Case study of an off-grid house energy system

Ebba Adolfsson Josefin Hellekant Linus Karling
Guillermo Márquez Lopéz

February 27, 2022

Contents

Glossary

AAEP - Average annualized electricity price

AF - Annuity factor

EAC - Equivalent annualized cost

EV - Electric Vehicle

LCC - Life-cycle cost

LCOE - Levelized cost of energy

LCOES - Levelized cost of energy storaged

SOC - State of charge

SDG - Sustainable development goal

Wp - Watt peak power

1 Introduction

In this chapter, the background, aim, limitations and research questions of this study will be presented.

1.1 Background

In 2019, the UN estimated that 759 million people lack access to electricity, with 75% of them living in Sub-Saharan Africa, constituting half of Sub-Saharan Africa's population [1]. The UN predicts the Sub-Saharan population to double and the world population to reach 9.7 billion by 2050, that is an increase of 23% from 2021 [2]. In the same period, the energy demand is projected to increase by almost 50% [3]. The UN's Agenda 2030 addresses the lack of energy in SDG no 7 by stating that all people on earth should have access to clean and affordable energy in 2030 [1]. Living standards around the globe are continuously increasing, contributing to rising energy consumption per capita. The need for expansion and development of electrical generation and grids is huge and will even increase more in the future. At the same time we face incomparable challenges of climate change. To avoid exceeding a 1.5°C temperature rise, the world needs to reach net zero CO_2 emissions in 2050 [4]. In solving the challenges of present and future energy demands, and meeting the requirements of emission reductions, developing, effectivising and expanding renewable energy sources will play a major role.

The absolute largest energy source we have, is the sun. The radiant energy that hits the surface of the earth is about 5000 times larger than the energy use from fossil fuels [5]. One can absolutely argue that most energy sources on earth, including fossil fuels, biomass and wind is in foundation solar power as the sun is and has been the driving force for all these phenomena. However, energy conversions always comes with a cost of efficiency loss, and harvesting biomass for energy production require about 100 times more land area [5] than solar cells for producing the same amount of energy. Furthermore, solar panels have little requirements in quality of land, while e.g. biomass can only be farmed on land with specific requirements.

There is no question that solar power will be an important brick in building the future. The last 38 years, the price of solar PV-modules have dropped by 24% for every doubling of cumulative production [5] and the share of electricity production from solar in the world have increased from 0.15% in 2010 to 3.27% in 2020 [6].

Solar power is an intermittent power source and have to be complemented with energy storage technologies to be able to function on broad scale. Continuous research and development is carried out on a wide amount of energy storage technologies for finding viable and efficient solutions. Examples of energy storage technologies are batteries, thermal energy storage, mechanical energy storage (e.g. flywheels), pumped hydropower and hydrogen production.

One of the enthusiastic pioneers driving the development of solar based energy systems is Hans Olof Nilsson on Nilsson Energy (https://nilssonenergy.com/), who initially built a complete off-grid energy system with solar power and storage technologies such as hydrogen and batteries for his private residence. Nilsson Energy is now endowed in delivering complete off-grid systems solutions and non-fossil hydrogen production to customers in both private and public sector.

This study will look into the case of off-grid electricity production and consumption on the basis of Hans Olof Nilsson's private residence.

1.2 Aim

The aim of this study is to contribute to the understanding of how solar PV can be used for small scale off-grid purposes on the 60th parallel, where Chalmers University of Technology is located.

1.3 Limitaions

This study will focus on the private residence of Hans Olof Nilsson. All data on system and energy will be based on Hans Olof's personal logs with averaged values over the year. There will be no in-depth analysis of any parts of the system as time and resources of this project does not allow such study. No detailed data on technology types and brands will be considered.

1.4 Research questions

- How much electricity can the subject of the case study produce in a year?
- What energy storage technologies are used?
- How much hydrogen can be produced every year and how much electricity can be generated from this hydrogen, according to the case study?

- What is the payback time for the proposed system?

2 Theory

2.1 Function of a solar PV

To better understand how energy can be produced from a solar photo voltaic (PV) some basic knowledge about the physics of light and its interaction with atoms and molecules are needed and will be presented in this section.

Light has the particle/wave duality and can be considered both electromagnetic radiation and photons. Light from the sun consist of a spectrum of different frequencies (or wavelengths) and the distribution of frequencies can effectively be described by Plank's law and black body radiation. Every object radiates light and the intensity and spectrum is determined by its absolute temperature according to Stefan Boltzmann's law

$$E = \sigma T^4 \tag{1}$$

Where E is to total power radiated per square meter, σ Boltzmann's constant and T the absolute temperature of the object. This is however only true for a *Black body*, a body with unity emissivity, which the sun is close to having [7].

The spectrum distribution is given by Planck's black body radiation law:

$$B_\nu = \frac{8\pi\nu}{c^3} \frac{h\nu}{e^{\frac{h\nu}{kT}} - 1} \tag{2}$$

where h is Plank's constant, k Stefan Boltzmann's constant, ν the frequency of the light, c the speed of light, T the absolute temperature of the black body and B_ν the power per unit area of the specified frequency. When this equation is used for the estimated temperature of sun, $T = 5778K$, and the relation for wavelength and frequency

$$c = \lambda\nu \tag{3}$$

irradiance as a function of wavelength can be plotted [8].

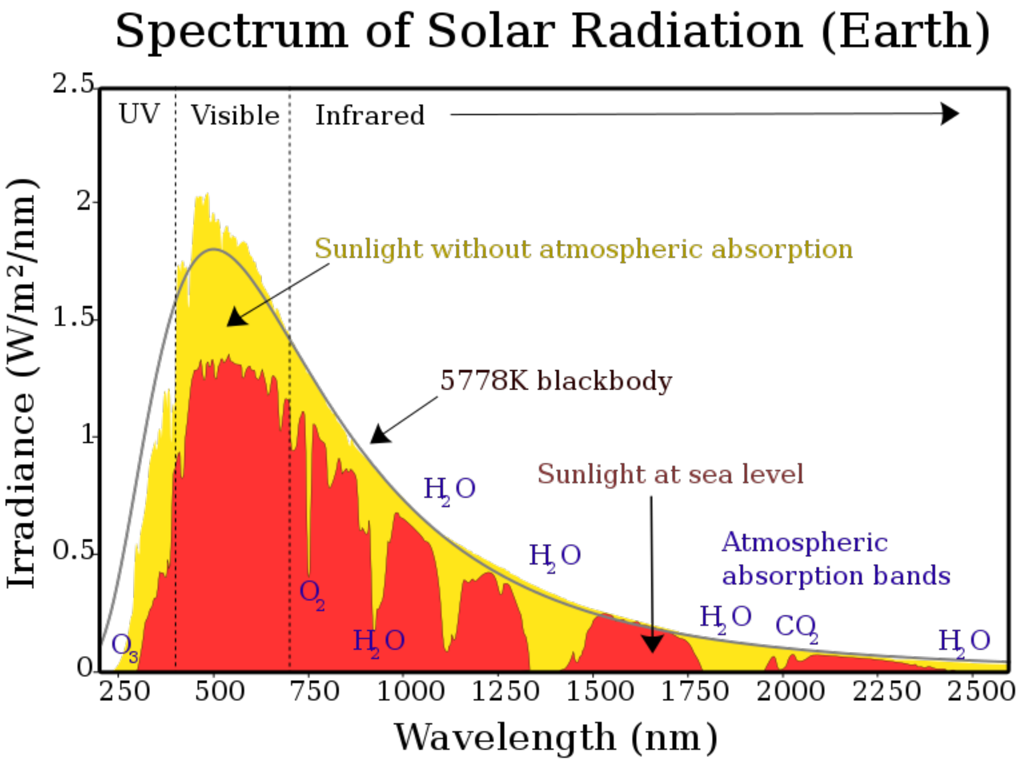

Figure 1: Theoretical irradiance spectrum for the sun as well as the actual sun that reaches the atmosphere and sea level. CC.BY.3.0

In Figure 3 the theoretical irradiance from the sun as well as a measured one for outside the atmosphere and at sea level can be seen. As seen the irradiance from the sun outside the atmosphere is very close to the theoretical black body for the given temperature.The irradiance at sea level however deviates quite a bit and especially in some intervals. This is due to the absorption from different molecules in the atmosphere which are also seen in the figure.

In which regions molecules absorbs the radiation is dependent on their excitation energies which are closely connected to the quantified energy levels for the electrons in the molecules but also the temperature of the material. The energy of a photon can be described by the following equation:

$$E = h\nu \tag{4}$$

where once again h is Planck's constant and ν the frequency of the light. In order to excite an electron from one energy level to another (band gap) the incoming photon must at least have the energy of the exact difference from one level to an other. This makes the molecules, or atoms, absorb specific wavelengths of light and is a important property for photovoltaics (PV) to work.

The most common PV cell is the Silicon PV, which properties comes from the semiconductor-element silicon. Silicon in elemental form has a very high band gap due to only having 4 valance electrons. Because of this the Silicon used in the cells are doped which means impurities are introduced to make some of the atoms in the silicon crystal deficient of electrons (p-doped) and others excessive (n-doped). These two types are then layered on top of each other to create a so called p-n junction. When photons, of sufficient energy, now strikes the n-doped part of the silicon a electron hole pair can be created, which means that the electron is separated from its nucleus. If the n- and p-doped layers are connected on the outside with a conductor this makes it possible for the electron to travel via the conductor while the "hole" travels through the junction and reunites with he electron again.

For this to work it is important that no incoming light is reflected, to determine if reflection will occur Snell's law can be utilized and is given by:

$$\frac{sin\phi_2}{sin\phi_1} = \frac{n_1}{n_2} \tag{5}$$

where ϕ_2 is the incoming lights angle to the normal of the interface, phi_1 the refracted lights angle relative to the interface, n_2 the refractive index of the incoming light travel medium and n_1 the refractive index of the refracted travel medium. If Equation 5 when solved for the refracted lights angle gives an angle outside the range of $\phi_1 = [0, \pi]$ the light is reflected. This makes it important that the sun is stranding high, which is not the case in winter time in Sweden.

2.2 Hydrogen production

One of the biggest challenges of solar power and other renewable energy systems is the issues concerning storage. Finding ways to facilitate utilization of the surplus energy from peaks of generation by effectively storing it for times of low/zero generation is crucial. One well researched solution to this problem that has shown high potential is hydrogen technologies, where hydrogen gas is produced and used as fuel to efficiently store energy.

Hydrogen is the lightest, most simple chemical element and the most efficient energy carrier. For comparison, hydrogen gas is around three times more energetic than methane and gasoline [9].

Hydrogen is not found in its pure state in nature, but can be obtained from different sources of raw materials, including water. There are many ways to produce hydrogen gas, some by the use of fossil fuels or natural gas, others more eco-friendly. Water electrolysis is one of the most prominent hydrogen gas producing methods, producing hydrogen of high purity with only oxygen as byproduct [9]. In the following section the fundamentals of water electrolysis will be explained.

Water electrolysis involves splitting water molecules into hydrogen and oxygen using electricity. A direct current is circulated through the water between two electrodes, one anode and a cathode. The electrodes are immersed in an electrolyte, a solution containing free ions that makes the substance electrically conductive, to raise the ionic conductivity. A diaphragm or separator, often consisting of micro-porous inorganic or organic materials like sintered glass, polymeric sheets, earthenware, nylon, cellophane or rubber, is used to avoid recombination of the hydrogen and oxygen molecules. It is also used to prevent short circuiting the electrodes by providing electrical resistance. The diaphragm should have a high ionic conductivity and show high physical and chemical stability [10].

The electrodes, the electrolyte and the diaphragm, are the elements forming the electrolytic cell, enabling the water molecules to undergo the following reaction:

$$2H_2O(l) \rightarrow 2H_2(g) + O_2(g) \tag{6}$$

This global reaction consist of two half-reactions; oxidation (release of electrons) and reduction (uptake of electrons) take place at the different electrodes. The ions from the electrolyte take up electrons at the cathodes surface(reduction), and the ions at the anodes surface release electrons(oxidation). The half-reactions taking place are:

$$Cathode: 2H_2O(l) + 2e^- \rightarrow H_2(g) + 2OH^- \tag{7}$$

$$Anode: 2OH^- \rightarrow 2H_2O(l) + 1/2O_2(g) + 2e^- \tag{8}$$

hence hydrogen is generated at the cathode and oxygen at the anode [11].

To calculate the potential needed to split the water molecule the standard potential for the cell can be calculated with Equation 9

$$E^0_{cell} = E^0_{cathode} - E^0_{anode} \tag{9}$$

For the half reaction at the anode the standard potential is $1.29V$ and for the half reaction at the cathode it is $0V$. This gives the total standard potential for the cell of $1.29V$ which is the minimum potential difference between the electrodes to split the water molecule. However this is for the ideal case and non-ideal conditions give rise to something called overpotential which is the extra potential needed to actually split the molecule. Effects that cause overpotential are concentration gradients in the electrolyte, bubble formation on the electrodes and resistance in the cell.

There are however ways to lower the standard potential and thus make the reaction more efficient. This is done by introducing other chemical elements in the solution as electrolytes. Also alliterative methods with a solid electrolyte can be used for greater efficiencies. For conventional use with liquid electrolyte the efficiency is about 60-80%[11].

3 Method

A literature study will be performed for a better understanding of the technologies considered in this study. The literature study will consist of collecting information provided by relevant companies, agencies and organizations, a data study to compare literature data on how the parameters affect the efficiency of the setup and interviewing people with relevant knowledge.

After collecting information, analyzing and sorting on relevance for the project, it was decided to focus on the information obtained by an interview, because of that, the project will be carried out as a case study using the information obtained through an interview with Hans Olof Nilsson. The information obtained will be used as an example of the operation principle of an off-grid photo voltaic generation system using batteries and hydrogen as storage systems. During the interview, the questions were mainly focused on the technical specifications of the existing system, dividing this system in three sections, the first one is the energy generation for the house, the second is the energy consumption and the third one is the energy storage system.

-Energy generation: in this section, the installed capacity for energy generation will be analyzed, to do so, the capacity and the disposition of the PVs and solar collectors will be discussed and the main generation difference related to summer and winter periods will be explored.

-Energy consumption: a general analysis will be done taking into account the main consumption sources which are electricity consumption over the day, heating demand for house heating purpose, electric vehicle (EV) consumption and heat for heating water. As it was done for the generation sector, the consumption differences between summer and winter period will be studied.

-Energy storage systems: as solar energy is known to be a variable renewable energy source, a variation management strategy will be needed to match this variable generation with consumption. In this section, the existing storage systems will be analyzed focusing on the installed capacity and its working principle to discuss the usability and prioritization when deciding which technology to use.

The last part of the project will be a cost analysis of the system but as no specific information was obtained about investment costs, they will be explored and assumed. Total costs of the installation will be calculated by adding the investment costs and the maintenance costs and this costs will be compared to the electricity savings which will be calculated from an average electricity price in Gothenburg.

4 Findings

The system includes a photovoltaic system with 23 kWp installed capacity, which, during summer, provides enough electricity to cover the demand and produce an excess of generation to first fill the batteries as they are used as daily storage system and once the SOC reaches a certain percentage, the excess of electricity generated will start being used to produce hydrogen through the electrolyzer and store it for the winter period when the daily generation is not large enough to cover the demand. During winter period, stored hydrogen will be used on a fuel cell to produce electricity that is used to charge the batteries and heat. In addition to the photovoltaics, there are solar thermal collectors fitted on the roof for heating of water and indoor climate. As a backup technology, there is a diesel generator that would start working in case is needed. For a better understanding of the existing system, figure 2 shows an schematic view of the installation.

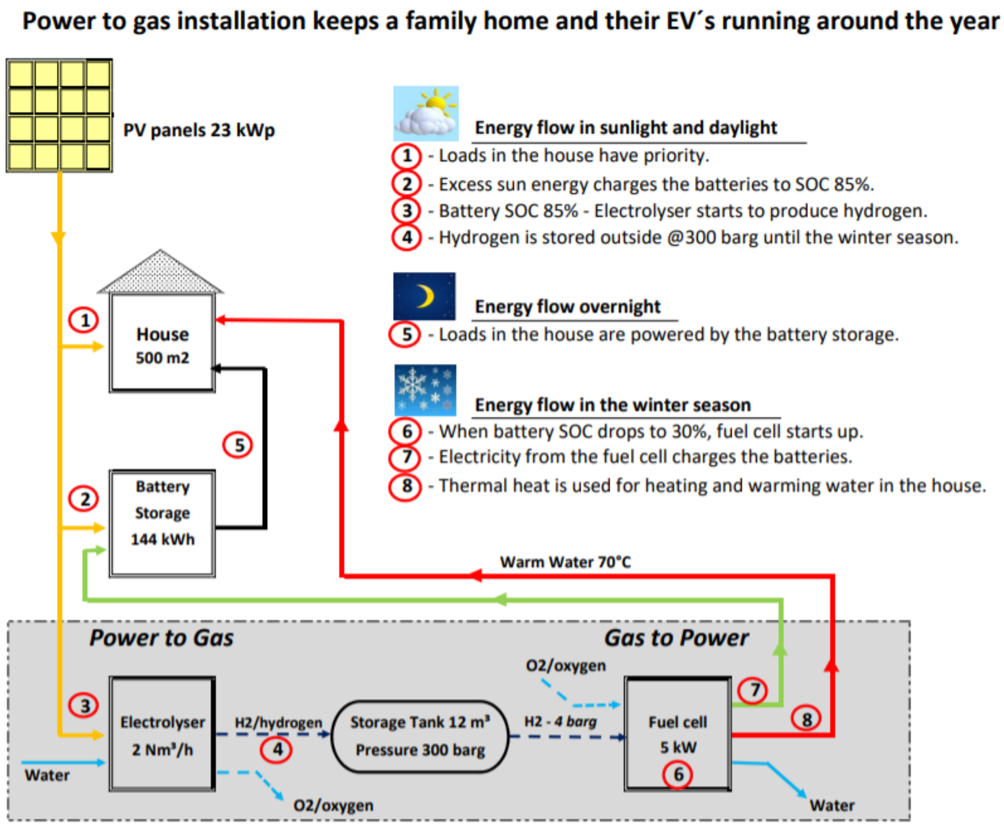

Figure 2: Main energy scheme for a family house off-grid based on Pv generation and battery and hydrogen storage.

4.1 Energy production

The setup of the installed production system should be based on what purpose the system is intended to fulfill. It should be able to cover the predicted demand at all times and to manage the nature of intermittency of renewable energy sources. The energy production capacity is a product of solar irradiance over time, technology of choice, age of the system and management methods.

When designing the system in the Nilsson house, a 500 m2 villa, the question ”what is needed to go offgrid” was to be answered. The system for energy production in the Nilsson house initially needs to cover a demand of 16500 kWh per year. This includes 13500 kWh of household consumption whereof 3750 and 700 kWh is required for heating wintertime and summertime respectively, 850 kWh for cooling and the 3000 kWh required to charge the electric vehicle.

The Nilsson house is equipped with solar PV panels producing 20 kWp on the roof, 2 kWp on the west facade and 1 kWp on the south facade. In addition to this there are 20 m2 of solar panels on the roof for heating of water, producing 6000 kWh of warm water each year, providing all heating of water and spaces in the house at summertime. However, these water heating solar panels are not used in new setups, as less heating is required in summertime and the water standing still reaches temperatures up to 350 °C. This leads to problems with pumps.

The PV panels have a size of 1x1.6 m^2 and produce 250 Wp which gives a peak production of 156 W/m^2. For the 20 kWp on the roof there are 128 m^2 distributed on 80 PV panels. Including the facade panels there is 23 kWp in total. The total generation from the PV panels in a year is about 21900 kWh. Beyond satisfying the direct consumption during summertime, the PV panels also produce an excess of around 15000 kWh, which is converted to hydrogen and stored for wintertime consumption. This conversion eventually ends up in 4100 kWh of electricity and the same amount of thermal energy.

In the winter season, more specifically the months between October and March, the sun is too weak for the solar PV's to produce sufficient amount of energy. Thus, the major part of the yearly demand of energy will have to be collected during the months of April to September, and parts of it to be stored for the share of the year with insufficient PV production for covering daily demand.

Even though most of the 16500 kWh yearly demand will need to be produced in the 6 summertime months when the insolation is high enough, the solar cells in the south facade provide about 900 Wh in the season with low solar radiation. Also the water heating solar panels provide about 950 Wh from October to March.

The productivity of solar PV drops to 30% if it is cloudy. To cover up for lengthy periods of cloudiness at summertime, there is always a buffer in the hydrogen tank so that the fuel cells can be used even in the summer if necessary. What needs to be considered when installing a system based on solar PV is that all panels drop in capacity the first years and evens out at ca 20% efficiency loss. Such decrease in production capacity should be accounted for in installation!

4.2 Energy consumption

The total yearly energy consumption of Nilsson Energy is 16500 kWh, whereas 13500 kWh is the housing demand and the additional 3000kWh/year is used to power an electric vehicle.

The energy demand is shifting through the day, with peaks in the morning and afternoon. An example of how the energy use of an average Swedish household could vary throughout the day is shown in figure 3 There is also an yearly variation, with higher demand during winters. Since the PV generates most electricity mid-day, and sufficiently more energy during the summer, the peaks of demand and supply do not match.

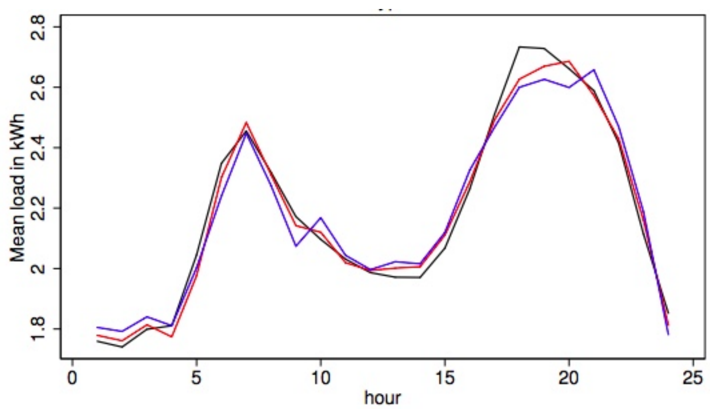

Figure 3: Average energy consumption of Swedish households throughout a day. CC.BY.3.0

Because of the intermittent nature of solar energy, Nilsson Energy are using a shifting strategy to manage the gap between demand and generation by using excess electricity during peaks to load batteries and produce hydrogen. The batteries are mainly used for short term storage, to operate the differences in supply and demand through day and night. The hydrogen is stored for a longer period and covers the winter demand.

During the summer months, by Nilsson Energy roughly counted April to September, the electricity generated by the PV is abundant and the water heating panels on the roof is enough to keep the house warm and supply hot water. As the sun rises and the PV starts to produce more electricity than the house consumes, the batteries with a capacity of 144kWh begin to charge. When the batteries are charged to 80%, the electrolysis process starts, producing hydrogen simultaneously as the rest of the battery capacity is filled. In one summer, 15000 kWh of surplus energy could be converted into about 275 kg hydrogen, that is stored for winter.

During winter hydrogen is the primary source of energy. When converting the hydrogen back to electricity, the fuel cells generate 4100 kWh electricity from the 275 kg hydrogen. The process also generate thermal energy corresponding to 4100 kWh, that can be used for heating the house.

To keep the house warm, Nilsson Energy also has heat pumps installed, that uses around 1200kWh per year on average, electricity that is mainly generated from hydrogen through fuel cell technology.

4.3 Energy storage systems

Nilsson case has 23kWp of solar PV and the excess in solar is $15000 kWh/year$. Producing H_2 takes $55 kWh/kgH_2$ to so in total about 273kg of H_2 can be produced in one year. Converting this back to electricity gives about 15kWh of electricity per kg of H_2 so in total $4095 kWh/year$. However, the low efficiency generates about 11kWh of heat that can be recovered with a heat pump and bringing up the efficiency to $\eta = 15/44 = 0.34$. Compared to batteries this is not good at all and that is why hydrogen is only produced once the batteries reach their full (preferred) charge of 85%. The reason for not going up to 100% charge is the battery health is affected negatively. This prioritization of energy systems is really important to keep the overall efficiency up, since the back and forth conversion gives a lot of losses that cannot be recovered.

With hydrogen lower explosion limit at 4(V%) there are safety considerations to be made, one of those are that the tanks are placed outside so that a leak at the tank would not accumulate hydrogen in the living area. For comparison a leak of only 0.25kg of hydrogen (0.09% of Nilsson's storage capacity) would be enough to create a explosive atmosphere in a room of $30m^2$ assuming 2.5m ceiling height. The flash point of hydrogen gas is -150C which means that the energy amount to ignite the hydrogen is very small and even a small spark, coming from example a regular light switch, could ignite it [12].

4.4 Cost analysis

A cost analysis is carried out to analyze if the project is profitable. To perform this cost analysis, the equivalent annual cost (EAC) will be calculated and compared with the average annual electricity price (AAEP) times his total consumption during the year [13]. The reason of using the equivalent annual cost is due to the data we have available and its simplicity, other methodologies such as the life-cycle cost (LCC) [14] and the Levelized Cost of Energy (LCOE) [15] and Levelized Cost of Energy Stored (LCOES) have been discarded due to the complexity of the system. To calculate the EAC first we need to calculate the Annuity Factor (AF) since we cannot compare present costs with future costs directly, to do so, a discount rate of 3% have been assumed and the selected life-spam is 40 years since we were told during the interview that it is usually in between 30 and 50 years. The life-span of the system is a rough simplification for the calculations since each equipment will have its own life-spam and they will be replaced individually. The calculation of the AF can be observed in equation 10.

$$AF = (1 - (1/(1 + r)^t))/r = 23.11 \tag{10}$$

Where, r is the discount rate (3%) and t the number of years (40).

Once the AF is calculated, we can obtain the equivalent annual cost (EAC) by dividing the investment costs (IC) over the AF plus the operation and maintenance costs (OM) as it can be observed in equation 11.

$$EAC = IC/AF + OM \tag{11}$$

During the interview, Hans-Olof refused to provide the investment costs of his installation, but market prices of the main investment costs were given and listed below table 1. OM costs are difficult to estimate but we were told to be approximately 0,4% of the total investment cost of the installation, its calculation is shown at the bottom of the investment cost table. Minor costs not included in the list were considered negligible and not taken into account.

Table 1: Investment cost

Component	Size	Price	Price
PV	23 kW	1180€/kW	27140€
Batteries	144 kWh	500€/kWh	72000€
Electrolyser	15 kW[16]	3600€/kW	54000€
Fuel cells	5 kW	4500€/kW	22500€
Heat pump	8 kWe	900€/kWe	7200€
Hydrogen tanks	280 kg	22000€/40kg	154000€
Inverter	23 kW	600€/kW	13800€
Solar Heaters	20 m2	390€/m2	7800€
Total investment cost			**358440€**
O&M		0.4% of investment cost	**1434€**

EAC=358440/23.11+1434=16944€/year

To compare the EAC, AAEP for Gothenburg is used. The AAEP has been obtained from Nordpool for 2021 and it is equal to 65,84 €/MWh [17], If we multiply the AAEP times 17MWh that Hans-Olof consumes per year we obtain 1120 €/year of savings since he is not using this electricity from the grid. From a financial point of view, this system is not worth since EAC is much larger than savings.

4.5 Sensitivity Analysis

We have analyzed the actual profitability of this system in Gothenburg and, even though the main purpose of the household is not to gain profit, It is important to know if this system will be cost competitive in the future. To know that a simple sensitivity analysis will be performed. As the main purpose is to analyze the profitability of the system, the only components that will be studied are the ones that are included in the cost analysis without making any change in the dimensioning of the system. It is important to add that a better dimensioning of the different installed capacities would reduce investment costs since it is over dimensioned and smaller capacities would be possible if demand side management strategies were done.

The sensitivity analysis will consider the investments done. It is a mixture of immature technologies that needs some development, studies, and more installed capacity to reduce costs. This is known due to the experience curve principle which shows how a immature technology is, when it is invented, very expensive, but the more installed capacity, the lower the prices. This is basically because once a new technology gain credibility and finds suitable niches to develop, more people and industries will invest to reduce manufacturing costs which at the end it is reflected on the consumer investment costs. Figure 4 will show how price for PV components is reduced with an increased installed capacity based on their learning rates (LR).

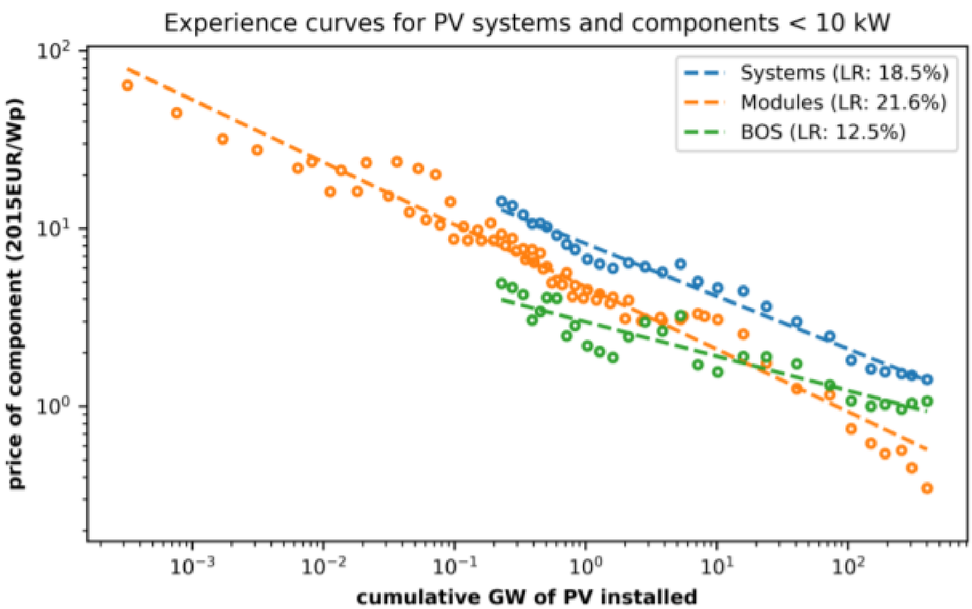

Figure 4: Experience curve for solar PV components.

By applying this concept to the presented costs in the cost analysis, the investment cost of the system will be reduced considerably. The following table 2 will present the new investment costs that have been found in the literature for 2050. Solar heaters are not included since this calculations are based on a future investment and we know they are not needed in the system.

Table 2: Reduced investment costs

Component	Size	Price	Price
PV	23 kW	610€/kW [18]	14030€
Batteries	80 kWh	100€/kWh [19]	8000€
Electrolyser	15 kW	720€/kW [20]	10800€
Fuel cells	5 kW	1400€/kW [21]	7000€
Heat pump	8 kWe	900€/kWe	7200€
Hydrogen tanks	280 kg	9900€/40kg [22]	69300€
Inverter	23 kW	240€/kW [23]	5520€
Total investment cost			**121850€**
O&M		0.4% of investment cost	**487€**

EAC=121850/23.11+487.6=5760€/year.

5 Discussion

5.1 Safety

As mentioned in the results the safety perspective is a really important aspect to consider when going off grid. If like Nilsson you are a retired engineer and knows all the installations and components of your off-grid house, because you made them yourself, you have some insight in where risks might occur and you take the necessary precautions. But if you for example buy a hydrogen and battery storage and productions unit and get it installed your missing the insight. The risk is also not only affecting you and your household but neighbors and the public in general when they are in the perimeter. Just as some person would not want a hydrogen factory next door they might have an opinion on you going off grid.

5.2 Cost and sensitivity

As we could observe in the cost analysis, the equivalent annualized costs will still be higher than the AAEP in Gothenburg which is 1120 €/year but if we compare it with Spain for example, which electricity price in 2020 was 118.03 €/MWh [24], the AAEP would be 2006.51 €/year. Electricity price in 2050 is an uncertainty since most countries are investing in new generation capacity to replace fossil fuel based generation, but the main alternative is renewable energy which running costs are smaller, theoretically, reducing the electricity price. This means that a system including PV generation, batteries and hydrogen is not willing to be cost competitive with electricity price connected to the grid, but it is a feasible option for people without access to the grid.

It is important to underline that this cost analysis is for a wealthy single house with large electricity demand. A completely different result would be obtained if it were considered a community with a mini-grid using the same technologies since investment costs would be higher, due to larger installed capacity, but as those costs are divided between consumers, it would result in reduced individual costs, it is cheaper to get one 10 kW fuel cell than two with half capacity and same with the others. A hydrogen market could be created so larger consumers can buy the excess of hydrogen from smaller consumers or trades with other sectors such as transport or industry with higher willingness to pay.

What is also worth noting is that the solar and green energy sector is undergoing rapid development with increasing diffusion and decreasing prices [5]. What at first glance does not seem to be economically defensible today, will most likely be in the future, thanks to investments of today, driving innovation development and diffusion further.

5.3 Larger scale challenges

Nilsson Energy is completely off-grid. But what would happen if large parts of a society would invest in photo voltaic systems and become small scale producers connected to the public grid?

Private households are connected to the low voltage grid, which would face technical challenges in case a large number of small scale PV systems would connect to it. The basic principle for the grid is that there needs to be a constant equilibrium between in- and output of energy, and the frequency need to be at a constant level of 50 Hz, therefore the intermittency of solar energy is a problem. If the grid is overloaded, meaning that the current is higher than the lines could handle, or if the voltage is too high or low, it can lead to disturbances, critical wear and damages on the equipment of connected actors [25].

If a large number of micro producers simultaneously feed the grid with high effect, while the demand of energy is low, the local voltage level rises. This may occur especially during summer days [25].

The real future scenario where a large number of solar energy producers and consumers are connected to the grid is in reality more complex, as factors like the producers own storage capacity and economical systems play a great role. Producers and consumers are paying tariffs and taxes when trading electricity on the grid. In the current Swedish energy price-regulating system, the daily prices for trading electricity is released one day ahead, enabling producers to adapt their pattern for selling and buying [26].

If a connected producer has invested in batteries, they would preferably charge their batteries with as cheap electricity as possible, to lower the cost of their own energy consumption. Often it is more beneficial for a producer to store their energy for their own consumption, but not always. As the energy price varies, the profitability of selling and buying varies accordingly. If a large number of private PV-owners would adapt their trade to favor their economical interest, it would lead to major variations of voltage and current levels, disrupting the quality of the grid. To enable a technically stable and economically profitable system of small scale producers towards the public grid would acquire new legislation as well as extensive systematic and technical adaptation.

6 Conclusion

The conclusion is that it is absolutely practically feasible to provide energy for an off-grid house from solar PV on the 60th parallel around the area of Gothenburg. However, the cost analysis shows that it is not cost competitive compared to electricity price from the grid, but for households living in rural areas without the opportunity to be connected to the grid, it is a technically and economically feasible option. With rapidly decreasing prices and accelerating development due to increasing pressure on finding green technologies, in the future such solutions will most likely be more economically feasible.

The research questions of this study is answered as such:

- **How much electricity can the subject of the case study produce in a year?**

On average, the electricity production from the PV's is 21900 kWh per year.

- **What energy storage technologies are used?**

  Hydrogen and batteries. To be able to provide for the energy demands during the whole year it is obvious that both the hydrogen and batteries serves their purpose. The hydrogen being the long term storage and batteries short term.

- **How much hydrogen can be produced every year and electricity from this hydrogen, according to the case study?**

  With the excess of 15000 kWh of electricity 273 kg of hydrogen can be produced. Converting it back yields 4090 kWh of electricity and 3000kWh of heat which is sufficient to cover the energy demand during October to March when production of hydrogen is negligible.

- **What is the payback time for the proposed system?**

  Considering the estimated lifetime of the equipment is longer than the actual payback period, there is technically no payback time.

References

[1] UN. Sustainable Development Goals.

[2] UN. Growing at a slower pace, world population is expected to reach 9.7 billion in 2050 and could peak at nearly 11 billion around 2100, 2019.

[3] Ari Kahan. EIA projects nearly 50% increase in world energy usage by 2050, led by growth in Asia.

[4] ipcc. Global emisson pathway characteristics.

[5] From Photons and Future Societal Impact. Solar Energy.

[6] Solar electricity share.

[7] David G. Foster Welty, James.R. *Fundamentals of momentum, heat and mass transfer*. John Wiley & sons, sixth edit edition, 2015.

[8] Dr. David R. Williams NASA. Sun Fact Sheet. 2018.

[9] Alfredo Ursua, Luis M Gandia, and Pablo Sanchis. Hydrogen Production From Water Electrolysis: Current Status and Future Trends. *Proceedings of the IEEE*, 100(2):410–426, 2012.

[10] M Paidar, V Fateev, and K Bouzek. Membrane electrolysis—History, current status and perspective. *Electrochimica Acta*, 209:737–756, 2016.

[11] S Shiva Kumar and V Himabindu. Hydrogen production by PEM water electrolysis – A review. *Materials Science for Energy Technologies*, 2(3):442–454, 2019.

[12] Thermo Fischer Scientific. Safety Data Sheet: Hydrogen. *Material Safety Data Sheet*, 4(2)(1):8–10, 2012.

[13] Will Kenton. Equivalent anual cost - EAC Definition, 2020.

[14] Tjark Thien, Tobias Blank, Benedikt Lunz, and Dirk Uwe Sauer. Chapter 21 - Life Cycle Cost Calculation and Comparison for Different Reference Cases and Market Segments. In Patrick T Moseley and Jürgen Garche, editors, *Electrochemical Energy Storage for Renewable Sources and Grid Balancing*, pages 437–452. Elsevier, Amsterdam, 2015.

[15] Rudnick Hugh, Daniel Charlín, Federico Heisig, and Andrea Mohr. Costo de abatimiento de nueva energía (LACE) y costo de desarrollo de la energía (LCOE): La nueva forma de determinar la entrada de nuevas tecnologías al sistema., 2016.

[16] PureH2 Hydrogen Electrolyser.

[17] NORD POOL. Day-ahead prices, 2022.

[18] Danish Energy Agency. Technology Data for Generation of Electricity and District Heating.

[19] Lukas Mauler, Fabian Duffner, Wolfgang G Zeier, and Jens Leker. Battery cost forecasting: a review of methods and results with an outlook to 2050. *Energy Environ. Sci.*, 14(9):4712–4739, 2021.

[20] Eero Vartiainen, Christian Breyer, David Moser, Eduardo Román Medina, Chiara Busto, Gaëtan Masson, Elina Bosch, and Arnulf Jäger-Waldau. True Cost of Solar Hydrogen. *Solar RRL*, n/a(n/a):2100487.

[21] Lacal Arantegui R, Jaeger-Waldau A, Vellei M, Sigfusson B, Magagna D, Jakubcionis M, Perez Fortes MDM, Carlsson J, Lazarou S, Giuntoli J, Weidner Ronnefeld E, De Marco G, Spisto A, and Gutierrez Moles C. ETRI 2014 - Energy Technology Reference Indicator projections for 2010-2050. Technical Report LD-NA-26950-EN-N, Luxembourg (Luxembourg), 2014.

[22] Hydrogen Council. Path to hydrogen competitiveness: a cost perspective. (January):88, 2020.

[23] Fraunhofer ISE. Current and Future Cost of Photovoltaics. Long-term Scenarios for Market Development, System Prices and LCOE of Utility-Scale PV Systems. *Agora Energiewende*, (February):82, 2015.

[24] Average Annual electricity price in Spain 2010 to 2021, 2022.

[25] Erik Axelsson, Peter Blomqvist, Katja Dvalin, Kjerstin Ludvig, and Thomas Unger. *Utbyggnad av solel i Sverige.* 2017.

[26] Så här fungerar elmarknaden.