# Business Case, Design and Simulation of Solar Powered Hydrogen Refuelling Stations

by

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*Abstract The thesis investigates some possible pathways for how solar powered Hydrogen Refuelling Stations (Solar-HRS) can be implemented in a economically viable way. This is done by the use of a custom simulation model in MATLAB/Simulunk to simulate and evaluate the inner workings of the Solar-HRS. Two cases for Solar-HRS is looked at, one "on-grid" and one "off-grid". The potential usefulness of the Solar-HRS providing additional services, such as selling excess electricity from its solar panels and more, is also looked at.

The thesis presents three main results:

1. A compilation of the technical and economic viability of some of the additional services that the Solar-HRS could provide.
2. Three small business cases, where the most competitive case presents a LCOH in the range of 70 - 100 SEK/kg H2.
3. Some key insights in how a Solar-HRS can be designed for a reduced levelized cost of Hydrogen (LCOH).

## Acknowledgement

Hello and welcome to my Master's thesis, enjoy your stay! I want to keep this section short and sweet, most of all I want to thank a few people.

First I want to thank my two supervisors Jens Klingmann at LTH and Anna Cornander at RISE. Both of you have provided me with valuable guidance and you have all ways been able to find time for me in your tightly packed schedules. Thank you. I also want to thank all of those who have provided me with other help, advice, guidance and ideas. I am speaking of Anna Alexanderson, Anders Lundblad and Ellinor Forsström at RISE and also Dr. Peter Raimann. Big thanks to all of you. I want to thank Marcus Thern for being the examinator of this work. Thank you for the time, effort and feedback that you have dedicated to me. I also want to thank all of my friends who have helped me along the way and also just for being my friends in general. Thanks, I could not have done this without you.

Then finally I want to thank my thesis itself. That may sound like a strange thing to do, I know, "but in times like these" having something to fully occupy my time that I also can do mostly by myself from home has been a blessing in disguise. Thank you thesis, although I'm tired of you now I'm glad you were there.

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# Equations - Nomenclature

| Symbol | Representation | Unit | Appears in: |
|---|---|---|---|
| $CAPEX$ | Capital Expenditure | [k SEK] | 4.11 |
| $P_c$ | Nominal Compressor Power | [kW] | 4.11 |
| $Q_{system}$ | System Heat Output | [kW] | **??** |
| $\eta_{H,system}$ | System Heat Transmission | [-] | **??** |
| $Q_{Electrolyser}$ | System Heat Output | [kW] | **??**, **??** |
| $Q_{system}$ | System Heat Output | [kW] | **??**, **??**. |
| $n$ | Asset lifetime | [years] | 4.12 |
| $r$ | Asset discount rate | [-] | 4.12 |
| $I_t$ | Investment Cost | [SEK] | 4.12, 4.13 |
| $M_t$ | Maintenance Cost | [SEK] | 4.12 |
| $F_t$ | Fuel (Electricity) Cost | [SEK] | 4.12 |
| $H_2$ | Annual Hydrogen Production | [SEK] | 4.12 |
| $a$ | Annual Return from Asset | [SEK] | 4.13 |
| $CAPACITY_{min}$ | Minimum Electrolyser Capacity Requirement | [kW] | 7.1, 7.2 |
| $\eta_{electrolyser,mean}$ | Mean Electrolyser Efficiency | [-] | 7.1, 7.2 |
| $LHV_{H2}$ | Lower Heating Value of Hydrogen | [kWh] | 7.1, 7.2 ... |
| $USER\ DEMAND$ | Hydrogen User Demand | [kg H2/year] | 7.1, 7.2 |
| $P_{solar}$ | Solar Panels Operational Power | [kW] | Text, A.12 |
| $P_{electrolyser}$ | Electrolyser Operational Power | [kW] | A.2, **??** ... |
| $P_{electrolyser,min}$ | Electrolyser Minimum Operational Power | [kW] | Text |
| $P_{electrolyser,rated}$ | Electrolyser Rated Power | [kW] | A.2, A.3 ... |
| $\eta_{electrolyser,electrical}$ | Electrolyser Electrical Efficiency | [-] | A.1 |
| $\eta_{electrolyser,losses}$ | Electrolyser Losses Efficiency | [-] | 4.2 |
| $\eta_{electrolyser,heat}$ | Electrolyser Heat Transmission Efficiency | [-] | 4.2 |
| $\dot{H}_{2electrolyser}$ | Electrolyser Hydrogen Output | [kg H2/h] | 4.2, 4.3 |
| $A, B, C$ | Electrolyser Efficiency Curve Parameters | [-] | A.1 |
| $k_1, k_2$ | Electrolyser Paralell Control Parameters | [-] | A.3 |

| Symbol | Representation | Unit | Appears in: |
|---|---|---|---|
| $P_{compressor}$ | Compressor Operational Power | [kW] | 4.3 |
| $\eta_{compressor,losses}$ | Compressor Losses Efficiency | [-] | 4.3 |
| $\eta_{compressor,is}$ | Compressor Isentropic Efficiency | [-] | 4.3 |
| $w_{compressor}$ | Specific Compressor Work | [kWh/kg] | 4.3, 4.4 |
| $Cp$ | Specific Heat for Hydrogen | [kJ/kg K] | 4.4 |
| $T_1$ | Compressor Input Temperature | [K] | 4.4 |
| $P_{out}$ | Compressor Output Pressure | [Bar] | 4.4 |
| $P_{in}$ | Compressor Input Pressure | [Bar] | 4.4 |
| $\gamma$ | Specific Heat Ratio for Hydrogen | [-] | 4.4 |
| $P_{battery}$ | Battery Operational Power | [kW] | 4.5, 4.6 |
| $P_{battery,rated}$ | Battery Rated Power | [kW] | Text |
| $E_{battery}$ | Battery Stored Charge | [kWh] | 4.5, 4.6 ... |
| $\eta_{battery,losses}$ | Battery Total Efficiency | [-] | 4.5, 4.6 ... |
| $\eta_{battery,internal}$ | Battery Internal Efficiency | [-] | 4.6 |
| $SOC$ | Battery State of Charge | [-] | A.4 |
| $State_{battery}$ | Battery Readiness State | [-] | Text |
| $H_{2,storage}$ | Hydrogen in Main Storage | [kg H2] | 4.7, A.5 |
| $H_{2,storage,capacity}$ | Main Storage Capacity | [kg H2] | Text |
| $\dot{H}_{2,in}$ | Hydrogen flow into Main Storage | [kg H2/h] | 4.7 |
| $\dot{H}_{2,out}$ | Hydrogen flow out of Main Storage | [kg H2/h] | 4.7 |
| $SOH2$ | State of Hydrogen in Main Storage | [-] | A.5 |
| $SOH2_{Low,OK,FC}$ | State of Hydrogen thresholds | [-] | Text |
| $State_{storage}$ | Storage Readiness State | [-] | Text |
| $P_{FC}$ | Fuel Cell Operational Power | [kW] | A.7, 4.8 ... |
| $P_{FC,rated}$ | Fuel Cell Rated Power | [kW] | A.7 |
| $\eta_{FC,electrical}$ | Fuel Cell Electrical Efficiency | [-] | A.6 |
| $\eta_{FC,losses}$ | Fuel Cell Losses Efficiency | [-] | A.7 |
| $\eta_{FC,heat}$ | Fuel Cell Heat Transmission Efficiency | [-] | 4.8 |
| $Q_{FC}$ | Fuel Cell Heat Output | [kW] | 4.8 |
| $State_{FC}$ | Fuel Cell Readiness State | [-] | Text |
| $P_{cooling}$ | Cooling Unit Operational Power | [kW] | 4.9 |
| $\eta_{cooling,is}$ | Cooling Unit Isentropic Efficiency | [-] | 4.9 |
| $\dot{H}_{2,ToBuffer}$ | Hydrogen flow into Buffer Storage | [kg H2/h] | 4.9 |
| $P_{facility}$ | facility passive power demand | [kW] | 4.10 |
| $\hat{P}_{balance}$ | Main Algorithm Power Variable | [kW] | A.12, A.13... |
| $\hat{P}_{electrolyser,low}$ | EL. Calculated Low Power | [kW] | A.16 |
| $P_{electrolyser,opt}$ | Electrolyser Optimal Power | [kW] | A.16 |
| $K_{low,high,battery}$ | EL./BAT. Control Variable | [kW/-] | A.16, A.17 |
| $SOH2_{Buffer}$ | Buffer Storage State of Hydrogen | [-] | A.28 |
| $\hat{P}_{CompHighP}$ | High P. Comp. Calculated Power | [kW] | A.28 |
| $K_{CompHighP}$ | High P. Comp. Control Variable | [kW/-] | A.28 |

# Abbreviations and Expressions

Some frequently used abbreviations and short-hand expressions in the thesis are:

- **HRS** - Hydrogen Refuelling Station
- **Solar-HRS** - Hydrogen Refuelling Station with photo-voltaic solar cells
- **SMR** - Steam Methane Reforming
- **Solar Panels** - Refers to photo-voltaic solar cells
- **Electrolysis** - Refers to the electrolysis of water
- **FCEV** - Fuel Cell Electric Vehicle, a hydrogen vehicle.
- **LCOH** - Levelized Cost of Hydrogen
- **TSO** - Transmission System Operator, the operator of the electircal grid.
- **Off-Grid** - Refers to a Solar-HRS that is not connected to the electrical. grid.
- **kWp** - KiloWattpeak, unit used to describe the installed capacity of the solar panels, example: 1000 kWp of solar panels will at most produce 1000kW.
- **SEK** - The swedish currency (krona).
- **KSEK** - 1000 of the swedish currency (krona).

# Contents

# 1. Background

## 1.1. Hydrogen Mobility

Hydrogen is an energy carrier that stores its energy in chemical bonds just as carbon-based fuels do, the difference is however when hydrogen is burned/consumed, no CO2 is emitted [9]. Hydrogen is therefor sometimes regarded as “The Fuel of the Future” and as of 2020 several countries, companies and institutions have announced plans to incorporate hydrogen as a key technology in their operations [10], [11], [12]. While the practical uses for hydrogen are multiple, the primary focus of the thesis is the use of hydrogen as a vehicle fuel. Hydrogen mobility is not widespread at the moment, as of writing only a total of four Hydrogen Refuelling Stations (HRS) have been built in Sweden [13].

There is a “Chicken and Egg”-type challenge that hydrogen mobility must overcome. The problem lies within that since there only few HRS exist, the incentive for buying hydrogen vehicles is low. Simultaneously the incentive to build HRS is also low as there are only few potential customers. A method must be found to encourage early adopters of the technology to invest, so that demand then naturally can grow. One such method is to find ways for HRS to be a profitable investment even if it only has few customers. In the thesis some pathways for how an HRS can increase its revenue while demand is low are investigated.

## 1.2. Other Hydrogen Applications

As stated, the practical uses for hydrogen are multiple. Other than being a fuel for vehicles hydrogen has uses within industry and as a form of energy storage [9]. For a HRS already having access to hydrogen and its production, this opens up several business opportunities. For example by supplying a nearby industry with hydrogen a HRS could manage to increase its revenue and it wouldn’t matter as much if there aren’t many customers at first.

The full list of business opportunities is only limited by the spirit of entrepreneurial imagination. The thesis only investigates some of these opportunities and focuses on those that seem the most implementable and useful in the present. In section 4.2.3 the potential business opportunities identified for the thesis are listed and explained.

## 1.3. Solar Powered Hydrogen Refuelling Stations

The main topic of the thesis is Solar Powered Hydrogen Refuelling Stations (Solar-HRS). There are many ways that a HRS could be constructed. They could be built just like a regular petrol station, where the station is built at one location and the fuel is produced at another location (like a large refinery) and then is delivered to the station. But HRS unlike petrol stations, have the option to produce its fuel by itself locally. This is possible thanks to the electrolysis of water (explained in 1.6.1). In addition, if it is possible to power the electrolysis with renewable energy (with solar panels for example) that would mean that the hydrogen produced by the electrolyser has a very low carbon-footprint [14], making a Solar-HRS an interesting contender for how more sustainable road transportation could be achieved.

From an environmental point of view Solar-HRS offer great benefits, from an engineering point of view this relatively novel concept poses new questions and challenges that beg to be investigated. (How big should the hydrogen storage be? What is the right amount of solar panels? etc.)

## 1.4. Hydrogen Station Mariestad

In 2019 the Swedish city of Mariestad could proudly inaugurate the worlds first Solar-HRS [15], it is also the third HRS overall built in Sweden. Hydrogen Station Mariestad is the main source of inspiration for this thesis and has served as a role model and example for how a Solar-HRS can be designed.

The thesis is not written with affiliation or endorsed by any of the representatives or participants of the Hydrogen Station Mariestad project. Any information presented in the thesis is also not representative of the Hydrogen Station Mariestad.

## 1.5. RISE

RISE stands for Research Institutes of Sweden. RISE is a national organisation with the stated purpose of working for sustainable growth in Sweden by strengthening the competitiveness and capacity for renewal of Swedish Industry, as well as promoting the innovative development of society as a whole [16]. The unit for “Energiomvandling” or Energy Transition at RISE consists of a small group of knowledgeable people within the field of Hydrogen. They work with questions on how the use of hydrogen can be promoted and implemented in Sweden and elsewhere. This thesis is written with the unit of Energy Conversion to investigate what possible implementations and improvements of HRS’s could look like.

## 1.6. Key Technologies

The thesis investigates how two key technologies can be combined to create successful a Solar-HRS. These two technologies are photo-voltaic solar cells (referred to as solar panels) and electrolysis of water (simply referred to as electrolysis). To read this thesis it is not necessary to have previous extensive knowledge about the specifics and inner workings of these technologies.

### 1.6.1. Electrolysis of Water

Electrolysis of water is the process of by applying a voltage across a source of water to split the water molecules into its constituent parts, oxygen and hydrogen [17]. For the sake of the thesis it is only necessary to know that an electrolyser takes water and electric power as its inputs and outputs hydrogen gas. There are different types of electrolysis, Alkaline, PEM and SOEC. The electrolyser model used in the thesis is based on alkaline electrolysers.

While there are also are other ways of producing hydrogen such as SMR [14], electrolysis has the advantage that it can produce hydrogen on demand at any place and without carbon emissions, assuming there is access to water and environmentally friendly electricity. The second criterion is of special interest, electrolysis of water is a power intensive process and if that source of electricity is not environmentally friendly, neither the hydrogen produced can be counted as such.

### 1.6.2. Photo-Voltaic Solar Cells

In context of the thesis it is only required to know that solar panels when hit by sunlight produce an electric power output. The power output of the solar panels will depend on the strength and direction of the sunlight directed at the panels.

Solar panels provide a cheap, renewable and relatively easy to implement source of power [18]. This makes them interesting, as the other key technology, electrolysis of water, requires a source of power. The main purpose of the solar panels is to provide the electrolyser and other components of the HRS with clean and renewable power.

The online tool PVGIS [19] is used to calculate the solar panels power output for a given capacity, place and time.

# 2. Introduction

## 2.1. Purpose

The purpose of the thesis is to further the understanding of Solar Powered Hydrogen Refueling Stations (Solar-HRS). Primary focus lies on understanding how a Solar-HRS would function and how it can be design after real-life circumstances, secondary focus is to identify and investigate additional business opportunities for so that the economic viability of the Solar-HRS can be increased.

## 2.2. Problem statement

The broad topic of research is: "How can a Solar-HRS be made to be economically viable?". This statement approached from and techno-economical point of view is divided into three questions:

- How can a Solar-HRS be designed to be the most economically viable?
- What are some scenarios where the implementation of a Solar-HRS could be beneficial?
- What can a Solar-HRS do to access additional sources of revenue?

These questions are best answered by breaking them down into smaller sub-questions:

- How does a Solar-HRS work?
- What are the key components of a Solar-HRS? How do they work and how do they interact?
- What external factors affects the performance of the Solar-HRS?
- What are some business opportunities that a Solar-HRS could participate in? How would it work and how useful would it be?

## 2.3. Delimitations

There are other approaches to increasing the viability of a HRS, such as by demand aggregation and economic policy, such approaches are not considered in the thesis.

The scope of the thesis and thesis model is limited. It is assumed that Swedish geography, costs and other circumstances apply, circumstances that certainly would differ in other countries.

The model includes selected components of a Solar-HRS. Primary focus lies on solar panels, electrolyser, main hydrogen storage and energy storage by fuel cell/battery, as these are what define the Solar-HRS and makes it different from other HRS. Compressors and cooling are also an essential part of any HRS and they are included in the model, but take a more secondary role. The level of detail in the model is also limited for the sake of simplicity.

The model is meant to provide an accurate yet simple and useful way of understanding a Solar-HRS. Therefor components are modeled on the level of electric power, the model does for example not consider what voltage, current or frequency goes into or out of a certain component. This approach is easier to implement, follow and use. Yet it still manages to capture sufficient information and detail.

# 3. Method

## 3.1. Model

A model for evaluation of the technical and economical performance of a Solar-HRS was developed for the thesis. The model can be divided in to three parts, first part is simulation in MATLAB/Simulink, where the storage and flow of energy, in terms of electric power and hydrogen gas through the HRS is simulated. A detailed explanation of the simulation model can be found in Appendix A. Second part is handling, processing and visualizing the output data from the simulations, this done in Excel and MATLAB. Last part is a simplified economic model for association of cost and revenue to the different components and activities of the HRS.

The simulations capture the specific interactions and inner mechanisms of the Solar-HRS, it is possible to monitor the status of each HRS-component at any given time. For example, a frequently used feature is the ability to tell how much hydrogen is in the storage at any given time, or how much electricity from the grid that the HRS uses. Real solar data is used as input, it is therefor possible for example to measure how sensitive a given HRS-design is to variations in solar radiation affects the performance of the HRS, or how the same design would fare at different times and locations. By providing this information, decisions can be made about the design of the HRS, for example whether to increase or reduce the storage size, what electrolyser, battery and/or fuel cell to use and more.

By associating costs to each component and activity the economic model then enables the possibility to compare different designs against each other, what design is the most cost effective and so on. It also becomes possible to make statements about the general economic viability of the HRS by comparing fuel costs to other non-hydrogen options.
The development of the model was guided after relevant literary sources, supervision from knowledgeable peers and colleagues and finally the authors own best experience and knowledge.

## 3.2. Case Studies

Simplified, The goal of the thesis is two to do two things. One is to analyse and understand the inner workings of the Solar-HRS. Two is to find ways that a Solar-HRS can be implemented and made economically viable. Economically viable has to be in what can be considered a realistic context. It is not very useful to know if a certain implementation of a Solar-HRS is economically viable if the foregoing assumptions made are such that there is no real-world resemblance. It is therefor important that the context in which the Solar-HRS is analysed can be considered to have similar real-world counterparts. What can be considered a “realistic Solar-HRS case” is difficult to know, as the first (prototype) Solar-HRS was only inaugurated in 2019.

The thesis uses two main cases for where a Solar-HRS is to be implemented. The cases are imaginary and made up, the purpose of the cases is to provide a context that illustrates well how certain variables affect the HRS. While the cases are made up they were still created in such a way that they to some extent resemble other real-life implementations of HRS. The first case resembles an "on-grid" case, where the Solar-HRS can use grid power and the second case is "off-grid", where it can not use grid power. The context of the first case is inspired by Hydrogen Station Mariestad. The second case is intended to resemble the implementations of public transport - HRS combinations that have been tried in the city of Cologne [20], but apply it to an island based context instead.

#### Case 1 - Commercial HRS

**Case Description:** On-grid Solar-HRS for commercial traffic.

**The Case looks at:**

- How a Solar-HRS works
- How user demand affects performance
- How energy storage can be used to reduce costs
- How the capacity of the main hydrogen storage affects performance
- The economics of three different design options
- How variations in solar radiation can affect costs
- How variations in pricing may affect the economics

#### Case 2 - Island HRS

**Case Description:** Off-grid Solar-HRS for public transport with strong seasonal variations in demand.

**The Case looks at:**

- Design process of a Solar-HRS
- How combinations of specific components affects the performance
- The economics of an "optimized" design
- How a off-grid Solar-HRS works
- How additional sources of reveneue can be used to improve the economics
- A specific sub-case where the HRS is considered to be part of a large solar park instead.

# 4. Model

## 4.1. Simulation Model

### 4.1.1. Overview

The simulation model consists of the essential components of the HRS. Each component has its own purpose and rules for how it will operate. The components are:

- Solar Panels
- Electrolyser
- Compressors
- Battery
- Hydrogen Storage(s)
- Fuel Cell
- Cooling, Facility and Fuel Dispenser
- Control Unit
- Customers/Users

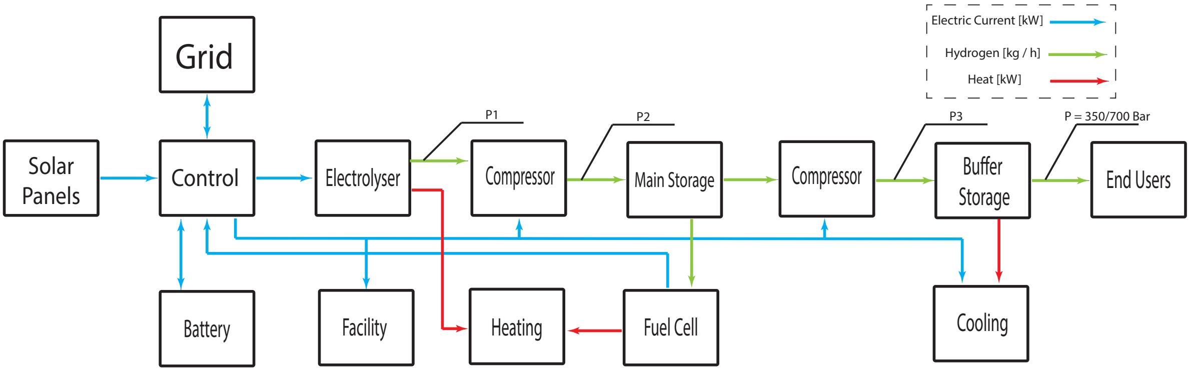

Figure 4.1.: Overview of HRS model

### Hydrogen Supply

The heart of the HRS is the hydrogen-supply-line. It consists of the componenets required to produce and deliver hydrogen. These are the electrolyser, low pressure compressor, main storage, high pressure compressor, buffer storage, cooling and a fuel dispenser (not included in the picture). The high pressure buffer storage is used to refill the customer vehicles (350/700 bar) by over-pressure, usually the pressure in the buffer is around 400 - 500 bar or 800 - 1000 bar, depending on the vehicle type. Precooling of the vehicle fuel is required due to regulation, generally the hydrogen is cooled to -40 °C [21],[22] before it is delivered to the vehicle.

The high pressure compressor will fill the buffer storage with hydrogen from the main storage, it will run as soon as there is space left in the buffer storage. The low pressure compressor will fill the main storage with hydrogen from the electrolyser. Since the electrolyser does not have its own storage the low pressure compressor must always run simultaneously as the electrolyser.

## 4.1.2. Components

A short description of the components purpose and functionality can be found in this section. All variables used are defined in the nomenclature. A full description of all the functions of the HRS's components and the algorithms used in the control unit can be found in Appendix A

### Solar Panels

The solar panels supply the HRS with electric power. The model uses the online tool PVGIS [19] to calculate the power output of the panels. PVGIS takes location, orientation, time, capacity of the panels and electrical losses as its inputs and returns power output for the panels on an hour-by-hour basis. The data is imported and then used in Simulink. The solar panels output the power ($P_{solar}$) which is simply a function of time as described by the downloaded data. The term for electrical losses $\eta_{solar,losses}$ is already included in the data when it is downloaded from PVGIS.

$$P_{solar} = P_{solar,PVGIS}(t) \tag{4.1}$$

### Electrolyser

The electrolyser takes electric power as its input $P_{electrolyser}$ and then outputs hydrogen gas $\dot{H}_{2,electrolyser}$. The electrolyser is an alkaline electrolyser and is modeled after the following sources[23], [24], [25]. The electrolyser must operate at a power within a range defined by a maximum operating power $P_{electrolyser,rated}$ and a minimum operating power, $P_{eletrolyser,min}$. The efficiency of hydrogen production $\eta_{electrolyser,electrical}$[1] is a function of operating power. There is also a factor for losses, $\eta_{electrolyser,losses}$. The electrolyser outputs hydrogen at a specified output pressure, $P_{electrolyser}$ which is what becomes the input pressure for the low pressure compressor as the electrolyser is connected directly to it.

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[1] Function description found in AppendixA

The amount of hydrogen the electrolyser then produces per hour $\dot{H}_{2,electrolyser}$ is:

$$\dot{H}_{2electrolyser} = \frac{P_{electrolyser}}{LHV_{H2}} \cdot \eta_{electrolyser,electrical}(P) \cdot \eta_{electrolyser,losses} \tag{4.2}$$

#### Compressor(s)

The compressors compress the hydrogen gas. There is a low pressure compressor and a high pressure compressor. Both compressors are modeled with isentropic compressor work and an isentropic efficiency. This means that the compressor work is a function of input and output pressure, mass flow and isentropic efficiency. There is also a factor for losses, $\eta_{compressor,losses}$.

$$P_{compressor} = \eta_{compressor,losses} \cdot \eta_{compressor,is} \cdot w_{compressor} \cdot \dot{H}_{2,electrolyser} \tag{4.3}$$

$$w_{compressor} = \frac{1}{3600} \cdot Cp \cdot T_1 \left( \left( \frac{P_{out}}{P_{in}} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right) \tag{4.4}$$

For the low pressure compressor the input pressure will be equal to the operating pressure of the electrolyser and the output pressure will be equal to the pressure inside the main storage. For the high pressure compressor the input pressure will be that of the main storage and the output pressure will be that of the buffer storage.

#### Battery

The battery can store electric power by charging and then discharging at a later point to release said power. The battery model is simplistic, the batteries charge in the battery is simply the sum of input and output power over time. The battery is limited in capacity and also has a defined efficiency for charging and discharging. The battery can not charge/discharge at a higher power than what it is rated for at $P_{battery,rated}$, in addition to this, when the battery is close to being full/empty the charging/discharging rate is limited. The charge stored in the battery can not be more than its capacity $E_{battery,capacity}$ or less than 0.

$$E_{battery} = \int \eta_{battery,losses} \cdot P_{battery}\, dt + E_{battery,initial} \tag{4.5}$$

$$\eta_{battery,losses} = \begin{cases} \eta_{battery,internal}\ when\ P_{battery} > 0 \\ \frac{1}{\eta_{battery,internal}}\ when\ P_{battery} < 0 \end{cases} \tag{4.6}$$

### Hydrogen Storage(s)

The hydrogen storage store the hydrogen produced by the electrolyser so that it can be used at a later point. There is a main storage and a buffer storage. Both function by the same principle, similar to the battery but with hydrogen instead of electricity, the amount of hydrogen in the storage is equal to the sum of hydrogen input and output over time, however unlike the battery there are no losses. The amount of hydrogen stored in the storage is $H_{2,storage}$. $H_{2,storage}$ can not be less than 0 or be more than storage capacity $H_{2,storage,capacity}$.

$$H_{2,storage} = \int \left(\dot{H}_{2,in} - \dot{H}_{2,out}\right) dt + H_{2,storage,initial} \tag{4.7}$$

For the main storage hydrogen input comes from the electrolyser and hydrogen output goes to either the buffer storage (via the high pressure compressor) or directly to the fuel cell. For the buffer storage the input comes from the main storage via the high pressure compressor and the output goes to the customer vehicles via the fuel dispenser.

### Fuel Cell

The fuel cell can take hydrogen from the main storage and convert it to produce electric power. Similar to the electrolyser, the fuel cell must operate within a range ($P_{FC,min}$ to $P_{FC,rated}$) and has an efficiency $\eta_{FC,electrical}$[2] dependant on the operating power. The factor for losses is $\eta_{FC,losses}$. The hydrogen consumption of the fuel cell equals to:

$$\dot{H}_{2FC} = \frac{P_{FC}}{LHV_{H2} \cdot \eta_{FC,electrical}(P) \cdot \eta_{FC,losses}} \tag{4.8}$$

### Cooling, Facility and Fuel Dispenser

Cooling, Facility and Fuel Dispenser are important components that only have a primitive representation in the model. Cooling of the hydrogen is required by standard [22], the cooler cools the hydrogen as it is pumped into the buffer storage.
The power needed to cool the hydrogen to delivery temperature is:

$$P_{cooling} = \frac{1}{\eta_{cooling,is}} Cp \cdot (T_{out} - T_{in}) \cdot \dot{H}_{2,ToBuffer} \tag{4.9}$$

Temperature control of the full system is an important factor not included in the model. It is assumed that a passive power demand, represented by $P_{facility}$ covers the requirements of temperature control and other essential power consuming activities such lights and computers that would be present on a real HRS. This power demand is assumed to be constant at all times.

$$P_{facility}(t) = P_{facility} \tag{4.10}$$

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[2] Function description found in AppendixA

The fuel dispenser is the interface between customer and the HRS, it can be thought of as the hose-and-card reader apparatus that can be found at any regular petrol station but for hydrogen instead. The model assumes that the HRS only has one fuel dispenser and the output of that dispenser is limited to 50 kg H2/h.

#### Control Unit

The control unit acts as the "brain" of the HRS and is programmed to do the following:

- Make sure that the HRS always can deliver hydrogen to its customers
- Run the electrolyser so that it uses up as much of the available solar power as possible.
- Make the HRS use as little power from the grid as possible

The control unit directs the flow of electric power to the HRS's components. It monitors the different states of the HRS and then makes and executes decisions based of that information. The algorithms used are described in A.2.

#### Customers/Users

Customers are included as a component of the model. Customers can be either cars or buses. Customer modeling is described in 4.1.3 and A.1.8

### 4.1.3. User Model

In the model, there are two types of users, cars and buses. Cars represent regular people who drive their car for their private purpose, such as to get to work, to the store or somewhere else. Buses are buses for public transportation, the following is assumed about the vehicle-types:

Table 4.1.: Hydrogen vehicle specification

| Vehicle Type | Fuel Pressure | Daily Mileage | Consumption | Demand/vehicle | Source |
|---|---|---|---|---|---|
| Car | 700 bar | 32 [km/day] | 1 [kg/100km] | 0.32 [kg/day] | [26],[3] |
| Bus | 350 bar | 200 [km/day] | 8 [kg/100km] | 16 [kg/day] | [1],[2] |

The model uses an algorithm to create a representation of the user demand that is compatible with the model, this is described in A.1.8

#### Cars

The model for cars assumes that the users driving behaviour is identical to as if they would drive a petrol/diesel car. This means they will drive just as much and refuel at the same times of day. At what time of day the cars will use the station is based on probability. The following assumptions are made:

- They will on average refuel every 17 days and fill their tank with 5.4kg H2 per refueling.[26]
- The probability of at what time of the day they will use the HRS will is represented by the Chevron profile. [27].

The Chevron profile is a distribution for how much fuel a fuel station dispenses of its total capacity at each hour of the day. The chevron profile has been used in other similar studies for the same purpose, such as the HDSAM3.0 program developed by NREL. [27]. The Chevron profile (figure 4.2, also see Appendix B.3) is used as a probability distribution. As a result, refuelling will most likely take place during the day between 06:00 and 19:00, while mostly being concentrated around 15:00.

**Buses**

Buses are simpler and will refuel at a predetermined time every day. It is assumed that a bus will refuel with 16 kg H2 per refueling. An example can be found in case 2 6.2.

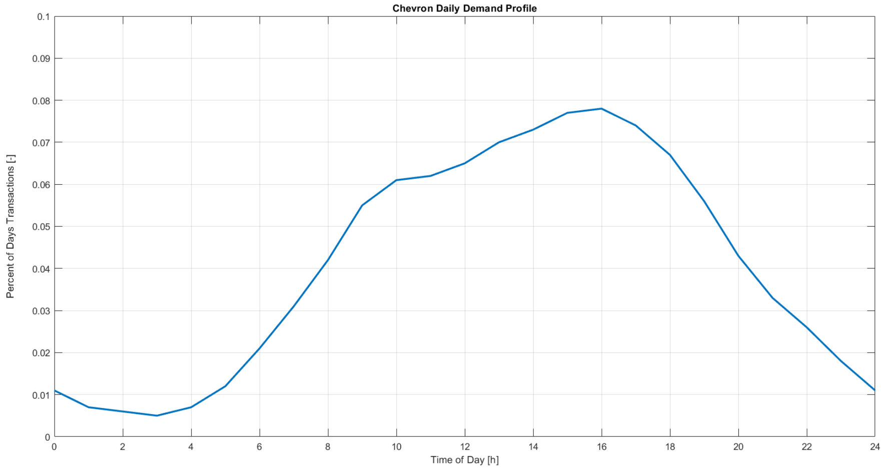


Figure 4.2.: The Chevron profile

## 4.2. Costs and Revenue

### 4.2.1. Component Cost

The following Cost-Scheme was used to evaluate the total investment and operational cost of the HRS. To receive the component cost for a component its capacity is multiplied by its Capex from 4.2. Some components also have an additional installation cost. The full investment cost is simply the component cost and investment cost added. For example a 10 kWh battery would cost 20 KSEK in component cost, 4 KSEK in installation cost and the combined investment cost would be 24 KSEK. For compressors the component cost is calculated with equation 4.11. Each componenet has an Operational and Maintenance cost that is paid annually. The O & M cost is a percentage of the componenent cost. After a components lifetime has expired that component is replaced for its full component cost. For example a 10 kW Fuel Cell would have a 54 KSEK investment cost and then cost an additional 45 KSEK every 10 years.

Table 4.2.: Cost Scheme

| Component | Capex [KSEK] | Installation [% Capex] | O & M [% Capex/year] | Lifetime [years] | Source |
|---|---|---|---|---|---|
| Solar Panels | 14 [/kWp] | - | - | 30 | [28],[18] |
| Electrolyser | 6.600 [/kW] | 0.57 | 0.08 | 10 | [29] |
| Compressor(s) | Eq 4.11 [/pc] | 1.87 | 0.04 | 30 | [29] |
| Storage | 10 [/kg] | - | 0.01 | 30 | [29] |
| Fuel Cell | 4.5 [/kWp] | 0.20 | 0.06 | 10 | [29] |
| Battery | 2 [/kWh] | 0.20 | 0.01 | 30 | [29] |
| Facility | 1000 [-] | - | - | 30 | [30] |
| Construction | 1000 [-] | - | - | 30 | [Assumption] |

$$CAPEX = 20.4 \cdot P_c^{0.8225}\ [k\ SEK] \tag{4.11}$$

## 4.2.2. Cost of Electricity

The main non-fixed cost is the cost of electricity. At times when the need for electricity is higher than what the solar panels can provide, electricity must be bought from the grid. The price of electricity will vary over time and location, it was assumed that the price of electricity is equal to the local hourly spot price, plus taxes and transmission fees.

Table 4.3.: Price of Electricity

| Spot Price | Energy Tax | Transmission Fee |
|---|---|---|
| NordPool Hourly | 0.3540 [SEK/kWh] [31] | 0.30 [SEK/kWh] [Assumption] |

## 4.2.3. Additional Sources of Revenue

It is possible for the HRS to provide valuable services (other than dispensing fuel to vehicles) that may act as a stream of revenue for the HRS. These alternative sources of revenue are interesting to investigate as they may provide a path-way towards economic viability for low user demands. A few possible sources were investigated but not all were applied to the cases. Some options, while technically possible, seem unrealistic for a HRS to implement.

### Selling Electricity

The solar panels can contribute with additional income by selling some of the excess electricity back to the grid. The simplest assumption is that all excess electricity is being sold at the hourly spot price, in reality however the precise economic situation will differ and is often subject to laws, taxes, tax-deductions, agreements and contracts. Two examples of that apply for private individuals in Sweden are[32], [31]:

- If the amount of electricity sold to the grid exceeds the amount of electricity bought from the grid the electricity provider can charge an additional fee for selling electricity.
- If the installed capacity of solar panels is under 255 kWp you do not have to pay energy tax for the sold electricity.

Because of the above, the true value of selling electricity can only truly be determined on a case-by-case basis.

### FCR - Frequency Containment Reserve

FCR (also known as Fast Frequency Reserve - FFR) is used by TSOs to stabilize the grid frequency, in essence its a way of handling load-surges on the grid. FCR can be thought of as on-demand providing extra power to the grid for a short moment. There are mainly two different types of FCR, FCR-N (Normal) and FCR-D (Disturbance). FCR is a crucial and important service which fuel cells and batteries potentially can provide for. The technical requirements to qualify for FCR consists of specifications on response time, for how long the response can be held and at what quantity. Depending on circumstances there may also be requirements on the capacity of the FCR-resource, its not uncommon that this minimum capacity is 1MW [1] however it is also possible for multiple smaller resources to “pool together” and act as one larger resource.

The economic compensation for providing FCR can be split into two categories, Capacity price SEK/kW/year and activation price SEK/kWh. The capacity price is a yearly fee paid by the TSO to the operator of the FCR in compensation for the resource being at standby at all times, independent of if the FCR is actually being used or not. The activation price is what is payed per kWh when the FCR is operating.

Whilst being an interesting option, only insufficient information could be found to truly evaluate the economic value of providing such a service, therefor FCR was left out of the case studies. It also seems unlikely that a single HRS would have the 1MW Fuel Cell / Battery combination required, although multiple HRS’s could in theory work together to achieve such a target.

### Back-up Power

A more common use for fuel cells is to act as back-up power for essential infrastructure during black-outs. Most commonly diesel aggregates are used for this purpose but hydrogen-fuel cell solutions are already well established with in certain areas such as telecommunications, for example approximately 120 radio base-stations in Denmark are equipped with fuel cell back-up power systems from the company Ballard [33].

Due to the high expense and damage potentially caused by black-outs, back-up power definitely is a valuable service but price estimations are difficult to come by. In some examples listed in the 2015 report “Guidance for handling of the back-up power process (Vägldedning för hantering av reservkraftsprocessen)” [34] the cost for the damage caused by a black-out can be estimated to be in the millions of SEK and be expected to occur every few years due to storms and accidents. A single example of the expenditure on diesel aggregates for back-up power is included in the report. In the years 2000 - 2006 the swedish municipality in the example spent in total 7364 KSEK (adjusted for 2% inflation in 2020) on 3500 kilowatt of back-up power, resulting in an (weighted) average price of 2.1 KSEK/kWp. The maintenance cost for the entire back-up resource of 3500 kw was estimated to 100 KSEK/year.

Diesel may currently be the cheaper option, however fuel cells have the advantage that they are clean and quiet, making them a strong option in inhabited areas with regulations on noise and emission. Batteries may also act as back-up power but are in general not as well suited for larger long-term back-up as fuel cells are [35].

### Heat

The fuel cell and electrolyser operate at an elevated temperature and can produce significant amounts of heat. The temperature is high enough so that it can be used in the radiators of a building, as made example in [36].

While such systems may be promising for housing applications the need for heating in an unmanned fueling stations seems low. For the heat to be useful it must be distributed elsewhere. This would in turn require investment into infrastructure to distribute this heat. Both the fuel cell and electrolyser operate at too low of a temperature to produce heat useful for district heating. Simultaneously the total heat output of a HRS is likely much to low to validate the investment. Estimates for heat output can be found in Appendix C. Other reports also indicate that using hydrogen for heating is likely a less cost competitive usage than other alternatives [37].

In conclusion, a HRS may be able to contribute with heating in an integrated and well-planned system but it is not a business-concept that will be generally applicable to all HRS. As a result heating was not included in any of the cases.

### Industrial Applications

Hydrogen and oxygen (in this case the by-products of electrolysis) have industrial and medical uses. Some are well established, such as the production of fertilizer [38], while some are developing, such as hydrogen-based steel production [39]. The perceived value of hydrogen will depend on its application, for this study it was assumed that any industry would pay as much for hydrogen from the HRS as they would pay for hydrogen produced through the conventional method of Steam Methane Reforming (SMR) [14]. The price for hydrogen in industrial applications in Europe is assumed to be around 14 SEK/kg [1].

Whilst implementations of HRS - Industry symbiosis do exist (such as Sandviken Pure Power [13]), no such case is included in the thesis.

#### Gas-Grid injection

It is possible to have a percentage of hydrogen injected into the natural gas grid. By providing hydrogen to this grid economic compensation can be received. However, the tolerance for hydrogen in the Swedish gas grid is low (maximum 0.5% by volume [1]) in addition with the potential value per kilogram of hydrogen for injecting into the natural gas grid is lower than alternative uses [1]. For this reason injection to the natural gas grid was not included as an option for any HRS-case.

### 4.2.4. Tools for Economic Evaluation

#### Levelized Cost of Hydrogen

The main metric used to measure the economic viability is the "Levelized Cost of Hydrogen" or LCOH, which simply is all the costs of the HRS divided by its total amount sold Hydrogen over its total lifetime, both discounted for interest. This exactly the same as how Levelized cost of Electricity LCOE is calculated for other applications.

For the calculations a lifetime (n) of 20 - 30 years and discount rate (r) 2 - 7% was used.

$$LCOH = \frac{\sum_{t=1}^{n} \frac{1}{(1+r)^t} (I_t + M_t + F_t)}{\sum_{t=1}^{n} \frac{1}{(1+r)^t} H_2} \tag{4.12}$$

### LCOH as a measure

The LCOH can be used to determine the economic viability of a HRS by comparing total fuel costs or total cost of ownership for FCEV's against petrol/diesel vehicles.

What this acceptable price level is depends on vehicle type and how it has been calculated, some estimates for different vehicles are:

Table 4.4.: Cost-Competitive LCOH (1/3) [1]

| Vehicle type (350bar) | Forklift | Urban Bus | Private FCEV(Taxi, etc.) |
|---|---|---|---|
| Price at Pumps [EUR/kg H2] | 11 - 12 | 6 - 7 | 9 - 10 |
| Price at Pumps [SEK/kg H2] | 115 - 126 | 63 - 74 | 95 - 105 |

Table 4.5.: Cost-Competetive LCOH (2/3) [2]

| Vehicle type | Fuel Cell car/van | Fuel Cell bus | Trains/Marine applications |
|---|---|---|---|
| Price at Pumps [GBP/kg H2] | 5.2 - 7.8 | 4 - 5 | 2.4 - 3.6 |
| Price at Pumps [SEK/kg H2] | 60 - 90 | 45 - 57 | 27.5 - 41 |

An estimate can be made specifically for Swedish markets. The estimate compares the fuel consumption for an average Swedish gasoline vehicle and gasoline prices in 2019/2020 to a reference FCEV. The reference FCEV used is the 2020 Toyota Mirai [26].

Table 4.6.: Cost Competetive LCOH (3/3) [3],[4],[5]

| Gasoline Consumption | Gasoline Price | H2 Consumption | Equivalent H2 Price |
|---|---|---|---|
| 5.8 [l/100km] | 13.58 - 13.98 [SEK/l] | 1 [kg/100km] | 77 - 80 [SEK/kg] |

The LCOH can give a good indication of the commercial viability of the HRS, but one should remember and consider what assumptions are made for the calculation of both the target-LCOH and actual LCOH for the HRS. The LCOH also functions as a tool within the thesis to compare the quality of different HRS-solutions.

### Simple Payback Time

Simple Payback is used for a quick first evaluation of an investment, it is simply the initial investment cost ($I_t$) divided by the yearly income/savings from the investment ($a$)

$$SP = \frac{I_t}{a} \tag{4.13}$$

# 5. Case 1 - Commercial HRS

## 5.1. Case Introduction

**Scenario:** An imaginary company wants to build a solar powered HRS in the outskirts of a swedish town, close to the highway. They have presented a design that needs evaluation. Mainly they wish to understand how the HRS will be affected by user demand and if any improvements can be done to the design. The HRS will be grid connected but the company wants to know how much grid power the HRS will use, and what can be done to reduce the grid usage.

## 5.2. System Design

The HRS has its own solar panels but is also grid connected. The HRS is intended to serve private customers in FCEV cars. The main idea is that during the summer the HRS will be solar powered while in the winter it will rely more on grid power and hydrogen stored since the summer. It was decided to install 250 kWp of solar panels, as this allows the HRS to count as a "microproducer" by swedish law. For selling electricity the following agreement was reached with the local energy company:

The HRS can sell excess electricity at the Nordpool spot-price as long as it sells less electricity than it consumes, for every kilowatt-hour sold that exceeds its own consumption there will be a fee of 0.20 SEK/kWh applied at the end of the year.

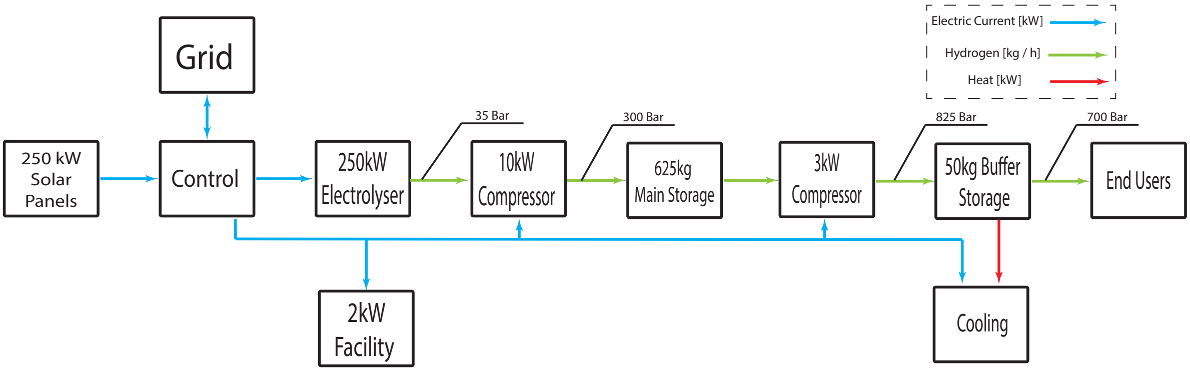


Figure 5.1.: Commercial HRS - System Design

### Specification Sheet

The full sheet of specifications including loss factors and more can be found in Appendix B.

Table 5.1.: Commercial HRS - Specification Sheet

| **Solar Panels** | |
|---|---|
| **Location** | Lat: 58.7 °; Lon: 13.8 ° |
| **Capacity** | 250 kWp |
| **Data** | PVGIS - SARAH - (2016) |
| **Electrolyser** | |
| **Nominal Power** | 250 kW |
| **Operational Range** | 10 - 100 % Nominal Power |
| **Operating Pressure** | 35 Bar |
| **Electrical Losses** | 10 % |
| **Low Pressure Compressor** | |
| **Nominal Power** | 10 kW |
| **Inlet Pressure** | 35 Bar |
| **Outlet Pressure** | 300 Bar |
| **Main Storage** | |
| **Capacity** | 625 kg |
| **Pressure** | 300 Bar |
| **High Pressure Compressor And Cooling** | |
| **Nominal Power** | 3 kW |
| **Inlet Pressure** | 300 Bar |
| **Outlet Pressure** | 825 Bar |
| **Buffer Storage** | |
| **Capacity** | 50 kg |
| **Pressure** | 825 Bar |
| **Other** | |
| **Facility Passive Power Demand** | 2 kW |
| **Electricity Price - Hourly Spot Price** | Nordpool SE3 2019 |

## 5.3. Studies

A series of studies were performed with the intention to gain understanding of the system and to identify possible improvements. Each study used the following two research questions:

- How does the HRS use energy from the grid?
- How does the HRS utilize its solar resource?

These two research questions were chosen because grid usage is directly associated to the only non-fixed cost of the HRS (electricity bought from grid) and better utilizing the solar panels is a way of reducing grid use. Answering these question will lead to insight towards what causes costs and how they can be reduced. The chosen topics of study were:

- Study 1: Detailed System Performance at fixed User Demand
- Study 2: Impact of User Demand
- Study 3: Cost Reducing Measures
- Study 4: Overall Costs
- Study 5: Sensitivity Analysis

### 5.3.1. Study 1: Detailed System Performance at fixed User Demand

Study 1 focuses on understanding the interactions between the individual components of the HRS and how they contribute towards costs. For the study user demand was set to a constant 4000 kg H2/Year.

First the year-round performance was studied in order to identify the expected seasonal variations. In this part the performance is studied over a time-span of weeks-months. The second part of the study uses a time span of hours - days and tries to identify how the system behaves on a day-by-day basis.

### 1a): Year-Round Performance

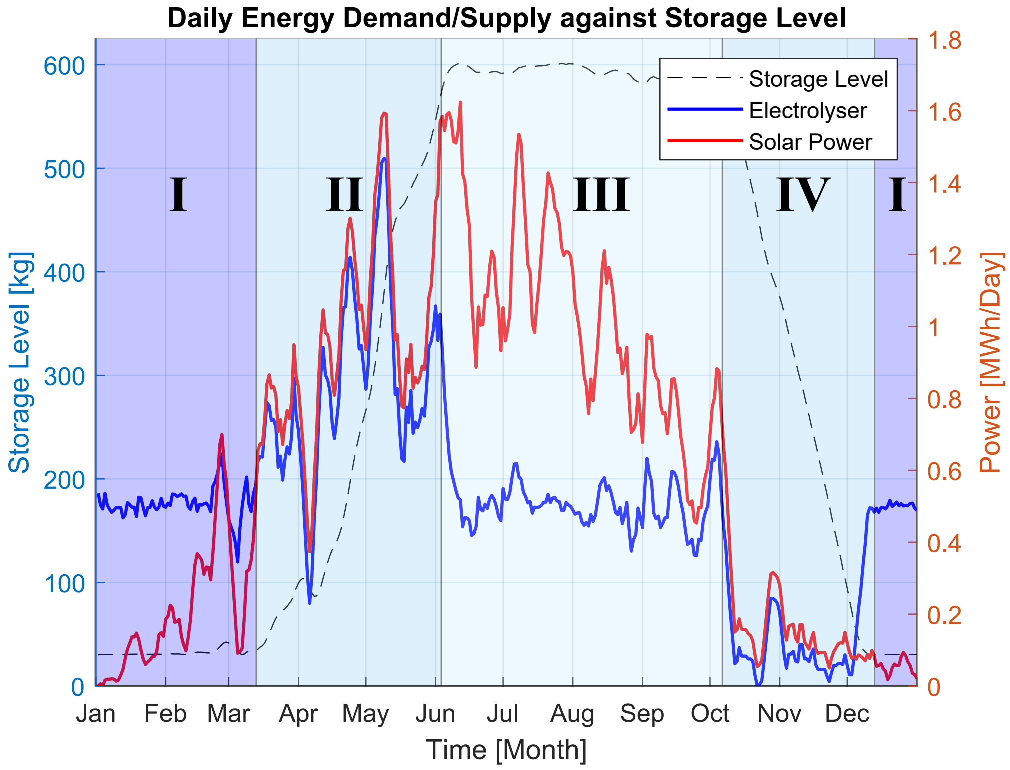


Figure 5.2.: Electrolyser Power Demand, (7-Day Moving Mean), ($\Delta t_{max} = 0.01$)

The electrolyser contributes to the vast majority of the total energy demand. Fig 5.2 illustrates how storage and solar power affects the electrolysers power demand and behaviour, four seasonal modes of behavior can be identified:

**I - Winter Mode (Dec - Mar)** The storage is low and there is little solar power available. The electrolyser consumes power from the grid when the storage level falls too low. The electrolysers power consumption does not strongly correlate to the available solar power.

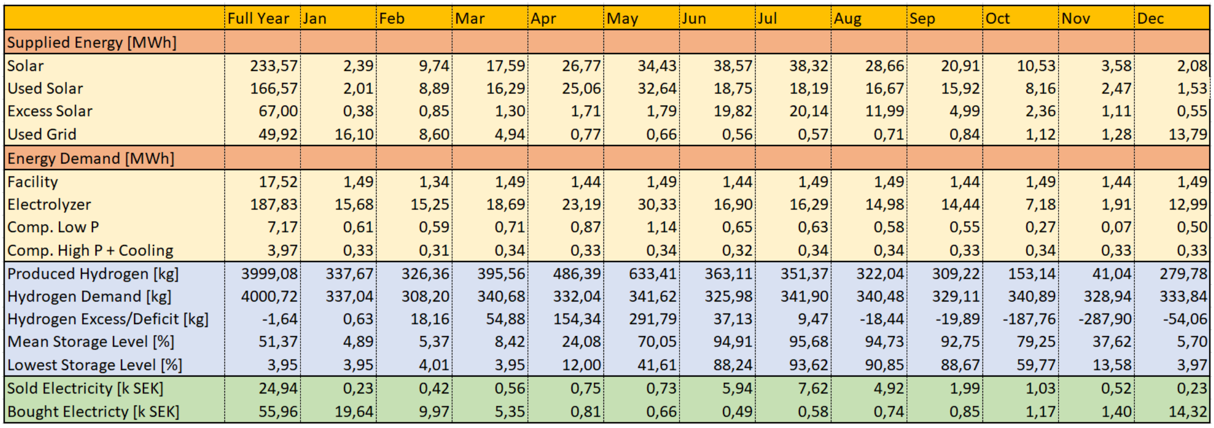
**II - Spring Mode (Mar - Jun)** Solar power is available in large amounts, the electrolyser is able to use most of the solar power to fill the storage from empty to full over a 2.5 month period. The electrolysers power consumption strongly correlate the available solar power.

**III - Summer Mode (Jun - Oct)** Solar power is available in large amounts but the storage is full. The electrolyser consumes just enough power to keep up with demand, any excess solar power is sold back to the grid. The electrolysers power consumption does not strongly correlate the available solar power.

**IV - Fall Mode (Oct - Dec)** Little solar power is available, the electrolyser is shut of most of the time or running on low power. The storage is slowly drained over a two month period. The electrolysers power consumption correlate the available solar power.

In the table below 5.3 a summary of demand & supply for electric energy and hydrogen can be found, together with associated costs.

Figure 5.3.: Energy, Hydrogen and Costs by month, ($\Delta t_{max} = 0.01$)



| | Full Year | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Supplied Energy [MWh] | | | | | | | | | | | | | |
| Solar | 233,57 | 2,39 | 9,74 | 17,59 | 26,77 | 34,43 | 38,57 | 38,32 | 28,66 | 20,91 | 10,53 | 3,58 | 2,08 |
| Used Solar | 166,57 | 2,01 | 8,89 | 16,29 | 25,06 | 32,64 | 18,75 | 18,19 | 16,67 | 15,92 | 8,16 | 2,47 | 1,53 |
| Excess Solar | 67,00 | 0,38 | 0,85 | 1,30 | 1,71 | 1,79 | 19,82 | 20,14 | 11,99 | 4,99 | 2,36 | 1,11 | 0,55 |
| Used Grid | 49,92 | 16,10 | 8,60 | 4,94 | 0,77 | 0,66 | 0,56 | 0,57 | 0,71 | 0,84 | 1,12 | 1,28 | 13,79 |
| Energy Demand [MWh] | | | | | | | | | | | | | |
| Facility | 17,52 | 1,49 | 1,34 | 1,49 | 1,44 | 1,49 | 1,44 | 1,49 | 1,49 | 1,44 | 1,49 | 1,44 | 1,49 |
| Electrolyzer | 187,83 | 15,68 | 15,25 | 18,69 | 23,19 | 30,33 | 16,90 | 16,29 | 14,98 | 14,44 | 7,18 | 1,91 | 12,99 |
| Comp. Low P | 7,17 | 0,61 | 0,59 | 0,71 | 0,87 | 1,14 | 0,65 | 0,63 | 0,58 | 0,55 | 0,27 | 0,07 | 0,50 |
| Comp. High P + Cooling | 3,97 | 0,33 | 0,31 | 0,34 | 0,33 | 0,34 | 0,32 | 0,34 | 0,34 | 0,33 | 0,34 | 0,33 | 0,33 |
| Produced Hydrogen [kg] | 3999,08 | 337,67 | 326,36 | 395,56 | 486,39 | 633,41 | 363,11 | 351,37 | 322,04 | 309,22 | 153,14 | 41,04 | 279,78 |
| Hydrogen Demand [kg] | 4000,72 | 337,04 | 308,20 | 340,68 | 332,04 | 341,62 | 325,98 | 341,90 | 340,48 | 329,11 | 340,89 | 328,94 | 333,84 |
| Hydrogen Excess/Deficit [kg] | -1,64 | 0,63 | 18,16 | 54,88 | 154,34 | 291,79 | 37,13 | 9,47 | -18,44 | -19,89 | -187,76 | -287,90 | -54,06 |
| Mean Storage Level [%] | 51,37 | 4,89 | 5,37 | 8,42 | 24,08 | 70,05 | 94,91 | 95,68 | 94,73 | 92,75 | 79,25 | 37,62 | 5,70 |
| Lowest Storage Level [%] | 3,95 | 3,95 | 4,01 | 3,95 | 12,00 | 41,61 | 88,24 | 93,62 | 90,85 | 88,67 | 59,77 | 13,58 | 3,97 |
| Sold Electricity [k SEK] | 24,94 | 0,23 | 0,42 | 0,56 | 0,75 | 0,73 | 5,94 | 7,62 | 4,92 | 1,99 | 1,03 | 0,52 | 0,23 |
| Bought Electricty [k SEK] | 55,96 | 19,64 | 9,97 | 5,35 | 0,81 | 0,66 | 0,49 | 0,58 | 0,74 | 0,85 | 1,17 | 1,40 | 14,32 |

### 1b): Day-by-Day Performance

Some chosen days of particular interest were studied more closely:

### Fall/Winter Day

The 6th of December displays one type of fall/winter day performance for the HRS. Some solar power is available and the HRS is able to be 100 % solar powered between 08.00 and 14.00 that day. However the available solar power is only enough to run the electrolyser for a little bit at low power between 11.00 and 13.00. At 14.00 and 15.00 some customers use the HRS, causing the storage to drop low enough to run the electrolyser. The electrolyser runs for 5 hours on grid power to get the storage back to an acceptable level.

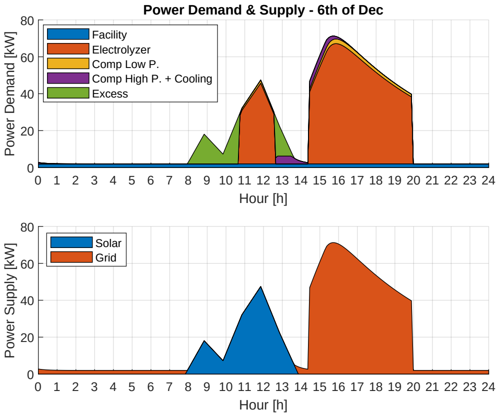


Figure 5.4.: 6th Dec, ($\Delta t_{max} = 0.01$)

Even though there is solar power available in winter, its difficult for the HRS to utilize it, a large part goes unused. The HRS is mostly grid powered throughout the winter. Fall exhibits very similar behaviour with the exception that the storage generally is at a higher level, meaning that the electrolyser wont run of grid power as often or even at all.
In this example there was solar power available but it is not uncommon that there are days where the solar power is next to none. For those days the HRS is entirely grid powered and behaves entirely as it does in the later part of the day in the above example.

### Summer Day

For the 6th of June a different type of behaviour is observed. The HRS is fully solar powered already from around 03.00 - 04.00 until the evening around 20.00. Plenty of solar power is available, however as the storage is close to full the electrolyser runs at reduced power causing large amounts of solar power to go unused. The HRS still requires small amounts of grid power through the night.

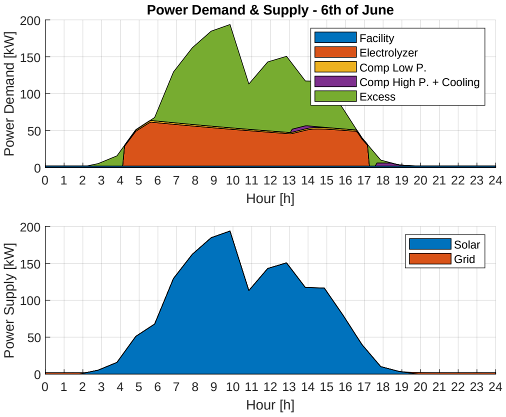


Figure 5.5.: 6th Jun, ($\Delta t_{max} = 0.01$)

### Spring Day

In spring the HRS is mostly solar powered between 04.00/05.00 until 17.00/18.00. Since the storage is not full yet the electrolyser is able to utilize almost all of the available solar power, very little goes unused. Its only during these days that close to the full capacity of the electrolyser gets used, usually it operates at lower power. Similar to summer days a small amount of grid power is still required for the nights.

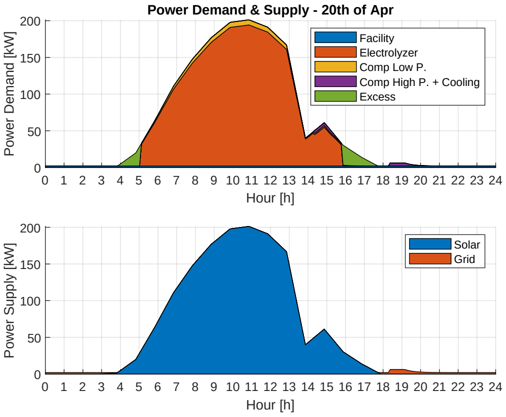


Figure 5.6.: 20th Apr, ($\Delta t_{max} = 0.01$)

### Study 1: Summary - Conclusion

The study reveals some inefficiencies. There are times throughout the whole year where there are small or even large amounts of solar power that can not be utilized even when the storage is not full. This is because the available solar power is less than the minimum operating power of the electrolyser. It can also be seen that the passive/uncontrollable power demands of the facility, high pressure compressor and cooling causes consumption of grid power even in the months where large amounts of excess solar power is produced.

Study 1a) showcased the interaction of available solar power and storage level and how this affects the power demand of the station. Study 1b) showed that there indeed are some improvements that can be done, for example, a battery could use the excess solar power to charge itself and then later cover power demand during night time.

### 5.3.2. Study 2: Impact of User Demand

The total user demand will have a large effect on the HRS. The electrolyser can at most support a theoretical demand of 42100 kg H2 / year, which roughly corresponds to the electrolyser operating at its maximum output level (5.4 kg H2/h) for every hour of the year. However the other components such as the buffer storage start running into difficulties at 30000 kg H2/year. The study primarily looks at how the storage and energy mix of the HRS is affected by varying user demand.

#### 2a): Storage

The study reveales that there are three types of interactions between the storage and the user demand, as illustrated in fig 5.7

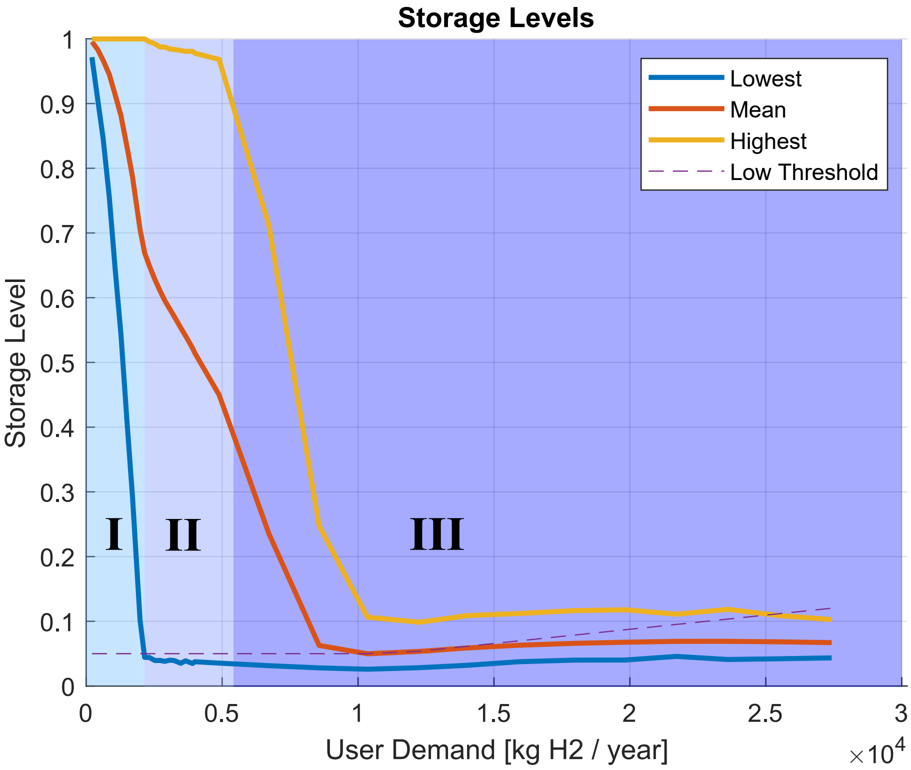


Figure 5.7.: Highest/Lowest Recorded Storage Level in a Year, ($\Delta t_{max} = 0.1$)

**I - Low Demand**. When the Hydrogen Demand is low (0 - 2500 kg H2/year). The HRS will produce more hydrogen than it can sell, as illustrated by the blue line in fig 5.7, that represents the lowest point of the Storage in a year. The demand is so low that the storage wont be emptied completely during seasonal mode IV, as a result seasonal mode I is skipped.

**II - Moderate Demand.** When the Hydrogen Demand is moderate of 2500 - 5000 kg H2 / year. The full capacity of the storage is utilized within a given year without that the storage ever is completely empty.

**III - High Demand.** When the Hydrogen Demand is high of 5000 - 30000 kg H2 / Year. The highest level of the storage within a year as illustrated by the yellow line in fig 5.7 starts to drop. The demand is so high that the storage never manages to fill up completely, even during summer months where production is high. At very high demands of 10000 kg H2 / Year or more the highest level within a year stabilizes around 10 % of storage capacity.

It can be concluded that the storage capacity is not relevant for all user demands. If the user demand is high enough the storage wont have time to fill up completely, so only a small storage is required, for low user demands large parts of the storage never deplete and are therefor not necessary.

### 2b): Energy Mix

The study found that at very low user demands the total energy demand remains low and the grid supplied amount remains constant, due to the passive power demand. As the demand increases a larger amount of the solar resource becomes utilized. Once the demand is at moderate amounts the grid usage starts to increase. At high demands the solar resource is almost entirely utilized but also more grid power is required.

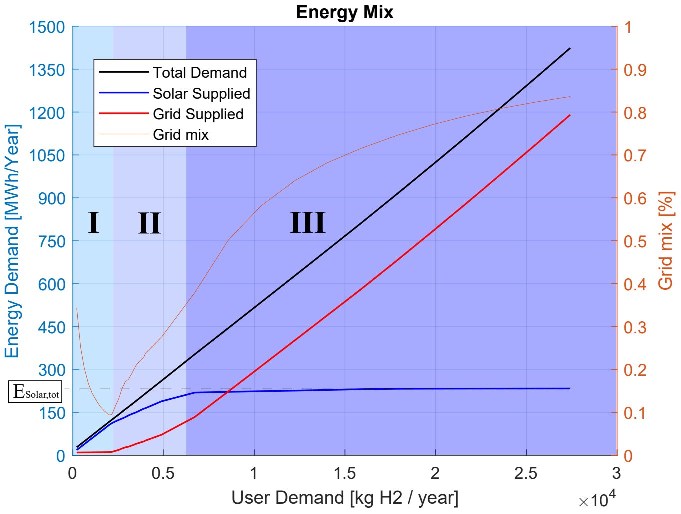


Figure 5.8.: Energy Mix, ($\Delta t_{max} = 0.1$)

At very high demands the HRS is mostly grid supplied. As demand increases so does the total energy demand but the solar panels can only supply a finite amount of energy so grid use has to increase. Since the storage is not full more often at higher demands the HRS becomes better at utilizing the solar resource.

### Study 2: Summary - Conclusion

User demand has a very large impact on the performance of the HRS. At very low demands the resources of the station are poorly utilized, large amounts of solar power and storage capacity is not utilized. Only a very small part of the total energy demand is grid supplied, however it is not zero. Only at moderate demands is the full storage capacity actually utilized. Increasing user demand will also increase the utilization of the solar resource, however that resource is finite so grid dependency will also increase. At moderate and low user demands there is still room for improvement by the use of some form of energy storage. Energy storage could increase the degree of utilization of the solar resource, while reducing some of the grid use. Also reducing storage capacity could be advantageous.

### 5.3.3. Study 3: Cost Reducing Measures

The previous studies have suggested that it should indeed be possible to reduce overall costs by doing one or more of the following:

- Use a fuel cell to cover passive power demand and utilize excess hydrogen
- Use a battery to cover passive power demand and utilize excess solar power
- Reduce (or possibly increase) storage size

#### 3a): Fuel Cell

Three options for fuel cells were considered: 3 kW, 5 kW or 10 kW.
For the study the storage size was kept to the default 625 kg.

Table 5.2.: Fuel Cell Options

| **Fuel Cell** | |
|---|---|
| **Nominal Power** | 3 / 5 / 10 kW |
| **Operational Range** | 10 - 100 % Nominal Power |

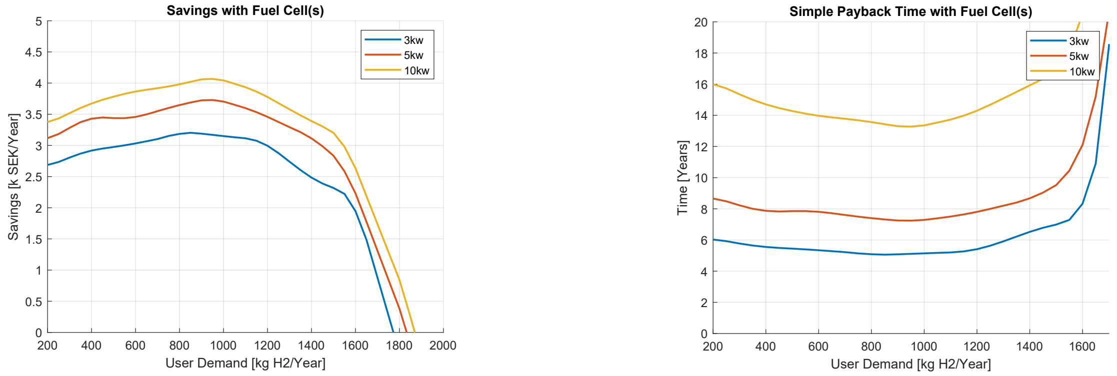


Figure 5.9.: Cost Savings and Payback Time, ($\Delta t_{max} = 0.1$)

The 3kW fuel cell was able to cover a majority of the passive demand from the facility but was not capable of completely covering demand peaks from the high pressure compressor and cooling which the larger fuel cells were better at. However these peaks were a relatively small part of the total passive demand, this is why the increase in saved power was relatively small when going from the 3kW fuel cell to the larger ones.

All three fuel cell options consume about the same amount of hydrogen per year (300 kg). For the fuel cells to be an efficient cost saving option, the user demand must be very low (0 - 1300 kg H2/year) so that there is excess hydrogen in the storage that the fuel cell can use. If user demand is higher, the fuel cell will only cause the electrolyser to produce more hydrogen in total but without that hydrogen being sold to customers. Overall this will not save any significant costs, it was even found that it might even increase costs at certain points.

The simple payback method showed that the smallest fuel cell has the best chance of paying itself off ideally within 5 - 6 years, well within its expected lifetime. However this requires that user demand will stay low for at least 5 years which might not be good for the HRS overall.

It should be noted that this assumed that the storage size would not be changed, a smaller storage which might be a viable option, would further decrease the potential usefulness of the fuel cell.

### 3b): Battery

For batteries, four options were considered, a small battery with:

$$P_{nom} = 13.8 \text{ kW and } E_{capacity} = 14.4 \text{ kWh}$$

or one out of three larger batteries with:

$$P_{nom} = 18 \text{ kW and } E_{capacity} = 19.2/24/38.4 \text{ kWh}$$

Table 5.3.: Battery Options

| Battery | |
|---|---|
| **Capacity** | 14.4 / 19.2 / 24 / 38.4 kWh |
| **Nominal Power** | 13.8 / 18 kW |
| **Operational Range** | 0 - 100 % Nominal Power |

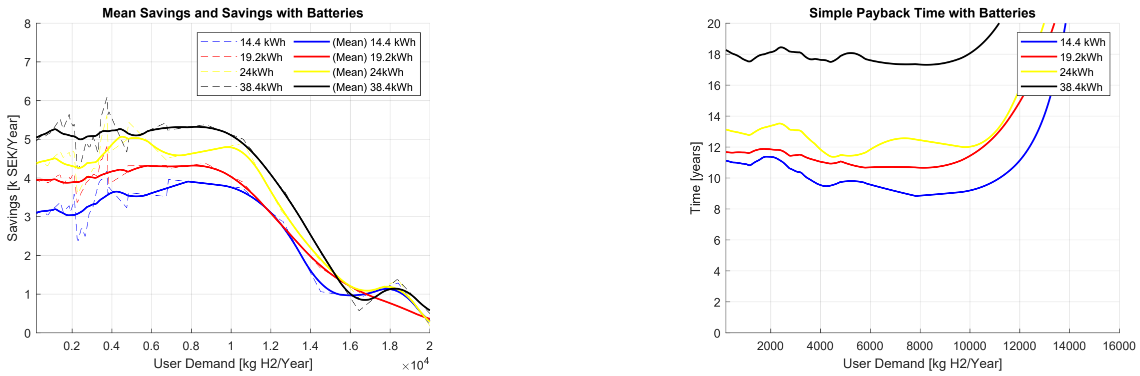


Figure 5.10.: Cost Savings and Payback Time, ($\Delta t_{max} = 0.1$)

The study found that batteries are indeed able of reducing total costs. And compared to the fuel cells the batteries are able to save costs for higher user demands than the fuel cell, up to 10000 kg H2 /year, where they start to fall off.

The simple payback method found that the smallest battery has the best chance of paying itself of within the advertised lifetime of the product.

### 3c): Altered Storage size

It was previously identified in study 2a) that the minimum storage size required to operate the HRS at high user demands is around 100 kg (with some safety margin included). In study 3c) it was investigated if there are any cost saving benefits in choosing a larger storage than the bare minimum of 100 kg.

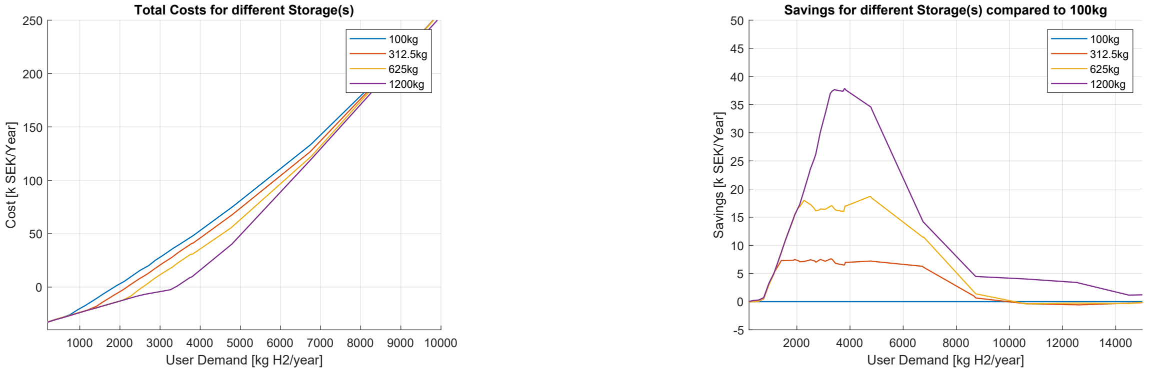


Figure 5.11.: Cost and Savings, ($\Delta t_{max} = 0.1$)

As previously identified the storage size can have an impact when the user demand is moderate but when the demand is either high or low the difference becomes unnoticeable. In general, a larger storage will allow the HRS to utilize the solar resource better, it will decrease the use of grid power, as excess hydrogen from the summer months can be stored longer for winter usage. The study found that a larger storage (using the 100 kg minimum storage as reference) can contribute to significant savings (up to 37 KSEK/year) at certain user demands. However it is unlikely to be worth it due to the high investment cost of storage. None of the larger options have a simple payback time of less than 280 years, even under optimal conditions.

Table 5.4.: Simple Payback Time for increased storage

| Option | 100 kg | 312.5 kg | 600 kg | 1200 kg |
|---|---|---|---|---|
| Capex Increase [KSEK] | 0 | 2125 | 5250 | 11000 |
| Best-Case Savings [KSEK/Year] | 0 | 7.1 | 18.7 | 37.5 |
| Simple Payback [Years] | - | 299 | 280 | 293 |

#### Study 3: Summary - Conclusion

Overall the study found that it possible to make overall savings with the use of energy storage but only at low - moderate user demands. The best option for energy storage seems to be a small battery, as it is not dependant on expensive storage capacity and is still useful up to very high user demands.

While increasing storage capacity can indeed drastically reduce grid use and increase solar utilization at certain demands, it is not worth it due to the high investment cost of storage. In conclusion storage capacity should be kept to the bare minimum.

### 5.3.4. Study 4: Cost Comparison

In study 4 the costs of three different solutions were compared. The default design, an improved version of the default design, with 100 kg main Storage and a 13.8 kW / 14.4 kWh battery and finally a non-solar Design with 100 kg main storage and 0 kWp solar panels (all else being the same as the default).

#### 4a): Fixed Costs

The fixed costs for the different solutions are presented in table 5.3.4. These are the costs that the HRS will present regardless of external factors such as user demand and solar power.

Not shown in table 5.3.4 but included in the calculations is that at the 10 year mark the electrolyser has to be replaced at a cost of 1650 KSEK (same for all solutions).

Table 5.5.: Investment and O & M for three HRS-designs

| | Default Design | | Improved Design | | No Solar Design | |
|---|---|---|---|---|---|---|
| Costs [KSEK] | Investment | O & M | Investment | O & M | Investment | O & M |
| Solar Panels | 3500 | - | 3500 | - | - | - |
| Electrolyser | 2590.5 | 132 | 2590.5 | 132 | 2590.5 | 132 |
| Compressor Low P. | 389.06 | 5.42 | 389.06 | 5.42 | 389.06 | 5.42 |
| Compressor High P. | 144.52 | 2.01 | 144.52 | 2.01 | 144.52 | 2.01 |
| Main Storage | 6250 | 62.5 | 6250 | 62.5 | 6250 | 62.5 |
| Buffer Storage | 500 | 0.5 | 500 | 0.5 | 500 | 0.5 |
| Battery | - | - | 34.56 | 0.29 | - | - |
| Facility | 1000 | - | 1000 | - | 1000 | - |
| Construction | 1000 | - | 1000 | - | 1000 | - |
| Total | 15374.08 | 206.94 | 10158.64 | 154.72 | 6624.08 | 154.43 |

### 4b): LCOH

The non-fixed LCOH is the part of the LCOH attributed to the non-fixed cost, i.e. grid use. The non-fixed part of the LCOH is higher for the non-solar HRS, although this difference is reduced at higher user demands. the default design is also slightly cheaper in non-fixed costs than the improved design. The non-fixed part of the LCOH is however not as important as the fixed part, which is much larger at low user demands.

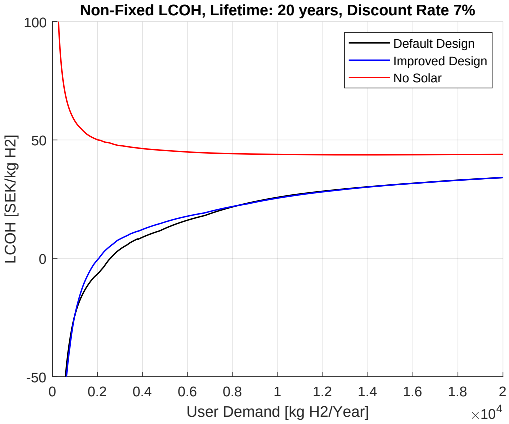


Figure 5.12.: Non-fixed LCOH, ($\Delta t_{max} = 0.1$)

The total LCOH (Figure: 5.13) reveals that the non-solar option is the cheapest, although it is comparable to the improved design. Lifetime and discount rate have a large impact on the outcome of the results, using short lifetimes and high discount rates will always favor solutions with lower investment cost. A cost competitive LCOH is assumed to be between 75 - 100 SEK/kg H2, the user demand required to reach this point is listed in table 5.3.4 for a few different discount rates and lifetimes.
For high user demands, long lifetimes and low discount rates the improved design becomes more economical over the non solar design.

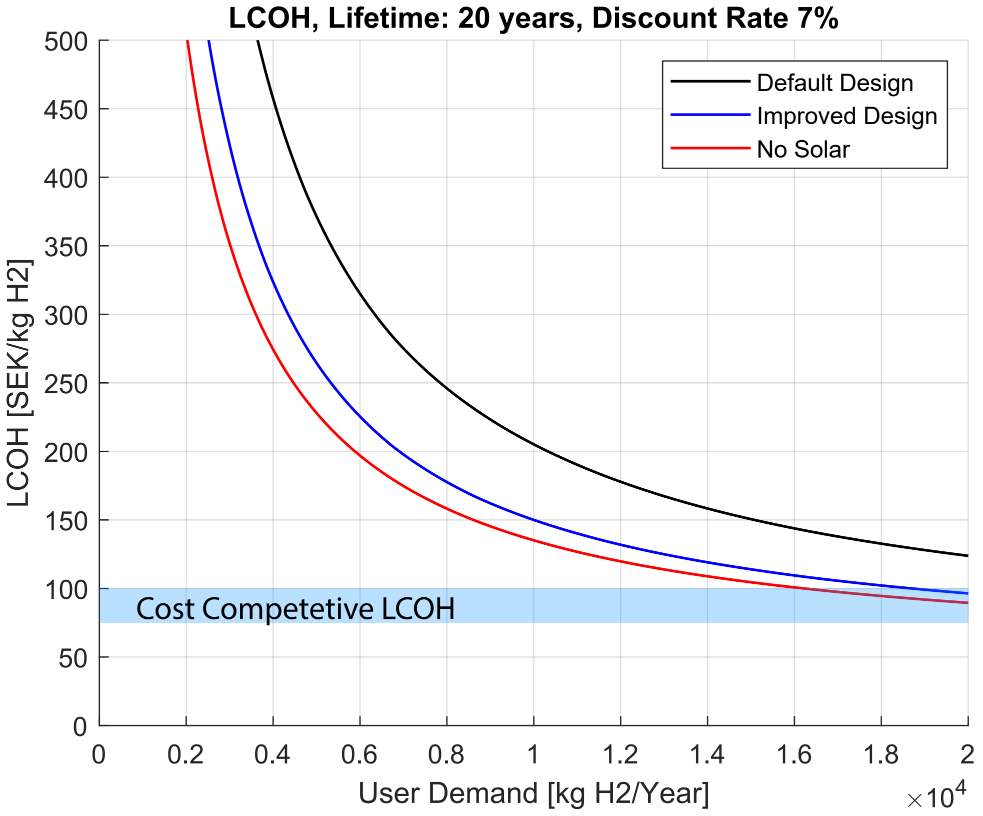


Figure 5.13.: LCOH, ($\Delta t_{max} = 0.1$)

Table 5.6.: Break-even User Demand, ($\Delta t_{max} = 0.1$)

| Discount Rate [%] | Lifetime [years] | Break-even User Demand [kg H2/year] | | |
|---|---|---|---|---|
| | | Default | Improved | No Solar |
| 2 | 20 | 19650 | 13100 | 12620 |
| 4.5 | 20 | 23760 | 15590 | 14180 |
| 7 | 20 | 28320 | 18470 | 15990 |
| 2 | 30 | 14450 | 9540 | 9990 |
| 4.5 | 30 | 18940 | 12390 | 11880 |
| 7 | 30 | 24220 | 15680 | 14040 |

#### Study 4: Summary - Conclusion

The study found that its difficult for any solution to be cost-competitive at low user demands. The solar options have the advantage of low to negative non-fixed costs at low user demands, however the increased investment cost overshadows this advantage. The precise outcome depends heavily on the assumption of lifetime and discount rate, but the conclusion can be made that finding ways to reduce investment cost is likely going to be more advantageous than any reduction to non-fixed costs is going to be. Cost-competitive prices are possible but depend on there being high user demand, regardless of solution. Similarly, the additional revenue from selling excess electricity at low user demands is also not really sufficient to make a significant improvement in the LCOH.

### 5.3.5. Study 5: Sensitivity Analysis

The above studies have all used certain base assumptions that are expected to be true. In the sensitivity analysis the influence of variations to some of the base assumptions were studied.

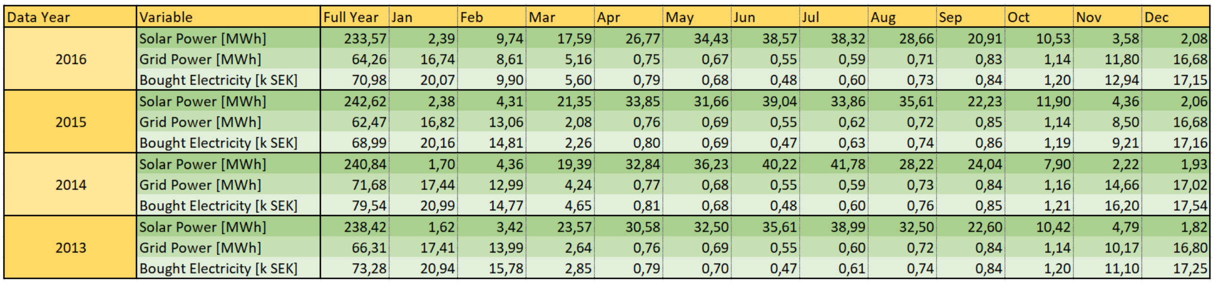
#### Analysis 1: Influence of Solar Data

All of the above studies used the same solar data, which was the most recent data for the location from the PVGis-SARAH database, from 2016. It was also assumed that the annual solar cycle would be entirely identical for every year of the full lifetime of the HRS. In this analysis the influence of variations in solar data was analysed by using solar data from 2013 until 2016 applied to the default model at a user demand of 4000 kg H2/Year.

The analysis found that while the total solar power in 2016 was lower than previous years the grid use and bought electricity as a whole was not higher than compared to other years. This is likely due to that 2016 had a much sunnier month of February than the other years. As a result the difference in electricity expenditure between 2016 and the worst year of 2014 is an increase of 12 %, even though the total amount of solar power in 2014 is slightly higher.

Another important aspect can also be seen when comparing the data for 2016 presented in tables 5.3 and 5.14. While the solar data is the same, the resulting grid use and cost differs. This

Figure 5.14.: Comparison of solar data and effect on grid use, ($\Delta t_{max} = 0.01$)



| Data Year | Variable | Full Year | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2016 | Solar Power [MWh] | 233,57 | 2,39 | 9,74 | 17,59 | 26,77 | 34,43 | 38,57 | 38,32 | 28,66 | 20,91 | 10,53 | 3,58 | 2,08 |
| | Grid Power [MWh] | 64,26 | 16,74 | 8,61 | 5,16 | 0,75 | 0,67 | 0,55 | 0,59 | 0,71 | 0,83 | 1,14 | 11,80 | 16,68 |
| | Bought Electricity [k SEK] | 70,98 | 20,07 | 9,90 | 5,60 | 0,79 | 0,68 | 0,48 | 0,60 | 0,73 | 0,84 | 1,20 | 12,94 | 17,15 |
| 2015 | Solar Power [MWh] | 242,62 | 2,38 | 4,31 | 21,35 | 33,85 | 31,66 | 39,04 | 33,86 | 35,61 | 22,23 | 11,90 | 4,36 | 2,06 |
| | Grid Power [MWh] | 62,47 | 16,82 | 13,06 | 2,08 | 0,76 | 0,69 | 0,55 | 0,62 | 0,72 | 0,85 | 1,14 | 8,50 | 16,68 |
| | Bought Electricity [k SEK] | 68,99 | 20,16 | 14,81 | 2,26 | 0,80 | 0,69 | 0,47 | 0,63 | 0,74 | 0,86 | 1,19 | 9,21 | 17,16 |
| 2014 | Solar Power [MWh] | 240,84 | 1,70 | 4,36 | 19,39 | 32,84 | 36,23 | 40,22 | 41,78 | 28,22 | 24,04 | 7,90 | 2,22 | 1,93 |
| | Grid Power [MWh] | 71,68 | 17,44 | 12,99 | 4,24 | 0,77 | 0,68 | 0,55 | 0,59 | 0,73 | 0,84 | 1,16 | 14,66 | 17,02 |
| | Bought Electricity [k SEK] | 79,54 | 20,99 | 14,77 | 4,65 | 0,81 | 0,68 | 0,48 | 0,60 | 0,76 | 0,85 | 1,21 | 16,20 | 17,54 |
| 2013 | Solar Power [MWh] | 238,42 | 1,62 | 3,42 | 23,57 | 30,58 | 32,50 | 35,61 | 38,99 | 32,50 | 22,60 | 10,42 | 4,79 | 1,82 |
| | Grid Power [MWh] | 66,31 | 17,41 | 13,99 | 2,64 | 0,76 | 0,69 | 0,55 | 0,60 | 0,72 | 0,84 | 1,14 | 10,17 | 16,80 |
| | Bought Electricity [k SEK] | 73,28 | 20,94 | 15,78 | 2,85 | 0,79 | 0,70 | 0,47 | 0,61 | 0,74 | 0,84 | 1,20 | 11,10 | 17,25 |

is because grid use is sensitive to previous states, best explained by that a dark November or December in one year may not cause problems until later in January or February the following year (read more about this in Appendix A.3.5). The analysis suggests that variations in solar power during the winter months can have a significant impact on non-fixed cost. However if user demand is very low or very high this is unlikely to matter. Further on, the other studies have also shown that non-fixed costs are only a small part of the total costs, it is therefor expected that these variations would have no significant impact on the LCOH.

### Analysis 2: Influence of Price Variations

Study 4 showed that fixed costs have a far greater impact on the LCOH than non-fixed cost. In future scenarios it is possible that fixed costs have decreased (components become cheaper and more efficient to manufacture) and non-fixed costs increase (the price of electricity increases). Analysis 2 studies how large variations in fixed and non-fixed costs would affect the LCOH of the default HRS design. It was found that as non-fixed costs become a larger part of the total costs and fixed costs a smaller part, the LCOH is less dependant on user demand to become cost competitive. At very low fixed costs a “local minimum” is introduced for the LCOH (around 4500 kg H2 / Year). As non-fixed cost rise in relation to fixed costs the viability and importance of energy storage further increases.

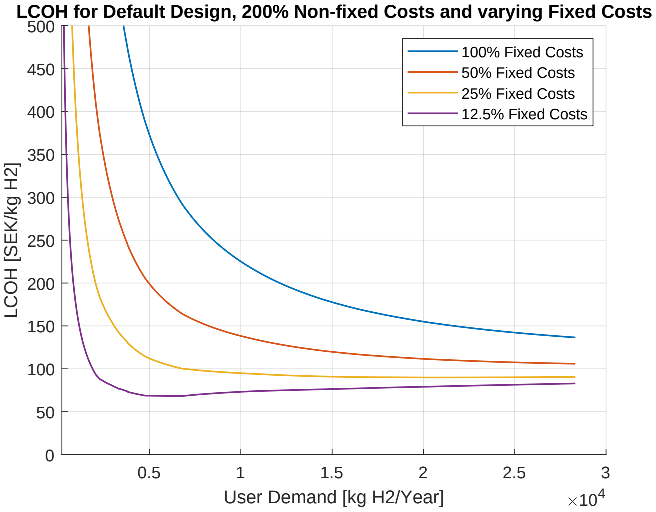


Figure 5.15.: Variations in costs, ($\Delta t_{max} = 0.1$)

# 6. Case 2 - Island HRS

## 6.1. Case Introduction

**Scenario:** An island in Sweden wants to introduce hydrogen buses to the public transport of the island. The island is small and has few permanent residents, however tourism is big on the island during the summer months. It was imagined that the local public authorities of the island have planned for one hydrogen bus that operates the year around and two additional buses that only operate through the tourism season of the 1st of April until the 31st of September.

The island is not to far from mainland shore, and it is connected to the mainland grid via underwater cable, however the cable is old and already operating at its full capacity. Upgrading the cable would be time consuming and costly. As a result the HRS that will supply the buses must be entirely self-sufficient from its solar panels. The public authorities have stated the requirements the HRS must fulfill and now request a matching HRS design. The authorities are also interested in knowing about any other utilities the station could provide.

Also as an option, there are plans of a large solar power park for the island. The authorities also want to investigate the possibility of combining this park with a HRS.

**Disclaimer:** The case is inspired by, and shares coordinates with, the island of Visingsö in Sweden. The island simply serves as a source of inspiration. No statements are made about the actual state of public transportation or electricity on the island.

## 6.2. System Technical Requirements

### Buses

The buses must refill in the early morning every day. Even though the island is relatively small the demand for public transport is high, the buses are estimated to drive as much and consume as much fuel as any other average bus. The buses consume an estimated 11680 kg H2/Year. Out of those 8760 kg are consumed between Apr - Sep and the remaining 2920 kg in Oct - Dec.

Table 6.1.: Specification for the buses

| Bus | Season | Consumption | Refills at [time] | Fuel Pressure |
|---|---|---|---|---|
| 1 | Full Year | 16 kg/day | 04.30 | 350 Bar |
| 2 | Apr-Sep | 16 kg/day | 05.00 | 350 Bar |
| 3 | Apr-Sep | 16 kg/day | 05.30 | 350 Bar |

#### Location

The station must be close to the harbor of the island, located at:

Table 6.2.: HRS Location

| | | | | | |
|---|---|---|---|---|---|
| Latitude: | 58.03° | Longitude: | 14.35° | Elevation: | 88m |

#### Self-Sufficiency

The station must be entirely self-sufficient and require no grid power to operate. It must generate all the required hydrogen by itself. It was assumed that the facility had a passive power demand of 1 kW.

The simulations were run as if there was a grid connection. Due to the implementation of the program this approach is the most convenient. A design was deemed as self sufficient if the total grid demand over a year was less than 0.05 MWh. Due to simulation inaccuracies small amounts of grid usage usually occur , often not larger than a kilowatt at most (read more about this in A.3.6), these load peaks are clearly distinct from actual grid usage and can be neglected.

## 6.3. Studies

A series of studies were performed.

- Study 1: Design Process
- Study 2: Design Evaluation
- Study 3: Further Improvements
- Study 4: Solar Power Park alternative

For all studies the most important metric to monitor was the “Lowest storage”, since if it ever is zero that would imply that the HRS is empty and unable to supply the buses. Grid use is also monitored since it determines whether the HRS is self sufficient or not.

### 6.3.1. Study 1: Design Process

In study 1 a design for the HRS was developed based on the previously presented conditions. In study 1a) a first draft of the design was developed that then could be further refined later on. The goal is to develop a design with as low capital investment cost as possible, since previous studies in Case 1 have identified that this is by far the largest contributor towards overall costs.

### 1a): Initial Design

The station must be able to produce around 11680 kg H2/Year. Assuming an average electrolyser efficiency of 52 kWh/kg H2 gives a yearly energy requirement of 607.4 MWh for the electrolyser only. With a capacity factor of 10-11 % for the solar panels, which is common for Sweden, the requirement becomes 693 kWp, rounded up to 700 kWp to include other power demands such as compressors etc.

Initially it was assumed that the main storage must be sufficient for an entire winter with no sun: 3000 kg. The pressure in the main storage was set to 200 Bar. For the buffer storage, 50 kg at 425 Bar was deemed appropriate.

The high pressure compressor was decided to be as small as possible, since there was no need to refill the buffer storage quickly as the buses only refuel once a day and always at the same time. It was found that 1kw does the job.

As for electrolyser(s), two HyProvide A-60 provide together at a combined capacity of 500 kW was chosen. Using two smaller electrolysers instead of one large alows the station to operate at lower powers, as low as 25 kW when only running one. The electrolysers operate at 35 Bar and provide at most 5.4 kg H2/h each, putting an estimated requirement of 15 kW on the low pressure compressor.

To cover the night time and winter time power demand of the HRS a fuel cell of 5kW and a battery of 3.3 kW/9.6 kWh were estimated to be sufficient. The control thresholds[1] for the system were modified from their default values as follows: The control thresholds are the variables that dictate the operation of the HRS, such as when the battery should be charged or when grid power can be used.

Table 6.3.: Modified Thresholds

| |
|---|
| $SOH2_{Low} = 0$ |
| $SOH2_{OK} = 1$ |
| $SOH2_{FC} = 0$ |

---

[1] Read about the control thresholds in Appendix A.1.7

### Specification Sheet

Table 6.4.: Island HRS - Initial Specification Sheet

| | |
|---|---|
| **Solar Panels** | |
| **Location** | Lat: 58.03°; Lon: 14.35° |
| **Capacity** | 700 kWp |
| **Data** | PVGIS - SARAH - (2016) |
| **Electrolyser(s)** | |
| **Nominal Power** | 500 kW (250 kW + 250 kW) |
| **Operational Range** | 2.5 - 100 % Nominal Power |
| **Operating Pressure** | 35 Bar |
| **Low Pressure Compressor** | |
| **Nominal Power** | 15 kW |
| **Inlet Pressure** | 35 Bar |
| **Outlet Pressure** | 200 Bar |
| **Main Storage** | |
| **Capacity** | 3000 kg |
| **Pressure** | 200 Bar |
| **Battery** | |
| **Capacity** | 9.6 kWh |
| **Nominal Power** | 3.3 kW |
| **Operational Range** | 0 - 100 % Nominal Power |
| **Fuel Cell** | |
| **Nominal Power** | 5 kW |
| **Operational Range** | 10 - 100 % Nominal Power |
| **High Pressure Compressor And Cooling** | |
| **Nominal Power** | 1 kW |
| **Inlet Pressure** | 200 Bar |
| **Outlet Pressure** | 425 Bar |
| **Buffer Storage** | |
| **Capacity** | 50 kg |
| **Pressure** | 425 Bar |
| **Other** | |
| **Facility Passive Power Demand** | 1 kW |
| **Electricity Price - Hourly Spot Price** | Nordpool SE3 2019 |

### 1b): Iterative Optimization of Storage and Solar Panels

Solar panels and Storage are the components which are expected to contribute the most towards total costs. As for the initial design the storage was intentionally oversized, the first goal will be to find the minimum viable storage by looking at how much hydrogen is left in the storage when it was at its lowest point of the year. Also by increasing the amount of solar panels it is possible to generate more hydrogen during the winter and thus have a smaller storage. With the current pricing model, 100 kWp of solar panels is worth the same as 140 kg of storage capacity. For every 100 kWp increase in solar panels the HRS must be able to save atleast 140 kg of storage for it to be worth it. The design was optimized for capital cost by simulating different design iterations and choosing the design iteration with the lowest observed capital cost.

Table 6.5.: Island HRS - Design Iterations. ($\Delta t_{max} = 0.1$)

| Parameter | | Cost [M SEK] | | | Performance | |
|---|---|---|---|---|---|---|
| Solar [kWp] | Storage [kg] | Solar | Storage | Total | Excess Solar [MWh] | Excess H2 [kg] |
| 700 | 3000 | 9.8 | 30 | 39.8 | 47.15 | 699.6 |
| 700 | 2500 | 9.8 | 25 | 34.8 | 54.24 | 392 |
| 700 | 2200 | 9.8 | 22 | 31.8 | 54.29 | 270.82 |
| 700 | 2100 | 9.8 | 21 | 30.8 | 54.36 | 49.77 |
| 700 | 2000 | 9.8 | 20 | 2.8 | 56.33 | Insufficient |
| 800 | 2060 | 11.2 | 20.6 | 31.8 | 155 | 315.386 |
| 800 | 1900 | 11.2 | 19 | 30.2 | 155.63 | 184.87 |
| 800 | 1800 | 11.2 | 18 | 29.2 | 155.68 | 100.08 |
| 800 | 1750 | 11.2 | 17.5 | 28.7 | 155.57 | 54.0365 |
| 900 | 1610 | 12.6 | 16.1 | 28.7 | 254.42 | 146.51 |
| 900 | 1500 | 12.6 | 15 | 27.6 | 254.31 | 48.15 |
| 1000 | 1360 | 14 | 13.6 | 27.6 | 352.42 | 70.04 |
| 1000 | 1300 | 14 | 13 | 27 | 352.42 | 19.76 |
| 1100 | 1160 | 15.4 | 11.6 | 27 | 451.33 | 11.3912 |

The most optimal solution is likely 1000 kWp of solar panels together with 1300 kg of storage. Increasing solar panels after this point did not result in significant reduction in costs. The total capital cost was able to be reduced by more than 10 M SEK compared to the initial design.
**Design Update:** Solar Panels: 1000 kW, Storage: 1300 kg

### 1c): Sensitivity Analysis - Impact of Solar Data

The new design presented by the iterative design process relies heavily on there being solar power available during the winter, it can thus be expected that variations in solar data can have a large impact on the performance of the HRS. In study 2b) solar data from 2016 were used. In this analysis data from 2013, 2014, 2015 and 2016 was be applied to the design new design.

The analysis found that using the better than average solar data of 2016 alone gave a distorted picture of reality. An analysis of the solar data from 2013 - 2016 found that previous years had less solar radiation, and that a particularly dark winter of 2014 caused the storage to be empty

Table 6.6.: Sensitivity Analysis Solar Data, ($\Delta t_{max} = 0.01$)

| | | Storage: 1300 kg | Storage: 1500 kg | Storage: 1600 kg |
|---|---|---|---|---|
| Year | Solar Power [MWh] | Lowest Storage [kg] | Lowest Storage [kg] | Lowest Storage [kg] |
| 2013 | 950.04 | Insufficient | 34.44 | 123.10 |
| 2014 | 954.64 | Insufficient | 79.03 | 168.12 |
| 2015 | 966.80 | Insufficient | Insufficient | 68.84 |
| 2016 | 971.51 | 121.25 | 307.14 | 399.97 |

by early 2015. To counteract this problem the storage size had to be increased by 300 kg.
**Design Update:** Storage: 1600 kg

### 1d): Energy Storage

The initial setup for energy storage has proven sufficient for previous studies, it can however be suspected that by modifying the choice of battery, fuel cell and control thresholds, it is possible to further improve the efficiency of the HRS.

The threshold $SOH2_{OK}$ influences the charging priority of the battery, that is at what point the control unit of the HRS decides it is better to charge the battery than to run the electrolyser. A lower $SOH2_{OK}$ threshold corresponds to a higher charging priority for the battery. If $SOH2_{OK} = 0$ the battery will always be charged if it is possible, if $SOH2_{OK} = 1$ The battery will only be charged if there is excess power that the electrolyser can not use. Three different thresholds were investigated for the latest design, while using solar data from 2013-2016.

Table 6.7.: Infulence of $SOH2_{OK}$, ($\Delta t_{max} = 0.01$)

| | | $SOH2_{OK} = 1$ | $SOH2_{OK} = 0.5$ | $SOH2_{OK} = 0$ |
|---|---|---|---|---|
| Year | Solar Power [MWh] | Lowest Storage [kg] | Lowest Storage [kg] | Lowest Storage [kg] |
| 2013 | 950.04 | 123.10 | 121.75 | 119.96 |
| 2014 | 954.64 | 168.12 | 166.76 | 164.53 |
| 2015 | 966.80 | 68.84 | 66.78 | 65.63 |
| 2016 | 971.51 | 399.97 | 398.51 | 398.71 |

The study seems to suggest that a higher priority is preferable, but mostly it suggests that the influence of $SOH2_{OK}$ is small. Different combinations of battery and fuel cell were also investigated but no improvements could be found. A precise relationship between choice of battery, fuel cell and threshold could not be identified but it is seems that one good solution is to have a balance between a battery that meets day-to-day demand and a fuel cell that picks up when the battery is insufficient, acting as a back-up.

The solution found by the study that seems to be the most effective relies on a synergy between the battery and fuel cell. Figure 6.1 illustrates the mix of energy supply for the 2nd of January 2014, which is a typical sunny winter day for the station. During daylight the HRS is solar powered and the battery charges, once the sun goes down the battery begins to discharge. The battery runs until it is empty, where after the fuel cell takes over until the sun rises again. At 04.00 the bus refills and the high pressure compressor starts, increasing the power demand. This cycle is typical for the station year round. In the summer time when days are longer and nights shorter, the fuel cell becomes used less as the battery is almost sufficient to last until sunrise. The battery supplies the HRS constantly throughout the year with about 14-15 % of its passive power demand. The fuel cell varies between around 3-5 % in the summer and 40-45 % in the winter. The rest of the passive power demand is met directly by the solar panels.

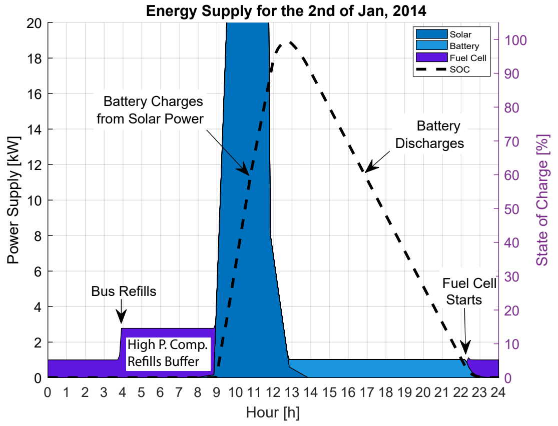


Figure 6.1.: Energy Supply Mix

In winter time it occasionally happens that not enough solar power, or none at all is available to charge the battery, for those days the fuel cell can supply the station to almost 100 %. Due to the occurrence of such days, the fuel cell can not be omited.

### 1e): Choice of Electrolyser and Electrolyser Implementation

#### Parallel Electrolysers

For the previous studies it has been counted as if the two electrolysers could be considered as "combined as one" and that there would be no significant difference to having an electrolyser of the combined size other than that they are able to operate at a lower minimum power. This assumption is accurate if the efficiency of the electrolyser is constant, which it is not in reality. In study 1e) it was investigated how parallel electrolysers can be implemented and if it makes any difference from the initial assumption. Also it was investigated if the choice of electrolysers can be improved.

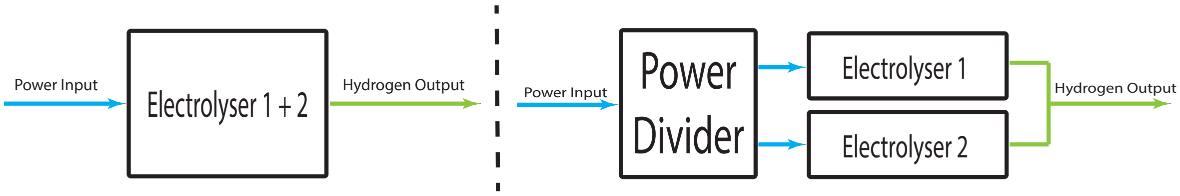


Figure 6.2.: Combined- against parallel implementation

The implementation of 2 parallel 250 kW electrolyser compared to 2 combined 250 kWs yielded a slight improvement of electrolyser efficiency (up to 7 %) at low input powers. However the difference quickly becomes negligible and is practically none already at 75 kW input power, which equals to 15 % of the combined rated power. It should also be noted that the model does not account for increased losses and complexity that may arise from a parallel implementation. In reality the gains may be even less.

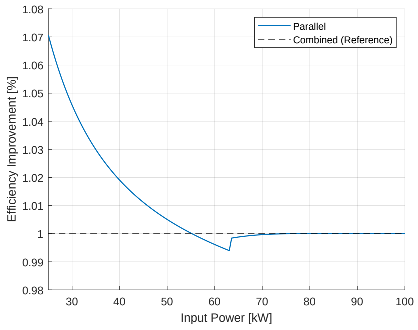


Figure 6.3.: Efficiency Improvement

Table 6.8.: Comparasion, ($\Delta t_{max} = 0.01$), Solar Data: 2013 - 2016

| Implementation | $\eta_{mean}$ [%LHV] |
|---|---|
| Combined | 69.75 |
| Parallel | 69.81 |

### Choice of Electrolyser

A few different electrolysers from the HyProvide A-Series catalogue [25] were compared in different arrangements. 2014 solar data was used in combination with parallel implementation. The study found that the 125 kW + 390 kW option is the most cost effective. With the improved efficiency it was possible to reduce the main storage by 50 kg, resulting in a net saving of 432.5 KSEK. An extra simulation 6.3.1 was run with data from 2013 - 2016 to ensure that the new choice of electrolysers would function well for all years.

Table 6.9.: Electrolyser Comparasion, ($\Delta t_{max} = 0.1$)

| Electrolyser(s) | $P_{min}$ | $P_{rated}$ | $\eta_{mean}$ [%LHV] | Lowest Storage [kg] |
|---|---|---|---|---|
| 250kW | 12.5kW | 250kW | 67.75 | Insufficient |
| 390kW | 39kW | 390kW | 68.90 | Insufficient |
| 125kW + 125kW | 12.5kW | 250kW | 67.58 | Insufficient |
| 125kW + 250kW | 12.5kW | 375kW | 68.89 | 23.29 |
| 250kW + 250kW | 25kW | 500kW | 70.08 | 102.62 |
| 125kW + 390kW | 12.5kW | 515kW | 70.24 | 171.48 |
| 250kW + 390kW | 25kW | 640kW | 70.92 | 175.82 |
| 390kW + 390kW | 39kW | 780kW | 71.40 | 132.95 |

**Design Update**: Parallel Electrolysers: 125 kW + 390 kW, Main Storage: 1550 kg.

Table 6.10.: Quality Control Simulation, ($\Delta t_{max} = 0.01$)

| Electrolysers: 125 kW + 390 kW, Storage: 1550 kg | | |
|---|---|---|
| Year | Lowest Storage [kg] | $\eta_{mean}$ [%LHV] |
| 2013 | 147.75 | 69.96 |
| 2014 | 193.99 | 69.89 |
| 2015 | 96.74 | 69.94 |
| 2016 | 395.69 | 70.06 |
| Mean | 208.54 | 69.96 |

### 1f): Sensitivity Analysis - Influence of Passive Power Demand

It was initially assumed that the passive power demand of the facility would be 1kW at all times. In this sensitivity analysis it was investigated if small variations from this initial assumption will have a significant impact on the performance of the HRS. Different values for $P_{facility}$ were tried, solar data from 2013 - 2016 were used with the most recent design iteration.

Table 6.11.: Influence of $P_{facility}$, ($\Delta t_{max} = 0.01$)

| $P_{facility}$ [kW] | 1.0 | 1.25 | 1.50 |
|---|---|---|---|
| Year | Lowest Storage [kg] | | |
| 2013 | 147.75 | 114.32 | 79.62 |
| 2014 | 193.99 | 160.60 | 125.94 |
| 2015 | 96.74 | 61.31 | 24.28 |
| 2016 | 395.69 | 368.30 | 340.12 |
| Mean | 208.54 | 176.13 | 142.49 |

The analysis found that the design could withstand an increase of at least 50 % in facility power demand. It was deemed that this was a sufficient safety margin and no change of design was necessary.

### Study 1: Summary - Conclusion

The finalized design includes a large main storage and high capacity in solar panels. The station relies on a large surplus of hydrogen from the summer that is intended to last through the entire winter. The station is also able to keep up some production during the winter to support this. The electrolysers were chosen so that the solar resource can be utilized optimally, both at high and low powers.

A small battery and fuel cell are enough to reliably support the stations power demand for when there is no sun. The battery does the bulk of this work and the fuel cell chips in when necessary.

### Specification Sheet

Table 6.12.: Island HRS - Final Specification Sheet (1/2)

| | |
|---|---|
| **Solar Panels** | |
| **Location** | Lat: 58.03 °; Lon: 14.35 ° |
| **Capacity** | 1000 kWp |
| **Data** | PVGis - SARAH - (2013 - 2016) |
| **Electrolyser(s)** | |
| **Nominal Power** | 515 kW (125 kW + 390 kW) |
| **Operational Range** | 2.5 - 100 % Nominal Power |
| **Operating Pressure** | 35 Bar |
| **Low Pressure Compressor** | |
| **Nominal Power** | 15 kW |
| **Inlet Pressure** | 35 Bar |
| **Outlet Pressure** | 200 Bar |
| **Main Storage** | |
| **Capacity** | 1700 kg |
| **Pressure** | 200 Bar |
| **Battery** | |
| **Capacity** | 9.6 kWh |
| **Nominal Power** | 3.3 kW |
| **Operational Range** | 0 - 100 % Nominal Power |
| **Fuel Cell** | |
| **Nominal Power** | 5 kW |
| **Operational Range** | 10 - 100 % Nominal Power |
| **High Pressure Compressor And Cooling** | |
| **Nominal Power** | 1 kW |
| **Inlet Pressure** | 200 Bar |
| **Outlet Pressure** | 425 Bar |
| **Buffer Storage** | |
| **Capacity** | 50 kg |
| **Pressure** | 425 Bar |
| **Other** | |
| **Facility Passive Power Demand** | 2 kW |
| **Electricity Price - Hourly Spot Price** | Nordpool SE3 2019 |

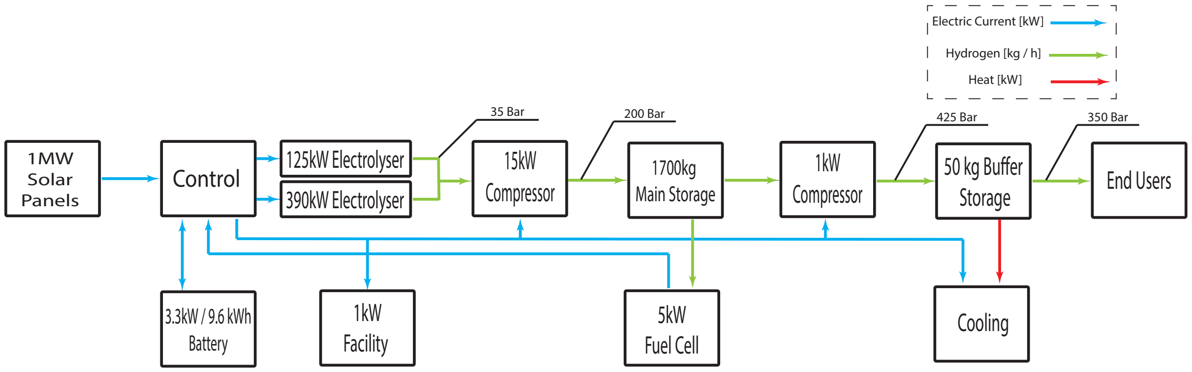


Figure 6.4.: Finalized Island HRS Design

### Investment and Operational Cost

The most expensive components of this HRS design is by far the solar panels and the hydrogen storages, making up around 80 % of the total investment cost. Not shown in the table is that the electrolysers and fuel cell must be replaced every 10 years at a combined cost of 3421.5 KSEK.

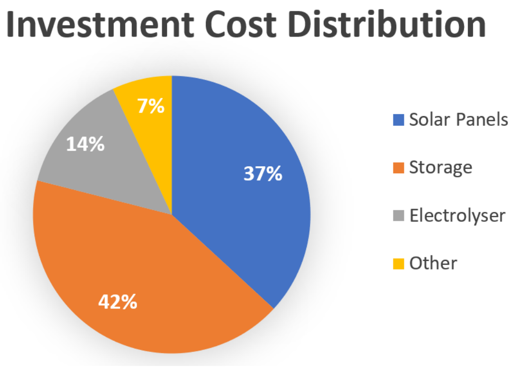


Figure 6.5.: Island HRS - Distribution of Investment Cost

Table 6.13.: HRS Costs - Island HRS (Investment is Capex plus installation)

| **Component** | **Capex [KSEK]** | **Investment [KSEK]** | **O & M [KSEK/year]** |
|---|---|---|---|
| Solar Panels | 14000 | 14000 | 0 |
| Electrolyser 1 | 825 | 1295.25 | 205.92 |
| Electrolyser 2 | 2574 | 4041.18 | 66 |
| Compressor Low P. | 189.219 | 543.06 | 7.57 |
| Compressor High p. | 20.4 | 58.548 | 0.816 |
| Main Storage | 15500 | 15500 | 155 |
| Buffer Storage | 500 | 500 | 5 |
| Battery | 19.2 | 23.04 | 0.192 |
| Fuel Cell | 22.5 | 27 | 1.35 |
| Facility | 1000 | 1000 | 0 |
| Construction | 1000 | 1000 | 0 |
| **Total:** | | **37988** | **441.85** |

### 6.3.2. Study 2: Design Performance

#### 2a): Functionality

The finalized design was tested on solar data from 2010 until 2016.

Table 6.14.: Design Performance, ($\Delta t_{max} = 0.01$)

| **Storage [kg] :** | | **1550** | **1650** |
|---|---|---|---|
| **Year** | **Solar [MWh]** | **Lowest Storage [kg]** | |
| 2010 | 886.31 | 545.21 | 732.83 |
| 2011 | 959.89 | 631.18 | 818.72 |
| 2012 | 896.22 | 506.59 | 714.78 |
| 2013 | 950.03 | Insufficient | 148.63 |
| 2014 | 954.64 | 193.98 | 375.10 |
| 2015 | 966.80 | 96.80 | 315.20 |
| 2016 | 971.51 | 395.69 | 568.27 |
| **Mean:** | 940.77 | 338.51 | 524.93 |

The study revealed that due to a dark winter in 2012 a shortage in 2013 was introduced that was not found earlier. To solve this the storage was increased by 100 kg and the control scheme for the electrolyser (See A.2.2) was adjusted to run on higher power when the storage is close to full. This would increase the safety margin to an acceptable level but also added an additional cost of 1000 KSEK to the investment cost and 1 KSEK/Year to the operational cost.

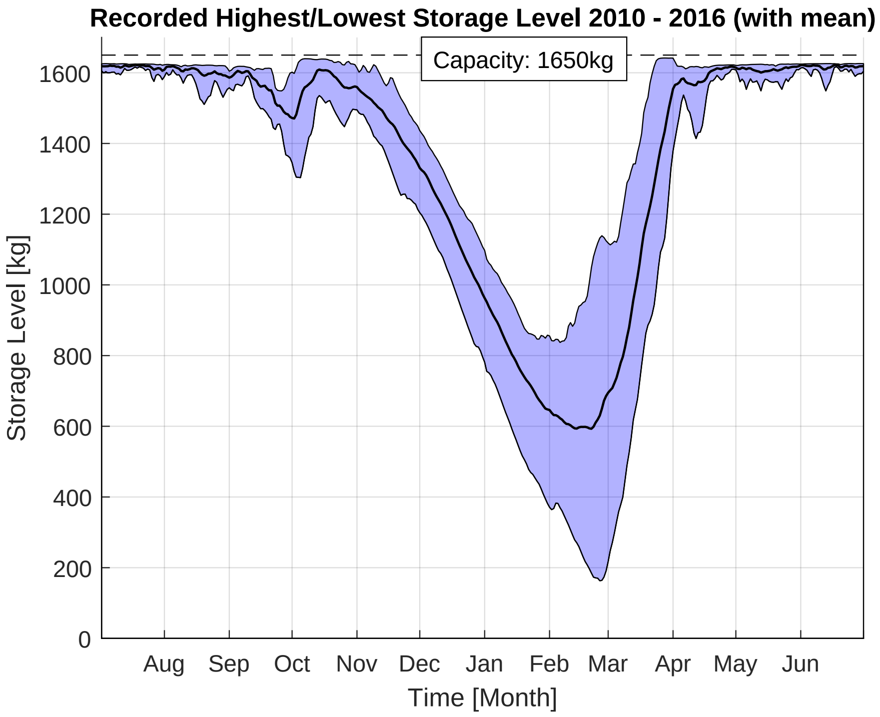


Figure 6.6.: Storage Level, Averaged by day, ($\Delta t_{max} = 0.01$)

Figure 6.6 and table 6.14 reveal the great variations in lowest storage level (Standard Deviation = 249.91 kg) that may occur between seasons, what the lowest storage level is within a given year may be as much as 375 kg less than the average lowest storage level.

It is also now shown that a large part of the storage mostly goes unused. If one were to measure the storage level at any given time, 54.14 % of the time, the storage level would be somewhere in between 1550 kg and 1650 kg. 31.69 % of the time the storage would be somewhere in between 850 kg and 1550 kg. And for the remaining 14.16 % the storage would be 850 kg or less. This means that around half of the storage (worth 8500 KSEK) goes completely unused 85 % of the time.

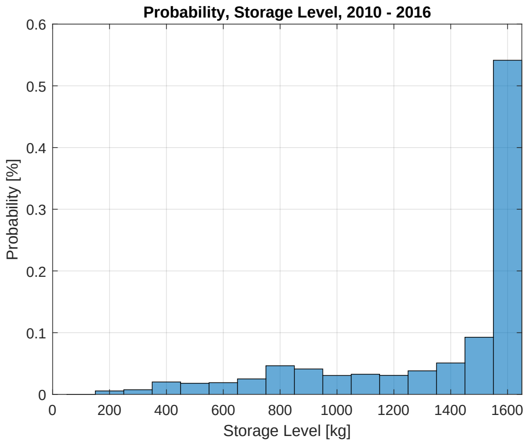


Figure 6.3.2: Storage Level probability ($\Delta t_{max} = 0.01$)

### 2b): LCOH

The levelized cost of hydrogen was calculated for a few discount rates and lifetimes. A cost-competetive LCOH for buses is estimated to be around 60-70 SEK at most [1], [2].

Table 6.15.: LCOH for multiple discount rates and lifetimes

| Discount rate [%] | Lifetime [year] | LCOH [SEK/kg H2] |
|---|---|---|
| 2 | 20 | 269.58 |
| 4.5 | 20 | 319.14 |
| 7 | 20 | 374.97 |
| 2 | 30 | 207.26 |
| 4.5 | 30 | 262.65 |
| 7 | 30 | 325.79 |

### Study 2: Summary - Conclusion

The study could conclude that the station functions reliably. But due to the high requirements set on self-sufficiency and reliability, a considerable amount of expensive redundancy was introduced into the design.

There are still improvements that can be made, which were investigated in study 3. Although it remains unlikely that any improvements to the design or modifications to the requirements would allow the station to become fully cost-competitive.

### 6.3.3. Study 3: Potential Improvements

#### 3a): Utilizing Excess Heat and Electricity

The HRS is not grid connected and any excess power from the solar panels is said to just be “wasted”. The amount of excess solar power turns out to be quite significant, often more than 300 MWh per year.

Table 6.16.: Unutilizied Electricity, ($\Delta t_{max} = 0.01$)

| Year | Excess Solar [MWh] |
|---|---|
| 2010 | 287.3 |
| 2011 | 362.0 |
| 2012 | 311.2 |
| 2013 | 339.7 |
| 2014 | 360.4 |
| 2015 | 357.9 |
| 2016 | 372.8 |
| Mean | 341.6 |

The wast majority of the excess electricity is generated during the tourism season of April - September, around 1.5 MWh/Week. This electricity could probably be used to support the tourism industry during the season. Using only NordPools SE3 hourly spotprice for 2019, the worth of the electricity is on average 130 KSEK per year. If it is assumed that 100 % of the electricity could be utilized directly and locally without large transmission losses (for example by a nearby hotel or similar), around 318 KSEK of electricity costs could be saved annually when transmission fees and taxes are included.

Two scenarios were analysed, one optimal where the electricity could be used 100 % optimally and including saving from reduced taxes and transmission fees, and one more moderate estimate that assumes 50 % Electricity but with taxes and fees saved.

Table 6.17.: LCOH for multiple increased energy utilization

| **LCOH [SEK/kg H2]** | | | |
|---|---|---|---|
| **Discount Rate [%]** | **Lifetime [Years]** | **100 %** | **50 %** |
| 2 | 20 | 242.35 | 255.97 |
| 4.5 | 20 | 291.91 | 305.53 |
| 7 | 20 | 347.75 | 361.36 |
| 2 | 30 | 180.03 | 193.65 |
| 4.5 | 30 | 234.42 | 249.04 |
| 7 | 30 | 298.56 | 312.17 |

### 3b): Utilizing Excess Hydrogen

Study 2 found that it often occurs that the storage has quite a large amount of hydrogen left as it reaches its lowest point in February each year. Assuming that at least 100 kg of H2 should be left in the storage at all times for unforeseen circumstances an average 420 kg H2 is left annually that could be used for other purposes.

One option is to burn this excess hydrogen in the fuel cell and generate electricity and heat that could be sold. When used in the fuel cell, 1 kg of H2 generates on average 21.8 kWh of electricity and 12 kWh of heat (Assuming adiabatic conditions and no other losses). If all the excess hydrogen was to be burned in the fuel cell during the month of February, an average revenue of 14 KSEK per year could be generated under the previously stated optimal conditions. It should although be noted, that the current fuel cell can not burn more than 0.229 kg H2/hour (5 kw and 21.8 kWh/kg H2), resulting in it being capable of burning at most 154 kg H2 in the month of February. If this option were to be considered an upgrade of the fuel cell would likely be required.

A second option is to generate less hydrogen by throttling down the electrolyser and instead produce more excess electricity. With this method, for every kilogram of hydrogen not generated, 47.7 kWh ($\eta_{electrolyser,mean} = 70.24\ \%LHV$) of electricity could be sold instead. Assuming that electricity is sold at average spot price and that taxes and transmission fee is saved, around 21.1 KSEK could be saved each year. This option would be more economical than burning the hydrogen but does instead require some sort of predictive modelling to function in reality. The HRS would have to know in advance that it has enough hydrogen to make it through the rest of the winter, currently the model does not include such a feature.

A third option is to use the hydrogen and fuel cell as back-up for power shortages. If there was to be a black-out on the island the fuel cell could supply essential services with power until main electricity was restored. Depending on the needs it could be required to upgrade the fuel cell, but there are examples in telecommunication were a 2 kW fuel cell is sufficient [33]. This approach seems the most realistic, however it was not possible to assign a definite economic value to it.

### 3c): Importing Hydrogen

It was stated as a requirement that the station must be entirely self-sufficient. As a result the station ended up being severely redundant most years in order to be capable of handling years of less favorable solar conditions. While connecting the HRS to the grid might not be an option, it could be possible to simply buy and import commercial hydrogen from vendors when required. This could allow for a smaller and cheaper HRS-Design with less storage. The required hydrogen import can be estimated by measuring the required grid power and calculating the equivalent amount of hydrogen of the grid power used. It is assumed that 47.7 kWh of grid power is equal to 1kg of hydrogen import. For a main storage size of 1000 kg and all other parameters unchanged from the finalized design, the following was received.

On average, 195 kg H2/year would have to be imported, but the standard deviation (209.36 kg H2/year) is quite large. Some years no import at all is required, some years more than double of

Table 6.18.: Importing Hydrogen, ($\Delta t_{max} = 0.01$)

| **Year** | **Grid** | **Eq. H2 [kg]** | **Import Cost [KSEK]** |
|---|---|---|---|
| 2010 | 0 | 0 | 0 |
| 2011 | 0 | 0 | 0 |
| 2012 | 0 | 0 | 0 |
| 2013 | 27.78 | 571.85 | 22.87 |
| 2014 | 14.28 | 299.39 | 11.98 |
| 2015 | 18.05 | 378.45 | 15.14 |
| 2016 | 5.52 | 115.63 | 4.63 |
| **Mean** | 9.31 | 195.09 | 7.80 |

the mean is required. 98.0 % of all hydrogen can still be considered as green. With this method it is possible to significantly reduce the LCOH, combined with energy utilization the LCOH can be reduced further. (A retail price of 40 SEK/kg H2 is was assumed)

Table 6.19.: LCOH for multiple increased energy utilization

| **LCOH [SEK/kg H2]** | | | |
|---|---|---|---|
| **Discount Rate [%]** | **Lifetime [Years]** | **Import only** | **Import + 50 % Electricity** |
| 2 | 20 | 230.65 | 217.04 |
| 4.5 | 20 | 271.46 | 257.85 |
| 7 | 20 | 317.55 | 303.93 |
| 2 | 30 | 177.52 | 163.90 |
| 4.5 | 30 | 223.59 | 209.97 |
| 7 | 30 | 276.04 | 262.43 |

#### Study 3: Summary - Conclusion

The different improvements/variants can significantly reduce the LCOH for the HRS, although not enough to make it fully cost-competitive.

It should be noted that the target set for cost-competitiveness is based on broader studies and does not take the specific circumstances of the island into account. It may very well be so that a higher price is acceptable for buses on an isolated island compared with an urban environment. Similarly, some of the benefits such as the HRS ability to provide the island with electricity and heat can only truly be evaluated in context. For this study it was assumed that electricity and heat on the island is as accessible and valuable as anywhere else in the region. Although it could be for instance that due to the limited capacity of the underwater cable to the island, electricity is more scarce and thus its value higher, similarly goes for heat.

### 6.3.4. Study 4: Solar Power Park Alternative

The local authorities on the island also consider an option to build a solar power park on the island to deal with its capacity limitations, 10 MW of solar panels are planned. The local authorities want to investigate the option of building the HRS in combination with this park instead of building the HRS separately. The location of the solar park and HRS remain the same as previously.

#### 4a): Design

The following modifications were made from the previous design: It was found that while the storage of 100 kg was sufficient most of the time, on average 64.1 kg H2 would have to be imported per year (or it can be produced with grid power as the solar park would be grid connected), still leaving 99.4 % of the hydrogen dispensed as solar produced.

Table 6.20.: Solar Park HRS design modifications

| | |
|---|---|
| Solar Panels | (10 MW) Solar Park |
| Electrolyser | 125 kW + 125 kW |
| Main Storage | 100 kg |
| Comp. Low P. | 8 kW |

#### 4b) Cost & LCOH

When analysing the design with solar data from 2010 until 2016 it was found that the park would on average produce 9407.3 MWh/year and that the HRS would consume 605.5 MWh/year. Compared to not having the HRS this results in a 6.44 % total decrease of energy output for the solar park and is equal to 245.5 KSEK in lost revenue per year assuming that the electricity is sold at an average price of 0.4055 SEK/kWh(Avg Spotprice for Nordpool SE3 2019). The

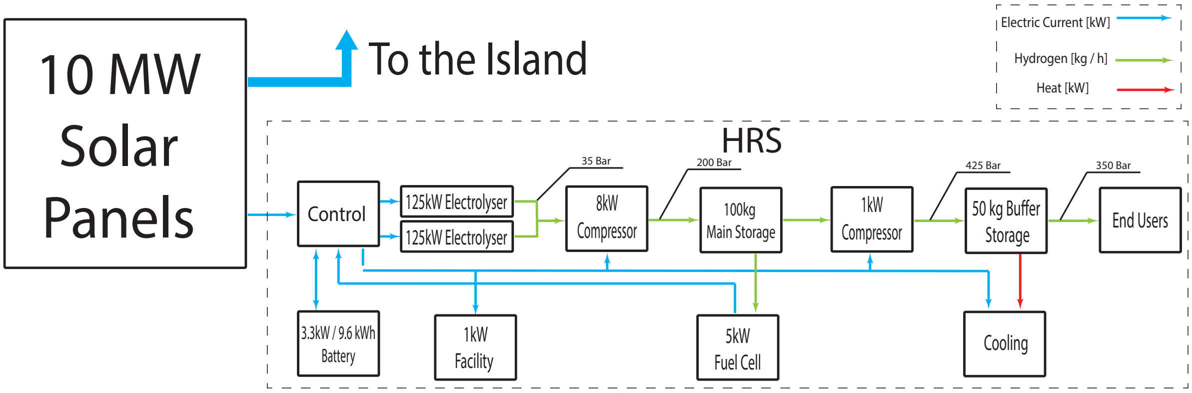


Figure 6.7.: Solar Park with HRS

revenue loss was added as an operational cost to the HRS. The new HRS design has a capital investment cost of 6522.9 KSEK and an operational cost of 401.93 KSEK/year. The annual cost of importing hydrogen, 2.56 KSEK/year (at 40 SEK/kg H2) was also added to the operational cost. The following LCOH was recieved:

Table 6.21.: LCOH Solar Park HRS ($\Delta t_{max} = 0.01$)

| Discount rate [%] | Lifetime [year] | LCOH [SEK/kg H2] |
|---|---|---|
| 2 | 20 | 81.64 |
| 4.5 | 20 | 89.00 |
| 7 | 20 | 97.49 |
| 2 | 30 | 68.90 |
| 4.5 | 30 | 78.00 |
| 7 | 30 | 88.26 |

The station does not generate any excess solar power anymore as this function now has been transferred to the solar park and heat generation is significantly reduced due to the reduction electrolyser capacity. As a result the HRS is now unable to provide much additional services other than the ability to act as a small power back-up during the summer months when the storage is high.

#### Study 4: Summary - Conclusion

This type of HRS implementation seems to be the most viable of all types compared so far. It does however assume that the solar park was going to be built either way and that the HRS does not cause any significant problems for the solar park. In this case the HRS would overall consume 6.44 % of the solar parks total power output, but up to 30 % of the solar parks power output was reduced due to the HRS in the winter.

# 7. Analysis

## 7.1. Commercial HRS

While it technically is possible for the HRS to reach commercial viability it only does so at a high user demand, at least 10000 kg H2/year or more. This corresponds to roughly 5 or more customers per day, this number does not seem very high when compared for regular petrol stations, but one must consider that the use of FCEV's is currently not that widespread in Sweden. While no figures could be found for total FCEV's in Sweden, the city of Mariestad, which case 1 is based on, has 15 FCEV's owned by the municipality and some owned privately by local citizens [40]. Roughly 85 private FCEV's all using only the same HRS would be required to reach the required user demand of 10000 kg H2/year. However, cars that are used for commercial purposes such as taxis have a higher daily mileage and consume more fuel per vehicle. If all cars were taxis, only around 17 cars would be required to reach the 10000 kg H2/year.

But the true challenge for the economic viability of commercial HRS's is to find a way to "survive" through the times of low user demand, as stated in the introduction. The possibility that a HRS would be economically viable at very low user demands seems unlikely, although the studies have shown that under such circumstances, measures can be made to at least marginally increase the economic viability.

The non-solar option was cheaper overall than its solar counterpart but not by much. If a non-solar and grid based solution is to be seen as the baseline, solar panels can be seen as a cost effective way of reducing grid use and therefor increasing the environmental friendliness of the HRS. It should also be considered that in this case, the price of solar panels was relatively high by international standards [18] and a higher economic compensation for selling electricity could be possible also.

#### Recap

- High user demand is required for economic viability.
- Grid use can be decreased at lower user demands with energy storage but diminishing returns apply.
- At low user demands the HRS can act as a producer of electricity.
- To reach economic viability it is better to decrease fixed costs than non-fixed costs, storage should be kept to a minimum.
- It is not possible for the HRS to be economically viable without using large amounts of grid power.

## 7.2. Island HRS

The island illustrates a case were all the circumstances are just right to justify an off-grid Solar-HRS. Despite this the costs were still very high. Due to the uncertainty of solar power large investments in redundancy must be made to achieve self-sufficiency. As illustrated by 6.3.3 if only 2% of all hydrogen sold would be allowed to be imported, the LCOH can be reduced by 15%.

Due to the inherent redundancy of the off-grid HRS concept, many resources are often left unused (such as excess hydrogen and solar power). These resources can indeed be useful and provide significant revenue to the HRS, boosting its economic viability. But even with far better than realistic utilization of these resources the HRS fails to be economically viable. A case could be imagined where an isolated environment where a Solar-HRS serves as a "multipurpose energy hub" by being a core provider of both electricity, heat and fuel, rather than just a single fueling station. It should also be noted again (6.3.3), that the standard for "economic viability" is measured by urban/common standards, and not the specific standards of the island. It may very well be that in praxis a higher price for heat, electricity and public transportation is acceptable for an isolated environment like the island, this should in theory increase the economic viability of the particular HRS.

#### Recap

- The HRS fails to be economically viable by the common standards for petrol based buses in urban environments.
- The HRS can provide the island with useful utilities such as heat and electricity.
- By proving utilities to the island the can increase its economic viability significantly.
- Designing for redundancy quickly becomes expensive, a less redundant design with additional support when necessary is better.
- Carefully designing and choosing components after the circumstances goes a long way in improving economic viability of the HRS.
- In winter the performance of the station is highly sensitive to solar radiation, meaning that some winters the HRS is "very expensive" while others its is cheaper.

## 7.3. Solar Park - Island HRS

The solar park case illustrates so far the most viable implementation of a solar powered HRS, although it should be noted that the case is rather a solar park with an HRS than an independent Solar-HRS. The case had a very advantageous user demand where demand was high in summer and low in winter, which clearly contributes positively towards the economic viability. A very favorable user demand like that should probably not be considered to be the norm, but also not entirely impossible for certain locations. It also seems unlikely (but not impossible) that an island would have the physical space to spare for a 10 MWp solar park. Specifically for Sweden also large solar parks are rare, as of February 2020 Sweden's largest solar park is of 5.8 MWp. However larger parks (up to 20 MWp) are planned[41]. Other European countries such as Germany also plan (and already have some) much larger parks (100+ MWp) [42].

Thus while this very specific case seems unlikely, the general idea of building a small HRS in combination with a larger solar park is not. Large solar parks already exist and more are planned, and if there is a need for public transportation or road traffic nearby the establishment of a HRS seems viable. The same principle could likely be applied to large wind farms too. It should also be noted that it is likely that the specific implementation of the HRS in relation to the solar park is important, in this specific case it was expected that the HRS would not have to pay energy tax and transmission fees for the electricity it used from the solar park, as the HRS was considered as a part of the solar park and not as a customer.

In this case, the HRS manages to deliver 99.4 % of its hydrogen as solar produced while at the same time being close to cost competitive by urban standards. It only reduces the overall output of the solar park overall by 6.44 % (but up to 30 % in winter), however for larger solar parks in relation to the HRS this impact can be expected to be even less significant.

#### Recap

- The HRS comes close to being economically viable by urban bus standards, while being essentially entirely solar powered (99.4 %).
- If the solar park is sufficiently large in relation to the HRS there is no significant loss in performance for the solar park.
- The case does require specific circumstances which may be somewhat uncommon but not unrealistic.
- The HRS has little/no ability to provide other utilities.
- It seems plausible that similar real world implementations could be economically viable.

## 7.4. Selected Components

The studies have revealed some key-insights in how the choice of some the HRS-components should be thought about.

### 7.4.1. Energy Storage

Energy storage of some sort is mandatory for “off-grid” solutions, but it was also found that even for grid-based solution energy storage can be advantageous. Both batteries and fuel cells can be economical solutions, provided that there is sufficient solar power. However for the presented cases, neither solution did much for the overall economics of the case. It was also found that the specific choice and implementation of energy storage can have a large impact on the performance and by extend economics of the HRS. It is likely that in a real implementation, more sophisticated means of control would be used, further improving the performance and consistency of the HRS.

While not discussed in any study, there also is room for improvement by demand-side management. In figure 6.1 it can be seen that the high pressure compressor starts compressing as soon as there is room for it in the buffer storage, this causes an increase in power demand which the fuel cell has to supply, causing it to consume more hydrogen. A more sophisticated implementation could wait with running the compressor until the sun rises and run directly on solar power instead, which is more efficient.

Both the battery and fuel cell have distinct advantages and disadvantages. The battery seems to be good at supplying the station day-to-day, but fails when there is a prolonged period of little to no sun available. For grid based solutions this is no major problem, but for off-grid solutions it becomes a problem. In such cases, it seems the most likely that a fuel cell is the best solution, that can be used once the battery is not sufficient anymore. If one would want to omit the fuel cell and only use batteries, a problem of redundancy is encountered, similar to in case 2. Using case 2 as an example, a 36 kWh battery is in theory enough to supply the HRS day-to-day, which it also can do most of the time. But just one day with insufficient solar power creates problems. In the 2014 data for example, there is in December two days in succession with little to no sun, in turn raising the storage requirement for the battery almost threefold. It should also be considered that the fuel cell also can provide other useful utilities, as discussed previously.
Whilst being useful for back-up power, the fuel cell is worse and less efficient at providing day-to-day power than the battery. The electrical round-trip-efficiency for the fuel cell is significantly lower than for the battery, as it requires solar power to be converted into hydrogen, that hydrogen to be stored and then converted back into electricity. Also, the fuel cell requires there to be excess hydrogen in the storage, something that so far has been proven to be costly but sometimes unavoidable.

#### Recap

- The battery provides a good day-to-day coverage while the fuel cell is better at reliably providing occasional back-up power when needed.
- Energy storage, most likely in the form of a battery, can be cost-efficient for grid-based

solutions, under the right circumstances.

- For off-grid solutions, a good balance between the battery and fuel cell seems to be the best solution.
- For solutions that would have excess hydrogen in the storage either way, a fuel cell can provide much utility relative to its cost.
- Choosing the right combination of energy storage is more important for off-grid solutions than for their grid based counterparts.
- It is suggested that demand-side power management can play a role, however it has not been fully investigated.
- Whilst being useful, energy storage is unlikely to be the factor which determines whether a HRS-solution is economically viable or not.

## 7.4.2. Electrolyser

In Case 2, Study 1e) it was shown how the particular choice of electrolyser can affect the overall efficiency of the HRS. By studying solar data, insight in how the choice of electrolyser matters is revealed. Hourly solar data for the location of case 2, years 2010 - 2016 was analysed.

The mean operating power for the panels was 23.3 % of nominal power, but only 18 % of the total energy was produced at this or lower powers. While it is more common for the solar panels to operate at low power, the total energy they produce is more evenly spread across the entire range. This suggests that it is important to have an electrolyser that can capture both high and low power well. Below a short study can be found on the influence of the the electrolysers minimum operational power.

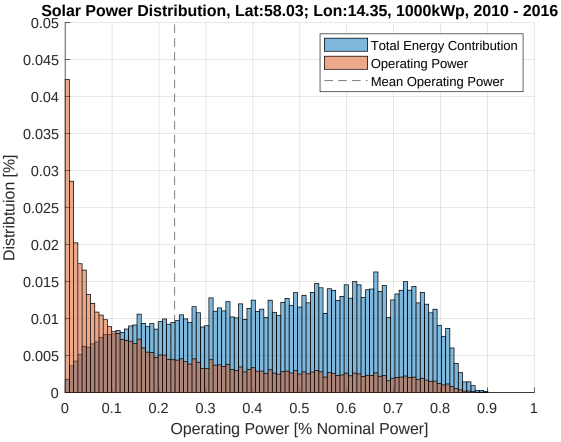


Figure 7.4.2: Distribution of Solar Power

Table 7.1.: Electrolyser Energy Utilization

| **Input** | | $P_{EL,min}[kW]$ | $E_{Electrolyser,tot}/E_{Solar,tot}$ |
|---|---|---|---|
| Solar Panels: | 500 kWp | 0 | 1.000 |
| Location: | Lat: 58.03; Lon: 14.35 | 12.5 | 0.991 |
| Data: | PVGis - SARAH (2010 - 2016) | 25 | 0.976 |
| Electrolyser: | 500 kW | 50 | 0.936 |
| Storage | Infinite | 100 | 0.8374 |

By decreasing the minimum operational power, the electrolyser is able to access more energy in total, increasing its total output, however the returns diminish after a certain point. Another important aspect not showcased in the data above, is that when hydrogen is low and access to solar power is the most critical (winter time), solar power will most often only be available at low power. This further reinforces the importance of choosing electrolysers in a manner that allows the utilization of low powers. In the model no additional cost associated to lowering the minimum operational power exist and can therefor only be regarded as an improvement.

As for the electrolyser capacity, a larger electrolyser will be able to produce more hydrogen, but will also cost more. Larger electrolysers will also require a larger low pressure compressor, further increasing costs and power demand. For applications were only solar power may be used, it is not sensible to use a capacity larger than 90 % of the installed solar capacity, as shown in the data.
Finding precisely what electrolyser combination and capacity is optimal for a given situation must be done through experimentation, however it can be shown that the minimum cumulative capacity for a given user demand must be:

$$CAPACITY_{min} = \frac{\eta_{electrolyser,mean}}{LHV_{H2}} \cdot \frac{User\ Demand}{365 \cdot 24} \tag{7.1}$$

If the cumulative electrolyser capacity is any less than this, the given user demand could not be met even if the electrolysers were to operate at full capacity year-round. If it is desired that the electrolyser should run entirely on solar power, the capacity must at least be doubled, since the available operational hours per day are decreased from 24 to 12 on average.

$$CAPACITY_{min,SolarOnly} = \frac{\eta_{electrolyser,mean}}{LHV_{H2}} \cdot \frac{User\ Demand}{365 \cdot 12} \tag{7.2}$$

Case 2, Study 1e) 6.3.1 found that a combination between a smaller and larger electrolyser gave a good mix between being able to access lower powers while also retaining the capacity to meet the demands.

At face value, the one small - one large type solution seems well suited for applications were the available operational power can be expected to vary. However the model does not take into account many of the practical complications that may arise from such a solution. The small increased benefit from using parallel electrolysers may not justify the additional complexity and potential costs they would cause in reality.

### Recap

- The electrolysers should operate well even at low and high power.
- In theory, using two smaller, or one small, and one mid-sized, is often better than using one large electrolyser.
- User Demand dictates the cumulative electrolyser capacity.
- If one wishes to operate the electrolyser(s) entirely on solar power, the capacity demands are increased significantly.

### 7.4.3. Main Hydrogen Storage

All results indicate that the storage should be kept as small as possible at all times. A larger storage does increase the potential and usefulness of the solar resource, and it is required for off-grid solutions that the storage is large, although any advantage associated by increasing storage size is unable to pay itself of. A larger storage increases redundancy and makes the HRS safer to deliver hydrogen even for days where there is little sun, however, compared to other options, increasing the storage is a very expensive way of increasing redundancy. Case 2 showed that it often can be smarter to look for other options, such as increasing the solar capacity or allowing the import of hydrogen when necessary. The study in 6.3.3, shows that by allowing a small The model is heavily biased due to the high cost associated with it. Chapter 9.1 shows that the actual cost of storage may differ in reality, suggesting that other outcomes are possible. Other technology options for storage that the model doesn't consider, such as geological or liquid storage, may also provide a different perspective, now or in the future.

In reality storage is also met by the constrain of physical space and legal regulations, which the model has not considered. Local prerequisites are in reality likely to be a large contribution towards the choice of storage capacity and type.

#### Recap

- Storage is expensive and should be kept to an absolute minimum.
- Increasing storage capacity improves redundancy and increases overall efficiency of the HRS, but other options are likely more cost efficient.
- The model is biased against large storage, other studies may find different results.

# 8. Summary of Results

The goal has been to investigate how a Solar-HRS can be made to be economically viable. The method used to answer this question has been to calculate what an optimal design could look like for the given situation. In addition to this it was then investigated if it is possible for the HRS to increase its revenue by providing some different utilities.

All investigations and their emerging results are specific to the case that they appear in. This section summarizes the results from chapter 5, 6 and 7 and how they can be applied to a broader context.

## 8.1. Viability of Additional Revenue Sources for a Solar-HRS

Several options for additional revenue were presented in section 4.2.3. The utilities of FCR, gas-grid injection and industrial applications were not included in any case as they were deemed either unlikely to be useful or heavily dependant on preexisting conditions.

Table 8.1.: Summary of Additional Revenue Sources

| Utility | Technical Feasability | Economic Value |
|---|---|---|
| Selling Electricity | **High** - Selling Electricity from solar panels is a proven method | **Mid - High** - The economic compensation is heavily affected by laws and regulations. |
| FCR | **Low** - The capacity requirements are not suitable for a single HRS. | **Uncertain** - Prices will vary and are difficult to predict. |
| Back-up Power | **Mid - High** - Is a proven method. Capacity requirements are suitable for some applications. | **Uncertain** - Is not always very useful. Also not much information could be found about prices. |
| Heat | **Mid** - Is proven to be possible, but is not common | **Low** - The economic compensation is small at best, usefulness depends. Would require additional investment. |
| Industrial Applications | **Mid** - Is proven to be possible, but depends on preexisting conditions. | **Low** - Prices are low. Depends on preexisting industry |
| Gas-Grid Injection | **Low - Mid** - Is proven to be possible, but depends on preexisting conditions. | **Low** - Prices are low. Depends on preexisting infrastructure. |

## 8.2. Viability Solar-HRS concepts

Three different Solar-HRS design concepts have been investigated, commercial (on-grid), island (off-grid) and solar-park.

Table 8.2.: Viability of Solar-HRS concepts

| **Concept** | **Suitable Application(s)** | **Aspects to consider:** |
|---|---|---|
| On-grid | Anywhere with large amounts of traffic.<br>Requires heavy grid use to be possible. | Requires high user demand to be viable.<br>Can provide some utility if user demand is low.<br>Only partially solar powered. |
| Off-grid | Where grid use is restricted or where independence is highly valued. | Very expensive to make 100% independent.<br>Fully solar powered.<br>High potential in utility. |
| Solar-Park | At very large solar parks | Most cost-competitive concept.<br>Fully solar powered.(99+ %)<br>Provides almost no other utility.<br>Applications are more scarce. |

## 8.3. Key Insights on Solar-HRS design

Some insight on the componenets of Hydrogen Storage, Electrolyser and Energy Storage was gained.

**Hydrogen Storage** Carries a very large cost in comparison to its usefulness. A small amount of storage capacity (around 100kg in these cases) is required for the HRS to function. Any capacity above that limit will let the HRS be less grid-dependant, up to a limit. All studies found that keeping storage as low as possible is always the most economical decision, however this does potentially come at the expense of increasing the use of non-environmentally friendly electricity or hydrogen, making the point of a Solar-HRS somewhat moot. Any operator of a Solar-HRS should in advance consider to what degree they wish the HRS to be solar powered and how much grid use is acceptable.

**Electrolyser** An electrolyser with a large operational range will increase the amount of solar power it can utilize, this is important for applications that are highly solar dependant. For applications with grid power the minimum operational power is less important as grid power can be used to reach the threshold. Carries some cost, but choosing electrolyser right can enable the reduction of storage, which is often a more significant cost.

**Energy Storage** For grid connected solutions some energy storage (such as a battery) can indeed reduce grid use and save costs, but with diminishing returns. For off-grid solutions energy storage is no longer optional, a synergy between short-time and long-time storage seems to be a good solution but is not verified to be the best possible option.

## 8.4. Influence of External Factors

A stated goal of the thesis was to gain understanding of how external factors influence the behavior and performance of the HRS. The two main external factors can be considered to be solar radiation and user demand. A third external factor could be considered the pricing of electricity and components.

**Solar Radiation** Solar radiation plays an important role for a Solar-HRS, particularly the amount of solar radiation received in the winter months can have pronounced effects on overall costs. For a grid based design such as in Case 1 a dark winter will cause an increase in grid use and increased costs. This cost is however not as large as it is for off-grid stations were dark winters make it so that expensive investments into redundancy have to be made. The distribution of solar radiation also matters for the choice of electrolyser.

**User Demand** It is difficult for any HRS to be profitable at low user demands. User demand has been found to be perhaps the largest factor when designing the HRS. What the expected user demand is sets the direction for how solar panels, electrolyser, storage and more should be dimensioned.

**Pricing** Cost is the metric by which the “successfulness” of the HRS is measured. 5.3.5 goes into how the modification of electricity and component prices can change what is considered a better Solar-HRS design. The pricing used in the model is based on present conditions, when Solar-HRS are built in the future those prices will likely have changed. This topic is further elaborated in the discussion below 9.1.

# 9. Discussion

As always there is a gap between reality and theory, which has already been touched upon a few times in previous chapters. In the discussion further such disparities and their consequences are brought to light.

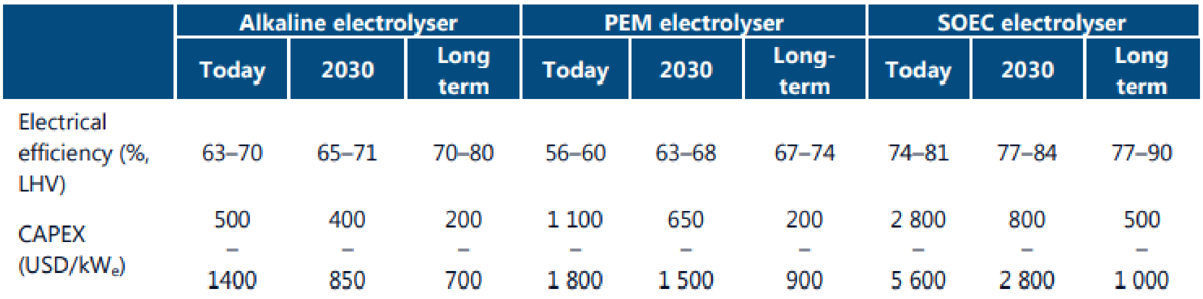
## 9.1. Cost Analysis

The model used a singular cost scheme based on reliable sources, the model assumed that those costs would remain relatively unchanged over the 20-30 years lifetime of HRS. The particular cost scheme used was chosen on the merit that it was consistent and current (2019) but the literature study also found many other different prices and cost estimations from a range of credible sources. Also some manufacturers of batteries, fuel cells, compressors and electrolyser were reached out to for price quotes that could have been used for benchmarking, however none of the contacted were willing to give a quote.

It must therefor be stated that the results of previous studies may differ from other similar studies or real-life examples. It should also be noted that many sources expect a price reduction and performance increase of essential components such as electrolysers, storage, battery and fuel cells within the foreseeable future of 10 years. This should have significant implications towards the lifetime economy of the HRS. In table 9.1 some examples of varieties in cost of electrolyser and storage are listed.

| Source | Electrolyser [SEK/kW] | Storage [SEK/kg] |
|---|---|---|
| [1] Tractebel, P2H | 8000 - 12600 | 5000 |
| [43] NREL, Hydrogen Station Compression... | - | 6500 |
| [8] IEA, The future of hydrogen | 4500 - 12500 | - |
| [44] CSIRO, National Hydrogen... | 9000 - 12000 | 9200 - 9700 |
| [29] NREL, Energy Storage, Days of Service... | 6600 | 10000 |

Table 9.1.: Example of Cost Variations for Electrolyser and Storage



| | Alkaline electrolyser | | | PEM electrolyser | | | SOEC electrolyser | | |
|---|---|---|---|---|---|---|---|---|---|
| | Today | 2030 | Long term | Today | 2030 | Long-term | Today | 2030 | Long term |
| Electrical efficiency (%, LHV) | 63–70 | 65–71 | 70–80 | 56–60 | 63–68 | 67–74 | 74–81 | 77–84 | 77–90 |
| CAPEX (USD/kW$_e$) | 500 – 1400 | 400 – 850 | 200 – 700 | 1 100 – 1 800 | 650 – 1 500 | 200 – 900 | 2 800 – 5 600 | 800 – 2 800 | 500 – 1 000 |

Figure 9.1.: Excerpt from [8], IEA - Future of Hydrogen (2019)

The thesis found that the price of electricity is a less important factor towards total costs than the component cost themselves, but it should not be understated that significant yet difficult to predict fluctuations in the price of electricity could be possible within the foreseeable future.

#### Discount rate and Lifetime

Previous results from both cases show that the choice of lifetime and discount rate can have a large influence over the LCOH. Choice of discount rate and lifetime have a significant impact for investments with high upfront investment costs and low operational costs. In the original Island case 6.3.2 the investment costs are high and the operational costs are low, as a result when going from a lifetime of 20 to 30 years the LCOH can be reduced by 12 - 22 %, changing the discount rate from 2 % to 7 % may increase the LCOH 38 - 55 %. For comparison, in the solar park case 6.3.4 where investment costs are reduced and operational increased, performing the same changes as previously will only change the LCOH by 8 - 15 % and 15 - 21 % respectively. In reality, lifetime and discount rate for a given project are often determined by a company based on their expectations and experience with a given or similar projects, the case for HRS's currently is as they are relatively new and emerging technology, as made example by the fact that 67 of the 87 (71 %) active commercial HRS's in Germany have been built since February 2017 [45].

#### Disclaimer

The research focus has been towards gaining better understanding of how a solar powered HRS can be designed and understanding how it functions. For this purpose assigning economic costs and values to different figures helps to form a clearer picture of what is an efficient solution and what is not. While it does in the present a final economic measurement in the form of an LCOH, this measurement should not be considered as absolute, for the reasons mentioned previously. All economic figures presented in the thesis should be considered as indicative but not representative of actual costs.

## 9.2. Environmental Impact

The focus of this thesis has been on the technical and economical aspects of building and designing a solar powered HRS. One must remind him/herself that the primary purpose of such a HRS should be to provide a fossil free and environmentally friendly transportation alternative. Therefor realistically one should try to consider and measure the environmental impact of such an HRS. This has not been done in this thesis. To fully understand the environmental impact of the HRS a full life-cycle analysis should be performed. Factors that could have a large contribution towards a negative environmental impact that have been encountered in the thesis is the use of grid power, import of commercial hydrogen and the emissions caused by producing and building the HRS and its components.

One good example present in the thesis the environmental trade-off of buying commercial hydrogen. Most hydrogen is currently produced through Steam Methane Reforming (which is a CO2 emitting process), importing hydrogen does therefor counteract the goal of fossil-free transportation. Although it could also in theory be entirely possible for the imported hydrogen to be produced as green (but likely at a somewhat higher price). The study "Assessment of Selected Hydrogen Supply Chains—Factors Determining the Overall GHG Emissions (2018)" [14] provides information on this topic but primarily in the context of Germany.

## 9.3. Locality

The scope of the thesis has been confined to Swedish conditions only. Many important factors for the economic viability of a Solar-HRS, such as price of components, access to solar power, price of electricity, laws and regulation, will vary from country to country. Due to its latitude Sweden experiences much longer days in the summer and and shorter days in the winter than countries closer to the equator. Sweden also has less solar radiation as a whole than said countries, further diminishing the usefulness of solar panels.

What is a good implementation of a Solar-HRS in a specific location in Sweden may not always translate well to other circumstances. The designs and implementations of Solar-HRS's that have been presented in the thesis should be regarded as examples and ideas, tailor-made for the specific circumstances, and not a template or golden rule for how a Solar-HRS should be built.

## 9.4. Compressor and Cooling Chain

Compression and cooling was included in the model but its effects were not as thoroughly investigated as for the other components. The modelling for compression and cooling is relatively simplistic and the cost carried by them is rather low impact when compared to the other components. In reality of course more thought and effort should be put into designing efficient and reliable compressor and cooling chains when building any type of HRS. For reading on this topic, look at the 2014 report "Hydrogen Station Compression, Storage and Dispensing Technical Status and Costs" by NREL [43].

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# A. Simulation Model Description

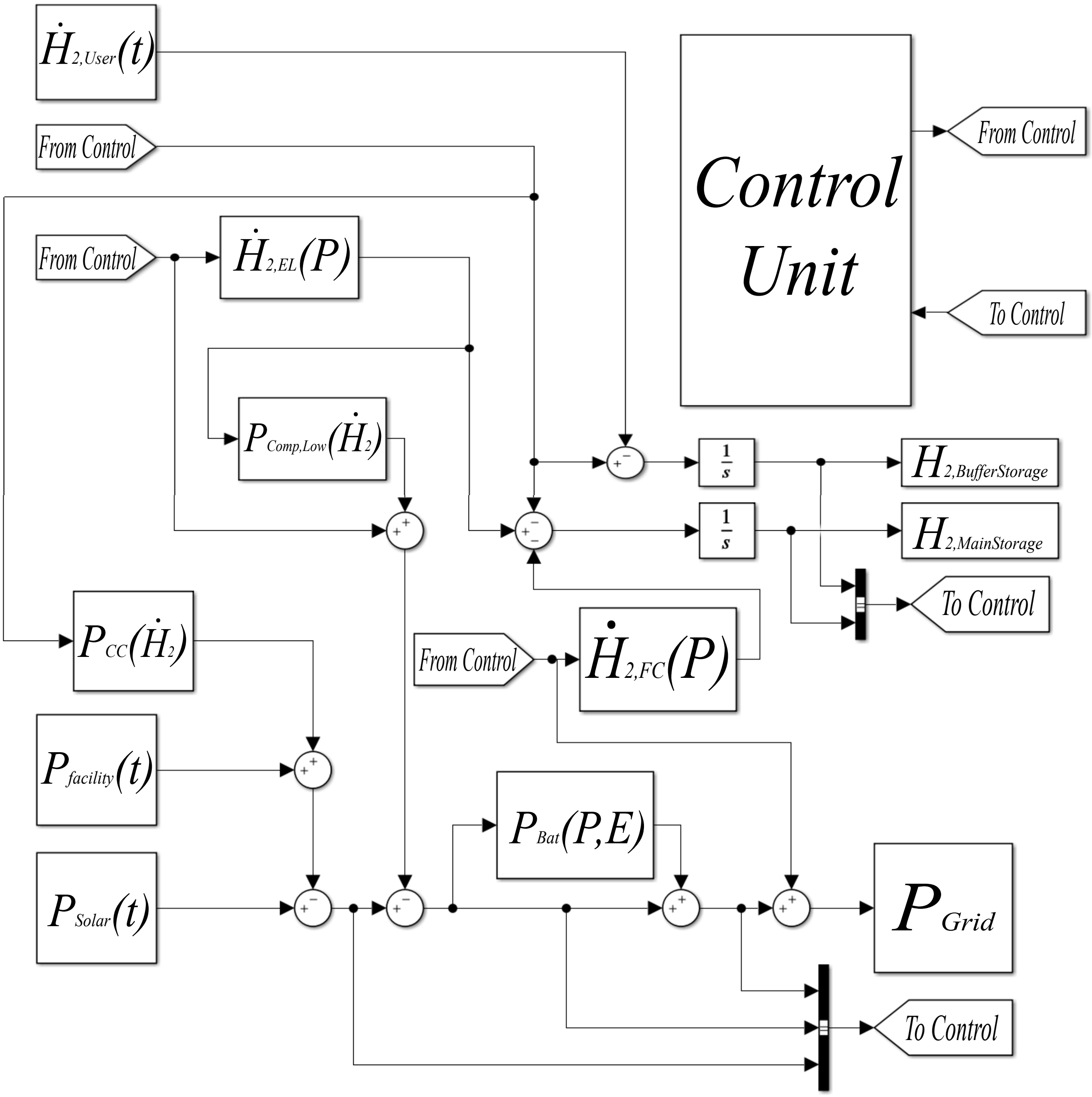


Figure A.1.: Priniciple Schematic Illustration of the HRS Model

Table A.1.: Functions and Variables in A.1

| **Functions:** | **Input** | **Output** |
|---|---|---|
| $P_{Solar}(t)$ - Solar Power | Time (h) | Power (kW) |
| $P_{facility}(t)$ - Facility Power | Time (h) | Power (kW) |
| $\dot{H}_{2,User}(t)$ - User Demand | Time (h) | Hydrogen flow (kg/h) |
| $\dot{H}_{2,EL}(P)$ - Electrolyser | Power (kW) | Hydrogen flow (kg/h) |
| $\dot{H}_{2,FC}(P)$ - Fuel Cell | Power (kW) | Hydrogen flow (kg/h) |
| $P_{CompLow}(\dot{H}_2)$ - Low P. Comp. | Hydrogen flow (kg/h) | Power (kW) |
| $P_{CC}(\dot{H}_2)$ - High P. Comp. & Cooling | Hydrogen flow (kg/h) | Power (kW) |
| $P_{Bat}(\dot{H}_2)$ - Battery & Cooling | Power (kW), Charge (kWh) | Power (kW) |
| **Variables:** | | |
| $H_{2,MainStorage}$ - Main Storage Hydrogen Level (kg) | | |
| $H_{2,BufferStorage}$ - Buffer Storage Hydrogen Level (kg) | | |
| $H_{2,P_{Grid}}$ - Grid Power (kW) | | |

### Overview

In this chapter follows are more detailed description of the simulation model. Each components function is described in detail here so that they can be replicated. The above illustration A.1 is a simplified representation for how the model was implemented in Simulink. It serves as a principle schematic for how the components interact and how the model is structured.

## A.1. Components

### A.1.1. Solar Panels

The solar panels supply the HRS with electric power $P_{solar}$. The online tool PVGIS - PV Performance Tool [19] is used to calculate the power production that the panels provide. PVGIS presents the data as hour-by-hour, linear interpolation is used for time-steps between full hours. PVGis will perform its calculation based on real collected data and uses the following parameters as input:

| |
|---|
| Latitude [decimal degrees] |
| Longitude [decimal degrees] |
| Elevation [m] |
| Radiation database |
| Slope [degrees] |
| Azimuth [degrees] |
| Nominal power [kWp] |
| PV Technology |
| System Loss [%] |

Table A.2.: PVGis - Input

### A.1.2. Electrolyser

The electrolyser uses electricity to split water into hydrogen and oxygen. The HRS model uses a generlised electrolyser model based on the functioning principles of real alkaline electrolyser [23],[23],[24].

#### Electrolyser Electrical Efficency Function

In reality the electrical efficiency of the electrolyser will depend on its operating conditions, such as temperature, pressure and power. However for simplicity it was decided that operating pressure and temperature would be treated as constant so that the efficiency will only depend on operating power. The efficency of the electrolyser is modeled based on information found in literature [23],[24]. The model uses a curve with tune-able parameters that approximates the real function for electrical efficiency:

$$\eta_{electrolyser,electrical} = C \cdot \frac{P^2}{A + P^2} \cdot \frac{1}{1 + B \cdot P} \tag{A.1}$$

Where:

$$P = \frac{P_{electrolyser}}{P_{electrolyser,rated}} \tag{A.2}$$

A, B and C are constants that can be used to calibrate the curve. A, B and C were chosen so that the curve would fit reasonably well with the chosen reference model HyProvide A-60 [25].

| **A** | **B** | **C** |
|---|---|---|
| $2.6980 \cdot 10^{-4}$ | $1.5194 \cdot 10^{-1}$ | $9.7828 \cdot 10^{-1}$ |

Table A.3.: Constants A,B and C

| $P$ [$\%P_{rated}$] | $\eta_{Datasheet}$ [-] | $\eta_{Model}$ [-] | Relative Error [-] |
|---|---|---|---|
| 0.25 | 0.9400 | 0.9385 | $0.0237 \cdot 10^{-4}$ |
| 0.50 | 0.9050 | 0.9083 | $0.1196 \cdot 10^{-4}$ |
| 1.00 | 0.8487 | 0.8490 | $0.0055 \cdot 10^{-4}$ |

Table A.4.: NOTE: In the datasheet the electrical efficiency was specified by the higher heating value (HHV), thus the HHV was used in place of the LHV

### Parallel Electrolysers

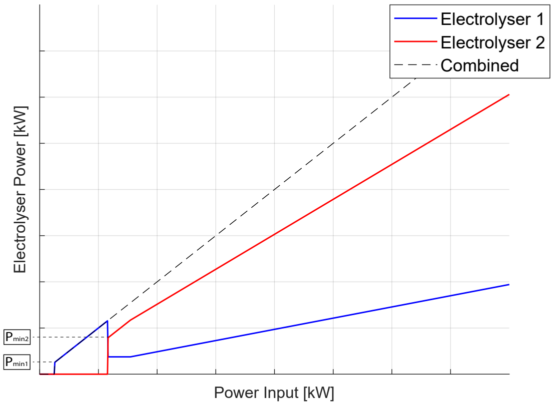
In Case 2, Study 1e) the option of implementing two electrolysers working in parallel was investigated. The following control-scheme was developed.

| $P_{in}$ | $P_{EL1}$ | $P_{EL2}$ |
|---|---|---|
| 0 - $P_{min1}$ | 0 | 0 |
| $P_{min1}$ - $\left(P_{min2} + P_{opt1}\right)$ | $P_{in}$ | 0 |
| $\left(P_{min2} + P_{opt1}\right)$ - $\left(P_{opt1} + P_{opt2}\right)$ | $P_{opt1}$ | $\left(P_{in} - P_{opt1}\right)$ |
| $\left(P_{opt1} + P_{opt2}\right)$ - $P_{rated1} + P_{rated2}$ | $k_1 \cdot P_{in}$ | $k_2 \cdot P_{in}$ |

Table A.5.: Control Scheme for power distribution for parallel electrolysers.

$$k_1 = \frac{P_{rated1}}{P_{rated1} + P_{rated2}}, \quad k_2 = \frac{P_{rated1}}{P_{rated1} + P_{rated2}} \tag{A.3}$$

The power divider does initially only provides power for the smaller eletrolyser (1). Once sufficient power is available electrolyser 1 will be throttled down and kept at optimal power to allow electrolyser 2 to start and ramp up. Once electrolyser 2 also has reached optimal operational power both electrolysers ramp up simultaneously as input power increases. At this point the electrolysers divide the input power in proportion to their capacity so that they reach nominal power simultaneously.



### A.1.3. Battery

The battery can be used to store electricity from the solar panels. The electricity can the discharge compliment the power demand at a later point or to even out load surges.

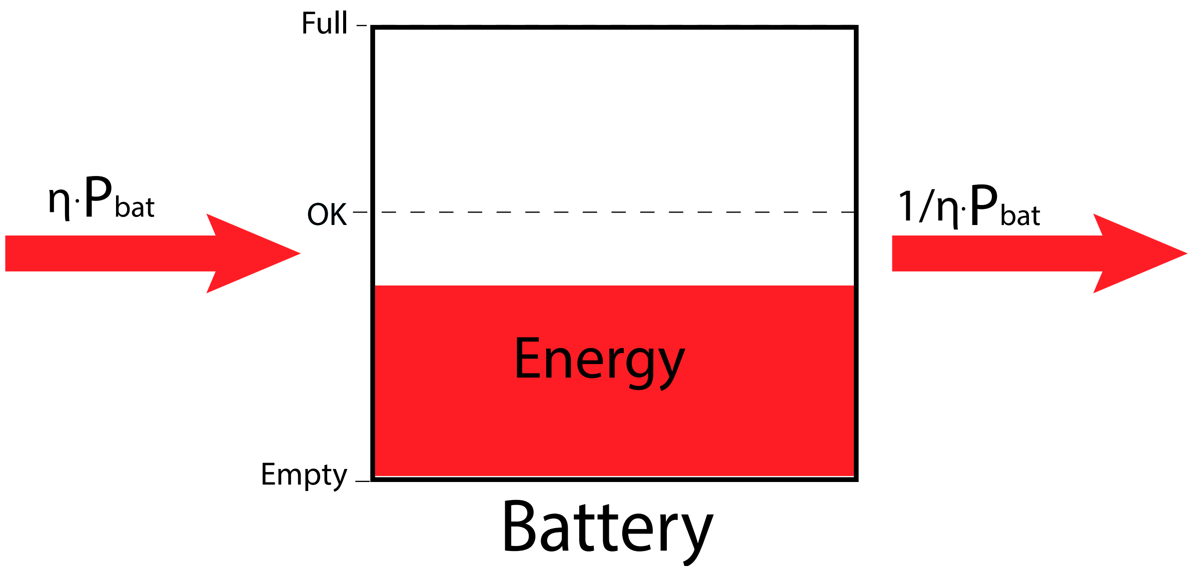


Figure A.2.: Battery function

#### Function

The battery can either draw from our input power into the system with power $P_{battery}$. Positive sign corresponds to drawing power from the system and charging the battery, negative to adding power to the system and discharging. The battery operates within the range: $-P_{battery,rated} < P_{battery} < P_{battery,rated}$. When the battery is close to being full (90%) it reduces in how much power it can be charged by linearly, from rated power down to 0 for when the battery is full. Similarly, when it is close to being empty discharging behaves in a the same but opposite way. The behaviour is illustrated in fig A.1.3.

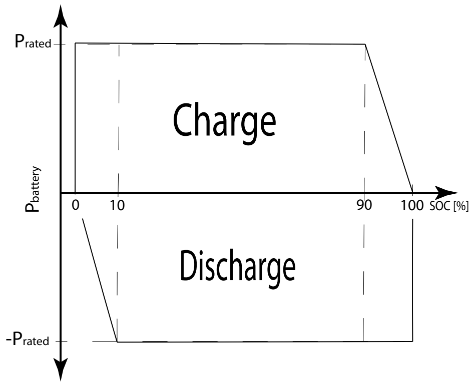


fig A.1.3

#### SOC - State of Charge

The state of charge in the battery $SOC$ is used to measure of how fully charged the battery is, it is defined as:

$$SOC = \frac{E_{battery}}{E_{battery,capacity}} \quad (A.4)$$

The state of charge compared to set threshold (empty or full) determines what state the battery $State_{battery}$ is in.

| **SOC** | $State_{battery}$ | The battery level is: |
|---|---|---|
| $SOC = 0$ | 0 | empty |
| $0 < SOC < 1$ | 1 | charged |
| $SOC = 1$ | 2 | full |

$State_{battery}$ is required for the control algorithms of the HRS to function, as explained in the chapter Operating Algorithms A.2.

### A.1.4. Hydrogen Storage(s)

The two hydrogen storage's serve two different purposes. The buffer storage is necessary for quick, easy and reliable refuelling. The main storage serves as a long time storage for hydrogen. They both function by the same principles.

#### SOH2 - State of Hydrogen

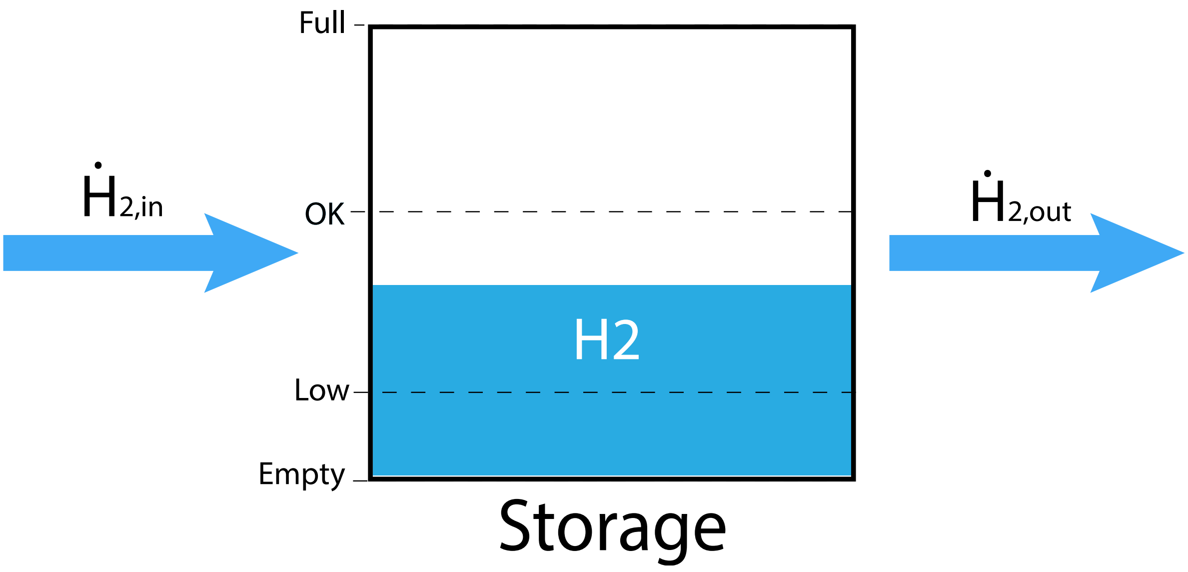


Figure A.3.: Storage function

For the main storage, the state of hydrogen is monitored. The state of hydrogen in the main storage $SOH2$ is used to measure how full the main storage is, it is defined as:

$$SOH2 = \frac{H_{2,storage}}{H_{2,storage,capacity}} \tag{A.5}$$

The state of hydrogen is compared to set thresholds (empty,low,ok and full) to determine what state the storage is in $State_{storage}$. How the thresholds are set will have a large impact HRS's ability to reliably deliver hydrogen. By default, $SOH2_{low}$ is set to equal one day of hydrogen consumption (or at least 5 % of the full storage), and $SOH2_{OK} = 2 \cdot SOH2_{low}$

| **SOH2** | $State_{storage}$ | The storage level is: |
|---|---|---|
| $SOH2 = 0$ | 0 | empty |
| $0 < SOH2 \leq SOH2_{Low}$ | 1 | low |
| $SOH2_{Low} < SOH2 \leq SOH2_{OK}$ | 2 | ok |
| $SOH2_{OK} < SOH2 < 1$ | 3 | high |
| $SOH2 = 1$ | 4 | full |

There is also the state $State_{FC}$ which determines if the fuel cell can be used or not.

| **SOH2** | $State_{FC}$ | The fuel cell can be used: |
|---|---|---|
| $SOH2 <= SOH2_{FC}$ | 0 | no |
| $SOH2_{FC} < SOH2$ | 1 | yes |

$State_{FC}$ and $State_{storage}$ are required for the control algorithms of the HRS to function, as explained in the chapter A.2.

### A.1.5. Fuel Cell

The fuel cell can use hydrogen from the main storage to produce electricity and heat when required. The fuel cell is modeled after a PEM fuel cell [46],[47].

#### Fuel Cell Electrical Efficiency Function

The fuel cell inputs Power $P_{FC}$ and Heat $Q_{FC}$ into the system and does so by consuming hydrogen from the main storage $\dot{H}2_{FC}$. The fuel cell is limited to operate with the range of $P_{FC,min}$ to $P_{FC,rated}$. The electrical efficiency of the fuel cell is modeled with a simple linear model as follows.

$$\eta_{FC,electrical} = m - k \cdot P \tag{A.6}$$

Where:

$$P = \frac{P_{FC}}{P_{FC,rated}} \tag{A.7}$$

The constants $m$ and $k$ were chosen so that the fuel cell would mimic realistic behaviour of a real fuel cell. Setting $m = 0.772$ and $k = 0.222$ makes the curve similar to ones found in literature [46].

### A.1.6. Physical Constants

All the physical constants were retrived from the book “Thermodynamics - An Engineering Approach” (7th edition) [6].

| | |
|---|---|
| $Cp$ | 14.307 kJ/kg K |
| $\gamma$ | 1.405 |
| $LHV_{H2}$ | 120000 kJ/ kg |
| $HHV_{H2}$ | 141800 kJ / kg |

Table A.6.: Physical Constants

### A.1.7. System States

The system state variables and thresholds introduced previously are summarized in this section.

#### SOC

The state of charge in the battery, it has no other predefined thresholds than “empty” (0) or “full” (1).

#### SOH2

The state of hydrogen in the main storage, it has a few thresholds:

| Threshold | Indication | Default Value |
|---|---|---|
| Empty | The storage is empty | 0 |
| $SOH2_{low}$ | The storage level is low | 0.05 |
| $SOH2_{OK}$ | The storage level is ok | 0.1 |
| Full | The storage is full | 1 |
| $SOH2_{FC}$ | Its ok to use the fuel cell | 0.2 |

Table A.7.: SOH2 Default Values

### A.1.8. User Demand

The user demand function used in the simulation model is calculated with an algorithm. The algorithm generates a user demand function $\dot{H}_{2,user}(t)$ for one year (for simulations spanning multiple year, the same function is simply repeated). This is done in advance of running the algorithm, so that the user demand is a timeseries that is loaded into the simulation as input. The user demand for both cars and buses are principally the same, but the algrotihm for cars has extra steps.

#### Car Algorithm

The car algorithm takes two inputs, user demand (Annual hydrogen demand as kg H2/year) and amount hydrogen per refill (size of the cars fuel tank as kg H2/use) and then calculates when the cars will refill based on the chevron profile.

First the algorithm calculates the annual refills as a whole number:

$$Annual\ Refills = floor\left(\frac{User\ Demand}{H2\ per\ Refill}\right) \tag{A.8}$$

Then the algorithm will distribute these refills evenly across the year so that there is about equally many refills per day. As not all numbers are evenly divisible by 365, the algorithm first makes sure to divide the annual refills as evenly as possible by dividing the annual refills over 365 with remainder.

$$\frac{Annual\ Refills}{365} = Daily\ Refills1, Remainder \tag{A.9}$$

Next the algorithm creates an array of length 365, one element for each day of the year. Each element of the array contains the value of $Daily\ Refills1$ as calculated previously. Below is an example of this array where the User Demand is 11000 kg H2/year and the hydrogen per refill is 5.4 kg H2/use.

$Refills\ per\ day$ =

| Index | 1 | 2 | 3 | 4 | 5 | 6 | 7 | ... | 365 |
|---|---|---|---|---|---|---|---|---|---|
| Value | 5 | 5 | 5 | 5 | 5 | 5 | 5 | ... | 5 |

The next step is to take the remainder a distribute it over the year. This is done by assigning one extra refill to a random day and repeating this $Remainder$ times.

**Algorithm 1** Pseudo code - Divide Remainder

```
for i = 1 to Remainder %For each refill in the remainder
    RndNbr = RandomInteger(1,365) %Assign a random day
    RefillsPerDay(RndNbr)++ %Increment the random day
end %repeat
```

After this step the previous array can now look something like this:

$Refills\ per\ day$ =

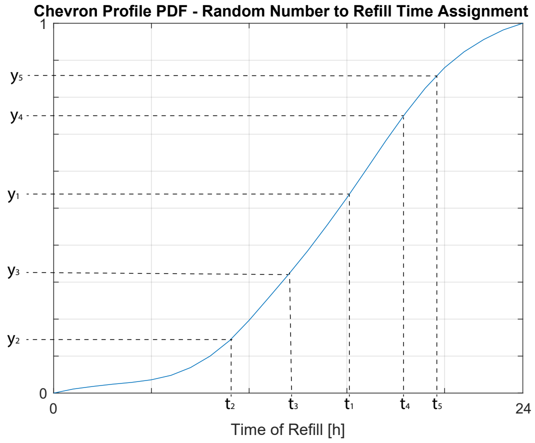
| Index | 1 | 2 | 3 | 4 | 5 | 6 | 7 | ... | 365 |
|---|---|---|---|---|---|---|---|---|---|
| Value | 5 | 5 | 6 | 5 | 6 | 5 | 7 | ... | 5 |

The array now has the property that:

$$\sum Refills\ per\ day = Annual\ refills \tag{A.10}$$

Now that is has been determined how many refills occur each day it is time to determine at what time of the day (00:00 to 24:00) they take place. This is what the chevron profile is used for. The algorithm calculates the refill times for each day, one day at time. For each refill in a day, a random number between 0 and 1 is generated, the inverse of the probability density function for the chevron profile is then used to assign this random number to a time between 0 and 24. The Chevron profile and its probability density function can be found in appendix B.3.

| Refill ($n$) | RndNbr ($y_n$) | Time [h] ($t_n$) |
|---|---|---|
| 1 | 0.514 | 15.06 |
| 2 | 0.146 | 9.21 |
| 3 | 0.321 | 12.30 |
| 4 | 0.754 | 16.83 |
| 5 | 0.867 | 19.52 |



(Example of assignment of refill time for one day)

Once the refill times for a day has been calculated the times are added to the complete list of refill times. The list of refill times is a list for all refills in a year (from 1 to $Annual\ refills$) and at what hour of the year that they occur (from 0 to 8760)

**Algorithm 2** Pseudo code - Calculate List of Refill Times

```
ListOfRefills(1) = 0 %The first entry must be zero
for i = 1 to 365 %For each day of the year
    n = RefillsPerDay(i) %Refills in day i
    for n = 1 to Refills %For each refill in a given day
        y = RandomBumber(0, 1) %Assign a random number between 0 and 1
        t(n) = $PDF^{-1}$(y) %Calculate Refill Time with the Chevron Profile
    end %repeat
    t = t + (i - 1)*24 %Add the hours of the day
    ListOfRefills.Append(t) %Add the times to the list
    clear t %If the next n is smaller than the current
end %repeat
ListOfRefills.Sort %Sort the list so that the refills are consecutive
```

Once the code has executed the list of refill times could look like the following example with $Annual\ Refills = 2037$ (Index is the n:th refill and Value is at what time it occurs):

(List of Refill Times)

| Index | 1 | 2 | 3 | ... | 1017 | 1018 | 1019 | ... | 2036 | 2037 | 2038 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Value | 0 | 6.23 | 8.12 | ... | 4388.12 | 4390.74 | 4392.22 | ... | 8745.12 | 8748.41 | 8751.29 |

Next step is to calculate the List of Fuel Use array which is an array that represents the cumulative fuel use from refilling, that is how much fuel in total should be dispensed to the cars. As an example, if 5.4 kg H2 is to be dispensed per refill, the fuel use i 0 after 0 refills, 5.4 after 1 refill, 10.8 after 2 refills etc. The last entry on the List of Fuel Use should be equal to (or very close to due to rounding) to the user demand.

(List of Fuel Use)

| Index | 1 | 2 | 3 | ... | 5486.4 | 5491.8 | 5497.2 | ... | 2036 | 2037 | 2038 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Value | 0 | 5.4 | 10.8 | ... | 4388.12 | 4390.74 | 4392.22 | ... | 10989.0 | 10994.4 | 10999.8 |

Now the array representing the cumulative user demand over time can be determined, in MATLAB this is done by declaring it as a timeseries object where the List of Fuel Use is the Data vector and and the List of Refill Times is the Time vector.

$$UserDemand_{sum}(t) = \text{timeseries(ListofFuelUse, ListofRefills)}$$

(Note: The interpolation method must set to “Zero-order hold” )

The timeseries $UserDemand_{sum}$ is in the units of hydrogen [kg H2] over time [h]. To obtain the user demand as a flow of hydrogen [kg H2/h] over time [h], the cumulative UserDemand is derived with respect to time. In Simulink this is done with through the numeric derivative block. A rate limiter block limiting the slew rate is added before the derivate block, this is to make it so that the user demand cant be higher than what the fuel pump is capable of, which is 50 kg/h.

$$\dot{H}_{2,user}(t) = \frac{\mathrm{d}}{\mathrm{d}t} UserDemand_{sum}(t) \tag{A.11}$$

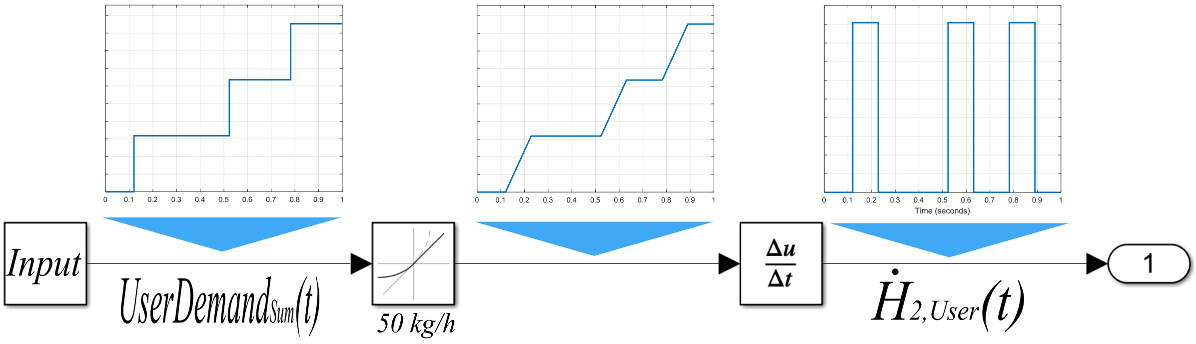
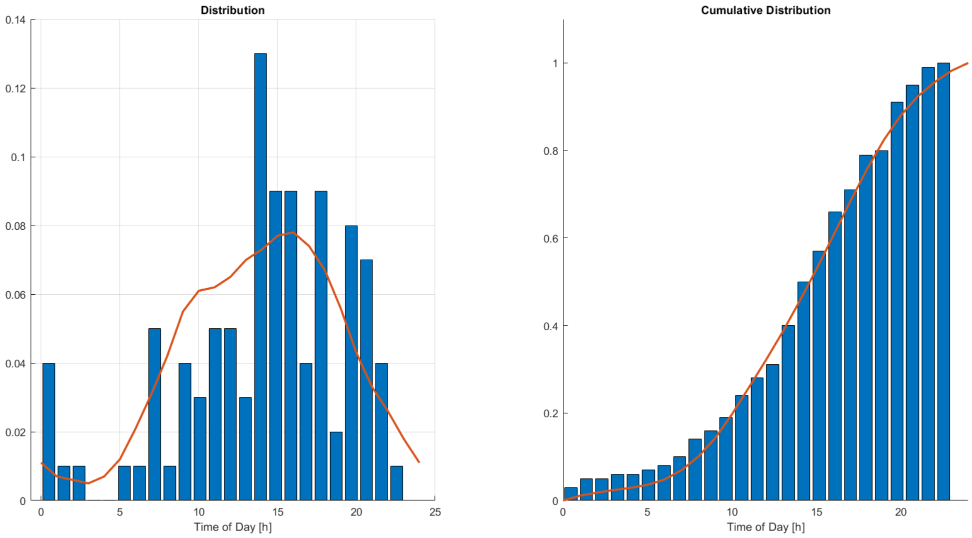


Figure A.4.: Use of rate limiter and numeric derivative block in Simulink


Distribution

Cumulative Distribution

Figure A.5.: Figure: Example of a day with 100 refills

The red line is the Chevron profile (As distribution to the left and cumulative distribution to the right) and the blue bars are the refills as generated by the algorithm, sorted by 1-hour bins.

### Bus Algorithm

The bus algorithm is in essence equal to the car algorithm, expect that the refill times are assigned directly instead of generated by random numbers and probability. For example, if it is said that there is one bus that refills at 07.00 every day and it refills with 16 kg H2/use, the resulting List of Refill Times and List of Fuel Use would be:

(List of Refill Times)

| Index | 1 | 2 | 3 | ... | 182 | 183 | 184 | ... | 364 | 365 | 366 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Value | 0 | 7 | 31 | ... | 4327 | 4351 | 4375 | ... | 8695 | 8719 | 8743 |

(List of Fuel Use)

| Index | 1 | 2 | 3 | ... | 182 | 183 | 184 | ... | 364 | 365 | 366 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Value | 0 | 16 | 32 | ... | 2896 | 2912 | 2936 | ... | 5792 | 5816 | 5840 |

Once the List of Refill Times and List of Fuel Use have been calculated the same steps are repeated as for the car algorithm.

## A.2. Operating Algorithms

The HRS executes a set of algorithms to ensure efficient operation. The model is structured in such a way that there is a main algorithm that dictates the flow and use of electric power within the system. Most of the algorithm is executed by the control unit. The control unit can control the flow of electric power to and from the electrolyser (and by extension the low pressure compressor), the battery and the fuel cell. The control unit can also controls the flow of power to the high pressure compressor and cooling, but it can not fully decide how it does so as this is controlled by the state of hydrogen in the buffer storage.

The algorithm uses measured and calculated states, to differentiate between the two, calcualted states are noteded with a hat, $\hat{P}$.

### A.2.1. Main Algorithm

The main algorithm works as a kind of "energy-budget", it will first measure how much disposable power in $\hat{P}_{balance1}$ there is by subtracting the uncontrollable power demands from how much solar power is available.

$$\hat{P}_{balance1} = P_{solar} - P_{facility} - P_{compHighP} - P_{cooling} \tag{A.12}$$

Next it will calculate what power the electrolyser should run at, it does so with its own separate algrotihm. It aims to utilize as much of the solar power as possible, while also making sure that the battery gets charged and that the storage remains at an acceptable level. When the power has been set it is subtracted from the balance. Since the electrolyser directly determines what power the low pressure compressor runs at this must also be included in this step.

$$\hat{P}_{balance2} = \hat{P}_{balance1} - P_{electrolyser} - P_{compLowP} \tag{A.13}$$

Then $P_{balance2}$ is fed to the battery. The battery has its own internal logic in order to match the power balance, the battery tries to bring the balance to 0. The battery power is then subtracted from the balance.

$$\hat{P}_{balance3} = \hat{P}_{balance2} - P_{battery} \tag{A.14}$$

If the battery couldn't match the power balance completely the fuel cell will attempt to fill in any remaining deficit. Finally this power will be subtracted from the balance.

$$\hat{P}_{balance4} = \hat{P}_{balance3} - P_{FC} \tag{A.15}$$

$P_{balance4}$ is then the finally power surplus/deficit and is what will be fed to or from the grid.

**Algorithm 3** Main Algorithm

```
$\hat{P}_{balance1} = P_{solar} - P_{facility} - P_{fuelpump}$
Calculate $Power_{electrolyser}$
$\hat{P}_{balance2} = \hat{P}_{balance1} - P_{electrolyser}$
$\hat{P}_{balance3} = \hat{P}_{balance2} - P_{battery}$
Calculate $Power_{FuelCell}$
$\hat{P}_{balance4} = \hat{P}_{balance3} - P_{FuelCell}$
$P_{grid} = \hat{P}_{balance4}$
```

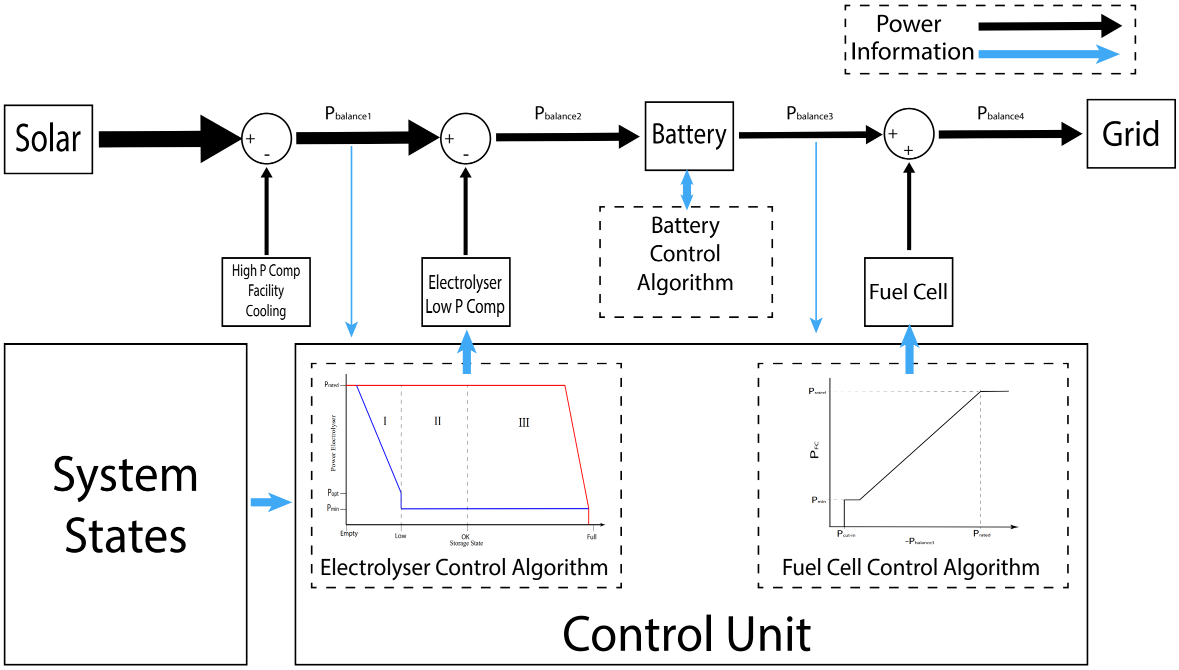


Figure A.6.: Schematic flow of information and power from the perspective of the control unit

### A.2.2. Electrolyser & Low Pressure Compressor

The control algorithm tries to match the power consumption of the eletrolyser and low pressure compressor to the amount of solar power available at the moment. It also makes sure the electrolyser runs when the hydrogen supply in the main storage gets to low. The control circuit uses as P-regulator and a feedback loop when it controls the power demand of the electrolyser and low pressure compressor (see A.3.6). What the algorithm does is to calculate the should-value that is fed to the regulator, it does not directly control the electrolyser.
The algorithm looks at the variables $State_{storage}$, $State_{Battery}$ and $\hat{P}_{balance1}$:

This makes it so that there are 3 different run-states for the electrolyser as illustrated in fig A.7. The blue line is the lower limit for what power the electrolyser will operate at (if it is operating) and the red line is the upper limit.

| $State_{storage}$ | $State_{battery}$ | $\hat{P}_{balance1}$ | What should the electrolyser do? |
|---|---|---|---|
| $\leq 1$ | X | $< 0$ | Run at low power |
| $\leq 1$ | X | $> 0$ | Run at available power but at least low power |
| $= 2$ | X | $< 0$ | Dont run |
| $= 2$ | X | $> 0$ | Run at available power |
| $= 3$ | X | $< 0$ | Dont run |
| $= 3$ | $\leq 1$ | $> 0$ | Run at available but reduced power |
| $= 4$ | X | X | Dont run |

Table A.8.: Electrolyser Run States

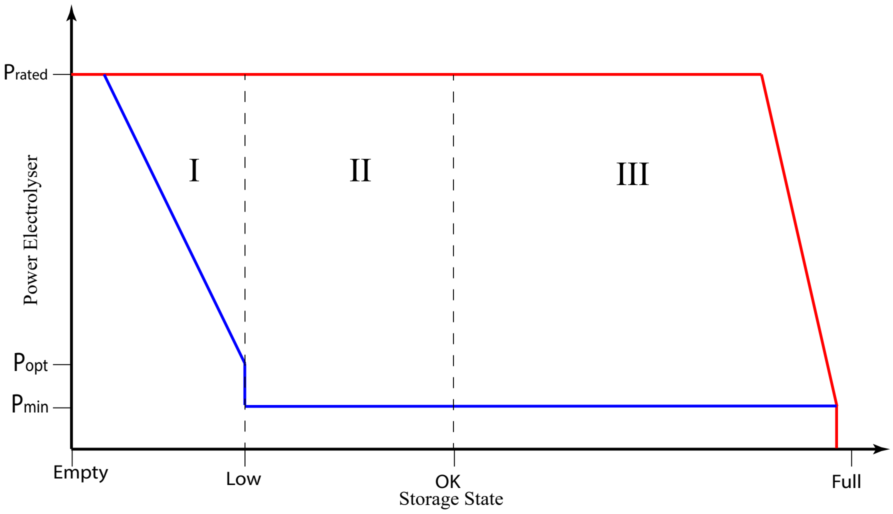


Figure A.7.: Electrolyser Run States

**I** - The electrolyser will always run at atleast low power $P_{electrolyser,low}$ if the storage is low, regardless if there is solar power available or not. It will however use more power if there is solar power available. $P_{electrolyser,low}$ is set so that it is relatively close to the optimal operating point of the electrolyser, where $\eta_{electrolyser,electrical}$ is at its highest (about 15% of $P_{electrolyser,rated}$). $P_{electrolyser,low}$ then increases as the storage gets lower.

$$\hat{P}_{electrolyser,low} = P_{electrolyser,opt} + K_{low} \cdot P_{electrolyser,rated} \cdot (SOH2_{low} - SOH2) \tag{A.16}$$

The constant $K_{low}$[1] should be set so that the storage remains at an acceptable level while minimizing power consumption, in the model a value of $K_{low} = 1$ was used.

**II** - If the storage is not on a low level, the electrolyser will only ever run when there is solar power available. The control unit and regulator try to match the power demand of the electrolyser and low pressure compressor so that:

$$P_{electrolyser} + P_{compLowP} = \hat{P}_{balance1} \tag{A.17}$$

---

[1] The K value is what determines the inclination of the high/low lines visible in A.7

This ensures optimal use of the solar resource. However if the available solar power is lower than $P_{electrolyser,min}$ the electrolyser will not run.

**III** - The electrolyser operates under the same conditions as in II, but will now also throttle down the power to charge the battery or if the main storage is close to full.

$$\begin{gathered}\hat{P}_{electrolyser,max} = K_{high} \cdot P_{electrolyser,rated} \cdot (1 - SOH2) \\ \hat{P}_{electrolyser,max} \leq P_{electrolyser,rated}\end{gathered} \tag{A.18}$$

(A value of $K_{high} = 5$ was used as default, in 6.3.2 it was adjusted to 20.)

Once The control unit has calculated how much power should be allocated to the electrolyser it will then also calculate how much power the battery needs:

$$\begin{gathered}\hat{P}_{battery,need} = K_{battery} \cdot P_{battery,rated} \cdot (1 - SOC) \\ \hat{P}_{battery,need} \leq P_{battery,rated}\end{gathered} \tag{A.19}$$

(A value of $K_{battery} = 10$ was used in the model.)

Then the control unit and regulator will control the electrolyser so that:

$$P_{electrolyser} + P_{compLowP} = \hat{P}_{balance1} + \hat{P}_{battery,need} \tag{A.20}$$

### A.2.3. Battery

The battery is not directly controlled by the control unit, instead it has its own integrated logical circuit to control its operation. It will always attempt to do so that $\hat{P}_{balance3} = 0$. If the battery is not full and $\hat{P}_{balance2} > 0$, the battery will charge, if the battery is not empty and $P_{balance2} < 0$, it will discharge, in all other cases it does nothing.

| $State_{battery}$ | $\hat{P}_{balance2}$ | What should the battery do? |
|---|---|---|
| $< 2$ | $> 0$ | Charge the battery |
| $> 0$ | $< 0$ | Discharge the battery |
| $= 2$ | $> 0$ | Do nothing |
| $= 0$ | $< 0$ | Do nothing |

Table A.9.: Battery Run States

**Do nothing** - The battery does nothing and is bypassed entirely.

$$\hat{P}_{battery} = 0 \tag{A.21}$$

And then:

$$\hat{P}_{balance2} = \hat{P}_{balance3} \tag{A.22}$$

**Charge the battery** - The battery will use all of $P_{balance2}$ to charge, up to $P_{battery,rated}$

$$\begin{gathered} \hat{P}_{battery} = \hat{P}_{balance2} \\ \hat{P}_{battery} \leq P_{battery,rated} \end{gathered} \tag{A.23}$$

And then:

$$\hat{P}_{balance3} = \hat{P}_{balance3} - \hat{P}_{battery} \tag{A.24}$$

**Discharge the battery** - The battery will try to match so that:

$$\begin{gathered} \hat{P}_{battery} = \hat{P}_{balance2} \\ \hat{P}_{battery} \geq -P_{battery,rated} \end{gathered} \tag{A.25}$$

And then:

$$\hat{P}_{balance3} = \hat{P}_{balance2} - \hat{P}_{battery} \tag{A.26}$$

### A.2.4. Fuel Cell

The algorithm controlling the fuel cell will attempt to balance out the power deficit so that $P_{balance4} = 0$ if $P_{balance3} < 0$. Since the fuel cell can not run below $P_{FC,min}$ the algorithm uses a cut-in value $P_{FC,cut-in}$. The fuel cell will only run if there is enough hydrogen in the storage, defined by $State_{FC}$. Another condition is that the electrolyser must be turned off for the fuel cell to operate, otherwise the fuel cell would simply consume hydrogen to generate power to produce hydrogen, which would be wasteful and pointless.

**Do nothing** - The fuel cell does nothing.

$$\hat{P}_{FC} = 0 \tag{A.27}$$

| $State_{FuelCell}$ | $\hat{P}_{balance3}$ | $P_{electrolyser}$ | What should the battery do? |
|---|---|---|---|
| X | X | $> 0$ | Do nothing |
| $= 0$ | $> 0$ | $= 0$ | Do nothing |
| $= 0$ | $< 0$ | $= 0$ | Do nothing |
| $= 1$ | $> 0$ | $= 0$ | Do nothing |
| $= 1$ | $< -P_{FC,cut-in}$ | $= 0$ | Run the fuel cell |

Table A.10.: Fuel Cell Run States

**Run the fuel cell** - The algorithm will run the fuel cell to match the power balance as illustrated in figure/table A.8

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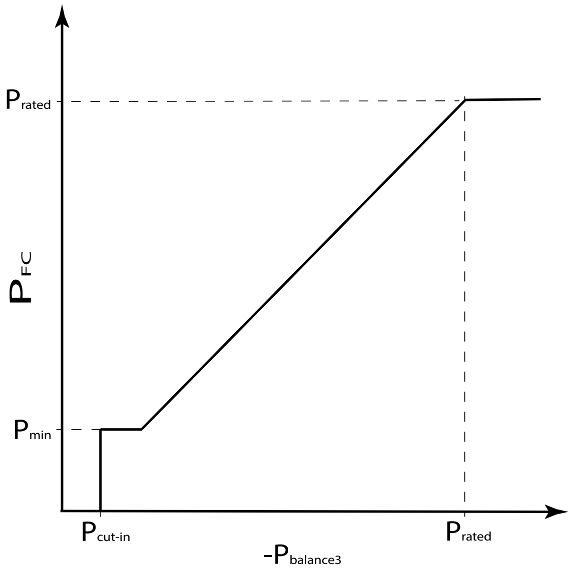

| $-\hat{P}_{balance3}$ | $FC$ |
|---|---|
| $0 - P_{cut-in}$ | $0$ |
| $P_{cut-in} - P_{min}$ | $P_{min}$ |
| $P_{min} - P_{rated}$ | $-P_{balance3}$ |
| $> P_{rated}$ | $P_{rated}$ |

Figure A.8.: Fuel Cell Function

### A.2.5. High Pressure Compressor and Cooling

The control unit always wants to make sure that the buffer storage is full. Therefor as soon as a user has taken hydrogen from the buffer storage the high pressure compressor will be ran in order to refill. The control monitors the state of hydrogen in the buffer storage $SOH2_{Buffer}$ and then decides at what power the high pressure compressor should run at. If the buffer is close to being full the compressor will run at reduced power. The cooling is always ran automatically when the high pressure compressor runs, hence this will also cause the cooler to consume power.

$$\begin{gathered}\hat{P}_{CompHighP} = K_{CompHighP} \cdot P_{CompHighP,rated} \cdot \left(1 - SOH2_{Buffer}\right) \\ \hat{P}_{CompHighP} \leq P_{CompHighP,rated}\end{gathered} \tag{A.28}$$

(A value of $K_{CompHighP} = 25$ was used)

## A.3. Simulation Implementation

The model is implemented in MATLAB/Simulink. The implementation follows the previous descriptions as close as possible, however computational and practical limitations exist. This section explains some of the programming methods used and how they are significant.

### A.3.1. User Demand Model

The user model for cars uses probability and random chance to generate at what times the users access the HRS. As a result of this a small degree of randomness is introduced into the results of the simulations, however the variations introduced by this were found to be negligible.

### A.3.2. Hysteresis

Sometimes during certain circumstances it was found that feedback-loops may occur, for example causing the electrolyser to rapidly switch on and off. While these feedback-loops were relatively rare and often didn't introduce any large errors in the end result, they would indeed increase computation time greatly. A practical solution to these feedback loops was to introduce a small hysteresis when comparing variables such as $SOH2$ and $SOC$. This change resulted in increased simulation speed without changing the results significantly. A hysteresis of 99% was used , meaning that the off-value always would be equal to the on-value times 0.99. Similarly, the value for "full" is 0.9999 instead of 1, for the same reason as previously.

### A.3.3. ODE-Solver and time-step size

The Simulink-model posses properties of stiffness, to which degree depends on the input variables. This means that sometimes the choice of solver and time-step is critical while other times less so. For all simulations the solver “ode23t (Stiff mod./Trapezoidal)” was used. This was Simulinks automatic choice when using default settings, it also is in accordance with the advice given on solver choice by Mathworks [48].

As for time-step, all simulations used a variable time-step with a maximum allowed step-size. Depending on the simulation, a maximum time-step of either 0.1 or 0.01 was used. A smaller step-size was always linked to longer simulation times, however not all simulations would improve much in convergence for a smaller step-size. Each time simulation results are presented in the thesis the maximum time-step ($\Delta t_{max}$) used is presented alongside.

Two convergence test were performed, one on the design presented in 5.3.1 and one on the design presented in 6.3.2. Two different solvers were also tested.

| **Case 1 - Study 1a) - 5.3.1** | | | |
|---|---|---|---|
| **ode23t** | | | |
| $\Delta t_{max}$ | **Lowest Storage [%]** | **Grid Use [MWh]** | **Approx. Sim. Time [min]** |
| 0.1 | 3.897 | 47.202 | >1 |
| 0.05 | 3.9017 | 48.4597 | 1 |
| 0.01 | 3.9488 | 49.9227 | 4 |
| 0.005 | 3.95 | 50.0588 | 9 |
| **ode15s** | | | |
| 0.1 | 3.95 | 49.628 | 1 |
| 0.01 | 3.9366 | 50.3676 | 8 |

Table A.11.: Convergence Test Case 1

| **Case 1 - Study 2a) 6.3.1** | | | |
|---|---|---|---|
| **ode23t** | | | |
| **Delta T_max** | **Lowest Storage [%]** | **Grid Use [MWh]** | **Approx. Sim. Time [min]** |
| 0.1 | 23.4044 | 0.0292 | >1 |
| 0.05 | 29.438 | 0.0076 | 1 |
| 0.025 | 25.9740 | 0.0095 | 2 |
| 0.01 | 31.1463 | 0.0050 | 4 |
| 0.005 | 31.1563 | 0.0051 | 9 |
| **ode45** | | | |
| 0.1 | 35.8271 | 0.0049 | 3 |
| 0.05 | 41.2961 | 0.0048 | 4 |
| 0.01 | 34.9583 | 0.0049 | 7 |
| 0.005 | 53.6258 | 0.0039 | 9.5 |

Table A.12.: Convergence Test Case 2

### A.3.4. Data Handling and Interpolation

The simulations are quite large, it is not uncommon for a two year simulation (one year for initialisation) to generate arrays with more than 3000000 elements in them and an output-data-file of 500MB or more. For multiple and longer simulations simple saving all this information as is is not practical. Output data from simulations is processed to be more compact and accessible. The data is re-sampled to 10 samples per hour, still generating arrays of 87600 elements per year.

Re-sampling and interpolation was also required sometimes to compare results between simulations. This is true for case 1, as different HRS designs are compared across user demand. The simulation uses probability to generate the user demand for cars, as a result between simulations there may be a small difference in precise user demand. For the sake of equal comparison the simulation results are interpolated to the same user demand when calculations are performed. The output data from PVGIS is presented as discrete hour-by-hour values, linear interpolation is used between these values to create a continuous curve.

For all interpolation purposes in the model, simple linear 1D-interpolation is used.

### A.3.5. Initialisation

A problem encountered early on in the development of the model was how the choice of initial storage in the main storage can cause vastly different results, for example if the initial storage is set to be 100% of capacity, no hydrogen shortages are likely to occur in January/February, which in reality when most hydrogen shortages occur. The solution to this problem has been to always simulate one extra year first, as an “Initialisation -Year”. This makes it so that by the start of the second year in the simulation, which is the first year with accurate results, the storage is at a realistic level. The solar data for the initialization year is always a copy of the data for the first real year, meaning that when a series of years was to be simulated, such as 2013-2014-2015-2016, the program simulated 2013-2013-2014-2015-2016. If only one year was simulated, the program would simply simulate that single year twice (for example 2013-2013, 2014-2014, etc.).

### A.3.6. Automatic Controls

The technical solution to matching the power demand of the electrolyser and low pressure compressor to the available solar power is a simple P-regulator inside simulink. It was assumed that the electrolysers system response to the control signal could be represented by a simple integrator.

The transfer function for the subsystem can be derived as:

$$Y = X\frac{K - Kf_C(s)f_E(s)}{s + K - Kf_C(s)f_E(s)} \tag{A.29}$$

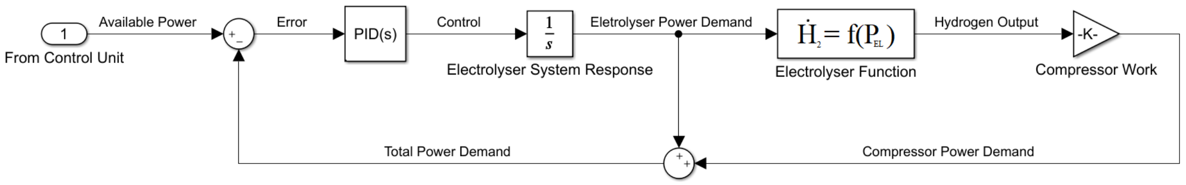

Figure A.9.: Signal flow of Regulator-Electorlyser-Compressor Subsystem

Where:

$Y$: Total Power Demand
$X$: Available Power
$K$: Regulator Proportionality Constant
$f_E(s)$: Electrolyser transfer function
$f_C(s)$: Compressor transfer function

The transfer function for the compressor $f_C(s)$ can be easily found as the power demand of the compressor is strictly proportional to the flow of hydrogen ($f_C(s) = const.$). However for the electrolyser no precise transfer function could be found, but if constant efficiency of the electrolyser is to be assumed, the resulting transfer function for the electrolyser still causes the transfer function of the subsystem to be strictly proper (ie it should behave nicely).

Ideally the regulator should be fine-tuned for each HRS design for optimal performance but it was found that a K-value of 250 results in a fast yet stable response for all cases tried. The mean absolute error is typically less than 0.1kW, however small overshoots are possible, causing the subsystem to consume more power than available, this causes it to draw power from the grid even though it is not necessary. This is what causes the small amounts of grid use that are present in the off-grid station in case 2.

# B. Other Input Data

## B.1. Simulation Variables

In this section the full inputs used for the simulations can be found, this includes variables such as the factors for losses $\eta_{losses}$ and more that are not listed in the specifications sheets. The following inputs were always used for all simulations presented in the thesis:

Table B.1.: Simulation inputs

| | |
|---|---|
| **Solar Panels** | |
| **Installation** | Slope: 15 °, Azimuth: 0 ° |
| **Technology** | Crystaline Silicon |
| **Losses Factor** | 5 % |
| *Note: These are inputs required by PVGIS* | |
| **Electrolyser** | |
| $\eta_{electrolyser,losses}$ | 0.90 |
| *Note: The electrolysers are based on the products listed in* [25] | |
| **Low Pressure Compressor** | |
| $\eta_{compressor,is}$ | 0.60 |
| $\eta_{compressor,losses}$ | 0.95 |
| **High Pressure Compressor And Cooling** | |
| $\eta_{compressor,is}$ | 0.60 |
| $\eta_{cooling,is}$ | 0.60 |
| $T_{in}$ | 300 K |
| $T_{out}$ | 260 K |
| $\eta_{compressor,losses}$ | 0.95 |
| **Battery** | |
| $\eta_{battery,internal}$ | 0.98 |
| *Note: The batteris are based on the products listed in* [49] | |
| **Fuel Cell** | |
| *Note: The fuel cells are based on the products provided by* [47] | |
| **Miscellaneous** | |
| **Fuel Dispenser Capacity** | 50 kg/h |
| **Electricity - Hourly Spot Price** | Nordpool SE3 2019 |
| **System Thresholds Case 1** | Default Values A.1.7 |

## B.2. Exchange Rates

The following exchange rates were used when converting prices to SEK. Exchange rates were retrieved from XE.com [50] on the 7th of October 2020.

| | |
|---|---|
| GBP - SEK: | 11.4430 |
| EUR - SEK: | 10.5101 |
| USD - SEK: | 8.9372 |

Table B.2.: Exchange Rates 7th-Oct-2020

## B.3. The Chevron Profile

In this section the values used for the Chevron profile ($p(t)$) is listed, they are retrieved from NRELs excel-spreadsheet Hydrogen_Refuelling_Station_Analysis_Model(HRSAM)_V2.0[51].The probability density function ($P(t)$)is simply the sum of the previous elements. To receive the inverse of the probability density function as in A.1.8 linear interpolation of the regular probability density function is used.

$$PDF(t) = \sum_{n=0}^{t} p(n-1) \tag{B.1}$$

$$t(y) = PDF^{-1}(y) = interp1(PDF, Time, y) \tag{B.2}$$

Table B.3.: Chevron Demand Profile input (1/3)

| Time - $t$ | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|---|
| prob. - $p(t)$ | 0.011 | 0.007 | 0.006 | 0.005 | 0.007 | 0.012 | 0.021 | 0.031 |
| PDF - $P(t)$ | 0 | 0.011 | 0.018 | 0.024 | 0.029 | 0.036 | 0.048 | 0.069 |

Table B.4.: Chevron Demand Profile input (2/3)

| Time - $t$ | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
|---|---|---|---|---|---|---|---|---|
| prob. - $p(t)$ | 0.042 | 0.055 | 0.061 | 0.062 | 0.065 | 0.070 | 0.073 | 0.077 |
| PDF - $P(t)$ | 0.100 | 0.142 | 0.197 | 0.258 | 0.320 | 0.3850 | 0.455 | 0.528 |

Table B.5.: Chevron Demand Profile input (3/3)

| Time - $t$ | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 |
|---|---|---|---|---|---|---|---|---|---|
| prob. - $p(t)$ | 0.078 | 0.074 | 0.067 | 0.056 | 0.043 | 0.033 | 0.026 | 0.018 | 0 |
| PDF - $P(t)$ | 0.605 | 0.683 | 0.757 | 0.824 | 0.880 | 0.923 | 0.9560 | 0.982 | 1 |

# C. Heat Output Estimations

## C.1. Energy Balance Electrolyser

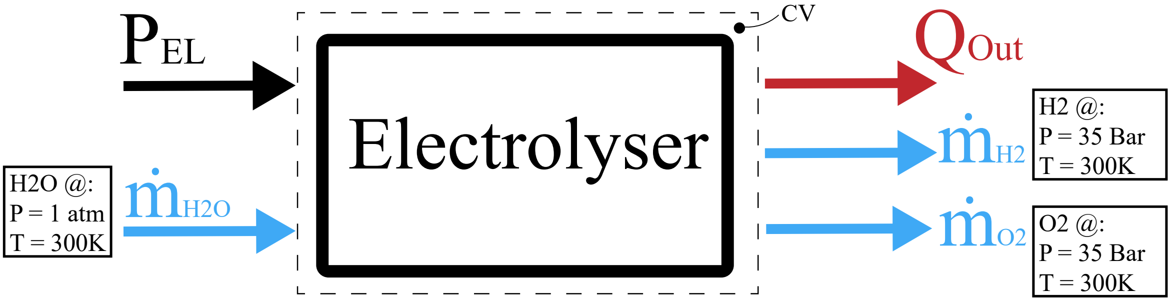

Figure C.1.: Caption

$$\dot{E}_{in} = P_{EL} + \dot{m}_{H2O} \cdot e_{H20} \tag{C.1}$$

$$\dot{E}_{out} = Q_{Out} + \dot{m}_{H2} \cdot e_{H2} + \dot{m}_{O2} \cdot e_{O2} \tag{C.2}$$

Energy Balance:

$$\dot{E}_{in} = \dot{E}_{out} \rightarrow P_{EL} + \dot{m}_{H2O} \cdot e_{H20} = Q_{Out} + \dot{m}_{H2} \cdot e_{H2} + \dot{m}_{O2} \cdot e_{O2} \tag{C.3}$$

Solve for $Q_{Out}$:

$$Q_{Out} = P_{EL} + \dot{m}_{H2O} \cdot e_{H20} - \dot{m}_{H2} \cdot e_{H2} - \dot{m}_{O2} \cdot e_{O2} \tag{C.4}$$

With internal energy $e$:

$$e = \bar{h}_f^o + h \tag{C.5}$$

Enthalpy $h$:

$$h = \int_{T_0}^{T} C_p(T)\, dT = [C_p = const.] = C_p\,(T - T_0) \tag{C.6}$$

The water must also be compressed from 1 atm to 35 bar.

$$e_{H2O} = \bar{h}^o_{f\,H2O} + h_{H2O} - w_{c,H2O} \tag{C.7}$$

$$w_{c,H2O} = v_{H2O} \cdot \; \Delta P \tag{C.8}$$

Table C.1.: Input Variables

$P_1 = 1\ atm$

$P_2 = 35\ Bar = 34.54\ atm$

$T = 300\ K$

$T_0 = 298.15\ K$

$v_{H20} = 0.001003\ m^3/kg$

Table C.2.: Physical Variables @ T = 300 K & P = 1 atm [6]

| Medium | $M$ [kg/kmol] | $\bar{h}_f^o$ [kJ/kg] | $C_p$ [kJ/kg] |
|---|---|---|---|
| $H20\ (l)$ | 18.015 | -15866.22 | 4.18 |
| $H2$ | 2.016 | 0 | 14.307 |
| $O2$ | 31.999 | 0 | 0.918 |

Reaction Electrolysis:

$$2H2O \rightarrow 2H2 + O2 \tag{C.9}$$

Mass Balance Electrolysis:

$$\left.\begin{aligned} M_{H2O} &= 18.015\ kg/kmol \\ M_{H2} &= 2.016\ kg/kmol \\ M_{O2} &= 31.999\ kg/kmol \end{aligned}\right\} 1\ kg\ H2 \Leftrightarrow 8.926\ kg\ H2O \Leftrightarrow 7.9363\ kg\ O2 \tag{C.10}$$

$$\dot{m}_{H2O} = 8.926\dot{m}_{H2}, \dot{m}_{O2} = 7.9363\dot{m}_{H2} \tag{C.11}$$

We receive:

$$Q_{Out} = P_{EL} + \dot{m}_{H2}\,(8.926\ e_{H20} - \ e_{H2} - 7.9363\ e_{O2}) \tag{C.12}$$

With internal energy $e$:

Table C.3.: Internal Energy [kJ / kg]

| Medium | $\bar{h}_f^o$ | $h$ | $w_c$ | $e$ |
|---|---|---|---|---|
| $H20\ (l)$ | -15866.22 | 7.73 | 3.408 | -15861.89 |
| $H2$ | 0 | 26.4680 | 0 | 26.4680 |
| $O2$ | 0 | 1.6983 | 0 | 1.6983 |

Result:

$$Q_{Out} = P_{EL} - 39.332[kWh/kg\ H2] \cdot \dot{m}_{H2} \tag{C.13}$$

With $P_{EL}\ \approx 47.5\ kWh/kg \cdot \dot{m}_H 2$:

$$Q_{Out} \approx P_{EL} \cdot 0.165 \tag{C.14}$$

## C.2. Fuel Cell Heat Output

Less information about the state of the in-and-outgoing mediums is available. Because of this, the approach for the fuel cell is more simplified, it is assumed that the energy contents of the hydrogen (using the higher heating value) is converted entirely into heat and electricity.

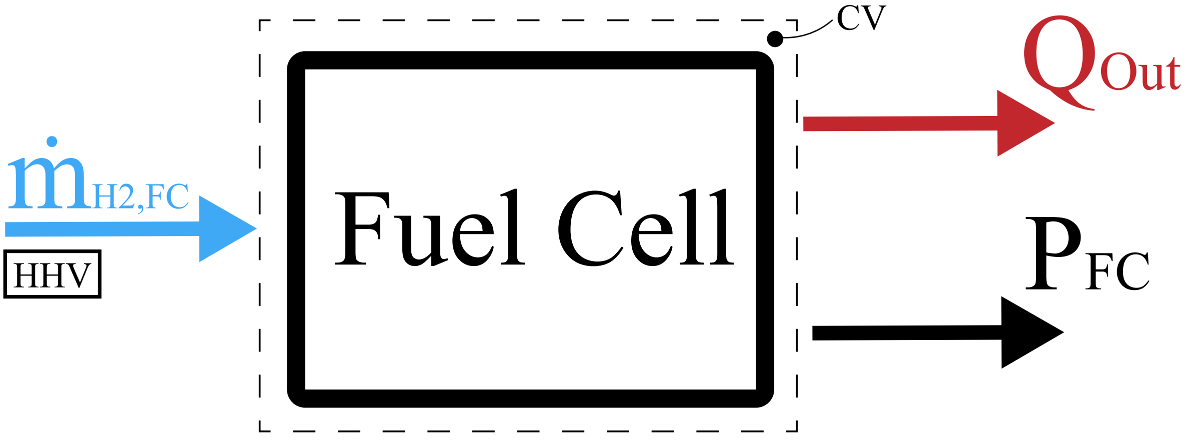

Figure C.2.: Fuel Cell Energy Balance

$$\dot{m}_{H2,FC} \cdot HHV_{H2} = Q_{out} + P_{FC} \tag{C.15}$$

With $P_{FC} \approx 20\ kWh/kg \cdot \dot{m}_{H2,FC}$ and $HHV_{H2} = 39.4\ kWh/kg$ [6]:

$$Q_{out} \approx 0.97 \cdot P_{FC} \tag{C.16}$$

The heat output of the fuel cell is close to or almost equal to its output electrical power. This claim is further validated by data provided by the company Powercell, that was willing to share some information about one of its products. In the data provided it can be seen that the electric power output (Net Power) is just slightly higher than the heat output.

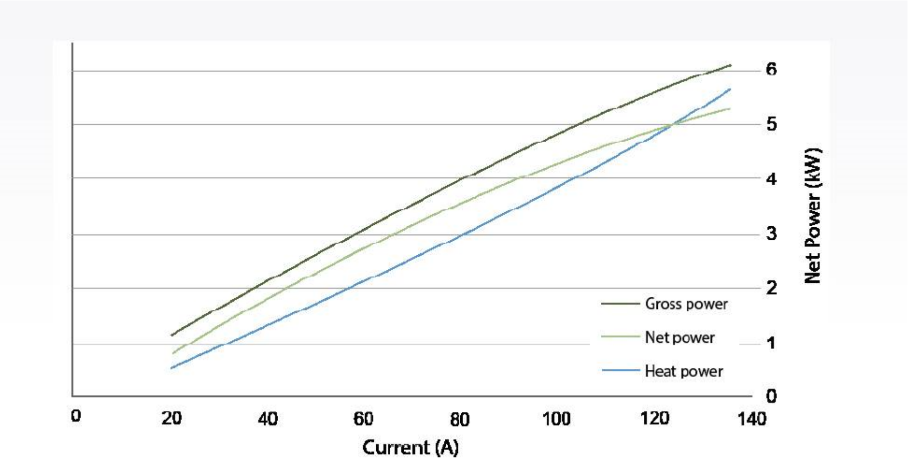

Figure C.3.: Performance of the Powercell PS-5, Source: Andreas Brodén at Powercell

## C.3. Total Heat Output

The above information can be used to estimate how much heat the HRS could output. Keep in mind this is a theoretical maximum, in reality the real output would be much lower due to losses and inefficiencies. Data from the simulation in 6.3.2 was used.

Table C.4.: Theoretical Max heat output of HRS in case 2

| | **Energy Output [MWh]** | | | | |
|---|---|---|---|---|---|
| | **Electric Power** | | **Heat** | | |
| | **EL** | **FC** | **EL** | **FC** | **Total** |
| **2010** | 566.62 | 3.33 | 93.21 | 3.23 | 96.44 |
| **2011** | 565.47 | 3.31 | 93.02 | 3.21 | 96.23 |
| **2012** | 550.84 | 3.63 | 90.61 | 3.53 | 94.14 |
| **2013** | 576.44 | 3.17 | 94.82 | 3.07 | 97.90 |
| **2014** | 559.16 | 3.50 | 91.98 | 3.39 | 95.38 |
| **2015** | 574.39 | 3.24 | 94.49 | 3.15 | 97.63 |
| **2016** | 565.88 | 3.45 | 93.09 | 3.34 | 96.43 |
| **Mean** | 565.48 | 3.37 | 93.02 | 3.27 | 96.30 |

If the average price of district heating (in sweden) [7] is to be used as a reference, the economic value of the heat can be estimated.

Table C.5.: Estimation of Heat price [7]

| | |
|---|---|
| Heat Use | 15 MWh/house/year |
| Heat Cost | 13700 SEK/house/year |
| AVG Heat Price | 913.33 SEK / MWh |
| Value HRS Heat | 87.95 k SEK/year |

This is the absolute maximum for what the heat can be estimated to be worth, in reality the value would be much lower for the following reasons:

- The majority of the heat from the electrolyser is generated in the summer when heat is less valuable.
- There would be losses and in-efficiencies.
- The heat is low grade [37].
- The heat is not useful where it is produced so it would have to be transported, requiring investment in infrastructure.

Even without these factors the total value of the heat would not be enough to offset the LCOH enough to achieve economic viability. As demonstrated previously in 6.3.2 with the increased revenue from selling electricity (300 k SEK/year) the LCOH was still about 4.5 - 5 times of the target LCOH for economic viability.

Because of the above reasons and due to the difficulty in accurately evaluating both the amount of useful heat and its economic value it was decided that selling heat is not a viable as a generic business alternative for a Solar-HRS. Perhaps it is possible for concepts where a Solar-HRS is integrated into a house/living space to utilize the heat better, this is however out of scope for this thesis.