7.3.3. illustrates that the more hydrogen that passes through the cheaper it gets in terms of SEK/kg of stored H_2. Since H_2 consumption in Forsåker varies annually, the hydrogen storage exchange rate and cost per kg of stored H_2 will vary during time as well. As seen in Figure 7.3.2. during LOW day ahead electricity price scenario, 231 ton H_2 is consumed by the fuel cell system in Forsåker which gives an additional depreciation cost of 5 SEK/stored kg H_2. The additional cost for HIGH is 4 SEK/stored kg H_2 due to a higher exchange rate of hydrogen in HIGH compared to LOW.

Figure 7.3.2. also shows how the 20,5 MSEK hydrogen refilling station CAPEX is distributed by the overall H_2 sales at its 15 years lifetime. Figure 7.3.3. illustrates how the H_2 refilling station costs of 1.4 MSEK annually are divided to the amount of hydrogen sales, the more hydrogen that passes through the cheaper it gets in terms of SEK/kg of sold H_2. H_2 sales varies between LOW, MEDIUM and HIGH day ahead electricity price scenarios with an average additional depreciation cost of 10 SEK/kg of sold H_2.

The overall cost to sell 1 kg of H_2 at the refilling station can be 13 SEK + additional costs of the 51 kWh required to produce 1 kWh of H_2. Distribution of additional depreciation cost for each component can be misleading, since some H_2 may be stored and later sold. Annual total amount of 356-584 tons of H_2 production could be distributed equally of both the hydrogen storage and refuelling station instead of divided as in Figure 7.3.2. The additional depreciation cost per kg sold and stored kg of H_2 would then change but the total energy system CAPEX would still remain the same. Overall system economy will therefore be the most vital thing to investigate. Maintenance costs is important to consider in real life operation since higher usage of the components leads to increased maintenance.

H_2 direct sales has not been investigated in the study more than it will be a demand for it 2031, the cost for 51 kWh +3 SEK are therefore all the known costs. Hydrogen is used in industries but then the purchase price is higher due to expenses for the transportation. As many options for hydrogen transportation are emerging, examples are NIKOLAs hydrogen distribution company HYLA, Plug power and NEL. The HYLA tube storage trailer is one example of transportation methods to use when transporting hydrogen sales to industries, it can transport 970 kg of hydrogen which is near 20% of Forsåker's total storage. No significant focus has been placed on investigating H_2 sales to industries in detail.

Battery

The inclusion of a battery in the storage system is crucial for the simulation and operation of the system. Estimating the specific CAPEX for the battery in terms of added cost per kWh stored is indeed complex and can vary depending on several factors.

To simplify the calculation, the thesis considers the battery CAPEX as an extra monthly expense that depends on the interest rate. This approach allows for the inclusion of the battery's cost in the overall financial analysis without explicitly quantifying it as a separate cost per kWh stored.

8. Financial comparison of storage and non-storage scenarios 2031

In this Chapter, the expenses for each scenario presented in Chapter 6 and 7 will be analysed from an economic perspective to facilitate a comparison. It is crucial to note that while a specific scenario may appear more profitable than others based on the analysis, it is essential to consider the uncertainties and potential changes that can arise until 2031. For all scenarios mentioned in Chapter 8, LOW is based on day a head electricity prices from 2016, which had the lowest average price of 0.278 SEK/kWh annually, MEDIUM is based on day ahead electricity prices from 2021 which had an annual average price of 0.672 SEK/kWh and HIGH is based on day-ahead electricity prices from 2022 with an average of 1.371 SEK/kWh annually.

8.1 Annual expenses for all scenarios

In Table 8.1.1, the annual expenses that impact the scenarios without storage are compiled based on the pie charts presented in Chapters 6 and 7. It is important to note that in the energy sharing scenarios, the CAPEX for hydropower and wind power investments need to be included to provide a fair estimate of the results between energy sharing and traditional ownership structure.

The assumed interest rate for the expenses is 2.5%. This rate is used consistently throughout the analysis, including in the decision to use a 2.5% interest rate in the overall comparison is influenced by the availability of "Green loans". Considering the expected increase in interest rates by 2023, the actual rates could potentially be closer to 5% now, whereas much can happen until 2031 when many of the loans are taken. It is worth noting that investments in green technology are generally perceived as future-proof, and this perception may lead to more favourable financing terms from banks. While the specific impact of "Green loans" and other subsidies has not been incorporated into the calculations, it is important to recognize that their availability could provide a positive aspect if such incentives can be obtained.

By providing a comprehensive overview of the annual expenses, the Table enables a comparative analysis of the different scenarios, considering factors such as interest rates and the inclusion of relevant investments.

Forsåker 2031 | High production- High consumption | Without energy storage

Annual expenses for scenarios without storage

Scenarios without energy storage		Energy sharing scenario (Exclusive CAPEX & OPEX for hydropower and wind power)			Traditional ownerchip scenario (BASELINE SCENARIO)		
Scenarios based on day-ahead electricity prices:		LOW (MSEK)	MEDIUM (MSEK)	HIGH (MSEK)	LOW (MSEK)	MEDIUM (MSEK)	HIGH (MSEK)
District heating expenses		5,2	5,2	5,2	5,2	5,2	5,2
Bank loan OPEX based on 2,5% interest rate from CAPEX Investments	Solar park	1,4	1,4	1,4	0	0	0
	Hydropower	–	–	–	0	0	0
	Wind turbines	–	–	–	0	0	0
Electricity purchases from:	Regional grid imports	1	2,6	4,7	1	2,6	5,6
	Local production imports	0	0	0	2,1	5,7	10,4
(Sales income: regional grid)	Exports to	(1)	(2,3)	(4,7)	0	0	0
Tax on electricity from:	Regional grid imports	1,6	1,6	1,6	1,6	1,6	1,6
	Local production export	1,7	1,7	1,7	0	0	0
	Local production import	0	0	0	3,4	3,4	3,4
Transmission fees on electricity from:	Grid import	0,2	0,2	0,2	0,4	0,4	0,4
	Local production export	0,2	0,2	0,2	0	0	0
	Local production import	0	0	0	0,2	0,2	0,2
Fixed costs:	Power fees	1	1	1	0,7	0,7	0,7
Total annual expenses		**12**	**14**	**16**	**15**	**20**	**28**

Table 8.1.1 Annual expenses for scenarios without storage.

As seen in Figure 8.1.1 expenses for “Without Storage scenarios” is gathered from the pie charts in Chapter 6, the baseline scenario results in increased expenses for both LOW, MEDIUM and HIGH day-ahead electricity scenarios. However, CAPEX and OPEX must be included to all Energy Sharing scenarios to get a fair comparison between them and the Traditional ownership structure. Energy Sharing scenarios contribute to an income based on electricity exports to the regional grid, Traditional ownership structure contributes to a tiny income based on electricity exports to the regional grid as well due to the roof and solar façade export of excess electricity to the regional grid.

In all the investigated day-ahead electricity price scenarios, higher average electricity prices or increased price fluctuations result in greater benefits for the Energy Sharing scenarios. However, if a LOW electricity price scenario were to become the new norm in 2031, the investments required for local production in the Energy Sharing scenarios might not be as profitable or worthwhile. Despite the additional Hydro and Wind CAPEX and OPEX in the Energy Sharing scenarios, the difference compared to the Baseline scenario would be minimal in such a scenario.

In Table 8.1.2 annual expenses that affect scenarios with storage are gathered from the pie charts in Chapter 7. Important to consider is that all electricity that is used for hydrogen consumption will not be consumed in Forsåker, hence hydrogen sales will be added in Chapter 8.2 as well.

Forsåker 2031	High production-High consumption	Energy Storage

Annual expenses for storage scenarios

Energy storage system scenarios		**Energy sharing scenario** (Exclusive CAPEX & OPEX for hydropower and wind power)			**Traditional ownerchip scenario**		
Scenarios based on day-ahead electricity prices:		**LOW** (MSEK)	**MEDIUM** (MSEK)	**HIGH** (MSEK)	**LOW** (MSEK)	**MEDIUM** (MSEK)	**HIGH** (MSEK)
Bank loan OPEX based on 2,5% interest rate from CAPEX Investments	Storage components	6,2	6,2	6,2	6,2	6,2	6,2
	Solar park	1,4	1,4	1,4	0	0	0
	Hydropower	-	-	-	0	0	0
	Wind turbines	-	-	-	0	0	0
Electricity purchases from:	Grid imports to electrolyzer	1,8	4,5	4	1,8	4,5	4
	Grid imports to battery or direct use	0,1	0,4	0,3	0,1	0,4	0,5
	Local production	0	0	0	3,2	7,9	16
Tax on electricity from:	Grid imports to battery or direct use	0,3	0,5	0,5	0,3	0,5	0,5
	Grid imports to electrolyzer	0	0	0	4	7,7	7,7
	Local production	0	0	0	5,3	5,3	5,3
Transmission fees on electricity from:	Grid import	0,5	1	1	1,2	1,7	1,7
Fixed costs:	Power fees	1,9	1,9	1,9	1,9	1,9	1,9
Total annual expenses without H2 taxation		**12**	**16** BEST CASE SCENARIO	**16**	**20**	**28**	**36**
Total annual expenses with H2 taxation		**16**	**24**	**23**	**24**	**36** WORST- CASE SCENARIO	**44**

Table 8.1.2. Annual expenses for energy storage scenarios.

As seen in Figure 8.1.2 expenses for "Storage scenarios" is gathered from the pie charts in Chapter 7, depending on the future tax regulations 2031 both the BEST-CASE and WORST-CASE scenarios of all investigated scenarios can be found in the Energy Storage - Energy Sharing respective Energy storage - Traditional owner structure scenarios. Based on the Figures at the bottom of the chart, these scenarios represent contrasting pools of annual expenses. What further determines the outcome is the hydrogen price for hydrogen sales, which is discussed in the subsequent Chapters.

For all the examined LOW, MEDIUM, and HIGH day-ahead electricity price scenarios, the annual expenses for Energy Sharing scenarios are lower compared to Traditional

Ownership structure expenses, regardless of whether electricity imports for hydrogen production are taxed or not. Additionally, it is evident that Energy Sharing scenarios become more advantageous as the 2031 day-ahead electricity price approaches the HIGH scenario compared to the LOW scenario.

8.2 Expenses in relation to income

To better assess the value of gross area in Forsåker, it is essential to consider rental incomes as they provide insight into the proportion of expenses in the studied scenarios. Rental incomes can vary significantly depending on various factors, particularly in a large district like Forsåker, where not all 245000 m^2 will be rented out equally. Table 8.2.1 presents the range of rental incomes per category in Forsåker for 2022, offering an estimate of the potential income generated in a range of 431-502 MSEK annually.

Property category	Gross area m2	SEK/m2 low rent	SEK/m2 high rent	Total rent income Low (MSEK)	Total rent income High (MSEK)
Residential property	180308	2000	2200	360	396
Office property	22622	1700	2000	38	45
School property	10073	2300	2600	23	26
Commercial property	16967	500	2000	8	33
Total rent income				**430**	**502**

Table 8.2.1. Rent incomes for the property types and gross areas in Forsåker, based on 2022 values in the current area. Values are provided by the company Croisette Real estate partner.

Table 8.2.2 showcases the income generated from hydrogen sales in the different scenarios studied. The income is based on the current hydrogen sales price in hydrogen stations, which is 90 SEK per kg of hydrogen. Additionally, the price target for 2030 is estimated to be in the range of 3-4 EUR per kg of H_2. It is worth mentioning that the USA Inflation Reduction Act (IRA) [16] provides subsidies of 3 USD per kg of green hydrogen produced to the producer. If Forsåker's hydrogen production were in the USA, it would likely be eligible for this subsidy. However, the inclusion of a similar subsidy system in the EU has not been factored into the calculations due to the uncertainty and potential changes in political decisions.

Annual H2 sales parameters

Based on day -ahead electricity price	H2 Sales (Ton)	H2 price target 2030(Low)	H2 price 2023 (High)	Annual H2 sales Low (MSEK)	Annual H2 sales High (MSEK)
HIGH	255,4	40	90	10,2	23
MEDIUM	251,7	40	90	10	22,7
LOW	67,6	40	90	2,7	6

Table 8.2.2. Hydrogen sales and incomes depending on scenarios and H_2 prices.

As observed in Tables 8.2.1 and 8.2.2, the income generated from hydrogen sales fluctuates based on the price of hydrogen and the quantity of hydrogen sold. However, in comparison to rent incomes, the share of income from hydrogen sales is relatively low. This indicates that the rental income from the district, which can vary depending on factors such as occupancy rates and rental agreements, plays a more significant role in the overall income estimation.

In Table 8.2.3, a comprehensive overview of annual incomes and expenses related to energy is presented. However, it is important to note that rent incomes have not been included in this calculation due to time limitations. If other expenses for the real estate operation, such as cleaning, gardening, and other maintenance costs, were taken into consideration, including rent incomes would provide a fair alternative. Additionally, maintenance expenses for power plants and hydrogen components would be added as well, although they were not included in the scope of the thesis work.

Forsåker 2031 | High production-High consumption

Energy related profits for all scenarios based on expenses and incomes

Energy storage system scenarios	Energy sharing scenario (Exclusive CAPEX & OPEX for hydro & wind power)			Traditional ownership scenario		
Day-ahead electricity price scenario	LOW (MSEK)	MEDIUM (MSEK)	HIGH (MSEK)	LOW (MSEK)	MEDIUM (MSEK)	HIGH (MSEK)
EXPENSES scenarios:						
Hydrogen production is not subject to taxation	12	16	15	20	28	36
If hydrogen production is subject to taxation	16	24	23	24	36	44
INCOMES scenarios:						
Hydrogen sales: High price	6	23	23	6	23	23
Hydrogen sales: Low price	2,7	10	10,2	2,7	10	10,2
Profit: Expenses+ annual income						
If H2 production is not subject to taxation & High H2 prices	**-6**	**7**	**8** (BEST-CASE SCENARIO)	**-14**	**-6**	**-13**
If H2 production is subject to taxation & High H2 prices	**-10**	**-1**	**0**	**-18**	**-14**	**-21**
H2 production is not subject to taxation & Low H2 prices	**-10**	**-6**	**-5**	**-17**	**-18**	**-26**
If H2 production is subject to taxation & Low H2 prices	**-14**	**-14**	**-13**	**-21**	**-26**	**-34** (WORST- CASE SCENARIO)
Scenarios without energy storage						
Total annual expenses	12	14	16	15	20	28
Sales of regional grid exports	1	2	5	0	0	0
Profit: Expenses+ annual income						
Annual profit	**-11**	**-12**	**-11**	**-15**	**-20**	**-28** (BASELINE-SCENARIO)

Table 8.2.3. Annual profit for all scenarios in income after known expenses, the expenses are a small share of the overall incomes even though the fluctuation between the results are high in MSEK.

As seen in Table 8.2.3 annual energy related expenses varies a lot depending on future regulations, H_2 prices and type of ownership structures in Forsåker for both LOW, MEDIUM and HIGH day ahead electricity price scenarios. As energy is traditionally perceived as an expense by property owners, it may be easy to assume that only the MEDIUM and HIGH day-ahead electricity price scenarios can be profitable since they are the only two showing positive results. It is indeed true that excluding hydro and wind CAPEX and OPEX, the

MEDIUM and HIGH day ahead electricity price scenarios are the only ones that lead to an annual net income from energy-related revenues and expenses overall.

Energy expenses are traditionally seen as costs for property owners, the ownership of renewable energy sources and energy storage can now generate annual income for property owners or the consortium as in MEDIUM and HIGH in the BEST-CASE scenario. Investments in renewable energy sources and/or energy storage result in varying degrees of savings compared to the BASELINE scenario, even though the final line does not show a positive result.

To clarify that more than just the MEDIUM and HIGH day-ahead electricity price scenarios in the BEST-CASE scenario contribute to savings compared to not making any changes at all, Table 8.2.4 below will display each scenario's savings or increased expenses compared to the BASELINE scenario, which remains unchanged.

Forsåker 2031	High production-High consumption

Comparison of investment savings across all scenarios based on the baseline scenario

Energy storage system scenarios	Energy sharing scenario (Exclusive CAPEX & OPEX for hydro & wind power)			Traditional ownership scenario		
Day-ahead electricity price scenario	**LOW** (MSEK)	**MEDIUM** (MSEK)	**HIGH** (MSEK)	**LOW** (MSEK)	**MEDIUM** (MSEK)	**HIGH** (MSEK)
If H2 production is not subject to taxation & High H2 prices	**9**	**27**	**36**	**1**	**14**	**15**
	BEST-CASE SCENARIO					
If H2 production is subject to taxation & High H2 prices	**5**	**19**	**28**	**-3**	**6**	**7**
H2 production is not subject to taxation & Low H2 prices	**5**	**14**	**23**	**-2**	**2**	**2**
If H2 production is subject to taxation & Low H2 prices	**1**	**6**	**15**	**-6**	**-6**	**-6**
				WORST- CASE SCENARIO		
Scenarios without energy storage						
	4	**8**	**17**	**0**	**0**	**0**
				BASELINE-SCENARIO		

Table 8.2.4. Table shows energy related savings or higher expenses compared to the non-storage- traditional ownership scenario.

As shown in Table 8.2.4 some scenarios result in annual savings compared to the BASLINE scenario whereas some scenarios result in increased expenses. Given that future parameters cannot be predicted, it is important to understand under which future conditions it is beneficial to take the risk and invest in production facilities and energy storage, as well as under which conditions it is not. For example, if the government does not allow Energy Sharing scenarios or if the involved owners of Forsåker choose traditional ownership structure. Additionally, the impact of taxation regulations and hydrogen prices on the system's economy is crucial. Therefore, the following ranking from BEST-CASE to WORST-CASE will be presented in a Table to highlight the importance of all influencing parameters.

Figure 8.2.5 shows the resulting annual profits for Forsåker's energy system for all investigates scenarios:

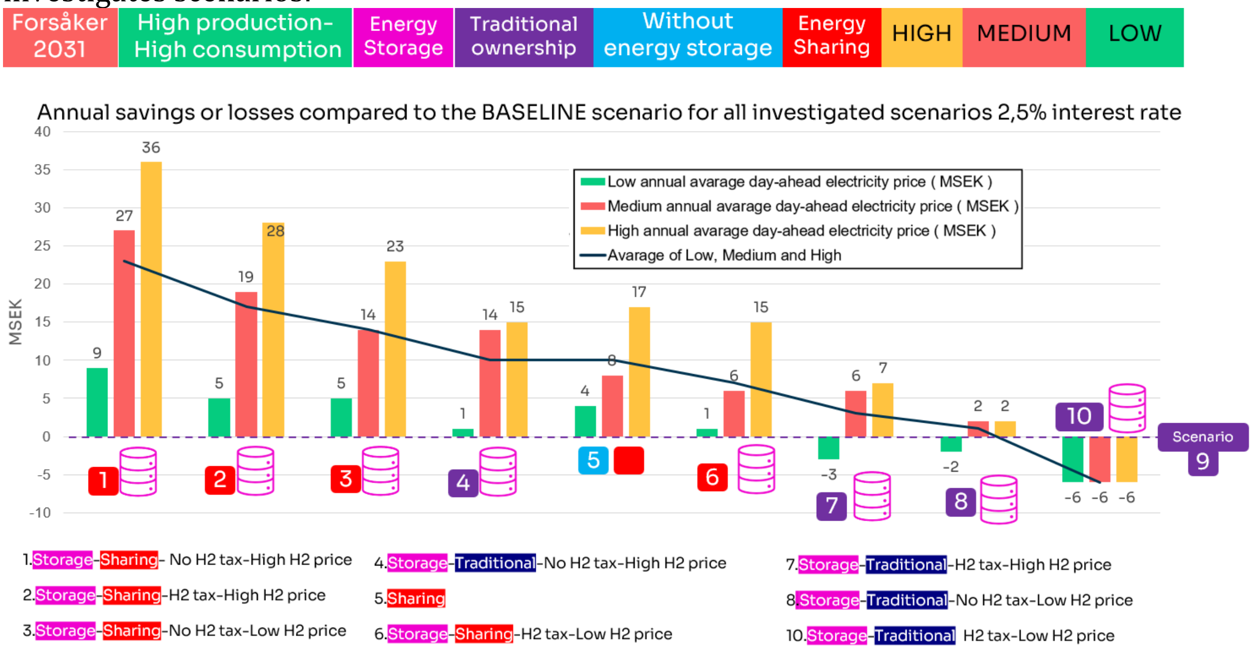


Figure 8.2.5. Annual savings or losses compared to the BASELINE scenario for all investigated scenarios. (The x-line showed 0 stands for scenario 9 (BASELINE) which equals annual energy expenses of 15 MSEK in the LOW, 20 MSEK in MEDIUM, and 28 MSEK day-ahead electricity price scenarios)

Important to know is that bars in Figure 8.2.5 are expected savings or losses compared to the Baseline scenario number 9, which represents no investment in electricity production, energy storage or energy sharing. All bars above 0 in Figure 8.2.5 illustrate a number in MSEK saved compare to scenario 9 and not necessarily a profit. Vise verse for numbers below 0 in Figure 8.2.5 which illustrate losses compared to scenario 9. Traditionally, real estate companies pay for heat and electricity. Investments in energy production and storage that lower those annual payments can be attractive even if no profit is generated, that is one reason that the scenarios are presented the way they are in Figure 8.2.5. The best case scenario number 1 is generating a real profit in MEDIUM and HIGH electricity price scenarios. Since all scenarios rely on future assumptions a certain safety margin in savings is necessary as compensation for the investment risk. Investing in energy production and storage components requires an additional 30% of CAPEX for component investments.

As seen in Figure 8.2.5 above all investigated scenarios are ranked from the number 1. BEST-CASE scenario to the number 10. WORST-CASE scenario by annual savings or losses compared to the BASELINE scenario.

1. The BEST-CASE scenario is Energy Storage - Energy sharing with high hydrogen prices (90 SEK/kg H_2) combined with assumption that the current hydrogen taxation of 2023 will remain until 2031 and forward, meaning that electricity imports for hydrogen production via electrolyzer is not a subject of taxation.

2. As long as the other circumstance from the BEST-CASE scenario remains, a political regulation changes so that electricity imports for hydrogen production will become a subject of taxation will be the second-best case scenario.

3. The third best case scenario is Energy Storage- Energy sharing with low hydrogen prices (2030 target price of 4 EUR/kg H_2) combined with assumption that the current hydrogen taxation of 2023 will remain until 2031 and forward, meaning that electricity imports for hydrogen production via electrolyzer is not a subject of taxation.

4. Energy storage- Traditional ownership structure is the fourth best alternative, if future H_2 prices 2031 and beyond remain high (90 SEK/kg H_2) combined with assumption that the current hydrogen taxation of 2023 will remain until 2031 and forward, meaning that electricity imports for hydrogen production via electrolyzer is not a subject of taxation.

5. The fifth and middle alternative is the Energy sharing principle without hydrogen storage scenario.

6. Energy Storage- Energy sharing with low hydrogen prices (2030 target price of 4 EUR/kg H_2) combined with assumption that the current hydrogen taxation of 2023 will be changed until 2031 and forward, meaning that electricity imports for hydrogen production via electrolyzer is a subject of taxation.

7. Energy Storage- Traditional ownership structure with high hydrogen prices (90 SEK/kg H_2) combined with assumption that the current hydrogen taxation of 2023 will be changed until 2031 and forward, meaning that electricity imports for hydrogen production via electrolyzer is a subject of taxation.

8. Energy Storage- Traditional ownership structure with low hydrogen prices combined with assumption that the current hydrogen taxation of 2023 will be remain until 2031 and forward, meaning that electricity imports for hydrogen production via electrolyzer is not a subject of taxation.

9. BASELINE scenario is the Traditional owner structure-Without energy storage, meaning no investment or change in structure are necessary. Depending on the future day ahead electricity price scenarios 2031 are close to a LOW, MEDIUM or HIGH scenario annual energy related expenses will range from 15 to 28 million SEK, which are set to zero in Figure 8.2.5 to enable a clearer comparison between annual savings or losses to see how attractive the investment in electricity production and storage components will become depending on future parameters in Forsåker 2031.

10. The WORST-CASE scenario, is if the future conditions 2031 and beyond involve Traditional Ownership structure, taxation on hydrogen production, and low hydrogen prices, the investment in energy storage is not economically attractive. However, other factors such as self-sufficiency and reliability, or the contribution to increased sector coupling may be crucial considerations for energy storage investments.

All simulations for energy storage scenarios have been conducted with a focus on benefiting Energy Sharing-Energy Storage scenarios. If other parameters become a reality in Forsåker in 2031, it is possible that new simulations with a focus on the actual outcome could improve the economic performance of the system. Additionally, increased optimization for the balance of control parameters between the storage components and their size could enhance the economics of the scenarios that are currently not economically attractive, as shown in Figure 8.2.5.

9. Discussion

9.1 How will future energy flows look like in the urban development project Forsåker?

The energy flows in Forsåker 2031 will vary significantly depending on the presence of energy storage. Therefore, the energy flows in Forsåker will first be examined without storage and then with energy storage.

9.1.1 Without energy storage

In this Chapter, the focus will be solely on the chosen scenario for investigation, which is "A fully developed Forsåker 2031 - High production High consumption." More comprehensive details about this scenario can be found earlier in the report.

Annual production and consumption preconditions:

The results indicate that in the Forsåker 2031 - High Production - High Consumption scenario. Without energy storage of hydrogen and batteries, the district has a higher local production than consumption on an annual basis, making it a positive energy district (PED). This conclusion is based on the assumption that the heat demand covered by Riskulla is not included. If the heat demand were instead met with a heat pump, the electricity consumption would increase by approximately 3 GWh. The predicted local production, which includes solar, wind, and hydropower, amounts to 14.5 GWh. Since, the predicted electricity consumption in Forsåker amounts to 13.9 GWh annually (excluded Riskulla's 8.4 GWh heat distribution), resulting in a self-sufficiency rate of 104.5%.

Hydropower plant accounts for 42.2% of the local production, while the Kikås solar plant contributes 26.7%. These two sources are crucial in meeting the criteria for a positive energy district (PED), as they significantly contribute to covering the annual consumption in Forsåker. Without them, only 30% of the annual consumption would be supplied by local production.

Even if the annual local electricity production equals 104.5% of Forsåker's consumption, only 4400 hours of the year can be covered by local electricity which is 50.2% of the year. During the 4400 hours 10.2 GWh is directly consumed in Forsåker, whereas 4.3 GWh are exported to the regional grid resulting in a local electricity usage of 71.8% of the total production. The remaining 4360 hours, which stands for 49.8% annually, requires grid imports of 3.6 GWh which is 25.9% of the total annual consumption. Only battery storage would in some degree provide a higher redundancy but has not been investigated in the thesis.

The local production reaches a maximum production of 5500 kWh/h and varies a lot depending on the weather, the hydropower is continuous during long periods but stops operating during summer due to less rainfall combined with a lack of damping capacity, a well-being flow must always flow in the river. The wind gives a steady contribution in all months during wind occurrence whereas the solar production peaks in summer and varies a lot on hourly basis. The combination of solar and water complement each other a lot especially since the hydropower stops operating during summer when the solar capacity contributes a lot.

Energy storage is an essential requirement to achieve self-sufficiency and maximize the benefits of local electricity production as part of achieving a climate-neutral power supply. Even if a PED is achieved annually, Forsåker will still be dependent on grid imports and exports every hour of the year. However, the benefits and possibilities of utilizing energy storage are not limited to this. Below are the key identified benefits of energy storage based on this preliminary study:

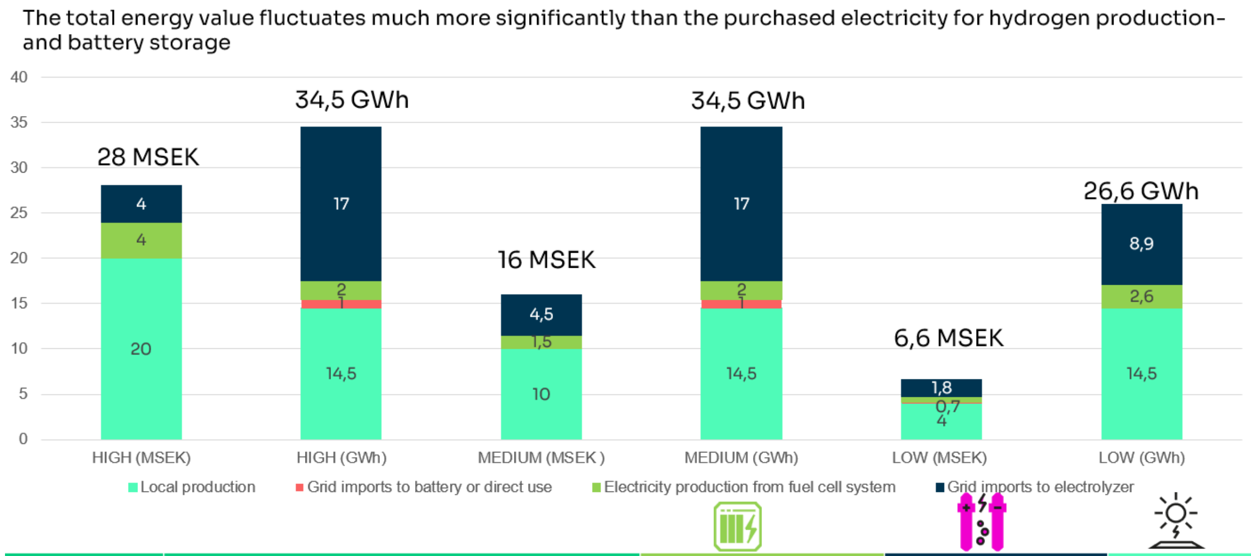
- Storing energy during surplus from local electricity production daily and over shorter time periods.
- Shifting the load of electricity demand to optimize the utilization of local electricity production daily.
- Reducing local peak power demands, such as for fast charging of electric vehicles.

Even if the hydro and wind CAPEX still are excluded the energy sharing scenario would result in a positive outcome regarding ownership structure, hence it is important for real estate owners to push this question to policy makers even if energy storage is not an alternative.

9.1.2 With energy storage

Figure 9.1.2.1 shows the investigated scenarios with energy storage in Forsåker consisting of 5-ton H_2 storage and 4 MWh battery.

Forsåker 2031	High production-High consumption	Energy Storage	LOW	MEDIUM	HIGH



	Total average energy value SEK/ KWh	SEK/ KWh	SEK/ KWh	SEK/ KWh
HIGH	0,81	2	0,24	1,38
MEDIUM	0,46	0,75	0,26	0,69
LOW	0,25	0,26	0,2	0,28

Figure 9.1.2.1 Investigated scenarios with energy storage in Forsåker.

A seen in Figure 9.1.2.1 Forsåker's local consumption only stands for 41% up to 54% of the energy flow demand for Forsåker's energy storage system annually. The LOW, MEDIUM and HIGH electricity flows are based on the day-head electricity price, respectively from 2016, 2021 and 2022. Important to note for a fair comparison is that the energy flows mentioned above in Forsåker's energy system with hydrogen and battery storage are also utilized to meet the heat demand and generate income through hydrogen sales.

Between 30% to 60% of the hydrogen produced annually is utilized within the energy system of Forsåker. This indicates that even though the energy system in Forsåker will always have a higher electricity flow with energy storage compared to without storage, there will be transmission losses associated with energy storage. The quantities of electricity within the energy system are heavily influenced by the control parameters. If the production of hydrogen was not desired when the hydrogen storage is at full capacity, the energy flows would have decreased. Depending on future H_2 prices and local demand from vehicles and industries the share of H_2 sales may differ a lot to the expectations in the scenarios which also will affect the heat production.

9.2 How would energy storage consisting of hydrogen and batteries contribute to the Forsåker district?

Self-sufficient values

Off-grid operation for Forsåker is not possible annually even if off-grid operation is possible in the range of hours to weeks depending on the circumstances of the seasonal variations visualised in Chapter 5.2. Even with an energy system including storage, Forsåker will still be dependent on the regional grid to avoid power outages, an energy storage will increase the dependency of the regional grid on annually basis but reduce or eliminate the dependency of the regional grid on hourly up to weekly basis.

Even if the total amount of annual local production is 104.5% of Forsåker's annual consumption demands, transmission losses related to energy storage results in that more than 104.5% of the yearly electricity consumption is required to enable coverage of the consumption. No specific minimum or maximum amount of electricity has been assumed to cover Forsåker's annual consumption, due to:

- The amount of electricity needed to meet Forsåker's electricity demand in an energy system where energy storage depends on the mix of direct electricity consumption and fuel cell-generated electricity varies based on the electricity prices.
- The optimal approach mixes to meet the electricity demand, whether through direct electricity usage of imports from the regional grid or fuel cell production, depends on the electricity prices and relevant regulations. The decision is based on cost-effectiveness and the most advantageous option at a given time.
- The total electricity consumption also depends on H_2 storage and battery size.
- If all hours of undersupply are covered by direct local production, battery stored electricity and grid imports, annual consumption would be 13.9 GWh and if all hours of undersupply would be covered by FC production annual electricity consumption would be 21.1 GWh. None of those scenarios are optimal from an energy storage or reality perspective so depending on the mix the variation will be minimum 13.9 and maximum 21.1.

Focus on all energy storage scenarios has been on import more electricity than needed during hours of favourable electricity prices for H_2 production for H_2 sales when the H_2 storage reach its MAX SOF, hence an exact duration period of self-sufficiency without electricity imports from the regional grid for Forsåker's energy system including energy storage has not been investigated.

Due to variations in local production and Forsåker's consumption needs, the time of year is decisive for the length of the self-sufficiency period. If the conditions are like the described week in July in Chapter 5.2, where the energy system allocates much local production to the electrolyzer. Hydrogen storage levels slowly decrease since area consumption are covered mostly by direct consumption of local production and battery storage, fuel cell operation rarely occur during the July week. The electrolyzer rarely operate during the September week whereas fuel cell system operation is high, causing the hydrogen storage to decrease from full capacity to approximately 2 tons.

Self-sufficiency and operational reliability in the event of a crisis

Most likely all local production and the regional grid will not disappear simultaneously. Despite the low risk, it can be useful to know how long the energy storage will last.

Operating scenarios under normal conditions, including Forsåker's minimum consumption, maximum consumption, and maximum fuel cell production, are therefore displayed in Figure 9.2.1 below:

Figure 9.2.1. Minimum self-sufficiency periods during event of a crisis.

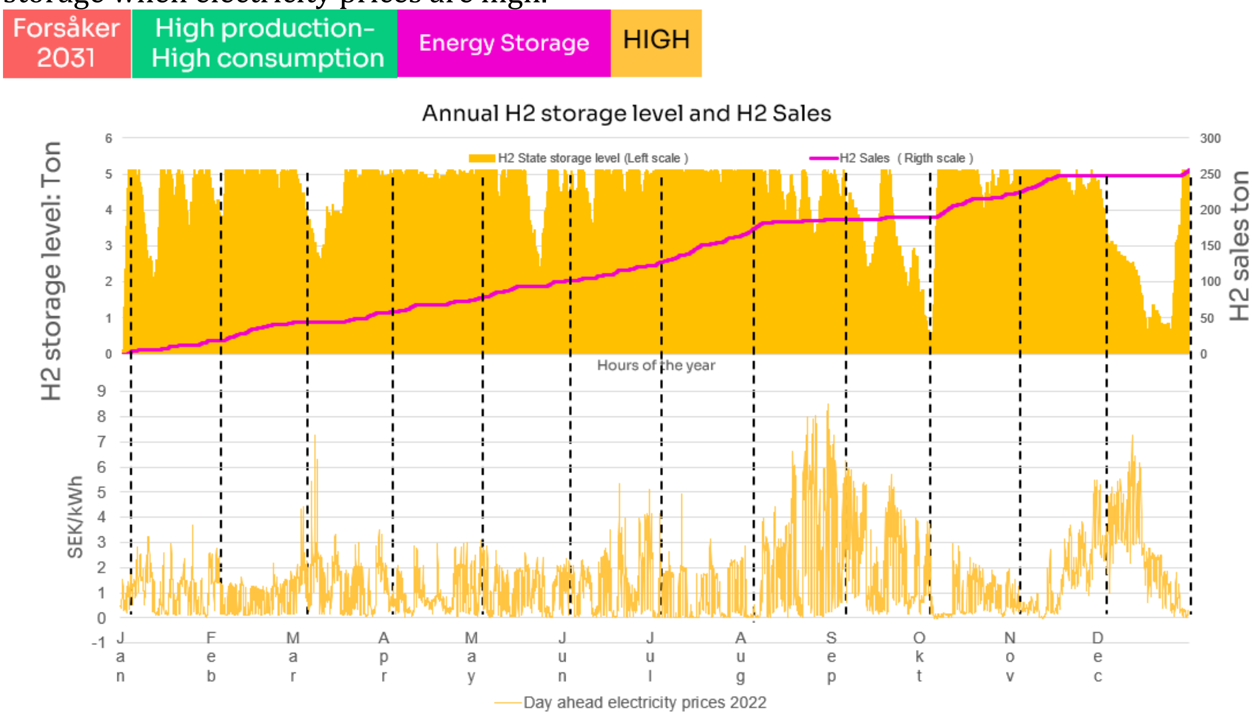
In an event of a crisis most likely only necessary consumption would be allowed depending on how critical it is for the district. In Swedish hospital buildings, different types of loads are differentiated based on the time-critical nature of the facility's electricity supply needs are. No such investigation has been made for Forsåker, therefore the minimum consumption are measurement points together with the maximum load of the FC system.

As seen in Figure 9.2.1 battery operation on its own can cover Forsåker's consumption demands for 1.5-4.5 hours depending on the consumption demand. FC production can provide Forsåker with electricity for 55 hours of maximum capacity and 91.7 hours of minimum consumption demand. The FC system on its own cannot manage Forsåker's peak consumption demands because of capacity limitations. The only noticeable change when the battery and FC system combined cover Forsåker's consumption demands without local production or regional grid availability is that 3.6 hours of peak consumption can be covered, otherwise the battery will add some hours of duration.

Self-sufficiency under normal operation

The focus on increased sector coupling has led to the lack of examination of a specific degree of self-sufficiency for Forsåker. In all the investigated years for energy storage scenarios, large amounts of electricity are imported from the regional power grid for further sales of hydrogen that is not necessarily used in Forsåker.

As seen in Figure 9.2.2 transfers of hydrogen sales occur as soon as the H_2 storage reach its maximum SOF. The control parameters of the energy management are set so that the H_2 storage system will never be empty. If the storage level decreases to a low level, it will increase grid imports on a higher average price under a longer period to avoid an empty storage when electricity prices are high.



Month:	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Excess (MWh)	-39	-100	-426	-549	-94	-33	-13					
Deficit (MWh)								199	221	70	84	61

Figure 9.2.2. Annual hydrogen storage SOF and hydrogen sales depending on the day ahead electricity prices from 2022 on hourly basis, as well as monthly electricity deltas from Forsåker's local production and consumption.

A relation between the H_2 SOF and day ahead electricity prices can be seen in Figure 9.2.2, during electricity price peaks the H_2 SOF decreases due to FC operation. During low electricity prices the electrolyzer operates and begin filling the storage with hydrogen. The electricity price is not always correlated with the hydrogen storage level since the hydrogen storage level also depends on Forsåker's' local production and consumption. However, electricity prices are often the controlling parameter as the quantity of imported electricity for H_2 production during low-price periods often exceeds the surplus of locally generated electricity. If there is an electricity deficit in Forsåker during low-price periods, the consumption demand is often covered by imported electricity for immediate consumption and electricity import for electrolyzer operation.

9.3 Sensitivity analysis of the results

The financial results in Figure 8.2.5 are based on many assumptions, but many influential factors have been overlooked as well. In this chapter some of those factors will be added to illustrate the behavior of the ranking between the scenarios rather than to give exact numbers for each scenario.

Interest rate variations

A determining factor for investments in general is the interest rate, the interest rate environment was more favorable at the beginning of the thesis writing, whereas a higher interest rate prevails during its completion meaning the cost of borrowed money has increased. The financial results in Figure 8.2.5 is based on the 2.5% interest rate whereas Figure 9.3.1 is based on the 5% interest rate to illustrate how savings for scenarios are shrinking compared to the Baseline scenario number 9 as well as increased losses for some scenarios.

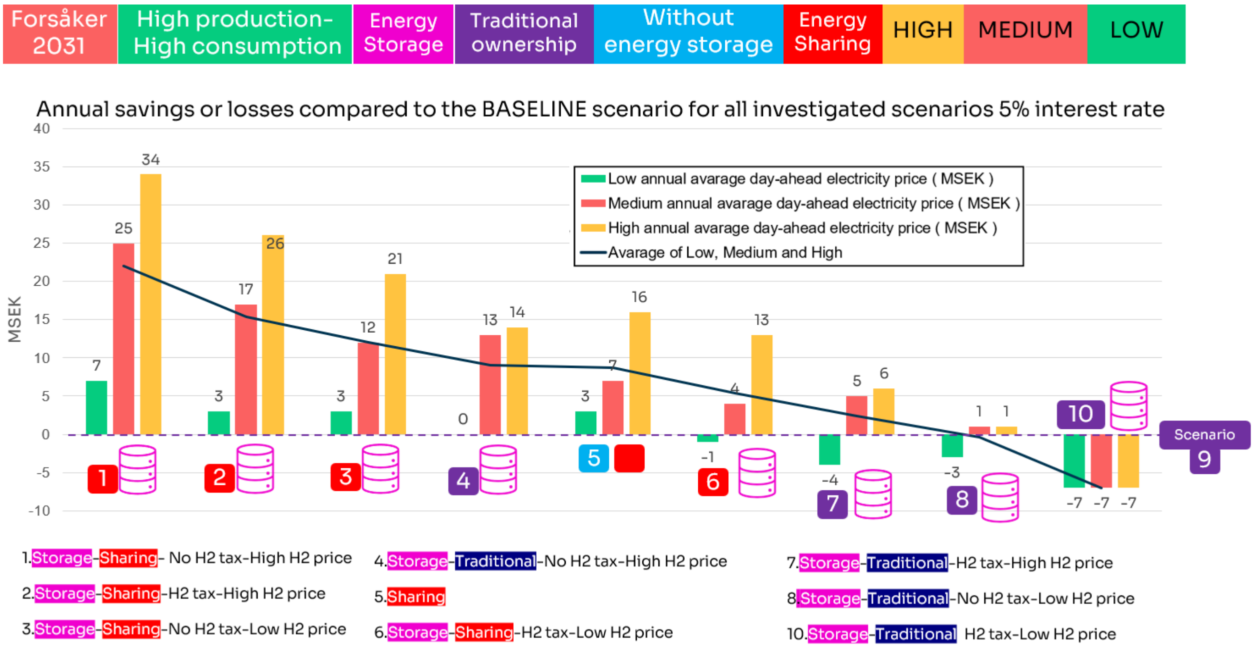


Figure 9.3.1. Modified results from Figure 8.2.5. Annual savings or losses compared to the BASELINE scenario for all investigated scenarios, in an 5% interest rate environment instead of 2.5%. (The x-line showed 0 stands for scenario 9 (BASELINE) which equals annual energy

expenses of 15 MSEK in the LOW, 20 MSEK in MEDIUM, and 28 MSEK day-ahead electricity price scenarios)

The only scenario remaining unchanged between Figure 8.2.5 and 9.3.1 is the baseline scenario 9. All the other scenarios will be affected by higher annual expenses in different variations due to increased interest rates. Several scenarios, especially those with LOW day-ahead electricity prices, have turned into losses compared to Scenario 9. Despite the change in interest rates the overall pattern between all scenarios remains unchanged.

OPEX for CAPEX of Wind and hydropower plants

Even if CAPEX for Hydro and wind powerplants are unknown for Forsåker they will cost and have an impact on the financial results. To illustrate hydro and wind OPEX impact for the scenarios Figure 9.3.2 illustrates scenarios with a made up OPEX for wind and hydropower plants for both 2.5 and 5% interest rates, based on CAPEX and OPEX for Kikås solar park and the amount of kWh annually produced.

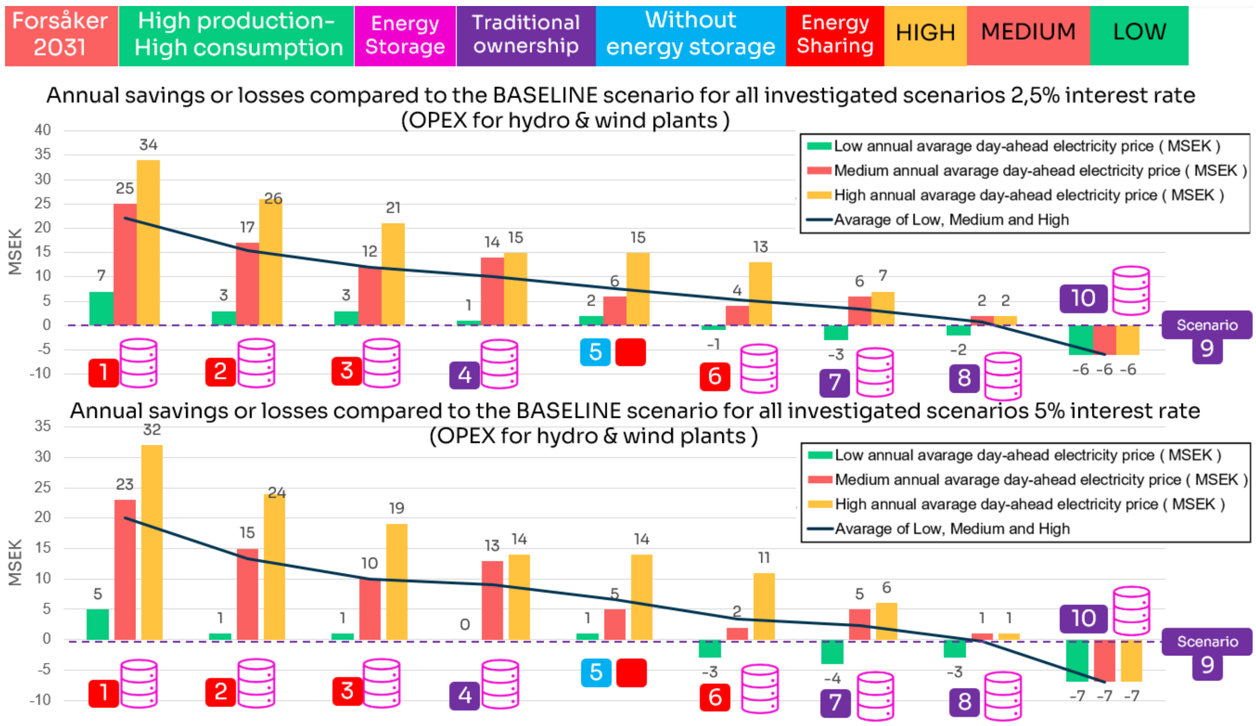


Figure 9.3.2. Modified results from Figure 8.2.5. Annual savings or losses compared to the BASELINE scenario for all investigated scenarios, in a 5% interest rate environment and 2.5%. Both scenarios include made up OPEX for hydro and wind plants as well (The x-line showed 0 stands for scenario 9 (BASELINE) which equals annual energy expenses of 15 MSEK in the LOW, 20 MSEK in MEDIUM, and 28 MSEK day-ahead electricity price scenarios)

An important conclusion can be drawn from the lower half of the Figure, the scenarios are still in the same order regarding best to worst case scenarios, regardless of the OPEX for hydro and wind and increased interest rate. From an economic perspective the LOW day ahead electricity scenario can be excluded. Only the best-case scenario will contribute to savings compared to the baseline scenario number 9 in LOW. Scenarios 2, 3 and 5 still show profitability for LOW scenario but a safety margin is required to make the investment since investments also entail risks since an estimated investment of 180 MSEK is required for storage components and the Kikås solar park which require a minimum of 50 MSEK in down payments. If the day-ahead electricity price stabilizes, regardless of if it is at a high or low level, the incentive for hydrogen storage for self-use will decrease. If electricity price frequently fluctuates between peaks and bottoms, as is indicated with increased installation of solar and wind, the incentive for storage increases, as seen in MEDIUM and HIGH scenarios.

Cash flow-driving functions that are not taken into account

If the government does not allow the energy sharing principle for large areas as Forsåker 2031 scenario 4 will have the highest safety margin in MEDIUM and HIGH scenario. Another possibility is that Mölndal Energi AB creates a similar system for their customers in the area, this alternative has not been considered in the thesis. Another possible income stream that has not been investigated in the thesis is Effekthandeln Väst, which is based on Svenska Kraftnät's grid flexibility services. Different service variants include the ability to consume a specific power capacity on demand for a specified duration from Mölndal's regional grid, as well as export a designated power capacity for a specific period. In return, consumers and producers are offered compensation through advance bidding to be on standby.

Effekthandeln Väst is relatively new and will most likely change until 2031. Forsåker's energy system offers an ability to consume 6 MW through the electrolyzer, use 4 MWh for charging the battery from empty to full. Combined with additional direct consumption from Forsåker, a fully charged battery can provide 4 MWh of production, 1.5 MW from the fuel cell system, and potentially surplus from Forsåker's local production if the area can lower or avoid self-consumption during times of demand. This would be beneficial both from an economic standpoint and from a broader system perspective in mitigating the gap between supply and demand in Mölndal's electricity grid. Enabling standby on flexibility services can jeopardize the security of supplying the energy needs of the Forsåker area, which is the top priority. Probably those demands can be combined but will add another layer of complexity for the control parameters to avoid a blackout in Forsåker.

Investing in relatively new technology, such as storage components, given the pace of their current development, entails both risks and opportunities. Investing entails a risk that someone else may later buy something better at a lower cost. Avoid investing entails a risk, competitors may become more attractive and tailored to society's future needs. Change is not easy and a balance between risks and competitiveness is required. Assumptions of future price targets used in the calculations can differ to the actual 2031 prices, but the stack and system efficiency will most likely improve until then. The combination of future price targets and the efficiency of today gives a hedge. If future prices of storage components will decrease slower than expected probably the efficiency improvements of the components performance will lead to a smaller system demand is required, examples of this from the assumptions can be if an average fuel cell operation performance greater than 50% can be expected.

The electrolyzer's of 2031 will most likely use less electricity to produce the same amount of hydrogen as the amount of electricity the electrolyzer of today requires combined with the ability to ramp up and down faster. As discussed in the fuel cell operational chapters, maybe 2031 fuel cells don't degrade as much at maximum operation so that 12 stacks are good enough instead of 15 at 80 kW operation as maximum for a 100 kW to increase its lifetime. On the other hand, these 50% is a simplification due to added transmission losses for the compressor for hydrogen storage. Except technological developments for storage components, adapted and developed control parameters will probably lower the operational costs due to an efficient operation of the overall system in a higher degree than in the simulations performed in the thesis.

In an early phase of the work, there was a discussion about conducting more detailed simulations with varied performance for the fuel cells and other components. The reasoning concluded that, at such an early stage, including more parameters could potentially yield better results. It was also acknowledged that introducing more parameters would further increase uncertainty, as it places higher demands on the accuracy of input data, which is challenging to ascertain before a more detailed study is conducted.

Subsidies as the Inflation Reduction Act

As depicted in the figures above, the willingness to invest in storage technologies and green energy production can vary depending on the outcome of a multitude of factors. To encourage more industries and investors to invest in renewable electricity production and storage, there are numerous grants and subsidies that have not been included in the calculations. This is due to the uncertainty and challenge to predict how these subsidies will look like in 2030. Additionally, sustainable investments must ultimately be financially self-sufficient. Subsidies can take the form of green loans, offering lower interest rates on bank loans as the investment is considered future-provided.

Klimatklivet is a Swedish subsidy program where sustainable energy production investments can receive contributions towards CAPEX investment. The U.S. Investment Tax Credit (IRA) is a beneficial program where the U.S. government pays out $3 USD per kilogram of produced green hydrogen. The Swedish government has other subsidies to apply for as well.

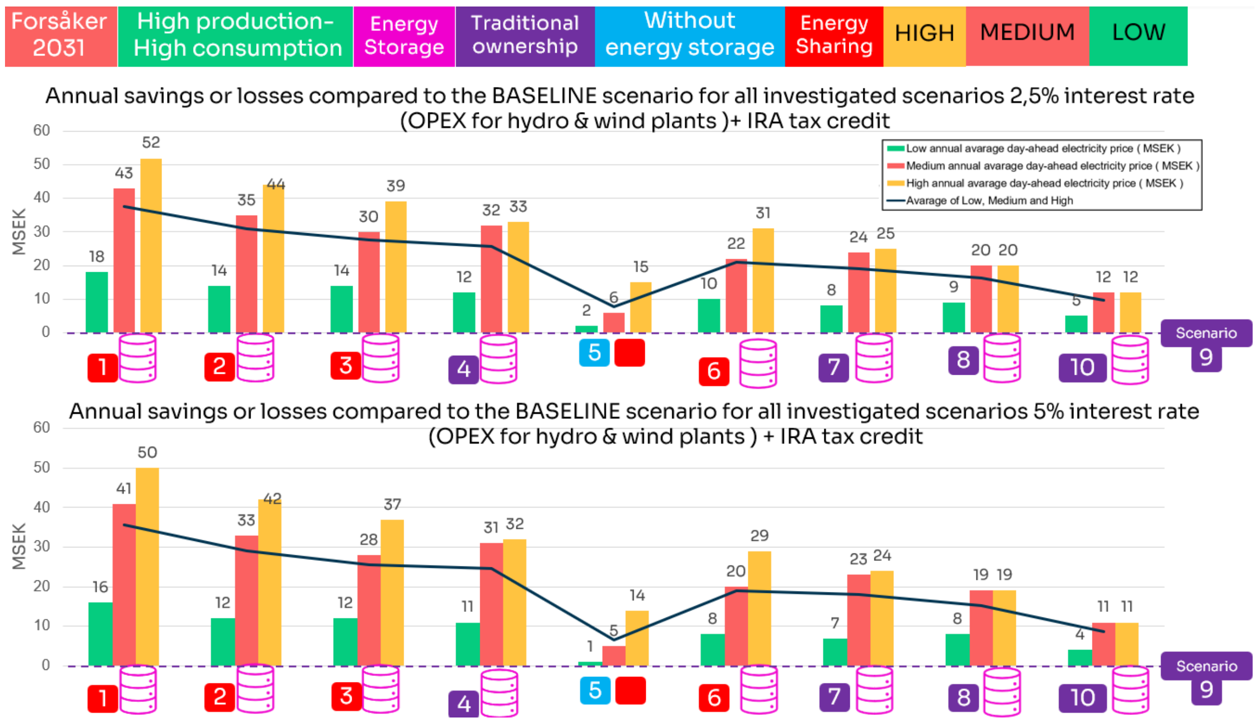


Figure 9.3.3. Modified results from Figure 8.2.5. Annual savings compared to the BASELINE scenario for all investigated scenarios, in an 5% and 2,5% interest rate environment. Both scenarios include made up OPEX for hydro and wind plants as well. Subsidies from the US Government program IRA is included. (The x-line showed 0 stands for scenario 9 (BASELINE), which equals annual energy expenses of 15 MSEK in the LOW, 20 MSEK in MEDIUM, and 28 MSEK day-ahead electricity price scenarios).

Figure 9.3.3 illustrates how powerful the IRA will be if Forsåker would be included in the IRA tax credit for green hydrogen production, then all hydrogen storage scenarios would be attractive compared to the Baseline scenario 9. If this would become a reality control parameter could be adapted to produce even more hydrogen at a higher electricity price due to the profitability of the powerful IRA subsidy.

The assumption to not include subsidies in this study was made due to the difficulties to predict the outcome of them at 2031 and beyond, the reason to include the IRA impact in Figure 9.3.3 is to illustrate how large impact government subsidies can make on development of non-established markets in order to incentivize capital towards specific technologies like hydrogen production.

Service and maintenance

Service and maintenance costs for storage components, powerplants, grid infrastructure must be included as well to get the actual outcome of the different scenarios. The more energy infrastructure owned by Forsåker consortium, the more service and maintenance costs occur. There are different alternatives for maintenance depending on the purchasing agreement. One option is to buy the system and then pay for service and spare parts when needed, which can work well for some customers if they have a good knowledge of repairing the system by themselves or by another firm. The other method is to buy power as a service which means the costumer pays for the system and then annually pays a fee to the producer, in return the producer or a maintenance company perform service and maintenance, which is a good option if the costumer does not have the knowledge inhouse.

Confidence can be instilled when the customer knows that the producer ensures operation and maintenance throughout the entire journey. Simultaneously, customers can plan their expenses, avoid unpredictable costs, and minimize system downtime in event of any breakdown. Regular service aims to prevent unprepared breakdowns, which depending on the time can jeopardize safety. No evaluation of service and maintenance has been conducted in this work, it is important to include this in a more detailed investigation.

Summary regarding the modified figures

As seen in Figure 9.3.1 to Figure 9.3.3 the numbers for all scenarios fluctuate a lot depending on which interest rates, subsidies and OPEX/CAPEX parameters are included. This illustrates that the figures presented do not provide a complete picture. Roughly the same pattern is followed under all scenarios, between the best-case scenario to the worst-case scenario regardless of the values used for these parameters. It shows that parameters that each scenario is built up on are vital to know for the investor, since it will determine the fundamental base of choosing energy sharing or not, and energy storage or not. The results are e.g., much depending on the hydrogen taxation for the long-term profitability of the investment. Since the system's lifetime ranges from 15-30 years depending on components used in 2031 to 2061, most likely regulations, subsidies interest rates, day a head price scenario, and other influencing factors will vary during this time. For an example maybe some kind of subsidy will be possible to receive the first years, then some years will be similar to the LOW day a head electricity price scenario, some as MEDIUM and HIGH.

10.Conclusions

From the study, valuable information can be derived that can be beneficial for property owners, policymakers, and other stakeholders in future planning of areas incorporating local energy production and storage. In the ScALES study, it was demonstrated that solar panels on roofs and facades contribute with around 30 % of the annual consumption demand. Hydropower, wind and Kikås solar park will result in an annual electricity production of 105 % of the consumption demand. Local production never equals consumption demands on hourly basis, resulting in either 100 % dependency on grid imports or exports for every hour of the year, or energy storage implementation.

Simulations shows that hydrogen and battery storage would contribute to a more redundant energy system in Forsåker in an event of a crisis combined with increased sector coupling enabling Forsåker to produce local hydrogen for vehicles and industries around. Regardless of other values the economic aspect is often vital in the end.

Energy is traditionally seen as an expense for property owners, which means that even though an investment in energy production and storage may not contribute to a profit, an accompanying saving compared to the baseline scenario of not doing anything could be interesting enough to make the investment. Results shows that investments in energy production and energy storage for the real estate owners in Forsåker could contribute to annual OPEX savings even annual profits, on the other hand it can entail to losses as well.

To facilitate future planning and enhance investment analysis, a comprehensive guide is presented as an investment ladder in Figure 10.1:

Investment ladder

Future parameters impact and changes the landscape of Investment opportunities

BEST-CASE SCENARIO	1	Storage	Sharing	No H2 TAX	High H2 price
	2	Storage	Sharing	H2 TAX	High H2 price
	3	Storage	Sharing	No H2 TAX	Low H2 price
	4	Storage	Traditional	No H2 TAX	High H2 price
	5	No storage	Sharing		
	6	Storage	Sharing	H2 TAX	Low H2 price
	7	Storage	Traditional	H2 TAX	High H2 price
	8	Storage	Traditional	No H2 TAX	Low H2 price
BASELINE SCENARIO	9	No storage	Traditional		
WORST-CASE SCENARIO	10	Storage	Traditional	H2 TAX	Low H2 price

LOW "LOW" Day-ahead electricity price scenario weakens the impact of the scenario

HIGH "HIGH" Day-ahead electricity price scenario strengthens the impact of the scenario

Figure 10.1. Investment ladder mapping attractiveness of local electricity production and energy storage components depending on which future parameters become reality around year 2031.

This investment ladder aims to provide valuable insights and guidelines for stakeholders making informed decisions regarding energy investments. It may aid policy makers to understand the impact of the outcomes depending on future laws and regulations. To enable them to create beneficial laws and regulations for attractiveness of energy storage investments to manage the electrification demand in society.

The most important factors for policy makers to keep in mind to attract and allocate renewable energy and storage investments to Sweden is listed below:

- Allow large areas like Forsåker to implement the energy sharing principle. Enable internal electricity transfers within a specific area, from producers to consumers as well as storage components, without tax liability.

- Keep the regulation regarding green electricity for hydrogen production through electrolysis free from taxation.

Due to transmission losses in energy storage a larger amount of electricity is required as input compared to the output electricity, therefore the tax cost gets a large impact of the benefit of both producing and storing electricity. Blocks in the investment ladder can be seen as fundamental parameters that guides the investor to invest or not invest. The ranking of scenarios from 1 to 10 on the attractiveness of the investment persists despite the impact from interest rates, subsidies, and OPEX/CAPEX cost parameters which will result in a variation of the exact profit, saving or loss numbers.

The greater the fluctuation in electricity prices are, as it is in HIGH day-ahead electricity price scenario, the more beneficial it is to invest in electricity production and storage components. Depending on the combination of future conditions, the scenarios suitable from an economic perspective become evident. A day-ahead electricity price scenario like HIGH enhances the investment's suitability, while LOW reduces it. Adjustments to the control parameters can be applied for each scenario to enhance performance.

Factors that impact the specific numbers for the future scenarios are:

- Interest rates.
- CAPEX for the systems, especially since water and wind CAPEX have not been included.
- Service and maintenance costs.
- Future component prices and technology developments.
- Subsidies.

The listed points above change the exact results and numbers in each scenario but not the ranking order in the investment ladder. Considering that the energy system is expected to operate for 15-30 years depending on the components lifetime, a likely actual outcome involves some form of combination of the scenarios studied. For instance, some years may resemble a pattern of LOW, followed by HIGH the next year, then alternating between LOW and HIGH with a variation of the interest rate. A system solution was identified for the dimensions and control parameters of the energy storage system simulations, which can manage Forsåker's consumption and production flows, including sector coupling for hydrogen sales. Future investigation regarding optimization of the energy system’s sizing and control parameters would improve economic and societal benefits.

Influential events afters study completion

An important milestone that has occurred after the completion of the work but before publication is the approval of energy sharing in a planned district in Örebro. The Swedish Energy Markets Inspectorate granted an exemption from the requirement for a grid concession of the planned grid network in Tamarinden [32]. The approval plays an important role for Forsåkers stakeholders, since the Swedish Energy Markets Inspectorates alignment in the question strengthens guidance regarding future planning for energy sharing scenarios.

"The development of Tamarinden is based on close collaboration between Örebro Municipality, ÖrebroBostäder AB, and construction companies Serneke, Peab Bostäder, Magnolia, Tornet, along with the local energy distributor E.on." [32] The stakeholder setup which seems to be similar to Forsåker, together with the approval, along with reference to the investment ladder, gives strong indications to recommend Forsåkers stakeholders to choose Energy sharing- Energy storage for future investigation when planning the energy system in Forsåker.

11.References

[1] ScALES. (2023, 31 maj). Scenarioanalys för att i ett nytt stadsutvecklingsprojekt hantera en alltmer elektrifierad fordons- och maskinflotta (Slutrapport). Retrieved from https://www.johannebergsciencepark.com/projekt/scales

[2] Mölndals Energi AB.(2022). Solpark på Kikås. Retrieved 2022-12-15 from https://www.molndalenergi.se/privat/solpark-kikas

[3] European commission. (2023). Solar energy. Retrieved 2023-05-16 from https://energy.ec.europa.eu/topics/renewable-energy/solar-energy_en#documents

[4] Fossilfritt Sverige. (2021-01-21). Vätgasstrategi för fossilfri konkurrenskraft. Retrieved 2022-09-24 from https://fossilfrittsverige.se/strategier/vatgas/

[5] Linde Gas. (2011-2023). Fakta om vätgas (hydrogen). Retrieved 2022-11-11 from https://www.linde-gas.se/sv/products_ren/hydrogen_energy_h2/facts_on_hydrogen/index.html

[6] Dyhr, K. (2001). Antändningsrisker genom statisk elektricitet vid vattenbegjutning av gasolutsläpp. Räddningsverket. Retrieved 2022-11-23 via https://lup.lub.lu.se/luur/download?func=downloadFile&recordOId=9073936&fileOId=9073937

[7] IVA. (2022). Om vätgas och dess roll i elsystemet: Syntesrapport från IVAs projekt Vätgasens roll i ett fossilfritt samhälle. Retrieved 2022-09-24 from [https://www.iva.se/publicerat/rapport-vatgas-och-dess-roll-i-elsystemet/]

[8] Energimarknadsinspektionen. (2023-04-21) Undantag från kravet på nätkoncession (IKN). Retrieved 2023-05-05 from https://ei.se/bransch/koncessioner/undantag-fran-kravet-pa-natkoncession---ikn

[9] Svensk författningssamling. (2021-11-03) Förordning om ändring i förordningen (2007:215) om undantag från kravet på nätkoncession enligt ellagen (1997:857). Retrieved 2023-05-05 from https://svenskforfattningssamling.se/sites/default/files/sfs/2021-11/SFS2021-976.pdf

[10] Wallentin, A. (2021-03-10). Några aktuella EU-frågor,hemställan om koncession & vätgasbeskattning. Retrieved 2023-05-05 from https://www.swedegas.se/-/media/Files/GMR/GMR-100321/7-Energigas-Sverige-20210310.ashx?la=sv-SE

[11] Vattenfall-energy plaza.(2019-11-19). Energiskatt på el - vår guide för 2022. Retrieved 2023-01-10 from https://energyplaza.vattenfall.se/blogg/energiskatt-pa-el-vad-ar-det-som-galler

[12] Mölndals Energi AB. (2023). Elnätspriser. Retrieved 2023-01-10 from https://www.molndalenergi.se/foretag/elnat

[13] Powercell Sweden AB. (2023). Hydrogen Fuel Cells. Retrieved 2023-05-10 from https://powercellgroup.com/hydrogen-fuel-cell/

[14] NEL AS. (2023) PEM electrolyzers. Retrieved 2023-05-10 from https://nelhydrogen.com/water-electrolysers-hydrogen-generators/

[15] DOE. (2022, September). DOE National Clean Hydrogen Strategy and Roadmap Draft. Retrieved 2023-02-10 from https://www.hydrogen.energy.gov/library/roadmaps-vision/clean-hydrogen-strategy-roadmap

[16] Yuanrong, Z. (2023-01-03). CAN THE INFLATION REDUCTION ACT UNLOCK A GREEN HYDROGEN ECONOMY?. ICCT. Retrieved 2023-02-10 from https://theicct.org/ira-unlock-green-hydrogen-jan23/

[17] NORDPOOL. (2023). Day-ahead prices. Retrieved 2023-02-10 from https://www.nordpoolgroup.com/en/Market-data1/Dayahead/Area-Prices/SE/Hourly/?view=table

[18] Reksten AH et al.,(2022) Projecting the future cost of PEM and alkaline water electrolysers; a CAPEX model including electrolyser plant size and technology development, International Journal of Hydrogen Energy, Retrieved 2023-03-30 from https://doi.org/10.1016/ j.ijhydene.2022.08.306

[19] MSB. (2022-01-21). Vätgas. Retrieved 2023-02-27 from https://www.msb.se/sv/amnesomraden/skydd-mot-olyckor-och-farliga-amnen/brandfarligt-och-explosivt/brandfarliga-gaser/vatgas/?fbclid=IwAR0BTyWgKL2qa6VxWoLUZv1V2-Lb8AqgjhsrchALxeA3_RjADQBCcT90syw

[20] HEXAGON PURUS. (2022-02-10). Hydrogen Storage & Distribution. Retrieved 2023-02-20 from https://www.energy.gov/sites/default/files/2022-03/Bulk%20Storage%20Workshop_Day2_04.pdf

[21] Johanneberg science park. (2023-05-25) Batterier i fastigheter för nybörjare, (2023, 25 maj). Retrieved 2023-05-25 from:

https://www.johannebergsciencepark.com/sites/default/files/Batterier%20i%20fastigheter%20f%C3%B6r%20nyb%C3%B6rjare_20230525.pdf

[22] Soltech Energy.(2022-11-10). Presentation - Erik Penser Bank. Retrieved 2023-02-25 from: https://www.youtube.com/watch?v=5xNdFkdPtGA
http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-485271

[23] Boverket. (2019-09-04). Centrala begrepp i exempelsamlingen. Retrieved 2023-04-23 from
https://www.boverket.se/sv/samhallsplanering/arkitektur-och-gestaltad-livsmiljo/arbetssatt/skolors-miljo/skolor-och-forskolor/centrala-begrepp/

[24] Karlsson, A. (2022). Beräkningsmodell för optimering av vätgaslager : Utformning och analys av beräkningsmodell för vätgasprojekt på ÅBRO bryggeri (UPTEC ES, ISSN 1650-8300 ; 22026). Retrieved 2022-11-12 from
https://www.divaportal.org/smash/record.jsf?pid=diva2%3A1697736&dswid=9846

[25] NIKOLA motor. (2022). TRE FCEV. Retrieved 2023-04-23 from _
https://www.nikolamotor.com/tre-fcev/

[26] Elanders. (2021-09). TOYOTA MIRAI. Retrieved 2023-04-23 from
http://tims.elanders.com/webbroschyr/Broschyrer/mir_psb_web.pdf

[27] Energy.gov. Heat Pump Systems Energy Saver. Retrieved 2023-04-23 from
https://www.energy.gov/energysaver/heat-pump-systems

[28] Skanska. (2022-09-13). Ljusekulla - Liv, odling och framtid. Retrieved 2022-11-23 from
https://www.skanska.se/vart-erbjudande/projektutveckling/stadsutveckling/h22/ljusekulla/

[29] Bergman, R och Wademyr, M. (2020). Vätgasproduktion och lagring av förnybar energi i en fastighet - Utformning och kostnadsanalys av energisystem med vätgas. Retrieved 2023-12-17 from
https://odr.chalmers.se/items/18e0b4c4-f505-4f7f-8442-d1b26429b5f5

[30] Volvo Energy. (2024). Battery Energy Storage System – BESS. Retrieved 2024-02-04 from
https://www.volvoenergy.com/en/energy-storage.html#accordion-e226499b7b-item-15161f545b

[31] Volvogroup. (2024). New batteries, new opportunities. Retrieved 2024-02-04 from

https://www.volvogroup.com/en/sustainable-transportation/sustainable-solutions/battery-electric.html

[32] Byggvärlden (2024-01-22). Får klartecken att testa ny typ av energisystem. Retrieved 2024-02-04 from
https://www.byggvarlden.se/far-klartecken-att-testa-ny-typ-av-energisystem/?_gl=1*k3dh8d*_up*MQ..*_ga*MTg3ODM4ODUzMi4xNzA3NzUwMjM1*_ga_NVLTVB0Z3D*MTcwNzc1MDIzNS4xLjAuMTcwNzc1MDIzNS4wLjAuMA..#