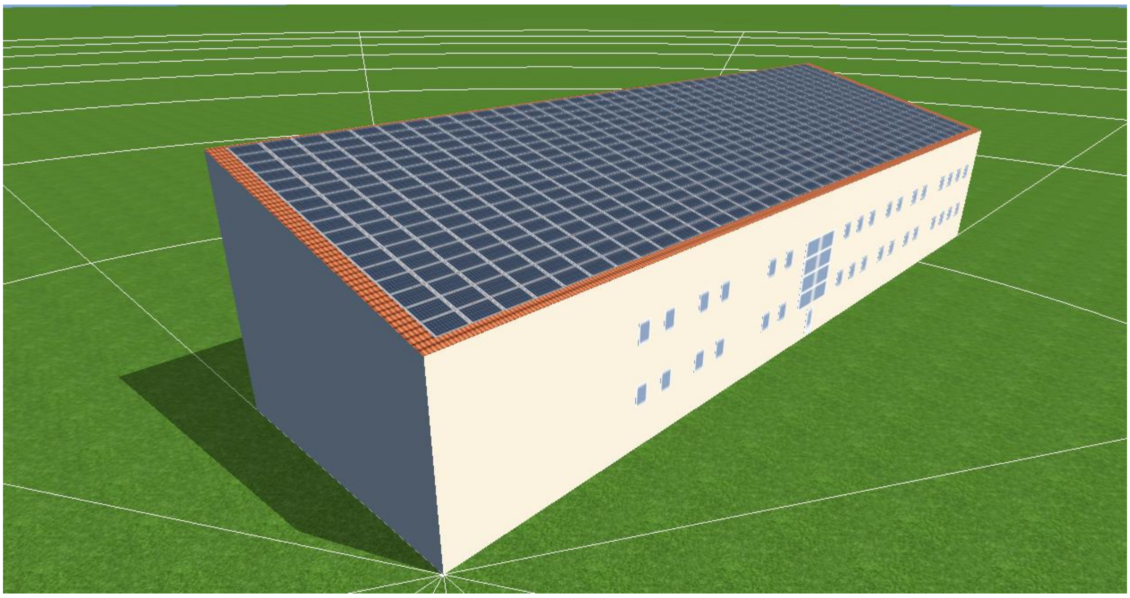
CHALMERS
UNIVERSITY OF TECHNOLOGY



Off-grid PV system with batteries and hydrogen storage

Design and feasibility for a multifamily building in Sweden

Master's thesis in Sustainable Energy Systems

MAX BÖRLING

Department of Architecture and Civil Engineering
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2018

Master's thesis ACEX30-18-56

Off-grid PV system with batteries and hydrogen storage

Design and feasibility for a multifamily building in Sweden

MAX BÖRLING

Department of Architecture and Civil Engineering
Building Services Engineering
Chalmers University of Technology
Gothenburg, Sweden 2018

Off-grid PV system with batteries and hydrogen storage
Design and feasibility for a multifamily building in Sweden
MAX BÖRLING

Supervisor: Lina Wideberg, Department of Sustainable Buildings, Renewable Energy, ÅF
Examiner: Jan-Olof Dalenbäck, Department of Architecture and Civil Engineering, Chalmers University of Technology

Master's Thesis ACEX30-18-56
Department of Architecture and Civil Engineering
Building Services Engineering
Chalmers University of Technology
SE-412 96 Gothenburg
Telephone +46 31 772 1000

Cover: An image of the reference building from the simulation software PV*SOL®.

Typeset in LaTeX
Gothenburg, Sweden 2018

Off-grid PV system with batteries and hydrogen storage
Design and feasibility for a multifamily building in Sweden
MAX BÖRLING
Department Architecture and Civil Engineering
Chalmers University of Technology

Abstract

The Swedish electricity system relies mainly on nuclear and hydro power which together constitute approximately 80 % of the annual electricity production, but the deployment of new, renewable technologies is increasing. This increase has initiated a development from a centralized system to a more distributed system where several small actors both supply and consume electricity to or from the grid. One such technology is solar photovoltaics (PV), which has experienced a rapid growth during recent years. Due to the intermittent production characteristics of solar PV, the demand for energy storage solutions such as batteries are on the up-rise as well.
This report evaluates how solar PV can be used in combination with a battery, a hydrogen storage (including an electrolyser and a fuel cell) and a heat pump to supply the annual heat and electricity demand of a building, without being connected to the grid. The building is assumed to be located in Gothenburg, Sweden and its energy demand is estimated based on the requirements from the Swedish passive house standard. The size of the components is determined and a functioning system configuration is found by modeling the system on an hourly basis. Furthermore, the cost of all components is estimated in order to evaluate the feasibility of the off-grid system also from an economic perspective.
The results show that a PV system of 164 kW_p, a battery of 300 kWh, a 66 kW electrolyser, a 20 kW fuel cell and a 25 kW heat pump is required to meet the annual demand of the building in off-grid mode. The results indicate that from a technical perspective, the mentioned technologies provide a feasible solution. However, from an economic perspective it is not viable with the current component costs. The results from the economic calculations show that the levelized cost of electricity (LCOE) ends up between 0,5 €/kWh and 1,43 €/kWh (1 € is approximately 10 SEK) depending on what assumptions are made. On the other hand, many of the technologies are still developing and not yet well-established on the market, which could mean that an energy system of this type can be an attractive alternative in the future.

Keywords: off-grid, solar PV, battery, electrolyser, fuel cell, hydrogen storage, renewable energy

Off-grid solcellsanläggning med batterier och vätgaslager
Design och genomförbarhet för ett flerfamiljshus i Sverige
MAX BÖRLING
Avdelningen för arkitektur och samhällsbyggnadsteknik
Chalmers Tekniska Högskola

Sammanfattning

Sveriges elsystem består till stora delar av kärn- och vattenkraft som tillsammans utgör cirka 80 % av den årliga elproduktionen. Dock ökar andelen nya, förnybara produktionstekniker vilket bidrar till att elsystemet utvecklas från ett centraliserat system till ett mer utspritt system där flera aktörer både levererar till och använder el från nätet. En teknik som ökat kraftigt de senaste åren är solceller. På grund av solcellers varierande produktionsegenskaper har efterfrågan på olika lagringslösningar så som batterier också ökat.
Denna rapport utreder hur solceller kan användas i kombination med ett batteri, ett vätgaslager (inklusive en elektrolysör och en bränslecell) och en värmepump för att försörja en byggnads årliga el- och värmelast, utan att vara påkopplad på nätet. Byggnaden antas ligga i Göteborg, Sverige och energilasten uppskattas utifrån de krav som ställs i den svenska passivhusstandarden. Storleken på komponenterna bestäms och en fungerande systemkonfiguration tas fram genom att modellera systemet på timbasis. Vidare uppskattas kostnaden för alla komponenter i off-grid systemet för att utreda hur de ekonomiska förutsättningarna ser ut.
Resultaten visar att det behövs en solcellsanläggning på 164 kW_p, ett batteri på 300 kWh, en 66 kW elektrolysör, en 20 kW bränslecell och en 25 kW värmepump för att förse byggnadens last off-grid. Resultaten visar att kombinationen av de nämnda teknikerna fungerar ur ett tekniskt perspektiv. Däremot är det inte ekonomiskt försvarbart med dagens kostnader. Elkostnaden beräknas hamna mellan 0,5 €/kWh och 1,43 €/kWh (1 € motsvarar ungefär 10 SEK) beroende på vilka antaganden som görs. Dock är många av de tekniker som används i systemet fortfarande under utveckling och har ännu inte etablerat sig på marknaden, vilket innebär att ett energisystem av denna typ kan komma att bli ett attraktivt alternativ i framtiden.

Keywords: off-grid, solcell, batteri, elektrolysör, bränslecell, vätgaslager, förnybar energi

Acknowledgements

First of all, I would like to thank my supervisor Lina Wideberg at the department of Renewable Energy at ÅF for the opportunity to carry out this thesis and for providing useful thoughts and ideas along the way.
I would also like to thank my examiner Jan-Olof Dalenbäck at the department of Building Services Engineering at Chalmers University of Technology for the support and guidance during my work.
Finally I would like to thank Hans-Olof Nilsson at Nilsson Energy AB for the opportunity to visit him in his off-grid house and for taking the time to answer all my questions.

Max Börling, Gothenburg, May 2018

Contents

List of Figures

List of Tables

1

Introduction

Heat and electricity are two very important utilities and much of today's society depends on a reliable energy system. In Sweden, the sector of buildings and services constitutes almost 40 % of the annual energy usage (Swedish Energy Agency, 2015), but national goals aim to reduce the amount of energy used in the sector. This requires improved energy efficiency and more renewable energy must be integrated on buildings.

Most multifamily buildings in Sweden are connected to the district heating system and the electricity grid. Connecting a newly produced building to the existing grid requires an expansion of the grid which involves costs for the developer. How large the costs are depend mainly on the distance between the building and the closest point of connection. The district heating system is not easily expanded and some new buildings may not be able to connect to it if they are too far away. In such a case, other solutions must be found.

The electricity system in Sweden can be simplified into three different actors: generation companies, transmission and distribution companies and customers (Bhattacharya, K., Bollen, M.H.J., Daalder, J.E., 2001). The generation companies produce the electricity, which is sold to the customers and delivered through the transmission system. The consumers thus pay both for the electricity they use and the transmission. Traditionally, the electricity price in Sweden has been low compared to many other countries thanks to large shares of nuclear and hydro power (Swedish Energy Agency, 2015). However, the Swedish nuclear reactors are old and will need to be replaced if Sweden is going to keep relying on nuclear power. Another option that is often debated is to abandon nuclear power and replace it with other technologies. Both options involve high costs that might lead to an increased price of electricity for the customers. On top of that, the national grid is very old and will require investments for expansion and reinforcement (Svenska kraftnät, 2016) which may lead to increased transmission costs in the future. The uncertainty about the future may be one of the reasons many customers have already started looking for alternative ways to supply their electricity demand.

One technology that has gained popularity during recent years is solar power. The benefits of solar power are that it can easily be installed on or in connection to buildings, it has a long lifetime and can provide cheap electricity since it does not require any fuel and needs no or very little maintenance. There is also an advantage of having the electricity source closer to the final user as it reduces the need for transmission capacity. However, the electricity production from solar power cannot be controlled as it varies with weather and the diurnal cycle, meaning that electricity will not always be provided when it is needed and the other way around. To overcome this mismatch, different types of storage can be used such as batteries or hydrogen storage.

The combination of solar power and energy storage systems provides new opportunities for electricity consumers to become independent from the grid and fulfill their demand themselves. So far, only a few such examples exist in Sweden. If this solution is to reach a broader market, the technical and economic outlooks must be evaluated further. This report aims to provide a deeper understanding of both the technical and economic outlook of this type of off-grid energy system.

1.1 Aim and objectives

The aim of this thesis is to evaluate the techno-economic outlooks of an off-grid energy system for an apartment building in Gothenburg, Sweden. The annual heat and electricity demand is fulfilled using solar power combined with a battery, a heat pump and a hydrogen system including an electrolyser, a hydrogen storage and a fuel cell. The energy system is configured and sized to find an optimal solution from an economic point of view while making sure the entire annual energy demand is fulfilled. The project can be divided into the following research questions:

1. Determine the required size of the different components to fulfill the yearly energy demand in the off-grid apartment building.
2. Find a feasible operation schedule for the energy system.
3. Evaluate the present and future economic outlook of the off-grid energy system and compare it with traditional heat and electricity supply.

1.2 Scope and limitations

The electricity generation will be covered by solar PV only and no other electricity generation technologies will be considered. The energy storage technologies considered are batteries and hydrogen storage. The heat demand of the building will be supplied with a fuel cell and a heat pump. The different alternatives within each above mentioned technology will be compared and evaluated from a feasibility perspective but no other technologies are considered.

Furthermore, the project focuses mainly on the economic outlook of the off-grid system. Other aspects such as environmental impact or legal requirements regarding safety or electrical installations are not studied in detail. Different subsidies and financial support exist for some renewable energy technologies. These are not taken into account in the economic calculations but the potential impact of such policy instruments may be discussed in the report.

1.3 Report structure

The report begins with a theoretical background in chapter 2. This chapter describes typical technical specifications of the different components in the off-grid energy system. It also explains the tools used to evaluate the economic outlooks of the system.

Chapter 3 introduces the reference building used in the project and explains what assumptions were made when estimating the demand curve of the building. Furthermore, this chapter describes how the simulation and modelling of the energy system was carried out.

The results from the simulation and modelling is presented in chapter 4. This includes the final system configuration and the sizing of the components. The operation characteristics of all components are presented as well. Chapter 4 also provides the results from the economic evaluation and explains the different economic scenarios that were evaluated.

Chapter 5 discusses how assumptions and choice of method may have affected the results. It also discusses additional aspects of off-grid energy systems that could have an impact on the results.

The final conclusions and recommendations are presented in chapter 6.

2

Theory

This chapter begins with a literature review describing some of what has already been done on the subject. It also explains shortly how the different technologies work and investigates what different options exist within each technology. Typical efficiencies and other important specifications are presented as well.

2.1 Literature review

A few previous studies have investigated different aspects of off-grid systems using solar PV, batteries and hydrogen storage.

A demonstration project by Cordiner, S. et al. (2017) concludes that an off-grid system based on solar PV, batteries and hydrogen storage is a technically feasible option for powering radio base stations in Italy. The project also shows that the system can be a competitive option regarding energy efficiency and fossil fuel consumption compared to traditionally used diesel generators.

Guinot, B. et al. (2015) investigates the potential of an off-grid system using solar PV, batteries and a hydrogen system by comparing it to two reference cases using solar PV in combination with either batteries or a diesel generator. Both the management strategies and the sizing of the components are studied. The authors found that a hydrogen storage system can reduce the battery capacity needed which resulted in a reduced cost of the system.

Other studies have analysed different system configurations to fulfill the energy demand in an off-grid system. An article by Lacko, R. et al. (2014) evaluates the technical feasibility of an off-grid system consisting of solar PV, wind power and hydrogen storage in Slovenia. Their results show that it is a technically feasible option but that the electricity cost in such a system is high compared to the price of electricity from the grid.

Mohammed, Y.S., Mustafa, M.W., Bashir, N. (2014) provides a review of the drivers and challenges associated with the emergence of hybrid renewable energy systems, including economic, environmental, political and technical aspects. The article also evaluates the potential of different energy generating technologies in such a system and highlights important issues when designing the system.

2.2 Solar photovoltaics

The physical background of solar photovoltaics (PV) is the photoelectric effect, which was discovered in 1839 by Alexandre-Edmond Becquerel. He found that certain materials could give off electric sparks when exposed to sunlight. The realization that this effect could be utilized resulted in the creation of the first PV cell in the late 1800s, but it was not until the 1950s that the first PV cells using silicon was created (Honrubia-Escribano, A. et al., 2018). Nowadays, crystalline silicon (c-Si) solar cells dominate the market with a 90 % market share in 2014 (International Energy Agency, 2014). Another solar PV technology is thin films, also known as the second generation of solar PV. Both technologies are described below.

2.2.1 Crystalline PV technology

The c-Si solar cells can be divided into two types, single-crystalline silicon (sc-Si) and multi-crystalline silicon (m-Si). The sc-Si solar cells are normally the most efficient type while m-Si solar cells tend to be cheaper since the manufacturing process is less energy and resource intensive (Honrubia-Escribano, A. et al., 2018).

A standard crystalline solar panel for household applications consists of 60 or 72 cells arranged as shown in figure 2.1. The efficiency of a solar panel is defined as the ratio between generated electricity and incoming solar radiation. The c-Si PV modules have experienced a rapid development during the last decade and the efficiency of average commercial modules has increased from 12 % to 17 % during this time (Frauhofer ISE, 2017). Record efficiencies of 24,4 % and 19,9 % for sc-Si and m-Si PV modules respectively have been reached in laboratory tests, indicating that there is a potential for further development (Frauhofer ISE, 2017).

The rapid development of the c-Si PV technology has also resulted in a rapid decrease of costs thanks to a significant reduction in material use, increased production levels and improved manufacturing efficiency. In Germany, the costs for a typical rooftop-installation of 10 to 100 kW_p decreased from around 14 000 €$/kW_p$ to 1 270 €$/kW_p$ between 1990 and 2016 (Frauhofer ISE, 2017). The experience curve shows that the price for solar PV panels has decreased by 24 % with each doubling of cumulative production over the last 36 years.

Another important aspect to consider when comparing solar panels is lifetime. Solar panels degrade with time meaning that the panels will have a lower power output when they are old compared to when they are new. Most manufacturers guarantee that their panels will retain a certain capacity after a certain number of years, normally 80 % after 25 years or 70 % after 30 years. Because of the degradation, investors in solar PV often assume a capacity reduction between 0,5 - 1 % per year when calculating the profitability of the investment (Honrubia-Escribano, A. et al., 2018).

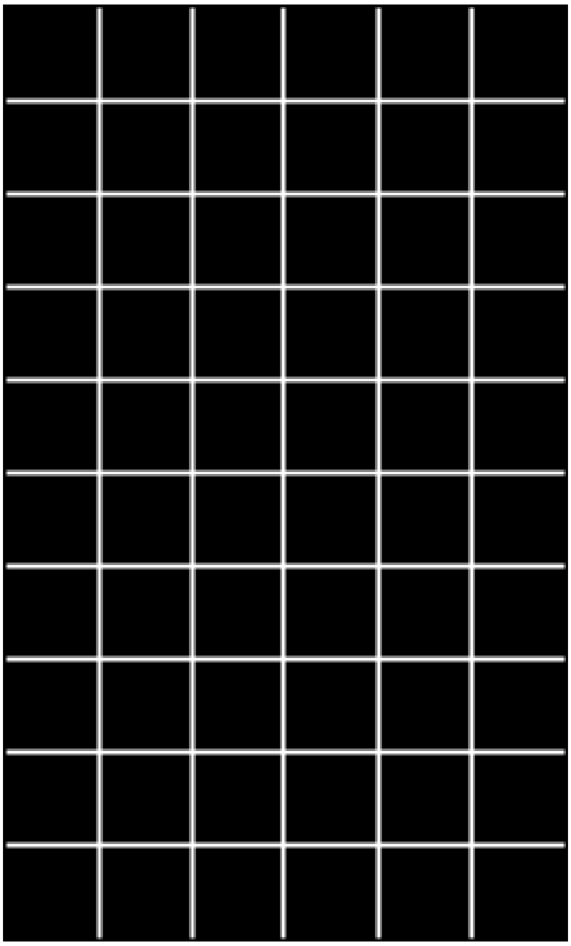


Figure 2.1: An overview of how the cells are arranged in a crystalline solar panel.

2.2.2 Thin film technology

The most common type of thin film solar cell is the cadmium-telluride (CdTe), followed by copper-indium-gallium-(di)selenide (CIGS) and amorphous silicon (a-Si) (International Energy Agency, 2014). Thin film solar cells tend to have a lower efficiency than the c-Si because of higher losses and thinner layers (Honrubia-Escribano, A. et al., 2018). However, the manufacturing process of thin films is resource efficient and fast, resulting in low production costs (El Chaar, L., Lamont, L.A., El Zein, N., 2011). Thin films also provide lower costs during installation as they often do not require the same amount of labour and mounting support as c-Si panels (Energysage, 2018).

Among the thin films, CdTe has the highest module efficiency of around 16 %, which is a big improvement compared to a decade ago when the efficiency was 9 %. CdTe also has the easiest production process making it suitable for large scale production (Honrubia-Escribano, A. et al., 2018). The CIGS thin films have similar performance as the CdTe (Frauhofer ISE, 2017) with the advantage that they do not contain cadmium, a toxic substance. The a-Si panels has the lowest efficiency of around 10 % (International Energy Agency, 2014). They also suffer from fast degradation during the first 100 to 1000 hours, making their energy output low compared to other PV technologies (Honrubia-Escribano, A. et al., 2018).

The thin films come in various different shapes, sizes and colours, making it possible to use them in a wider range of applications than the c-Si panels (International Energy Agency, 2011). They can also be manufactured on several different materials such as glass or steel giving them properties such as being flexible or transparent.

2.3 Battery storage systems

Batteries are an important part of the everyday life for most people and many electronic devices used today rely on batteries. The size and type of battery depends on the application as different battery types have different characteristics. For large applications such as for households, battery energy storage systems (BESS) can be used to handle the daily variations in generation from solar PV systems. By converting the electrical energy from the PV system into chemical energy, the energy can be stored and converted back into electricity when it is needed (MIT Electric Vehicle Team, 2008).

There are several important battery characteristics that must be considered when designing the BESS in household applications. These include capacity, power rating, depth of discharge (DoD), round-trip efficiency, cycle life and cost (Energysage, 2017). The total amount of energy a battery can store is described by the battery capacity, measured in kWh. Several batteries can normally be combined in order to increase the capacity to a desired level. Another important battery property is the charge and discharge power rating, which describes at what rate the battery can receive or deliver electricity at a given moment, measured in kW. The depth of discharge (DoD) describes how much of the battery capacity that can be used without damaging the battery. This is very important to consider when the battery capacity is determined as the actual useful capacity will be lower than the maximum battery capacity.

When a battery is charged and discharged, some electrical energy will be lost as heat. The round-trip efficiency describes the ratio between how much useful electricity that can be recovered from the battery and how much it took to store it. The capacity of a battery decreases the more cycles, charge and discharge, it has gone through. Battery manufacturers normally guarantee that their battery will retain a percentage of its capacity after a certain number of cycles or years, similar to solar panels (Energysage, 2017).

Several different battery types exist and the most common types for household applications are lead-acid, lithium-ion (Li-ion) and nickel-metal-hydride (Ni-MH). The characteristics of the different types depend on the manufacturer. There are also different chemical compositions within each battery type that influence the battery properties. Some general advantages and limitations are presented in table 2.1.

Table 2.1: Advantages and limitations of lead-acid (Buchmann, I., 2016), Li-ion (Buchmann, I., 2017b) and Ni-MH batteries (Buchmann, I., 2017a).

Battery	Advantages	Limitations
Lead-acid	Low cost, low self-discharge, high specific power, good performance at low and high temperatures	Low specific energy, slow charging, limited lifetime, uses toxic materials
Li-ion	High specific power and energy, low self-discharge, long lifetime, fast charging	High cost
Ni-MH	Easier to recycle, high safety	Short lifetime, lower efficiency, sensitive to overcharge, high self-discharge

2.4 Hydrogen storage systems

The hydrogen storage system consists of three steps, production, storage and consumption. These steps are explained below.

2.4.1 Hydrogen production

Hydrogen can be produced in many different ways and from many different raw materials. Conventional technologies produce hydrogen from fossil fuels such as coal, oil or natural gas but several renewable technologies for hydrogen production exist as well. This report focuses on the renewable technologies and more specifically water splitting by electrolysis. This is because it is the most suitable technology for off-grid household applications since it is compact and requires only water and electricity as input. Electrolysis is also the most efficient and established technology for water splitting (Nikolaidis, P., Poullikkas, A., 2017).

Three technologies exist for water splitting through electrolysis. These are alkaline, proton exchange membrane or polymer electrolyte membrane (PEM) and solid oxide electrolysis cells (SOEC) (Koumi Ngoh, K.,Njomo, D., 2012). Alkaline is the most commonly used for commercial purposes since it is the most developed and cost-efficient technology. It can produce hydrogen with high purity, up to 99,7 vol.%, without external purification equipment. The efficiency of an alkaline electrolyser is normally in the range of 62-82 % (Bhandari, R., Trudewind, C. A., Zapp, P., 2014).

PEM electrolysers normally have a more compact design compared to alkaline (International Energy Agency, 2006), giving them an advantage for household applications. The PEM electrolysers also have a safety advantage over alkaline electrolysers as they do not use potassium hydroxide (KOH) which is a toxic and corrosive substance. PEM electrolysers also have the advantage of being able to work with variable power supply while alkaline electrolysers have a longer response time. The efficiency of PEM electrolysers is in the same range as alkaline electrolysers, while the purity of the produced hydrogen is even higher. The major drawback of PEM however, is the higher cost (Bhandari, R., Trudewind, C. A., Zapp, P., 2014) and shorter life time (International Energy Agency, 2006).

SOEC has, compared to alkaline and PEM, a higher efficiency of 81-86 % and uses less electricity. On the other hand, it operates at high temperatures of 900-1000°C and temperature fluctuations can cause cracks in the membrane, reducing the life-time of the electrolyser. The high operating temperature also results in a longer start-up time compared to alkaline and PEM electrolysers. Thus, SOEC electrolysers are not suitable in combination with renewable energy sources (Bhandari, R., Trudewind, C. A., Zapp, P., 2014). Table 2.2 provides an overview of the specifications of the different electrolysis technologies.

Table 2.2: A comparison between the different electrolysis technologies (Bhandari, R., Trudewind, C. A., Zapp, P., 2014).

Specification	**Unit**	**Alkaline**	**PEM**	**SOEC**
Cell temperature	°C	60-80	50-80	900-1000
Cell pressure	bar	<30	<30	<30
Voltage efficiency	%	62-82	67-82	81-86
Energy consumption	kWh/Nm^3	4,5-7	4,5-7,5	2,5-3,5
Life time, stack	hours	<90 000	<20 000	<40 000
System life time	years	20-30	10-20	-
Hydrogen purity	%	>99,8	99,999	-
Cold start-up time	minutes	15	<15	>60

2.4.2 Hydrogen storage

Hydrogen has a high specific energy (energy per mass) but a low energy density (energy by volume), which is why the hydrogen properties must be altered to achieve feasible storage (Sinigaglia, T. et al., 2017). The storage types can be divided into physical and chemical storage. In physical storage, the hydrogen is compressed, liquefied or cryo-compressed while for chemical storage, the hydrogen is bonded to different sorbents or hydrides (Sinigaglia, T. et al., 2017). This report focuses on the physical storage type as these are less complex than the chemical ones.

Among the physical storage options, compression is the most common due to its simplicity. The pressure of the storage typically ranges from 20-70 MPa depending on the space requirements of the application. It is important to keep in mind that the behaviour of compressed hydrogen deviates from that of an ideal gas, meaning that the gas density does not increase linearly with increased pressure. At pressures of 20, 40 and 60 MPa the respective gas densities are 0,015, 0,027 and 0,037 kg/l (Sherif, S. (Ed.), et al., 2014). Liquid hydrogen storage offers higher hydrogen density of up to 0,07 kg/l but requires very low temperatures due to the low boiling point of hydrogen. This is a very energy intensive and expensive technology which affects the feasibility of the liquid hydrogen storage (Sinigaglia, T. et al., 2017).

Hydrogen is normally stored in tanks or cylindrical tubes which, depending on the storage type, can be made of steel, aluminum or composite materials. Steel offers a cheap solution with the disadvantage that the cylinders are heavy compared to composite materials. Thus, composite is preferable for mobile applications whereas where weight is not an issue, steel can be an attractive option (Sherif, S. (Ed.), et al., 2014).

2.4.3 Hydrogen consumption

Hydrogen can be used as fuel for conventional combustion technologies to generate electricity. This report however focuses on the fuel cell technology. Fuel cells use hydrogen and oxygen to generate electricity without combustion and operates like an electrolyser in reverse. The same technologies exist for fuel cells as for electrolysers, namely alkaline, proton exchange membrane (PEMFC) and solid oxide fuel cells (SOFC). Among the technologies, PEMFC is the most commonly used because of advantages such as high efficiency of up to 60 %, high power density and the fact it operates at low temperatures around 60-80 °C. However, it is a costly alternative which has delayed its commercialization (Sinigaglia, T. et al., 2017). Alkaline fuel cells also operate at relatively low temperatures, below 120 °C, but suffer the same safety issues as alkaline electrolysers since they use KOH. The SOFC operates at high temperatures, 900-1000 °C and suffers the same disadvantages as the SOEC.

2.5 Economic evaluation tools

There are several economic indicators that can be used to determine the value of an investment. The ones used in this project are net present value, life cycle cost and levelized cost of energy. These are further explained below.

2.5.1 Net present value

A very important number to consider when evaluating investments is the net present value (NPV). The NPV describes the current value of a future payment or saving (Ong, T.S., Thum, C.H., 2013) and is calculated as shown in equation 2.1 where C is a future cost or saving, r is the discount rate and n is the year in which the cost or saving occurs.

$$NPV = \frac{C}{(1+r)^n} \tag{2.1}$$

When calculating the present value of a future cost or income it is important to decide the discount rate. The discount rate is an individual preference that can depend on for example what an individual expects in the future or what other investment options exist. Another way to view the discount rate is that it is the return an investor demands from the investment in order to go through with it.

2.5.2 Life cycle cost

Another tool that can be used to evaluate the economic outlooks of an investment is the life-cycle cost (LCC). The LCC describes the total cost of the system during its entire lifetime. This is useful because it includes not only the cost of the investment but also what it costs to operate and maintain the system. The LCC is calculated by summing up the NPV of all costs that occur during the lifetime of the system, as shown in equation 2.2.

$$LCC = \sum \frac{C_i}{(1+r)^n} \tag{2.2}$$

2.5.3 Levelized cost of energy

Another indicator that is used a lot in energy system context is the levelized cost of electricity (LCOE). It describes the price for each kWh of electricity the system provides during its lifetime. It is very useful because it gives a value that can easily be compared to the alternative of buying electricity. It is calculated by dividing the LCC of the system with the total, net present adjusted amount of electricity generated during the same lifetime (Strid, B., Larsson, D., 2017) as shown in equation 2.3.

$$LCOE = \frac{LCC}{\sum_{i=1}^{i=n} \frac{E_i}{(1+r)^n}} \tag{2.3}$$

3 Methods

This chapter begins with a presentation of the reference building and how it was designed. It also explains how the modelling of the energy system was done and finally presents how the economic indicators were used to evaluate the profitability of the results.

3.1 The reference building

The initial idea for this project was to use an existing building as a reference building. However, due to difficulties in finding a suitable building, a reference building was instead designed based on an existing building.

The reference building is a two-story multi-family building with 26 apartments and a heated floor area of 1900 m^2. Among the 26 apartments, 16 are one room apartments of 34 m^2, six are two room apartments of 53 m^2 and four are three room apartments of 69 m^2. The remaining floor area of 762 m^2 is used for the energy system components, public space and as additional storage for the residents. The building has a pent roof with a 15° angle facing straight towards south. Figure 3.1 shows the building when it is drawn in PV*SOL®.

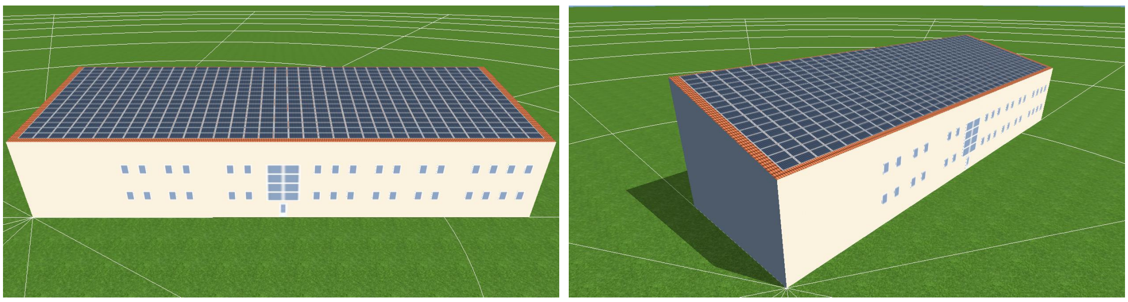


Figure 3.1: The reference building. The pictures are taken from south and south west in the simulation software PV*SOL®.

The demand curve of the reference building was constructed based on the Swedish passive house requirements (FEBY, 2018). Table 3.1 presents the assumed values used to calculate the total energy demand of the building.

Table 3.1: The assumed energy demand of the reference building.

Specification	**Value**	**Total**
Space heating demand	$15\ kWh_{heat}/m^2/year$	$28\ 500\ kWh_{heat}/year$
Hot water demand	$20\ kWh_{heat}/m^2/year$	$38\ 000\ kWh_{heat}/year$
Building electricity	$10\ kWh_{el}/m^2/year$	$19\ 000\ kWh_{el}/year$
Household electricity	$47\ kWh_{el}/m^2/year$	$53\ 600\ kWh_{el}/year$

The monthly distribution for space heating, hot water and building electricity were assumed based on discussions with experts within the passive house field. Figure 3.2 shows the demand of the reference building each month, including household electricity.

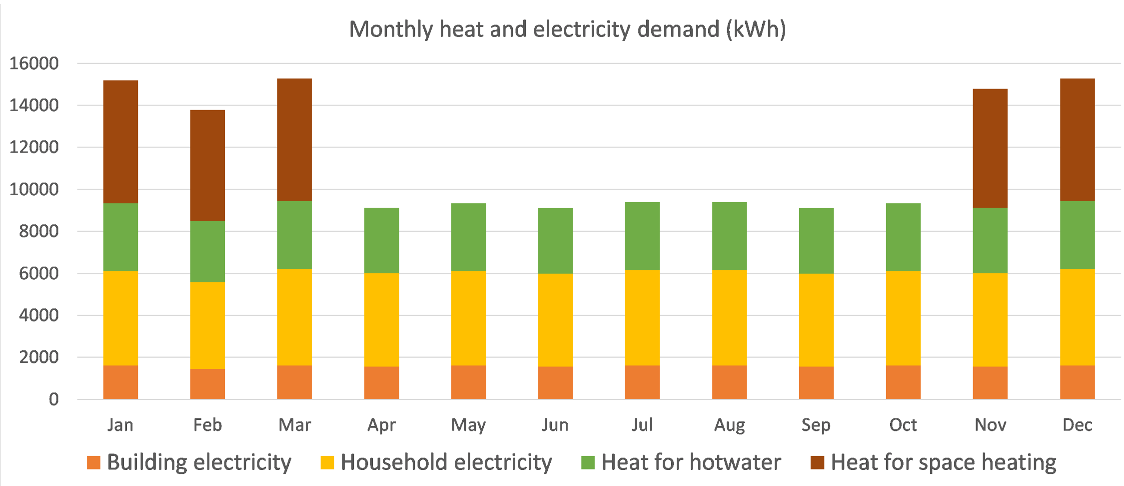


Figure 3.2: The monthly heat and electricity demand of the reference building. The red bars represent building electricity, the yellow bars represent household electricity, the green bars represent heat needed for hot water and the brown bars represent the heat needed for space heating.

The building is assumed to be built with good energy efficiency making space heating only needed during the coldest part of the year, November to March. Hot water demand and building electricity is assumed to be constant over the year. The heat needed for hot water and space heating is assumed to be partly supplied from the fuel cell, which for every generated kWh of electricity also generates one kWh of heat. The heat provided from the fuel cell is assumed to be provided between November and March, when the fuel cell is in operation. It is also assumed that the heat from the fuel cell is fully utilized. The heat generated due to losses in other components is not utilized and is assumed not to affect the energy demand of the building. The remaining heat needed is supplied by a heat pump which has an assumed seasonal performance factor (SPF) of 3, meaning that for each kWh of electricity it consumes it provides 3 kWh of heat. The above assumptions result in a relatively even annual electricity consumption profile compared to buildings without a fuel cell and with higher space heating. The electricity consumption profile is shown in figure 3.3.

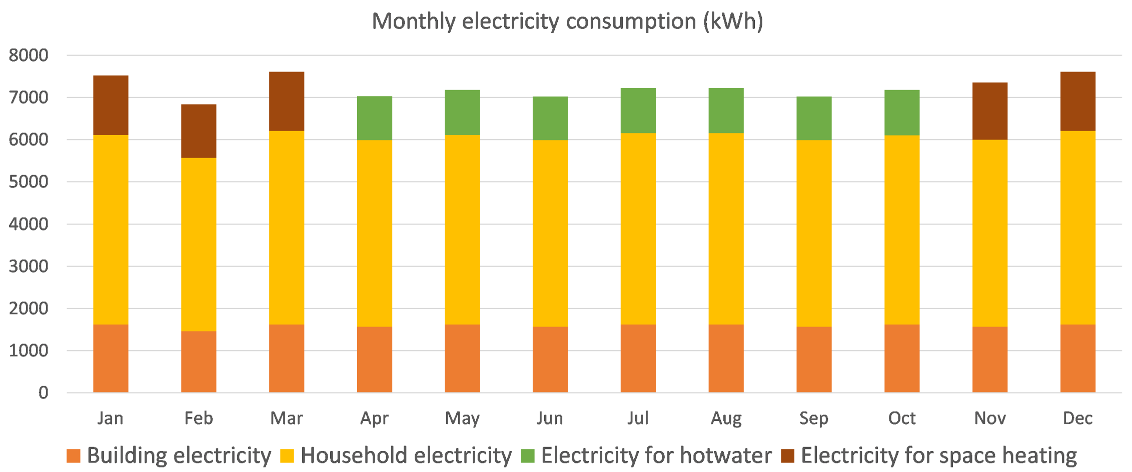


Figure 3.3: The monthly electricity consumption profile of the reference building. The red bars represent building electricity, the yellow bars represent household electricity, the green bars represent electricity needed for hot water and the brown bars represent electricity needed for space heating.

The electricity use in each apartment is based on typical numbers from the Swedish Energy Agency. The demand is assumed to be constant over each day of the year but varies on an hourly basis. Figure 3.4 shows some example days during different parts of the year. Note that these curves are randomly selected as an example of how the demand varies and are not representative for all days during the respective month.

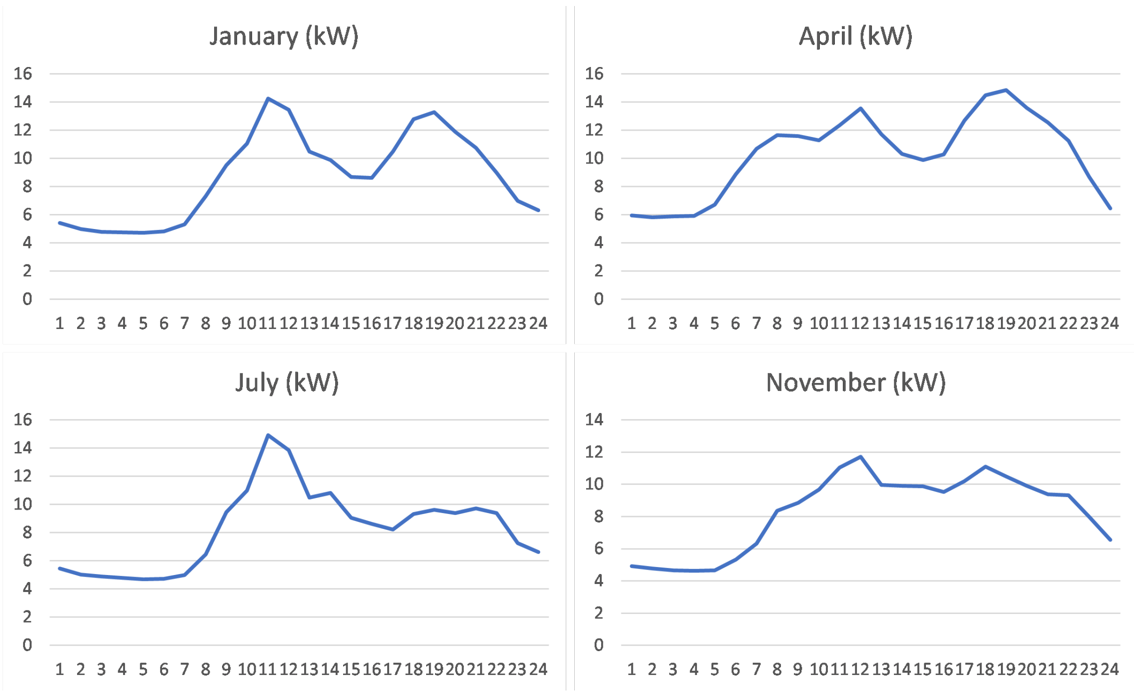


Figure 3.4: An example of how the household electricity demand can vary during different days.

3.2 Constraints and assumptions

Before the simulation of the energy system began, a few constraints were identified. These constraints had to be fulfilled to make sure that the results from the simulation were reliable and accurate.

The first and maybe the most important constraint regarded weather forecasts. It was assumed that the energy system had access to an accurate 24-hour weather forecast and could thus adapt the operation according to the coming weather. This enabled the electricity from the PV system to be utilized better. Without a forecast, a lot of electricity would need to be curtailed. However, as the forecast was limited to 24 hours into the future, it still prevented the system from having a too high degree of adaptability.

Another constraint that was used during the modelling was that the electrolyser and fuel cell had a minimum up-time of two hours. This constraint was used to prevent the hydrogen system from being used as short term storage. The electrolyser and fuel cell were also assumed to operate at a fixed production or consumption rate meaning that also the power supply or output is constant. This is to ensure that the hydrogen produced by the electrolyser maintains a constant high quality.

3.3 Simulation and modelling the energy system

When the reference building had been completed and the constraints had been identified, the next step was to simulate the production from the PV system and compare it to the demand. This was done using the simulation software PV*SOL®. The simulation was carried out on an hourly basis and the results were exported to Microsoft Excel where the complete energy system was modeled. The modeling was done by first calculating the energy balance, production minus consumption, for each hour to determine which hours had a deficit or surplus of electricity. During hours with a deficit of electricity, the battery was used to supply the current load and during hours with a surplus of electricity, the battery was instead charged. The electrolyser and fuel cell were used to keep the battery from becoming fully charged or discharged by either producing or consuming hydrogen.

Because of the seasonal weather variations, the year was divided into two periods with different operation schedules. During the dark period of the year, the fuel cell was used to charge the battery whenever the battery state-of-charge (SOC) was below 20 %. Normally, the fuel cell would charge the battery up to 75 % and then stop. However, as the system was assumed to have access to a 24-hour weather forecast, it could adapt the charging by either charging less or by postponing the charging from hydrogen if a lot of electricity was expected from the PV system during the coming hours.

During the sunnier half of the year the operation schedule was very different. During this period, the battery capacity was regulated to make use of as much of the PV electricity as possible. On days with high PV production, the battery was used to produce hydrogen in the beginning of the day in order to have battery capacity available during production peaks. If the battery was still fully charged during the day, some electricity was curtailed. Once again the weather forecast played an important role as it would not be desirable to drain the battery before summer days when the PV system generated no or only little electricity.

3.4 Economic evaluation

When the system configuration had been determined, the economic outlooks of the system were evaluated using the economic indicators presented in chapter 2. Several different scenarios were considered including both the present and a potential future situation. Different scenarios with varying discount rate were evaluated as well. No subsidies or other governmental support were included in the cost calculations.

When the cost of the off-grid energy had been determined in different scenarios, the cost of a traditional heat and electricity supply was estimated as well and used as comparison. Again, several scenarios were evaluated to provide an overview of the economic situation.

4

Results

This chapter begins with the results and findings from the simulation and modelling of the energy system, followed by the results from the economic analysis.

4.1 The energy system

The modelling results show that the combination of solar PV, batteries, a hydrogen system and a heat pump provides a technically feasible solution for being off-grid in Gothenburg. Both the battery and the hydrogen system are needed to have both short term and long term storage. The suggested system configuration is presented in figure 4.1.

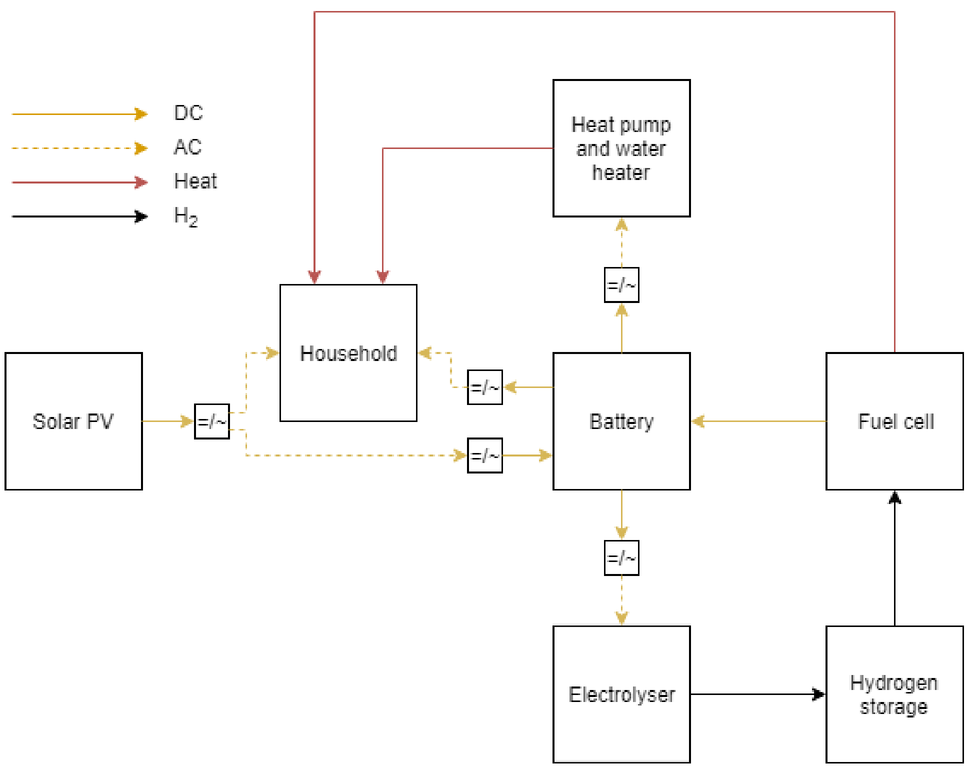


Figure 4.1: An overview of how the components in the off-grid system are connected. Yellow lines indicate DC electricity, yellow dotted lines indicate AC electricity, red lines indicate heat and black lines indicate H_2.

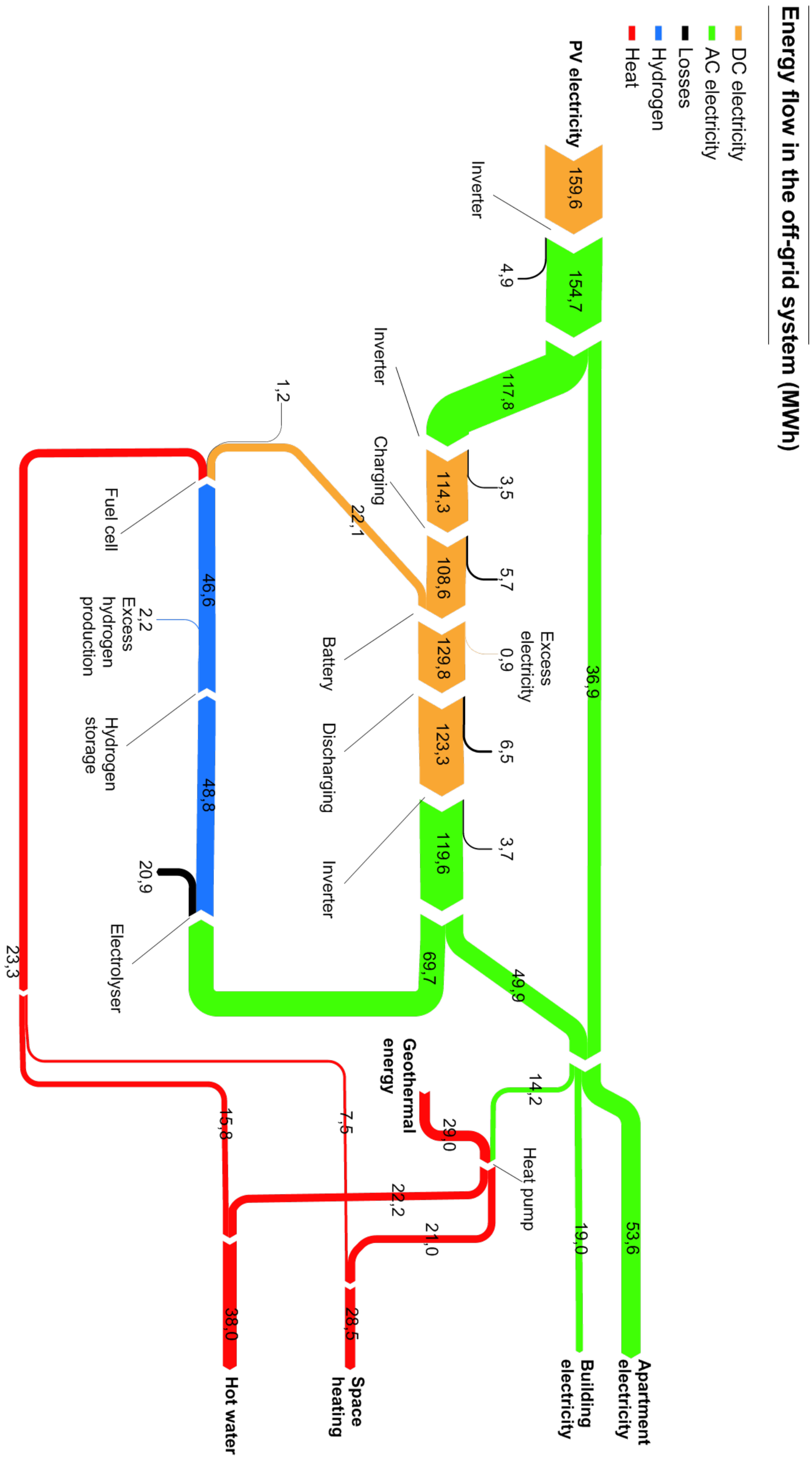


Figure 4.2: A sankey diagram of the energy flow, in MWh, in the off-grid system. Orange lines represent DC electricity, green lines represent AC electricity, red lines represent heat, blue lines represent hydrogen and black lines represent the losses.

As can be seen in figure 4.1, all electricity generated by the PV system is first converted into AC to cover the building demand. If the PV production is insufficient to cover the demand of the building, the additional demand is supplied by electricity from the battery and if excess electricity is available, it is instead stored in the battery. During seasons with high excess PV production, the battery feeds electricity to the electrolyser to produce hydrogen and during seasons with low PV production, hydrogen is consumed by the fuel cell to charge the battery. This system configuration involves high conversion losses but was still considered the best option as it enables a flexible system operation where the utilization of the PV electricity is maximized. Figure 4.2 shows how the energy is used in the off-grid system and where the losses occur.

4.1.1 The PV system

The PV system consists of 596 panels mounted horizontally on the roof of the building, with a total installed capacity of 164 kW_p. The panels are sc-Si and are assumed to have an efficiency of 16,9 % corresponding to a rated power of 275 W_p per panel. The simulation in PV*SOL® resulted in annual electricity generation from the PV system of 160 MWh DC, corresponding to 155 MWh AC with an inverter efficiency of 97 %. The annual electricity demand of the building is 87 MWh, meaning that the annual generation is approximately 80 % higher. This generation surplus is needed in order to cover the losses in the system. Where in the system the losses occur is shown in figure 4.2. Figure 4.3 shows how the electricity generation is distributed on a monthly and hourly basis, in comparison to the demand.

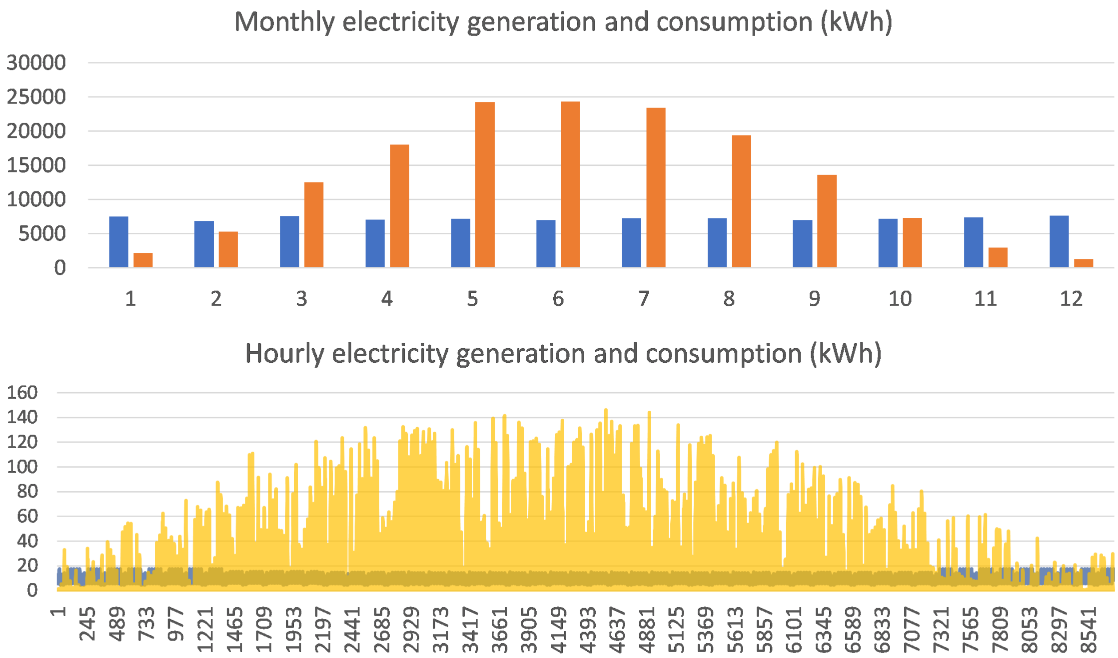


Figure 4.3: The monthly and hourly electricity generation (AC) in reference to demand. Yellow and orange represents the generation and blue represents the demand.

The panel specifications above correspond to those of the currently most affordable panel on the market. A m-Si panel with similar specifications and size could have been used as well. Thin films on the other hand would require a larger area to reach the same installed capacity and would not fit on the roof.

4.1.2 The battery system

A Li-ion battery is considered the best option for this application because of its longer lifetime compared to lead-acid or Ni-MH. Compared to a lead-acid battery it also has the advantage that is does not require any maintenance, which is desirable from an owners perspective. The Ni-MH has safety advantages over Li-ion, but its shorter lifetime limits its suitability for this application.

Modelling the energy system in Microsoft Excel shows that a battery of 300 kWh is needed to provide enough flexibility in the off-grid energy system. The round-trip efficiency of the battery is assumed to be 90 %, simplified as 5% losses during both charging and discharging. Furthermore, it is assumed that the usable capacity of the battery is 97 % of the total capacity, meaning that the battery can be discharged all the way down to 3 % SOC. Furthermore the charge and discharge rating of the battery is assumed to be 118 kW and 85 kW respectively. Note that this is a modelling result of what is required from the battery rather than a specification that has been determined in advance.

The battery is a key component in the energy system as it is responsible for handling all variations in the PV production and can be compared to the grid connection for a traditional PV system. Figure 4.4 shows how the battery SOC varies on an hourly basis over the year.

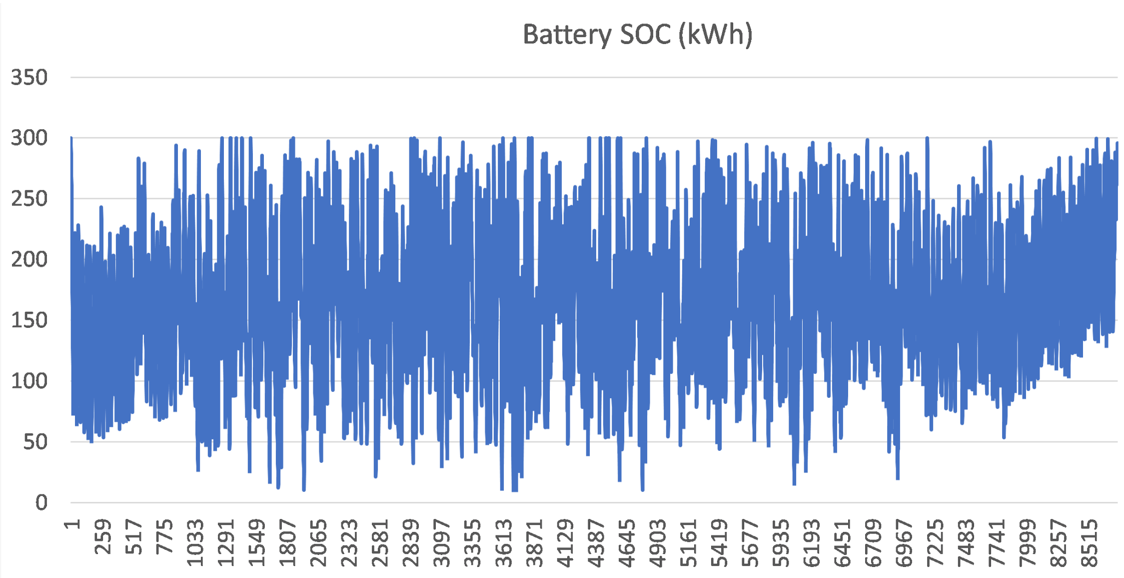


Figure 4.4: The variation in battery state-of-charge on an hourly basis.

4.1.3 The hydrogen system

As mentioned previously in the report, the hydrogen system consists of an electrolyser, a storage tank and a fuel cell. The PEM technology is considered the best option for both the electrolyser and the fuel cell because it operates at low temperature compared to the other two and has the shortest start-up time. It is also preferable from a safety perspective that it does not use KOH unlike alkaline. Regarding the storage of the produced hydrogen, compressed gas is considered favourable because it is simple and not as expensive as the liquefied or cryo-compressed.

The electrolyser is assumed to have an efficiency of 70 % which includes both the losses in the electrolyser and the compression of hydrogen. The optimal rated power of the electrolyser is 66 kW, which corresponds to a hydrogen production of 1,08 kg/h. The hydrogen is stored at 300 bar and the maximum amount of hydrogen that needs to be stored is 1415 kg, which is equivalent to 71 m^3. It is assumed that there are no losses during storage. The fuel cell is assumed to have an electrical efficiency of 50 % and a rated power of 20 kW is considered optimal. The hydrogen consumption of the fuel cell is 1,18 kg/h when it is operating.

The hydrogen system provides a completely different type of storage than the battery. Instead of charging and discharging on a daily basis, it instead operates on a seasonal basis where it produces hydrogen approximately from mid March to mid October and consumes hydrogen during the remaining part of the year. A few exceptions exist where hydrogen is consumed during the production period and vice versa. This occurs in the transition period between the production and consumption phase where the PV production can differ a lot from day to day. Figure 4.5 shows how the hydrogen SOC changes over the year.

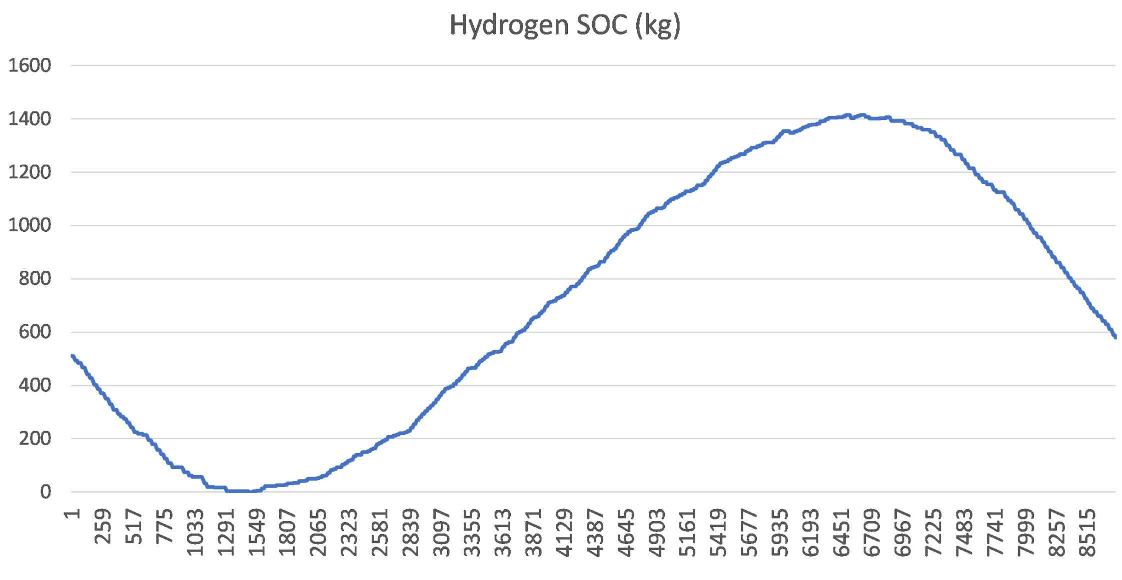


Figure 4.5: The variation in hydrogen state-of-charge on an hourly basis.

4.1.4 The heat pump and additional components

The heat pump operation has not been modeled to the same extent as the other components of the energy system. This is because the heating demand was already converted into electricity and included in the building's electricity consumption as explained in chapter 3. It is estimated based on guidelines from (Swedish Energy Agency, 2018) that a heat pump of 25 kW should be sufficient to cover the heating demand. The heat pump is assumed to have a SPF of 3 meaning that it provides 3 kWh of heat for each kWh of electricity it uses.

The energy system also includes other components that are important for the system to function properly. The battery and PV system use or generate DC current while the electrolyser, heat pump and the building demand requires AC current. It is thus important to have inverters that can convert between AC and DC when necessary. The inverters are assumed to have an efficiency of 97 % and figure 4.1 shows where in the system these are placed.

Another important component for the system operation is the control system. The control system is a crucial part of any off-grid system as it is needed to properly manage the operation of the battery and hydrogen system. However, when looking at the off-grid energy system from a theoretical perspective, the control system becomes quite invisible. In a real off-grid installation several sensors and other electrical components are likely to be needed for the control system which may incur losses in the system. These losses have been neglected as this project evaluates the off-grid system from a wider perspective and does not go in to detail in the electrical requirements.

4.2 The cost of the off-grid system

The cost of the different components in the energy system has been estimated based on literature and discussions with different actors operating within the respective fields. The estimated investment cost of the different components is presented in table 4.1. Note that the cost of the battery is assumed to be including a battery management system (BMS). The cost of the control system and other electrical components has been neglected. All costs are calculated in € and 1 € is approximately 10 SEK.

While the investment cost is important, it does not say much about what the actual electricity price is. Thus, in order to present some more comprehensible indicators, the LCC and LCOE of the off-grid system are calculated and compared to the cost of a traditional electricity supply. The LCC and LCOE depend on several factors including system lifetime, component lifetime and discount rate and the results vary a lot depending on what assumptions are made. In an attempt to provide an overview of what the LCC and LCOE may be, several different scenarios are evaluated. Costs and energy production that will occur in the future are adjusted with the NPV. This means that when a component in the off-grid system needs to be replaced, the cost of replacing that component is lower compared to the initial investment. On the other hand, the energy production that will occur in the future also has a lower value than the energy produced on day one. This means that the LCC decreases with increasing discount rate while the LCOE increases with increasing discount rate.

Table 4.1: The assumed investment cost of all components in the energy system.

Component	**Cost**	**Size**	**Total cost**	**Share**	**Comment**
Solar PV	900 €/kW$_p$	164 kW$_p$	147 600€	14 %	
Inverter	100 €/kW$_p$	164 kW$_p$	16 400 €	2 %	
Battery	600 €/kWh	300 kWh	180 000 €	17 %	incl. BMS
Electrolyser	3 500 €/kW	66 kW	231 000 €	22 %	
Fuel cell	3 500 €/kW	20 kW	70 000 €	7 %	
Gas storage	5 000 €/m^3	71 m^3	355 000 €	34 %	
Heat pump	1 500 €/kW	25 kW	37 500 €	4 %	
Total cost	-	-	**1 037 500 €**	**100 %**	

The first scenario considers a system lifetime of 30 years. During this period, the battery, fuel cell and electrolyser will be replaced twice, first after 10 years and a second time after 20 years. The heat pump, hydrogen storage and PV panels are assumed to be functional during the entire system lifetime and will not be replaced. The inverters for the PV system on the other hand will be replaced after 15 years. These assumptions result in an LCC of 1 298 370 € and 2 015 900 € for a discount rate of 10 % and 0 % respectively. The corresponding LCOE is 1,43 €/kWh and 0,75 €/kWh respectively. The relationship between the LCOE and the discount rate for the first scenario is shown in figure 4.6.

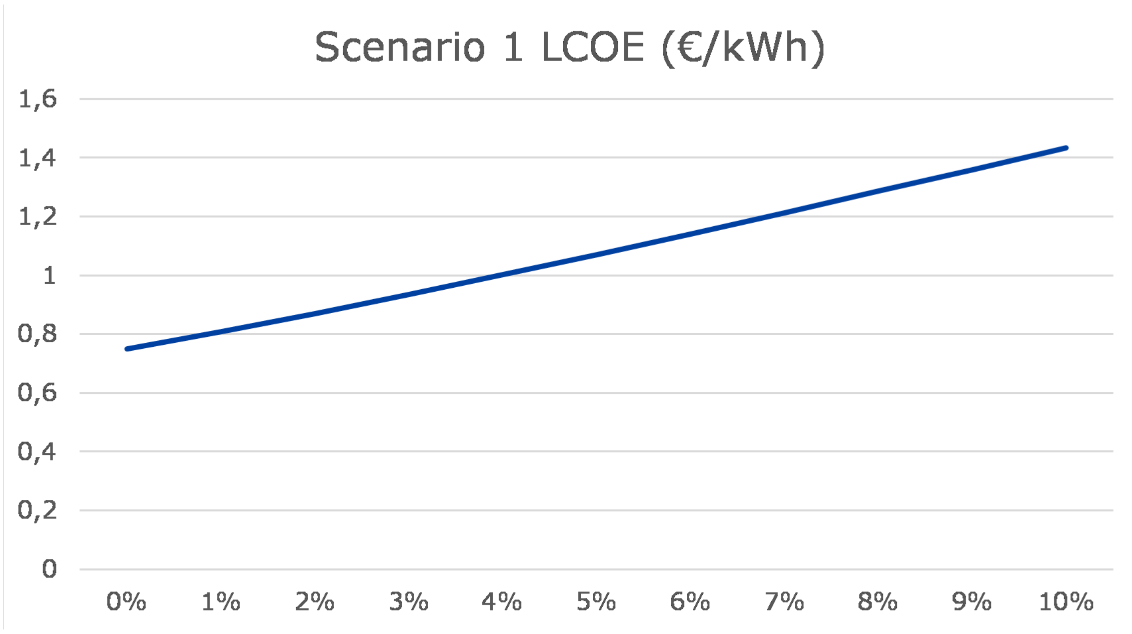


Figure 4.6: A graph of how the LCOE varies with varying discount rate in the first scenario.

The LCOE in the first scenario is quite high compared to the current electricity price in Sweden. The electrolyser has the largest impact on the LCC of the off-grid system, followed by the hydrogen storage, the battery, the PV system and the fuel cell. Because of this, a potential future scenario is evaluated as well. This scenario uses the same assumptions as the first scenario regarding system and component lifetimes, but with reduced investment costs. The investment cost for the electrolyser, battery and fuel cell are reduced by 70 %, a number similar to the price reduction of PV panels that has occured during the last decade. The price of the PV panels and the hydrogen storage are reduced by 20 % compared to the first scenario and the price of the remaining components are unchanged. These assumptions result in an LCC of 678 229 € and 902 000 € for a discount rate of 10 % and 0 % respectively. The corresponding LCOE is 0,75 €/kWh and 0,34 €/kWh respectively. The relationship between the LCOE and the discount rate for the second scenario is shown in figure 4.7. As can be seen in the figure, the LCOE of the off grid system remains relatively high compared to the current electricity price in Sweden, even when the cost of some components has been reduced. However, as described in chapter 1, the electricity price may increase in the future and in such a case, the off-grid system might be a competitive option.

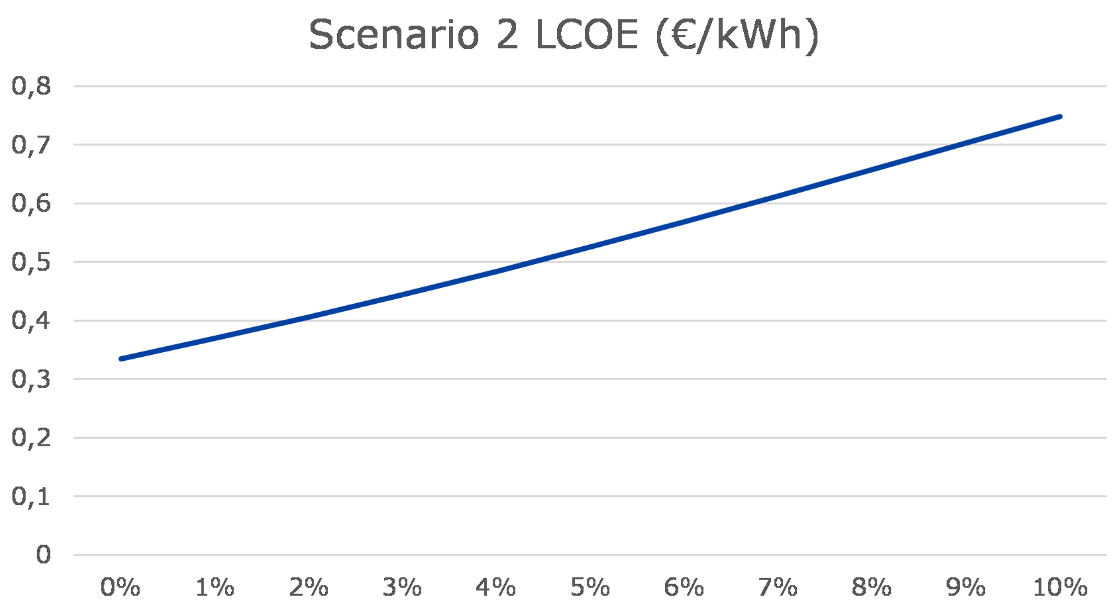


Figure 4.7: A graph of how the LCOE varies with varying discount rate in the second scenario.

As mentioned above, the first two scenarios include the cost of replacing certain components at the end of their expected lifetime. Another option could be to have a continuous fee that covers the maintenance and any replacements in the system. A solution like this will likely be the case if the interest for this type of systems increases and companies that deliver turnkey solutions emerge on the market. The cost of such a solution is evaluated in the third and fourth scenario.

The third scenario uses the costs presented in table 4.1 with an additional, annual cost of 1 % of the total investment cost. The annual cost is assumed to cover all costs except the initial investment and thus, no cost for replacing components is included. This results in an LCC of 1 135 672 € and 1 349 920 € for a discount rate of 10 % and 0 % respectively. The corresponding LCOE is 1,25 €/kWh and 0,5 €/kWh respectively. The relationship between the LCOE and the discount rate for the third scenario is shown in figure 4.8.

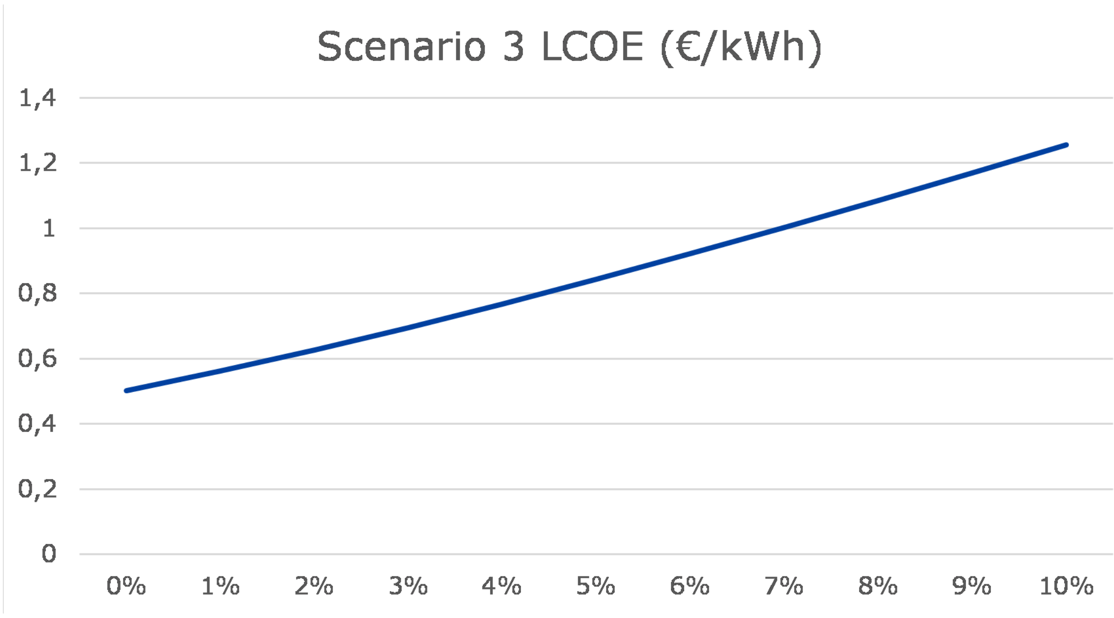


Figure 4.8: A graph of how the LCOE varies with varying discount rate in the third scenario.

The fourth scenario evaluates a similar option as the third, but uses the same reduction of costs as in scenario two. This results in an LCC of 653 646 € and 777 270 € for a discount rate of 10 % and 0 % respectively. The corresponding LCOE is 0,72 €/kWh and 0,29 €/kWh respectively. The relationship between the LCOE and the discount rate for the fourth scenario is shown in figure 4.9.

There are also other aspects to consider that affect the economic outlook of the off-grid system. One such aspect is space requirement. When the reference building was designed, a floor area of 240 m^2 was reserved for the system components. From a property owner's perspective, this means that the income from rent is reduced. The yearly income loss is estimated to 42 000 €. Using the same assumptions as in the first scenario but including the lost income from rent as a cost, results in an LCC of 1 694 300 € and 3 275 900 € with a discount rate of 10 % and 0 % respectively. The corresponding LCOE is 1,87 €/kWh and 1,22 €/kWh respectively. The relationship between the LCOE and the discount rate for the fifth scenario is shown in figure 4.10.

The result from the fifth scenario shows that if the space requirement for the system components is included in the economic calculations, the cost of the off-grid becomes very high compared to the current electricity price.

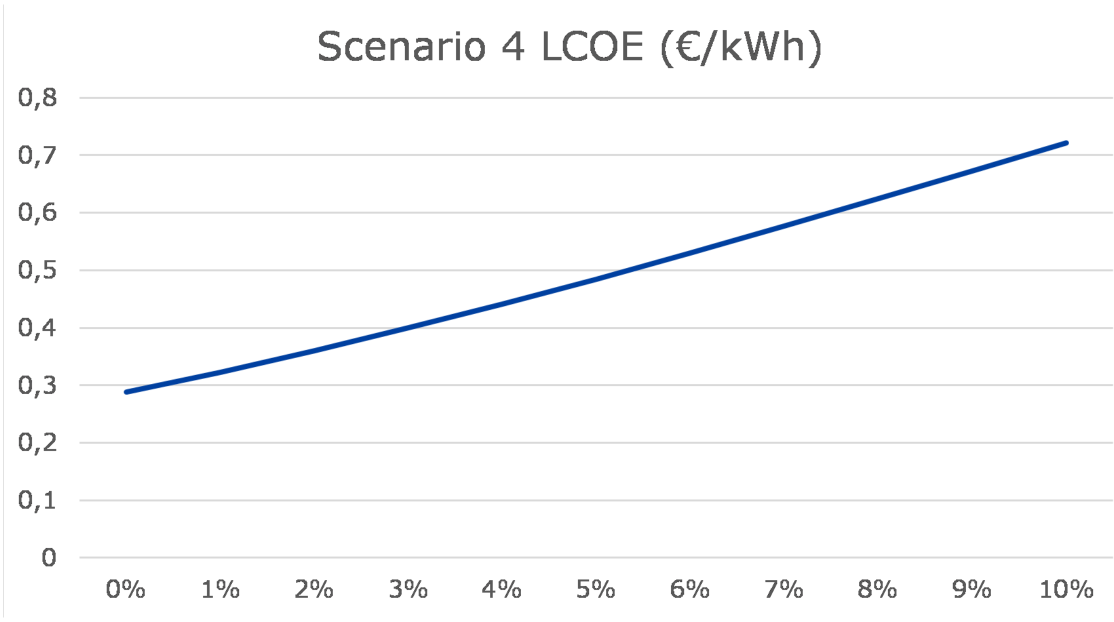


Figure 4.9: A graph of how the LCOE varies with varying discount rate in the fourth scenario.

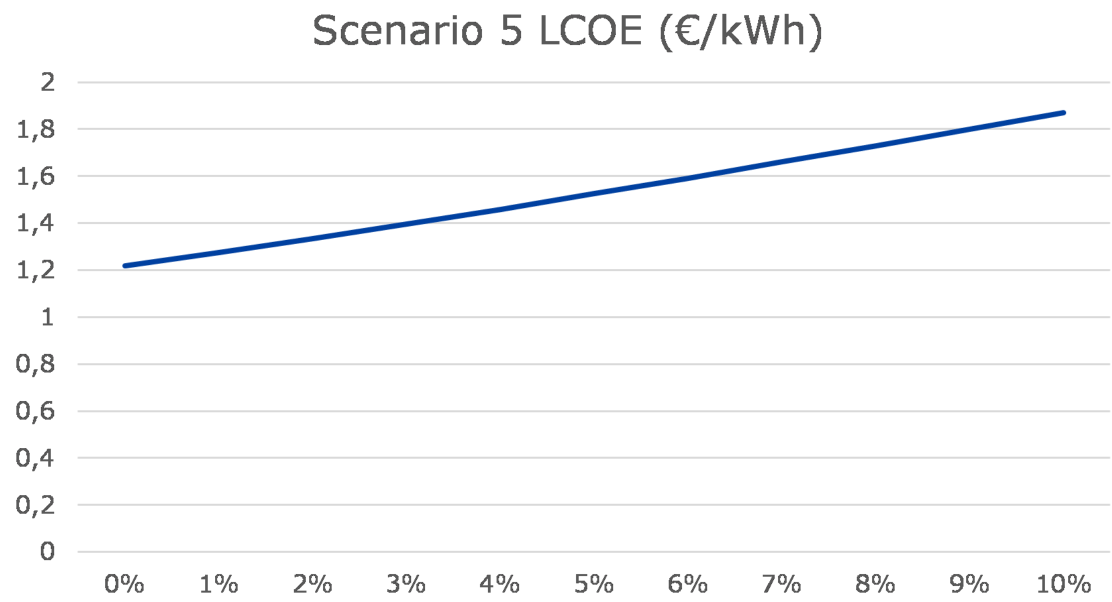


Figure 4.10: A graph of how the LCOE varies with varying discount rate in the fifth scenario.

4.3 The cost of a traditional energy supply

To be able to compare the costs of the off-grid energy system with a traditional grid connection, the costs involved for the traditional case are estimated as well. The cost of connecting a new building to the grid depends mainly on the distance between the building and the closest point of connection. Two scenarios are thus evaluated, one where the building has 25 m to the closest connection point and one where the building is 1800 m away. The first option is also considered to be connected to the district heating network, while the second option instead uses a heat pump because of the distance. The assumed investment costs are based on price examples from different companies in the Swedish energy sector. The electricity price is assumed to be 0,15 €/kWh, including the cost of transmission. The price for district heating is assumed to be 0,06 €/kWh. The total investment and annual costs of the two alternatives are presented in table 4.2.

Table 4.2: The costs of a traditional heat and electricity supply.

Alternative 1: 25 m		
Utility	**Investment cost**	**Annual cost**
Electricity	2 210 €	10 890 €/year
District heating	8 000 €	4 410 €/year
Total cost	**10 210 €**	**15 300 €/year**
Alternative 2: 1800 m		
Utility	**Investment cost**	**Annual cost**
Electricity	48 410 €	10 890 €/year
Heat pump	37 500 €	3 325 €/year
Total cost	**85 910 €**	**14 215 €/year**

The above mentioned assumptions result in an LCC of 260 709 € and 318 644 € in scenario six and seven respectively with a discount rate of 5 %.

Another option that was evaluated for the traditional electricity supply was a scenario where the electricity price increases by 2 % per year. This alternative results in an LCC of 327 690 € and 380 876 € respectively with a discount rate of 5 %.

An overview of the LCC in all scenarios, both traditional and off-grid, is shown in table 4.3. As can be seen from the table, the most expensive traditional system, scenario nine, is still cheaper than the cheapest off-grid system, scenario two. In order for the off-grid system to become economically viable, the cost of the components must both decrease further and the electricity price must increase more than 2 % annually.

Table 4.3: An overview of the LCC for all scenarios using a discount rate of 5 %.

Scenario	LCC	Description
Off-grid systems		
1	1 521 965 €	Present scenario
2	747 862 €	Pontential future scenario
3	1 197 589 €	Present scenario incl. 1 % annual cost
4	689 373 €	Future scenario incl. 1 % annual cost
5	2 167 608 €	Present scenario incl. cost of lost floor area
Traditional systems		
6	260 709 €	Present scenario 25 m
7	318 664 €	Present scenario 1800 m
8	327 690 €	Scenario 6 incl. 2 % electricity price increase
9	380 876 €	Scenario 7 incl. 2 % electricity price increase

5

Discussion

In this chapter, the results are discussed based on the assumptions made and the methods used. Furthermore, some additional aspects to consider regarding off-grid buildings are discussed as well.

5.1 Methods and assumptions

One assumption that was made during the modelling of the complete energy system was that an accurate weather forecast was available for the coming 24 hours. Thanks to the forecast, the system operation could be optimized to utilize the electricity to a much greater extent compared to a situation where no forecast was available. In a real off-grid energy system, it is likely that a weather station is installed or that the system can acquire a forecast from online sources, but with a lower accuracy. A lower forecast accuracy would require a larger battery to handle the deviations from the predictions, which in turn would result in a higher system cost.

The size of the components in the energy system was minimized by modelling the first year of operation. However, PV modules are known to degrade over time and the capacity of batteries is reduced the more they are used. This means that the size of these components would be insufficient after a few years. To account for this capacity reduction, the components must be oversized when designing the off-grid system. Another thing to keep in mind regarding the size of components is that it might be desirable to have a margin in case of unexpected situations such as demand peaks or reduced PV production. Any increase in component capacity would of course result in an increased system cost.

As mentioned in chapter 4, the cost of the control system and other minor electrical components that may be required in the off-grid system has not been included in the cost calculations. This means that the cost of the off-grid system may be a bit higher in reality. On the other hand, there are also aspects that could have a positive impact on the economic outlook of the off-grid system. For example, in the first two scenarios from chapter 4, the lifetime of the battery, electrolyser and fuel cell is assumed to be ten years. After ten years, it is assumed that these components will be replaced. However, these components may be functional for a longer time than ten years, especially the battery which, according to some manufacturers, is expected to have up to 80 % of its initial capacity left after ten years. Not having to replace the battery would have a positive impact on the economy of the off-grid system.

Reducing the losses in the system could have both a positive or negative impact on the costs. Reduced losses would mean that a smaller PV system would be needed as the electricity is better utilized. One way to reduce the losses could be to feed electricity directly from the PV system to the electrolyser. However, doing so could compromise the quality of the produced hydrogen and could require a larger and more expensive electrolyser. Another way to reduce the losses could be to use a hybrid inverter that only converts a part of the electricity from the PV system to cover the demand of the building. The downside of this is that the hybrid inverters normally cost more than the regular ones.

The costs used in the economic calculations were estimated based on literature and information from experts within each field of operation. This means that the cost of the components can differ depending on the manufacturer. Furthermore, the cost of the fuel cell and electrolyser varies a lot with capacity, meaning that the cost situation may look different for an off-grid system of different size. It is also possible that the costs can be reduced by buying more of the same component, for example if several systems of this type are to be built.

Another thing that could have a positive impact on the economic outlook of the off-grid system is that no subsidies or governmental support have been considered in the calculations. Several policy instruments exist that favour the implementation of renewable energy technologies. These could potentially reduce the cost of the off-grid system greatly.

5.2 The future of off-grid buildings

It is difficult to predict the future of this type of off-grid energy systems due to the many aspects that must be considered. The results show that it is a technically feasible but currently very expensive solution compared to being connected to the grid. In order for the off-grid system to be competitive from an economic point of view, the cost of the components must be greatly reduced. Furthermore, as shown in the fifth scenario in chapter 4, the space needed for the off-grid system could instead be used to build more apartments. This has a negative impact on the property owner's willingness to invest in the system and to overcome this, the off-grid system would need to provide other benefits.

There are also other aspects to consider such as sustainability and legal requirements. Laws regarding electrical installations and fire safety may have an impact on the feasibility. The environmental impact is important to determine if off-grid buildings are to be implemented on a large scale. As mentioned in chapter 1, the background of this work is that the sector of buildings and services needs to reduce its energy consumption and environmental impact. Because the off-grid system uses solar power as its only source of energy, it does not have any direct emissions during operation. However, producing the components within the off-grid system is likely an energy intensive process and may, depending on how and where these components are produced, be subject to high emissions. Moreover, batteries, electrolysers and fuel cells often contain rare materials that require complicated extraction methods which sometimes involve unsustainable working conditions and negative environmental impact. Thus, in order to determine whether an off-grid system of this type is beneficial from a sustainability perspective, a complete life-cycle assessment is required.

6
Conclusion

Solar power has gained increased popularity during the last decade as a renewable alternative to the traditional generation technologies. In combination with energy storage technologies, the variations in PV production can be handled to better fit the demand of the consumers.

This report has evaluated both the technical and economic feasibility of an off-grid energy system using solar PV, a battery, a hydrogen storage system and a heat pump to fulfill the annual heat and electricity demand of an apartment building in Gothenburg, Sweden. The required size of the different components has been determined through simulation and modeling in PV*SOL® and Microsoft Excel. The results indicate that the combination of the above mentioned technologies provides a technically feasible solution, without compromising the convenience or comfort of the residents. It can also be concluded that both the battery and the hydrogen storage are needed and using only one of them is not sufficient due to the seasonal weather variations in Sweden.

When evaluating the off-grid system from an economic point of view, it can be concluded that it is not viable compared to a traditional heat and electricity supply. In order for the system to become cost-competitive, the cost of the system components, especially the battery and the electrolyser, must decrease significantly.

Furthermore, it can be concluded that more aspects of the off-grid system must be evaluated to fully determine the overall feasibility. From both a technical and economic perspective, a deeper investigation of the control system and the electrical requirements is needed. This could improve the accuracy of the economic calculations and highlight any potential difficulties from the technical perspective. It would also be valuable to investigate how other technologies could affect the economic outlook of the system.

Evaluating the off-grid system from a sustainability and legal perspective would also provide valuable information that could help determine whether off-grid systems are something to consider for the future or if other options have a brighter outlook.

Bibliography

Bhandari, R., Trudewind, C. A., Zapp, P. (2014). "Life cycle assessment of hydrogen production via electrolysis – a review". In: *Journal of Cleaner Production* 85, pp. 151–163. DOI: https://doi.org/10.1016/j.jclepro.2013.07.048.

Bhattacharya, K., Bollen, M.H.J., Daalder, J.E. (2001). *Operation of Restructured Power Systems*. Boston, MA: Springer.

Buchmann, I. (2016). *BU-201: How does the Lead Acid Battery Work?* URL: http://batteryuniversity.com/learn/article/lead_based_batteries (Accessed: 14 Feb. 2018).

– (2017a). *BU-203: Nickel-based batteries.* URL: http://batteryuniversity.com/learn/article/nickel_based_batteries (Accessed: 8 May 2018).

– (2017b). *BU-204: How do Lithium Batteries Work?* URL: http://batteryuniversity.com/learn/article/lithium_based_batteries (Accessed: 14 Feb. 2018).

Cordiner, S. et al. (2017). "Fuel cell based Hybrid Renewable Energy Systems for off-grid telecom stations: Data analysis from on field demonstration tests". In: *Applied energy* 192, pp. 508–518. DOI: http://dx.doi.org/10.1016/j.apenergy.2016.08.162.

El Chaar, L., Lamont, L.A., El Zein, N. (2011). "Review of photovoltaic technologies". In: *Renewable and Sustainable Energy Reviews* 15.5, pp. 2165–2175. DOI: https://doi.org/10.1016/j.rser.2011.01.004.

Energysage (2017). *How to choose the best battery for a solar panel system.* URL: https://www.energysage.com/solar/solar-energy-storage/what-are-the-best-batteries-for-solar-panels/ (Accessed: 13 Feb. 2018).

– (2018). *Thin film solar panels: Do they make sense for residential?* URL: https://news.energysage.com/thin-film-solar-panels-make-sense/ (Accessed: 15 Feb. 2018).

FEBY (2018). *Kravspecifikation för energieffektiva byggnader.* Stockholm, Sweden.

Frauhofer ISE (2017). *Photovoltaics report.* Freiburg, Germany.

Guinot, B. et al. (2015). "Techno-economic study of a PV-hydrogen-battery hybrid system for off-grid power supply: Impact of performances' ageing on optimal system sizing and competitiveness". In: *International Journal of Hydrogen Energy* 40.1, pp. 623–632. DOI: https://doi.org/10.1016/j.ijhydene.2014.11.007.

Honrubia-Escribano, A. et al. (2018). "Influence of solar technology in the economic performance of PV power plants in Europe. A comprehensive analysis". In: *Renewable and Sustainable Energy Reviews* 82, pp. 488–501. DOI: https://doi.org/10.1016/j.rser.2017.09.061.

International Energy Agency (2006). *Hydrogen Production and Storage - R&D Priorities and gaps*. Paris, France.

– (2011). *Solar Energy Perspectives*. Paris, France.

– (2014). *Technology Roadmap - Solar Photoviltaic Energy*. Paris, France.

Koumi Ngoh, K.,Njomo, D. (2012). "An overview of hydrogen gas production from solar energy". In: *Renewable and Sustainable Energy Reviews* 16.9, pp. 6782–6792. DOI: https://doi.org/10.1016/j.rser.2012.07.027.

Lacko, R. et al. (2014). "Hydrogen energy system with renewables for isolated households: The optimal system design, numerical analysis and experimental evaluation". In: *Energy and Buildings* 80, pp. 106–113. DOI: https://doi.org/10.1016/j.enbuild.2014.04.009.

MIT Electric Vehicle Team (2008). *A Guide to Understanding Battery Specifications*. URL: http://web.mit.edu/evt/summary_battery_specifications.pdf (Accessed: 13 Feb. 2018).

Mohammed, Y.S., Mustafa, M.W., Bashir, N. (2014). "Hybrid renewable energy systems for off-grid electric power: Review of substantial issues". In: *Renewable and Sustainable Energy Reviews* 35, pp. 527–539. DOI: https://doi.org/10.1016/j.rser.2014.04.022.

Nikolaidis, P., Poullikkas, A. (2017). "A comparative overview of hydrogen production processes". In: *Renewable and Sustainable Energy Reviews* 67, pp. 597–611. DOI: https://doi.org/10.1016/j.rser.2016.09.044.

Ong, T.S., Thum, C.H. (2013). "Net Present Value and Payback Period for Building Integrated Photovoltaic Projects in Malaysia". In: *International Journal of Academic Research in Business and Social Sciences* 3.2, pp. 153–171. ISSN: 2222-6990.

Sherif, S. (Ed.), et al. (2014). *Handbook of Hydrogen Energy*. Boca Raton: CRC Press.

Sinigaglia, T. et al. (2017). "Production, storage, fuel stations of hydrogen and its utilization in automotive applications-a review". In: *International Journal of Hydrogen Energy* 42.39, pp. 24597–24611. DOI: https://doi.org/10.1016/j.ijhydene.2017.08.063.

Strid, B., Larsson, D. (2017). *Investeringskalkyl för solceller*. Stockholm, Sweden.

Svenska kraftnät (2016). *Grid development, driving forces*. URL: https://www.svk.se/en/grid-development/driving-forces/ (Accessed: 2 May 2018).

Swedish Energy Agency (2015). *Energiläget 2015*. Bromma, Sweden.

– (2018). *Välj rätt värmepump*. Eskilstuna, Sweden.