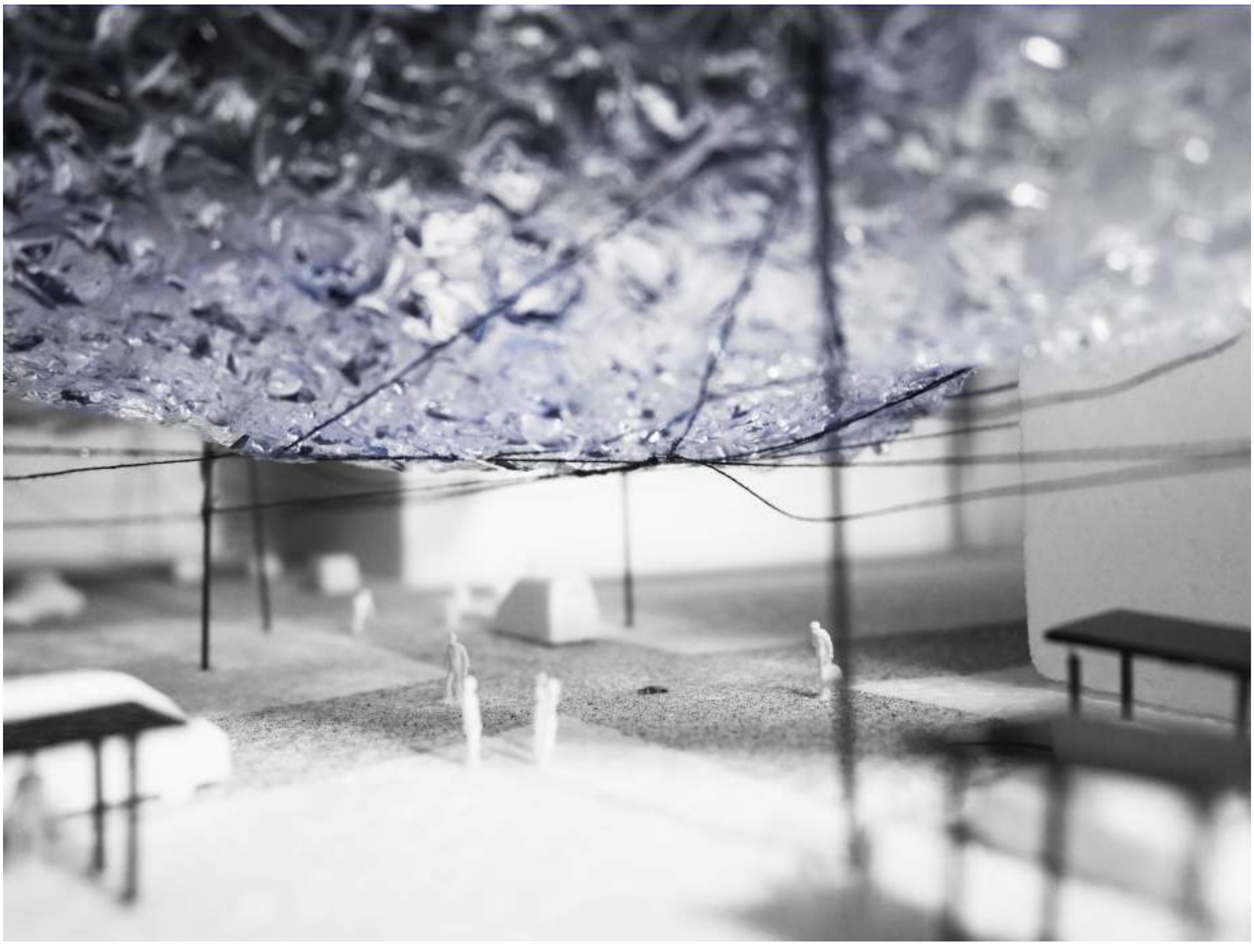

Artificial Leaf

Leaf-inspired photosynthetic canopies for synthesis of energy and architectural space

MADELEINE KÄLLMARKER

Department of Physics
CHALMERS UNIVERSITY OF TECHNOLOGY

Gothenburg, Sweden 2018

Master's thesis 2018

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Cover: Physical model of the architectural space under the transparent and flexible energy-generating canopy.

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Abstract

In nature, there are countless design solutions which have been developed through evolution. Many of these solutions can be the answer to the challenge of sustainable living, thus nature has solved many of the challenges humans are facing today. With the challenge of climate change, there is a need to reduce and replace the use of fossil fuels with environmentally safe energy with the potential to supply the world's high energy demand without being harmful to our planet.

Fortunately, renewable energy sources existing on earth neither run out nor have any significant harmful effects on our environment. The sun has the potential to supply all the energy that humanity requires. Solar cells, where solar energy is converted directly into electricity, has been improved over the last decades. However, the issue with solar panels is that the electricity is not produced when and where it is needed the most. Thus, a way to efficiently store the energy is needed. By converting solar energy into storable chemical energy, the intermittency problem with solar energy can be solved. Hydrogen gas with its great characteristics of storing energy could be the answer to this problem.

With inspiration from the leaf of a tree, the aim of this project is to design energy generating canopies by mimicking the leaf's photosynthesis as well as utilizing the structural characteristics of the leaf. Furthermore, the project aims to inspire cross research as well as innovative sustainable solutions.

As a result of the project, a physical built prototype has been constructed where hydrogen gas is generated from water through electrolysis. The design of the canopy is based on the characteristics of the present elements water and hydrogen gas. The prototype is a 1:1 scale canopy of 4 x 3 meters where hydrogen gas is generated by solar energy. The hydrogen gas is then stored in an inflatable structure until it is needed for usage.

The project is a result of interdisciplinary research between the department of Physics and the department of Architecture and Civil Engineering of Chalmers. Through inspiration from nature, this thesis shows how the challenge of sustainability can be solved with new technology within the field of renewable energy sources. With research and new technology of today, we can solve the challenge of today; to make the world independent of fossil fuels. This project is one example of biomimicry, there are countless solutions in nature waiting to be explored by human research.

Keywords: solar energy, artificial leaf, bionic leaf, hydrogen, renewable energy, water splitting, electrolysis, electrolyzer, biomimicry.

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Introduction

1.1 Background

Energy is essential for our existence and development. As a result of the increase in Earth's population as well as the increased energy consumption per capita [1], the world's population consumes more and more energy and the future energy demand is expected to increase significantly [2]. The sun has the potential to supply all the energy consumption of our world. The energy from one hour of solar illumination is more than the total energy consumed in our planet during an entire year [3]. The net increase of CO_2 in the atmosphere due to human activities is approximately $3 * 10^{12}$ kg/year, which corresponds to an annual increase of 0.4% of CO_2 [1].

Fossil fuels are limited and harmful to our planet. Although fossil fuels are continuously being formed via natural processes they are being depleted much faster than the new ones are being made, the use of fossil fuels are limited and thus they are considered to be non-renewable resources. The combustion of fossil fuels leads to climate change and as a result the global warming continues. It is becoming clear that other ways to produce energy without the release of carbon dioxide and other greenhouse gases must happen in the near future. For a sustainable future, there is a need for environmentally safe energy sources with potential to supply the worlds high energy demand without being harmful to our planet. Fortunately, renewable energy sources existing on earth neither run out nor have any significant harmful effects on our environment.

Solar cells, where solar energy is converted directly into electricity, have been improved over the last decades. However, the issue with solar panels is that the electricity is not produced when and where it is needed the most. By converting solar energy into storable chemical energy, the intermittency problem with solar panels can be solved. Solar energy can be used to generate hydrogen gas, which can be used as energy storage, an energy carrier or used directly as a fuel. Hydrogen does not exist freely on earth in its usable form, it must be produced [1]. One way to produce hydrogen is through electrochemical electrolysis where water molecules are separated into hydrogen and oxygen gas powered by electrical current, which can be created by solar energy. The combustion of hydrogen gas releases only pure water to the atmosphere, which makes the hydrogen cycle closed [1]. The use of hydrogen as energy storage and energy carrier offers great possibilities for society to move towards a carbon-free economy. But, to be able to realize a hydrogen infrastructure, cheap and efficient hydrogen production is necessary.

1.1.1 Aim of the project

The aim of this project is to design energy generating canopies by mimicking the leaf's photosynthesis process as well as utilizing the structural characteristics of the leaf to create an interesting spatial experience in an urban context.

The project shows how renewable energy can be generated and stored in a sustainable way. By a physical built large-scale prototype an investigation of how hydrogen gas can be generated and stored through electrolysis has been made. Furthermore, the technique is integrated into a canopy design to show how the technology can be used in our cities. The result shows a design proposal, a prototype and some measurements of the prototype. The prototype itself is not optimized, rather it shows a large-scale application of how the technique of water-splitting can be used in our cities today, to generate and store renewable energy independent of fossil fuels.

1.1.2 Thesis implementation

The project is divided into two parts, the architectural part where a design proposal of a solar hydrogen canopy is developed and the physics part where a physical functional prototype is constructed in detail. This report presents the physics part and the physical prototype. The architectural design proposal is described in an accompanying report including the design process and the design proposal.

The method of the project is characterized as research by design where research and design are treated simultaneously. The research which begins in the leaf is then developed to consider artificial photosynthesis where hydrogen is studied as an energy carrier with the potential to represent a renewable energy source. The design program of the architectural part of the thesis is shaped by the research, and the physical part of the thesis is informed by the design process.

The scale of the project shifts from electron level to a spatial scale which can be explored by a human. Difficulties with the prototype have been to construct it to be both fully functional and to have the design from the design proposal. To only construct a functional electrolyzer required a lot of research and construction time. Due to the time restrictions, simplifications of the design of the prototype have been made to prioritize getting the prototype to work.

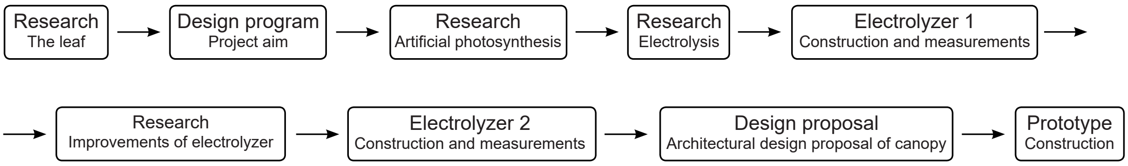

Figure 1.1: Process of work flow.

2

The leaf

Plants are the only photosynthetic organisms to have leaves. A leaf may be viewed as a solar collector of photosynthetic cells. Water enters the root and is transported up to the leaves by the veins. In the leaf mass, the water together with sunlight and carbon dioxide from the surrounding air is converted by the photosynthetic reaction to chemical energy which is stored and, in the case of a tree, transported to the tree trunk by the veins [4].

The other function of the leaf is the mechanical stabilization [4]. The high E-modulus, ratio between stress and strain of the leaf, makes the leaf venation system suitable as a stabilizing structure, the higher E-modulus, the stiffer the leaf is. It is to be expected that the architectural structure of leaf venation influences these main tasks and other functional properties.

2.1 Form and function

Across environments, natural selection has shaped the form and function of the leaf [5]. Variations observed in leaves are mostly attributed to their genetic control, but environmental factors also play an important role in the shape of the leaf although probably act at a later stage of development. In this chapter, the main relation between form and function will be explained.

2.1.1 Photosynthesis

Photosynthesis is a process used by plants and other organisms to convert light energy into chemical energy. The chemical energy is stored in carbohydrate molecules, such as sugars. Photosynthesis involves four steps: light harvesting, charge separation, water splitting and fuel production. The photosynthesis consists of two half-reactions, where water is split and sugar is produced.

$$2H_2O \rightarrow O_2 + 4H^+ + 4e^- \tag{2.1}$$

Equation 2.1 shows the first step of the photosynthesis reaction where water is split into oxygen, hydrogen ions and electrons.

$$CO_2 + 4H^+ + 4e^- \rightarrow H_2CO + H_2O \tag{2.2}$$

Equation 2.2 shows the second half of the photosynthetic reaction where carbohydrates (H_2CO) are produced by carbon dioxide (CO_2) and the hydrogen ions and electrons released by water splitting.

$$6CO_2 + 6H_2O \rightarrow C_6H_{12}O_6 + 6O_2 \tag{2.3}$$

Equation 2.3 shows the overall reaction of the photosynthesis reaction that converts water, carbohydrates and sunlight to sugar and oxygen.

2.1.2 Environmental factors

The environmental factors such as light and temperature affects the shape of the leaves. In the case of leaf size, the size decreases with increasing altitude, decreasing rainfall and soil and nutrient content. Small-sized leaves are better adapted to hot and dry environments. Differences in light intensity result in leaves with varying forms. Low intensity induces petiole elongation blade expansion, but inhibits the elongation of the leaf petiole.

2.1.3 Leaf venation

The venation of leaves has two main purposes: it constitutes the mechanical stabilization of the leaf and the leaf's energy transportation [5].

Generally, the first-order veins, called primary veins, are the thickest veins of the leaf with origin at the leaf base. Primary veins support sequences of secondary veins, which may branch further into higher order veins. Secondary veins are the next smaller size class of veins which arise from the primaries. Finer veins and veinlets have progressively higher orders. The secondary veins and their descendants may be free-ending, which produces an open, tree-like venation pattern, or they may connect, forming loops in a closed pattern. Tertiary and higher-order veins usually link the secondary veins together, forming a ladder-like (percurrent) or netlike pattern (reticulate) [4].

The leaf is a lightweight structure with the veins providing the mechanical stability. Primary and secondary veins act as cantilevered beams for the leaf and its structure maximizes the surface-to-volume ratio [5]. They support the weight of the leaf and provide resistance to mechanical loading. This ensures that the leaf presents a maximal effective surface without deformations. The mechanical considerations imply scaling relationships between the surface area of the leaf and its leaf mass, and between venation and non-venation tissue. A high mechanical stability is given by a small leaf size, high E-modulus of leaf tissue and additional stabilization of the leaf margin [5].

Networks that only branch hierarchically and do not reconnect, have the highest supply rates for a given mass [5]. Closer veins correspond to higher water flux and higher carbon assimilation rates. A reconnected network is selected when there is a high risk of damage and ensures that damage of one sector does not affect function in other parts of the leaf [5]. Long life span is also achieved by increasing the mechanical strength of leaf tissue, which is increased by thicker leaves with high mass.

The mathematical relationship between density, distance and loopiness in the venation pattern is described by figure 2.1 [5]. where:

d is the mean diameter of the largest circle that can fit within each closed loop (arole) within a region of interest (ROI),

σ is the density, i.e. the total path length of the veins within an ROI divided by the area,

ξ is the number of aroles within the ROI (loopiness).

From [5], assuming rectangular aroles with width $\Delta x \cdot k\Delta x$, the conclusions are the following:

$$\begin{aligned} d &= \Delta x \\ \sigma &= (k+1)/(k \cdot \Delta x) \\ \xi &= 1/(k \cdot (\Delta x)^2) \end{aligned} \tag{2.4}$$

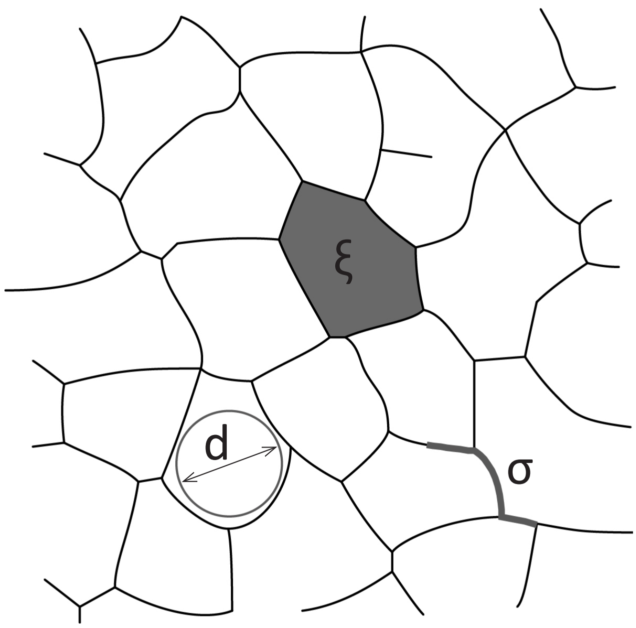

Figure 2.1: Mathematical description of leaf venation.

A figure of different patterns of leaf venation can be seen in figure 2.2.

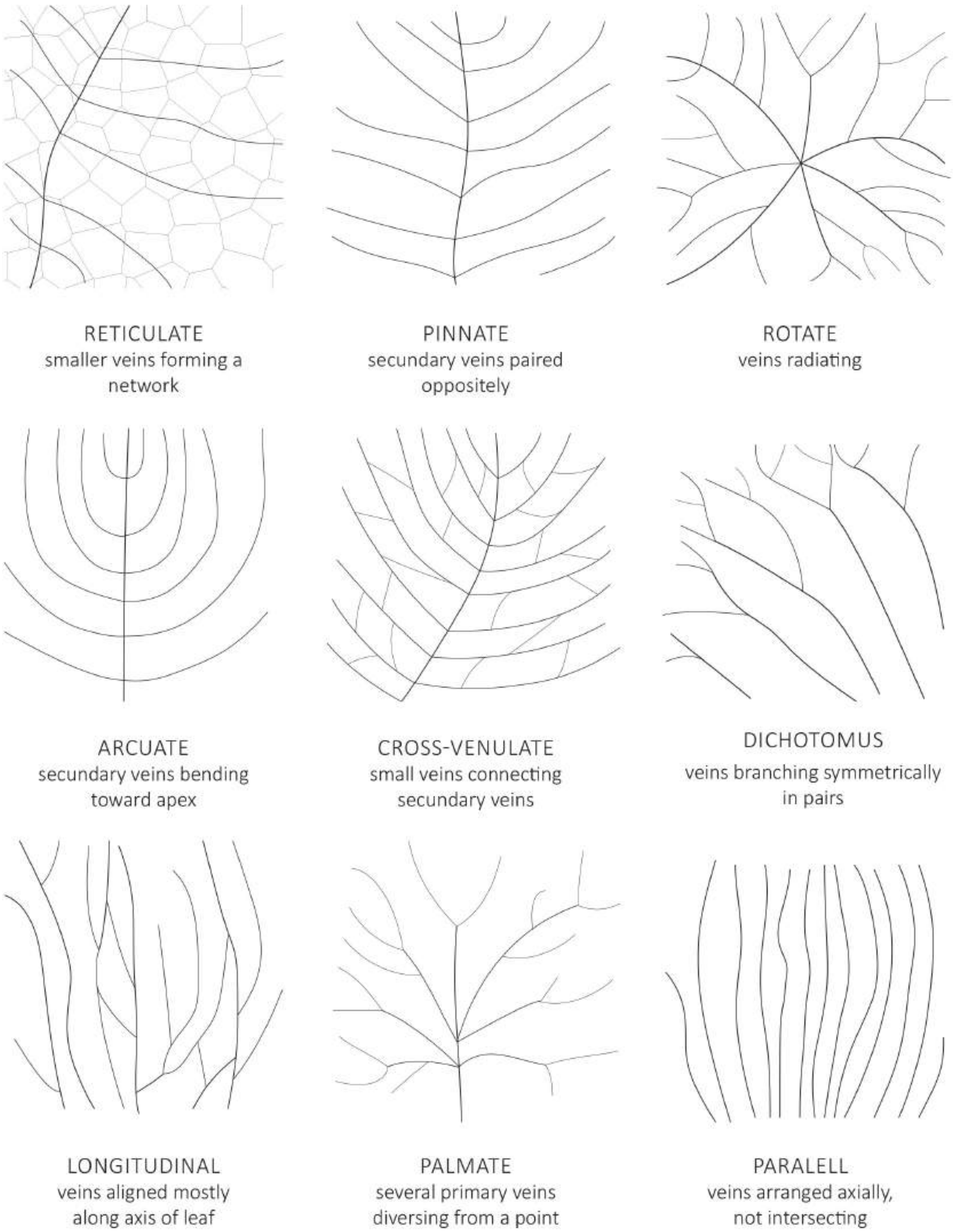

Figure 2.2: Leaf venation patterns.

3

Theoretical background

3.1 Biomimicry

The best ideas are borrowed. The practice of borrowing ideas to solve technical challenges is called design by analogy, or biomimicry, and is a technique widely applied by innovators and designers [6]. Biomimicry takes inspiration from the amazing biological forms, processes, patterns and systems found in nature [7] and explores how the ideas of nature can be applied to the real world. Some examples of areas where biomimicry can be applied are medicine, smart computers, structural efficiency, materials and energy supply. Natural solutions found in nature have benefited from years of research and testing through evolution, and each solution can provide researchers with new solutions to the challenge of sustainable living [8].

3.1.1 Artificial photosynthesis

Nature has invented a way to harvest power from the sun in the leaf. By the leaf's photosynthesis, sunlight is converted into chemical energy which is stored as sugar in its cells. The photosynthesis is an entirely renewable process, the plant harvests the solar energy, absorbs carbon dioxide and water and releases oxygen. The only waste is clean oxygen.

Today's technology makes it possible to convert sunlight into chemical fuel in an artificial way by using water splitting. This process is called artificial photosynthesis and mimics the process of the leaf's photosynthesis. The artificial leaf is made of silicon and catalysts to speed up the process. When the leaf is in contact with water an electric charge generated by electrons splits the water molecules into their component parts hydrogen and oxygen. Sugar is the leaf's chemical storage of energy and is easy to release when needed. The artificial leaf mimics the process of storing energy, but instead of making sugar, it produces an even more efficient fuel, hydrogen gas. Artificial photosynthesis may become the future of energy. Nature's rate of efficiency is 1%. The artificial leaf can be more than ten times more effective, reaching up to 10% [9].

3.1.1.1 Bionic leaf

In photosynthesis, CO_2 from the air fixes by using sunlight. The bionic leaf is a merge of the artificial leaf and genetically engineered bacteria that eats hydrogen to create liquid fuels such as isobutanol. The bionic leaf uses the catalysts of the artificial leaf in combination with the bacterium Raistonia eutropha to convert CO_2 into biomass and liquid fuels [10]. With this process, the CO_2 reduction efficiency exceeds the natural photosynthetic systems. The metabolic engineering of the bacterium enables the renewable production of an array of fuels and chemical products. Artificial photosynthesis also allows the production of powerful fertilizers. The method uses the soil bacterium Xanthobacter autrotrophius consuming hydrogen generated by the water splitting reaction and taking nitrogen from the atmosphere to produce ammonia and phosphorous [11].

3.2 Solar energy

Sunlight that each day allows our planet to live, is a direct source of energy. The amount of energy produced by the sun is enough to supply all the energy needs of everyone in the world [3]. The sunshine we receive every day could provide more than enough power for our global needs, even with a future bigger population. The energy supply is enormous, the earth's surface receives about $1.2 \cdot 10^{17}$ W [12] of solar power, which means that in less than one hour, enough energy is supplied to the earth to satisfy the entire energy demand of the human population for a whole year. This means that there is far more energy potentially available then we could ever use. But, solar energy is still a new technology compared to fossil fuels because the challenge with solar energy lies in harvesting the energy with efficient and cost-effective devices [3], as well as finding a way to store the energy in an efficient way.

3.2.1 Photovoltaics

Unfortunately, the sunlight cannot provide electricity directly, it must be captured and transformed [13]. There are several ways of turning sunshine into electricity. Photovoltaics, PV, uses the sun's light [12] to generate electricity. Solar radiation consisting of electromagnetic waves is converted into useful heat or electricity. These processes require a material that is able to absorb a photon's energy by exciting an electron into a higher energy level. If the atoms containing electrons at this excited state are somehow separated from the rest of the atoms, an electrical potential difference is created.

3.2.1.1 Silicon cells

A silicon cell is composed of two layers of silicon. When a photon hits the atoms of the silicon material, its energy is transmitted to an electron, knocking it into a higher energy level. The amount of energy needed to achieve this is determined by the band gap of the material, which affects what portion of the solar spectrum a PV cell can absorb. Ordinarily, the electron would fall back because its negative charge is attracted to the positive charge of the atom's nucleus. So, the structure of the cell is designed to capture the electron with minimum energy loss and make it flow in a circuit.

To achieve this, the cell is composed of two layers. The upper layer of the silicon is N-doped and the lower layer is P-doped. N-doped means that the crystal has an outer electron more acting as a free charge carrier. P-doped means that one electron is missing, causing a hole in the conduction band. The P-doped and N-doped layers of the cell gives the layers respectively a negative and positive potential. The electron emitted from the upper layer is attracted to the lower layer, leaving behind a hole. If the cells are connected in a circuit, the electrons produce a current. Voltage is created by a reverse electric field around the junction between the layers, a p-n junction.

Sunlight is made up of a spectrum of frequencies and the efficiency of a solar cell is therefore partly dependent on the range of frequencies it can respond to. Photons with insufficient energy will not excite the electrons to jump the band gap. Higher frequency equals more energy. Photons with more energy than required will lose the excess energy as heat, causing the cell to heat up and reducing its efficiency. A high band gap means that the range of frequencies that can excite electrons is smaller, and a low band gap means more of the incoming radiation can be absorbed. However, a lower band gap implies that the voltage of the cell will decrease (although the current will increase). There exists therefore an optimal band gap that is wide enough so that the voltage is high, but still low enough so that enough radiation can be absorbed [14].

The best established photovoltaic technology based on the elemental semiconductor silicon is either monocrystalline or polycrystalline. Their names refer to the arrangement of the silicon, determined by the process of manufacture. Monocrystalline cells use high quality pure silicon and have an efficiency up to 24% [12], but are more expensive than polycrystalline cells. Polycrystalline cells are made out of silicon that is melted and cast and contains many crystals. This method is slightly less costly, and the result is slightly less efficient cells. Polycrystalline cells are the most common type, representing about 85% [12] on the market.

3.2.1.2 Thin-film modules

The thin-film modules of solar cells are a more recent technology, which is very popular. The types of thin-film cells that are most likely to be of commercial importance in the next few years are the amorphous silicon cell, thin polycrystalline silicon cell grown on a low-cost substrate, the copper indium diselenide cell and the cadmium telluride cell [15]. The modules work in a similar way to silicon cells, but are constructed differently. An extremely thin layer of photosensitive materials is deposed onto a low-cost backing such as glass, stainless steel or plastic. The thin-film modules are more tolerant of shade and high temperatures. They are cheaper to manufacture than the silicon cells, but less efficient. The efficiency is 7-13% [12], but could go much higher in the future. To obtain the same output of power, double the surface area of thin film modules would be needed compared to silicone modules.

3.3 Electrochemistry

3.3.1 Thermodynamics

When discussing solar absorption, electrodynamics and thermodynamics are relevant topics. The first law of thermodynamics may be stated as [16]

$$\Delta U = q + w, \tag{3.1}$$

where ΔU is the change in the internal energy of the system, q is the heat absorbed by the system and w is the work done on the system.

Gibb's free energy (ΔG) is the change in energy resulting from a reaction at a certain temperature and pressure. The sign of Gibb's free energy tells us whether a reaction is spontaneous in one direction or the other. For a fixed temperature and pressure, Gibb's free energy is defined as [17]

$$\Delta G = \Delta H - T\Delta S, \tag{3.2}$$

where ΔH is the change in enthalpy ($P\Delta V + \Delta U$), T is the temperature and ΔS is the change in entropy of the process.

A system which undergoes a reversible process at constant temperature and pressure in which both mechanical work and electrical work are done, the work done on the system, w, is [16]

$$w = w_{mech} + w_{elec} = -P\Delta V + w_{elec} \tag{3.3}$$

For a reversible process at constant temperature, the heat absorbed by the system is

$$q = T\Delta S. \tag{3.4}$$

Equations 3.3 and 3.4 in combination with equation 3.4 gives

$$w_{elec} = \Delta U + p\Delta V - T\Delta S = \Delta G \tag{3.5}$$

When a charge Q is moved through a potential difference E, the electrical work done by the system on the surroundings is [16]

$$w_{elec} = -EQ, \tag{3.6}$$

where E is the difference in potential and Q is the charge moved through the potential difference. If the charge carriers are electrons, the charge is given by [16]

$$Q = nF \tag{3.7}$$

where n is the number of moles of electrons and F is the Faraday constant, the charge on one mole of electrons, 96484.6 coulombs (C). The electrical work is negative if the system transfers energy to the surroundings,

$$w_{elec} = -nFE. \tag{3.8}$$

Equations 3.5 and 3.8 gives the change in Gibbs free energy of the system,

$$\Delta G = -nFE \tag{3.9}$$

where ΔG have the units of joule per mole (J/mol) if E is measured in volts (V), F in C/mol and n is the number of moles of electrons per mole of reaction. The result demonstrates a method for determination of the changes in the Gibbs free energy, without recourse to measuring equilibrium constants or enthalpy and entropy changes [16].

3.3.2 Water splitting

The electrolysis of liquid water into hydrogen and oxygen gas, called water splitting, can be written [18]

$$H_2O(l) \rightarrow \frac{1}{2}O_2(g) + H_2(g) \tag{3.10}$$

Consider the reaction for one mole of water, the reaction generates one mole of hydrogen gas and half a mole of oxygen gas. In case of water splitting the change of enthalpy, ΔH, at room temperature and atmospheric pressure is 286 kJ, which is the amount of energy needed for the reaction to occur. As seen in equation 3.5, the volume of the gas generated have a larger volume than the water. Of the added energy, 4 kJ goes into pushing the atmosphere away to make room for the gas produced. The rest of the energy, 282 kJ, remains in the system itself [18].

$$\Delta G = \Delta U + p\Delta V - T\Delta S \tag{3.11}$$

By determining the change in the system's entropy, the amount of electrical work needed can be calculated. The entropy values for one mole of each molecule is shown by

$$S_{H_2O} = 70 \text{ J/K}$$

$$S_{H_2} = 131 \text{ J/K}$$

$$S_{O_2} = 205 \text{ J/K}$$

The change in entropy is given by the equation

$$\Delta S = S_{H_2} + \frac{1}{2} S_{O_2} - S_{H_2O} \tag{3.12}$$

and equals $\Delta S = 163.5$ J/K which is the increased entropy of the system [18]. Equation 3.5 with given ΔS gives the maximum heat absorbed by the system at room temperature

$$q = T\Delta S = 298 \text{ K} \cdot 163.5 \text{ J/K} = 49 \text{ kJ}. \tag{3.13}$$

According to equation 3.11 the change in the Gibbs free energy which is equal to the electrical work done on the system is 237 kJ.

$$\Delta G = \Delta U + p\Delta V - T\Delta S = 286 \text{ kJ} - 298 \text{ K} \cdot 163 \text{ J/K} = 237 \text{ kJ} \tag{3.14}$$

In order to split one mole of water, the minimum amount of electrical work that must enter the system is 237 kJ [18]. The remaining 49 kJ to reach the 286 kJ required for the reaction to occur can be absorbed by ambient heat, it is an endothermic reaction.

By Avogardo's constant, the amount of electrical work required to split one single water molecule can be calculated by the equation

$$\Delta G = \frac{237 \cdot 10^3}{N_A} J = \frac{237 \cdot 10^3}{N_A} \cdot 6.242 \cdot 10^{18} \text{ eV} = 2.46 \text{ eV}, \tag{3.15}$$

where

$$N_A = 6.022 \cdot 10^{23} \tag{3.16}$$

mol^{-1} is the Avogardo constant.

A minimum electrical work of 2.46 eV is required to split one water molecule according to the reaction in equation 3.10.

Including the photons, the overall reaction of water splitting is

$$H_2O(l) + 2hv \rightarrow \frac{1}{2} O_2(g) + H_2(g) \tag{3.17}$$

where hv is the energy of a photon. To split one water molecule, there is a need for two photons. As calculated in equation 3.15, 2.46 eV is required to split one water molecule. This means that the photon energy band gap is 1.23 eV.

3.4 Hydrogen

Hydrogen is the first element in the periodic table with atomic number 1. Hydrogen is the most abundant of all elements in the universe. Compared to electricity, hydrogen is easier to store and easier to transport. Hydrogen creates no harmful emissions when used and the only by-product is clean water. Over the past century, humans have switched from wood fuel to coal, to oil and now to natural gas [1]. This shift reflects a slow reduction in the amount of carbon contained in the fuel and an increase in its hydrogen content. The next step is to eliminate carbon and use pure hydrogen. Unlike oil or natural gas, production of hydrogen consumes energy [19]. Hydrogen does not exist freely in a usable form, it must be produced. This is because hydrogen atoms are almost always bonded with other elements into compounds like water, which require energy to break up. Hydrogen can be produced from any energy source and can be obtained from one of our planet's most common substances: water.

The concept of a hydrogen economy envisions a future where all our energy needs will be met by hydrogen that is produced from renewable energy sources like solar energy. Rather than being an energy source, hydrogen is considered an energy carrier, a way to transport and store energy. Compared to electricity, hydrogen is easier to store.

Hydrogen and electricity are closely related and together can satisfy most of our energy needs. Electricity can be used to produce hydrogen, and hydrogen can be used to produce electricity. This means that if hydrogen and electricity were in wide-spread use, they could easily be substituted for each other. This flexibility would be valuable in terms of getting the most out of our existing equipment and infrastructure. Renewable energy sources would generate electricity, and hydrogen would store and deliver it. Hydrogen could complement electricity as an alternative energy delivery service. In the challenge of storing energy coming from renewable and intermittent power sources, hydrogen is often considered the best [1]. The growing capacity of renewable energy requires a storage system of equal magnitude.

3.4.1 Hydrogen cycle

In electrolysis, hydrogen is produced by water and stored as hydrogen gas. Hydrogen in reaction with oxygen generates energy and water, as shown in figure 3.1.

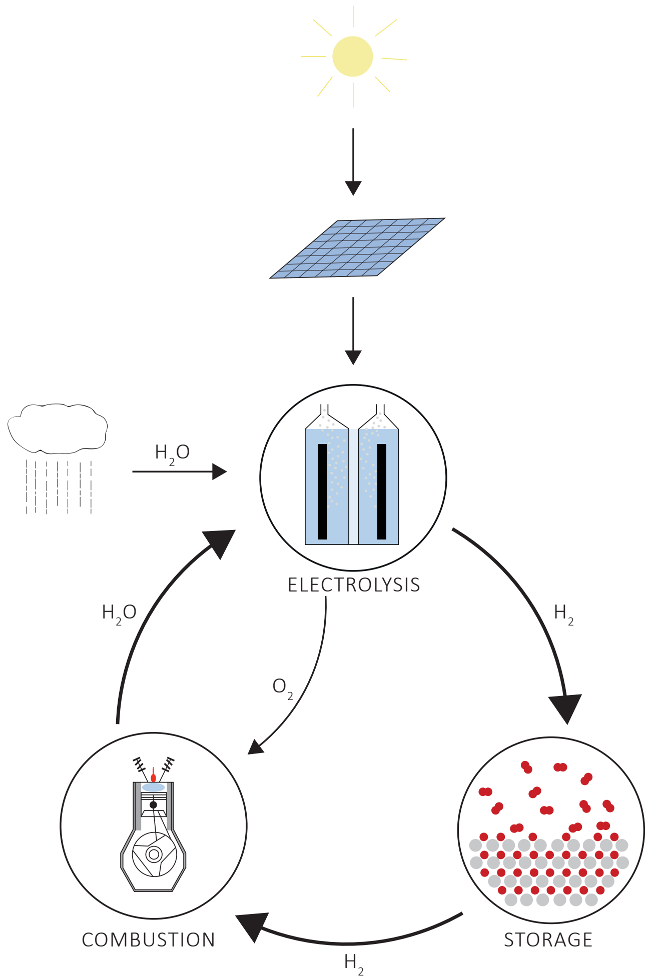

Figure 3.1: The hydrogen cycle: water is split into hydrogen gas which is stored and then used.

3.4.2 PEM electrolysis

The principle of a proton exchange membrane (PEM) electrolysis is to separate water molecules via water splitting to hydrogen gas, in which the hydrogen gas is stored in chemical bonds. The cell consists of an anode, cathode and a proton exchange membrane in between. Figure 3.2 shows the cell including the chemical reactions. The catalysts are made of metallic components. On the anode side of the cell, platinum or platinum alloys are typically used and for the cathode side oxides as iridium or ruthenium is used.

At the anode, the oxidation takes place [19]. Water molecules are split into oxygen, protons and electrons by applying a DC voltage higher than a reversible potential. This reaction is commonly referred to as the oxygen evolution reaction (OER).

$$\text{Anode reaction: } 2H_20(l) \rightarrow O_2(g) + 4H^+ + 4e^-$$

The reduction takes place at the cathode [19]. The protons from the anode pass through the membrane and on the cathode combine with electrons to form hydrogen. Passage of protons through the membrane is accompanied by water transport.

$$\text{Cathode reaction: } 4H^+ + 4e^- \rightarrow 2H_2(g)$$

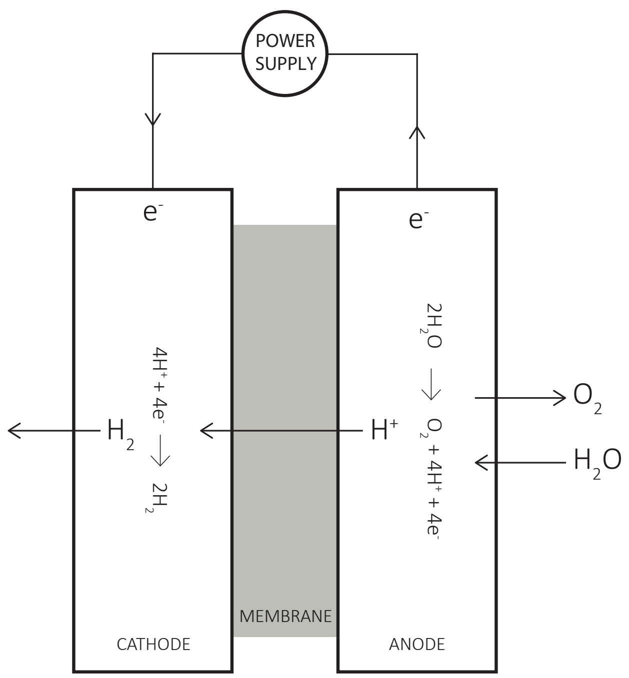

Figure 3.2: PEM electrolysis.

4
Architectural design proposal

In this chapter, the architectural design proposal is briefly described.

Figure 4.1: Siteplan of the canopy at Vasaplatsen, Gothenburg.

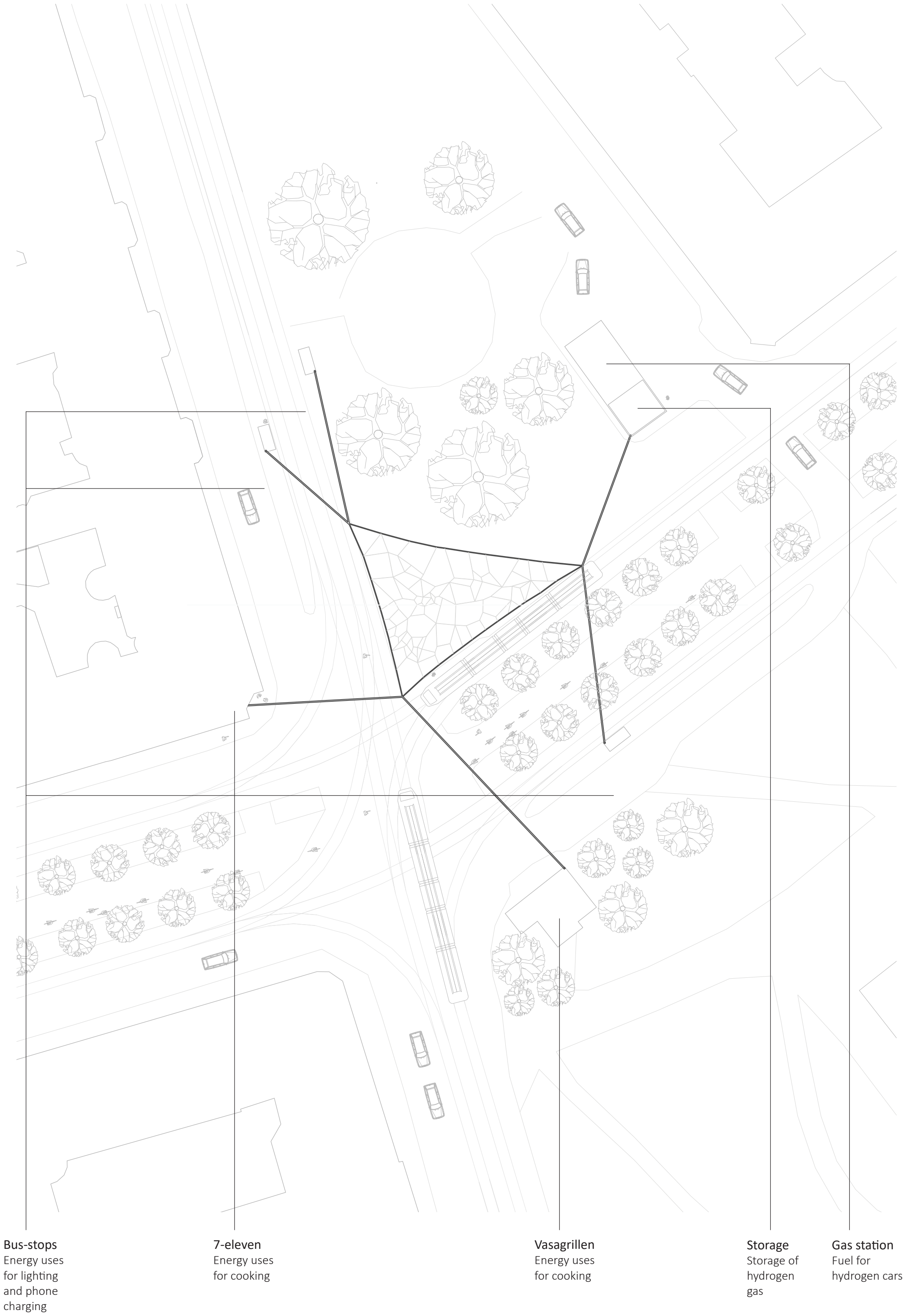

Figure 4.2: Plan of the canopy.

The two main purposes of the structure of the canopy are to produce and distribute energy. As the leaf distributes energy through the veins, the structure of the canopy distributes energy through its construction through pipes.

The electrolysis is running on rainwater and sunlight collected by the structure. The produced hydrogen is stored in the inflatable structure of the canopy. The canopy experiences three phases. In the first phase the canopy is empty and collects rainwater using its flexible structure. In the second phase the canopy uses rainwater to produce hydrogen gas through electrolysis. In the third phase the hydrogen gas inflates the structure. The canopy changes form as the chemical reaction of electrolysis is happening.

Figure 4.3: Render of canopy in phase 1. The canopy is empty.

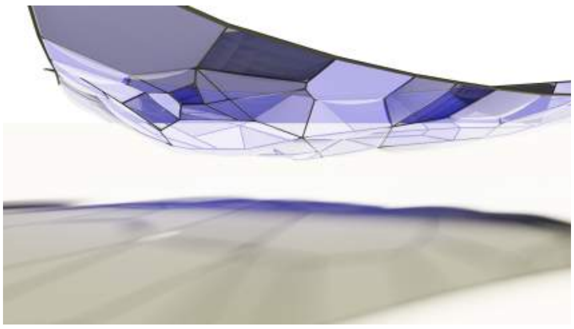

Figure 4.4: Render of canopy in phase 2. The canopy is collecting rainwater.

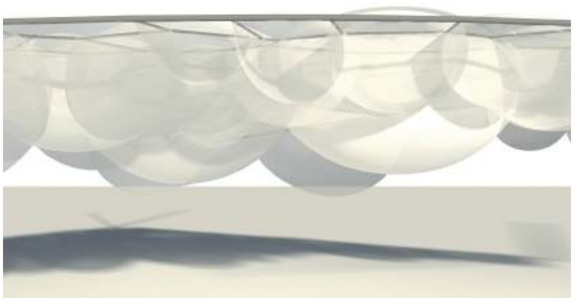

Figure 4.5: Render of canopy in phase 3. The canopy is inflated with hydrogen gas.

5

The prototype

The prototype is designed to meet the architectural conditions as well as being fully functional. The main parts of the prototype consist of solar cells creating the current needed for the electrolyzer to run the reaction of water splitting and a storage where the hydrogen gas is stored. The output of the solar cells has a high voltage with low current, while the electrolyzer needs a high current with low voltage, meaning a DC-DC converter is required.

5.1 Solar panels

Polymer solar cells have many advantages such as their light weight, flexibility and low material and manufacturing costs. The photovoltaic solar cells in the prototype convert sunlight into electrical energy, which is later used by the electrolyzer.

Inorganic solar cells have a record power conversion efficiency of 39%, while commercially available solar panels have an efficiency of 15-20%. Organic solar cells have certain disadvantages including their low efficiency of only 5% compared to 15% for silicon cells and a short lifetime. With their numerous benefits, the organic solar cells can justify the current international research in developing new materials to enhance efficiency and achieve a low-cost and large-scale production within the next years.

The solar panels for the prototype are infinityPV, which are chosen for their design freedom suitable for the design of the canopy. The technology of infinityPV is printed organic solar cells. The modules do not include toxic or scarce elements and offer a sustainable alternative to traditional solar cells. The solar modules are entirely prepared on plastic foil using ambient roll-to-roll printing and coating methods.

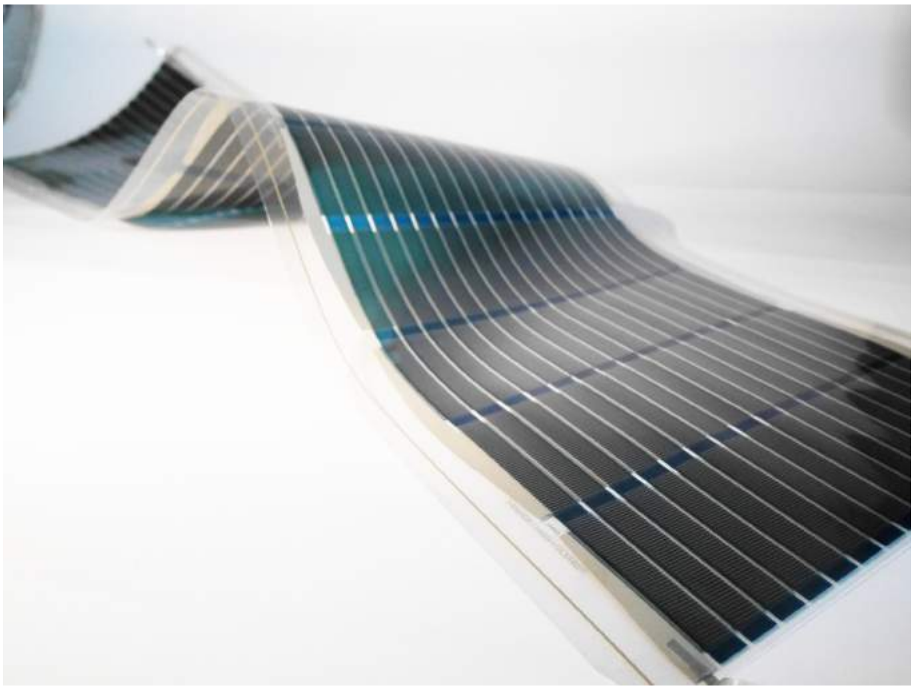

Figure 5.1: Organic solar panel from infinityPV.

5.1.1 Current and voltage

The prototype consists of 6 solar panels, with dimension 100 cm x 30.5 cm. By connecting the solar panels in series the voltage increases, and by connecting them in parallel the current increases. The chosen DC-DC converter has an input voltage level of 160-250 V and a limit power of 30 W, and the solar panels are connected to match this value. Each solar panel generates V_{oc} = 144 V and I_{sc} = 23 mA, which gives a maximum power P_{max} of 2.7 W according to equation

$$P_{max} = I_{sc} \cdot V_{oc} \cdot FF \tag{5.1}$$

where the fill factor (FF) is 80% [3] of the maximum values of V and I as shown in 5.2. The fill factor is essentially a measure of quality of the solar cell and is defined as the ratio of the maximum power from the solar cell to the product of V_{oc} and I_{cs}.

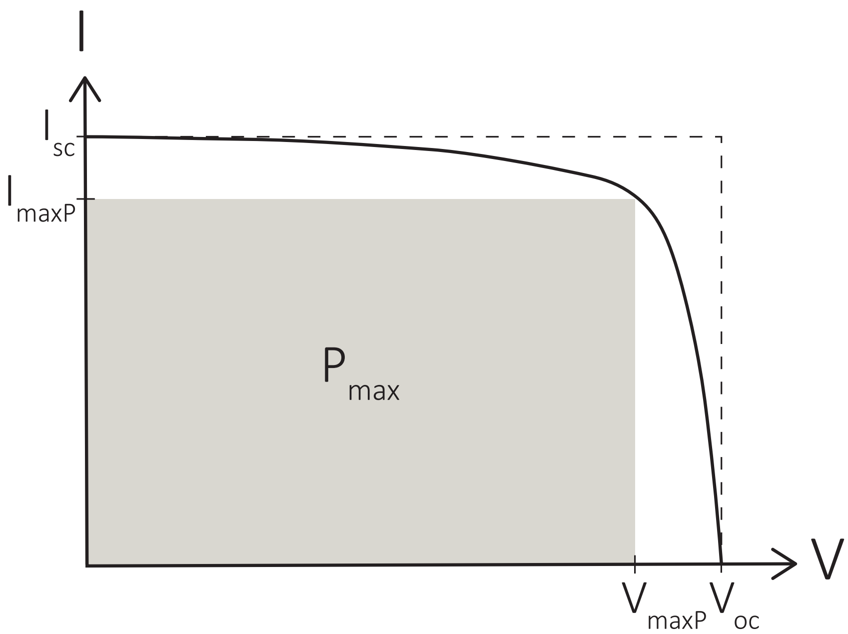

Figure 5.2: Maximum current and voltage.

To match the span of the input value of the DC-DC converter, the panels are connected in series and parallel according to figure 5.1. For this, $I_{sc} = 69$ mA and $V_{oc} = 288$ V giving the maximum power $P_{max} = 16$ W when the panels are connected in such a way. Note that $V_{maxP} = 230$ V and $I_{maxP} = 55.2$ mA.

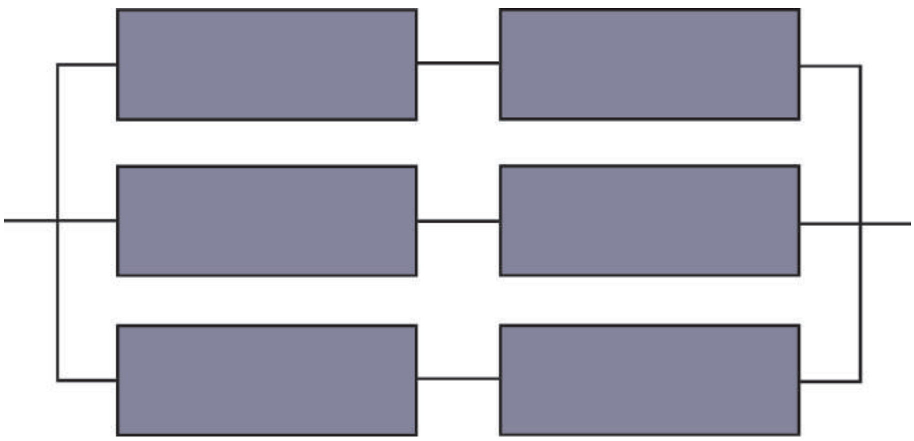

Figure 5.3: Connection of solar panels.

5.2 Electrolyzer

The system of the electrolyzer consists of three main components: a membrane and two electrodes. The anode uses energy from the sun to oxidize water molecules to protons, electrons and oxygen gas. The cathode uses the protons and electrons from the anode to form hydrogen gas. Hydrogen and oxygen are explosive in contact with each other, and this means the electrolyzer needs to keep the gases separated at all times. The membrane splitting the water consists of a nafion plastic, which allows the hydrogen ions to flow freely to complete the electrical circuit in the cell. Water, however, cannot pass the membrane. The anode and cathode require catalysts to drive the water splitting reaction. For the anode side of the nafion membrane, iridium ruthenium oxide is used for catalysts. Platinum is used on the cathode side. See figure 3.2 for a schematic description.

Two electrolyzers have been constructed in the project, called electrolyzer 1 and 2. The electrolyzer used for the prototype is purchased from Fuelcellstore. In figure 5.4 the electrolyzer 2 when put together is shown.

Figure 5.4: Electrolyzer 2.

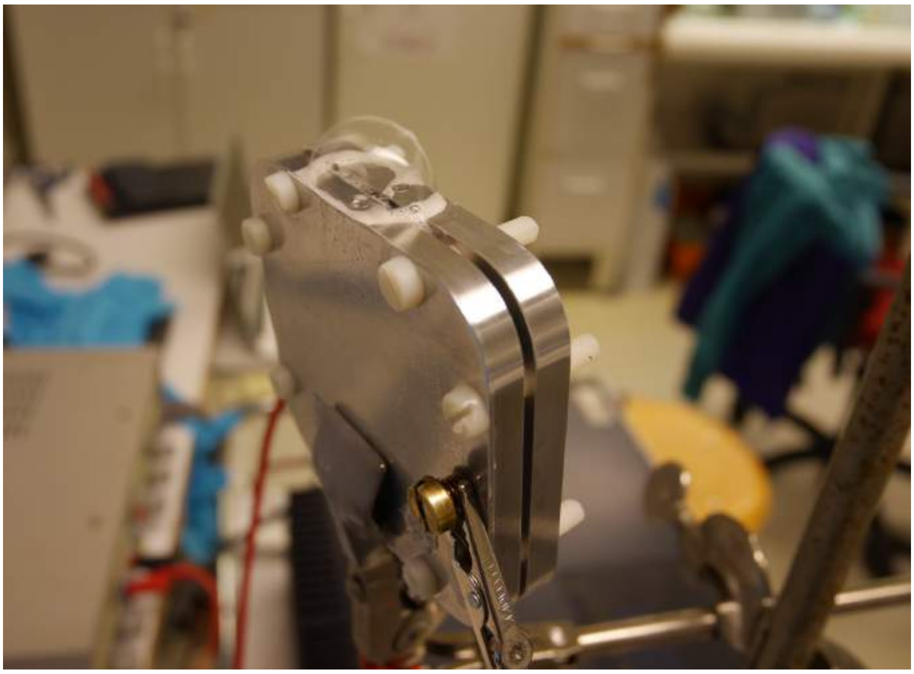

Figure 5.5: Electrolysis, electrolyzer 1.

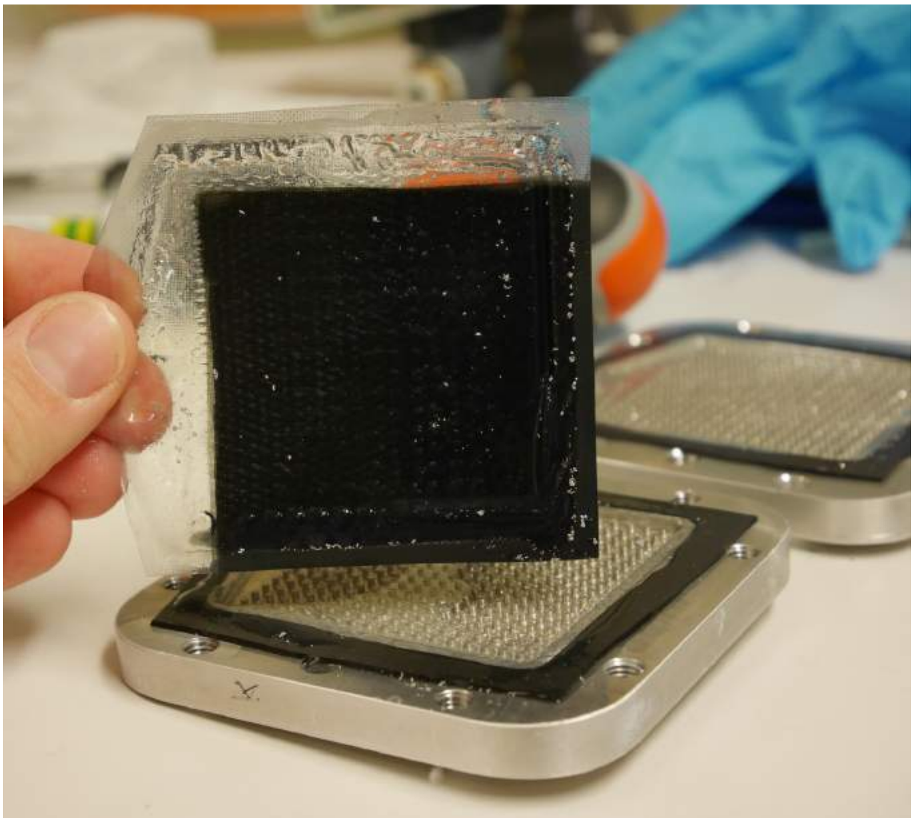

Figure 5.6: MEA after running electrolysis, electrolyzer 1.

5.2.1 Components

5.2.1.1 End plates

The construction of the frames is designed to fulfill the chemical reaction of water splitting. The large outer brass plate keeps the construction parts together, as in figure 5.4. On the anode, there is one connection for water to enter and one for oxygen to leave. On the cathode, there is a connection for hydrogen to exit the electrolyzer. The plates are made of brass and have a thickness of 2 cm.

Figure 5.7: End plates with connections for water, oxygen and hydrogen gas.

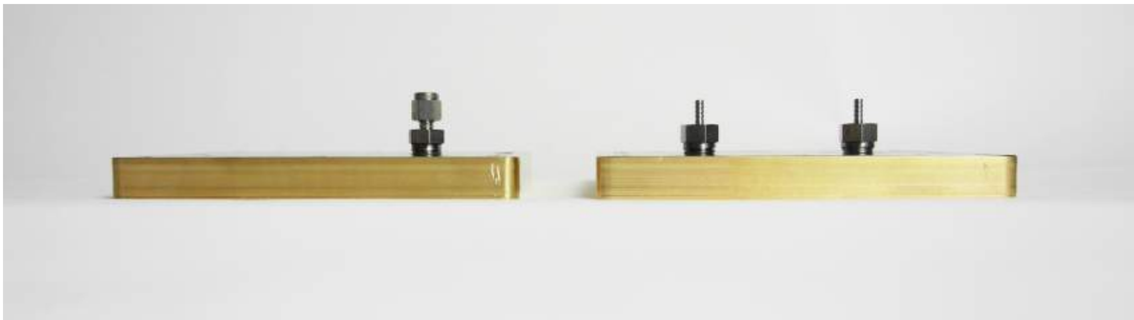

Figure 5.8: End plates electrolyzer 2.

5.2.1.2 Flow field plates

The inner plates, i.e. the flow field plates, have holes for water to enter and oxygen to exit at the anode and hydrogen to exit on the cathode. These plates are separated from the outer plates by a thin layer of silicon. The plates are connected to the solar cells to receive current to run the reactions. On the inside of the plates, channels are made to get a good flow of the gases. The plates are made of brass coated with a thin layer of gold.

Figure 5.9: CNC-milling of flow field plates.

Figure 5.10: Flow field plates with channels for the gases, electrolyzer 2.

5.2.1.3 Titanium screen mesh cloth

Titanium Screens are primarily used in electrolyzer stacks as part of the flow field or diffuser material. The titanium screen is produced from expanded titanium that has been flattened and annealed, ensuring a smooth, flat surface suitable for use in electrolyzer or fuel cell stacks. The titanium screens are used on both the cathode and on the anode side of the electrolyzer and have a thickness of 0.25 mm.

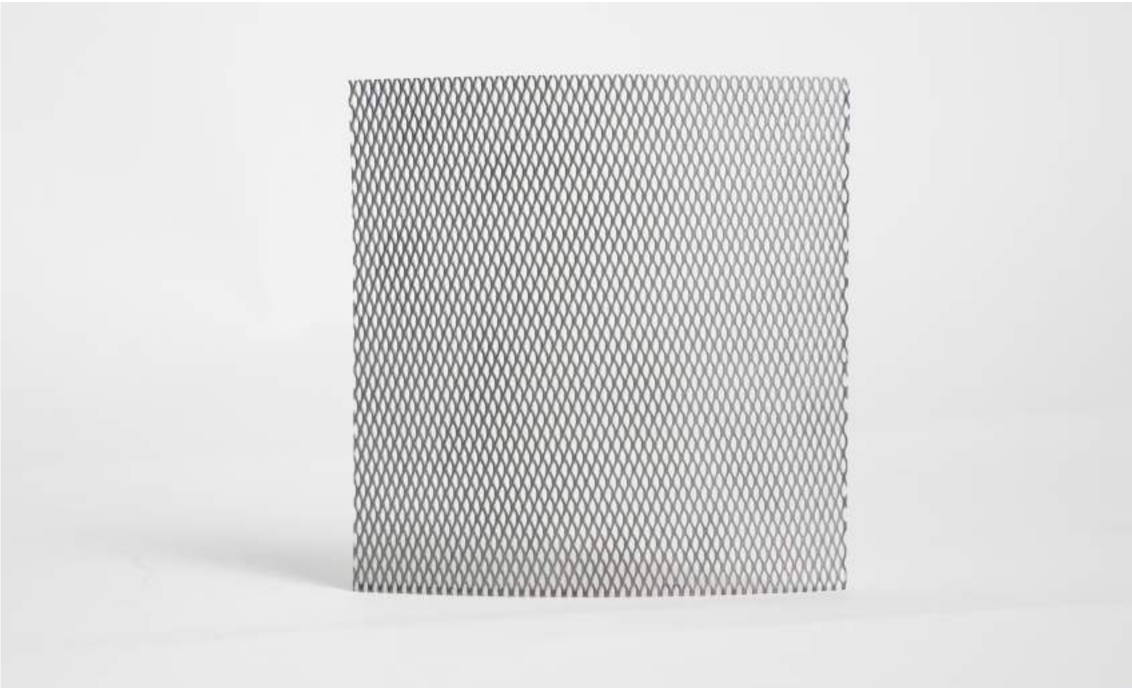

Figure 5.11: Titanium screen.

5.2.1.4 Silicon gasketing

Silicon Rubber Gasketing is used to seal the construction so it is completely tight. Like other silicon, this rubber stays flexible over a wide temperature range and its softness gives it good conformability. The silicon used has a thickness of 0.38 mm.

5.2.1.5 Electrolyzer MEA

Electrolyzer membrane electrode assemblies (MEA) are used for high efficiency production of hydrogen and oxygen gas. They are designed to provide some of the highest efficiencies and purest hydrogen via electrolysis. The membrane is constructed in 3 layers by a nafion 115 layer coated with iridium and ruthenium oxide on the anode (loading 3.0 mg/cm^2) and platinum black on the cathode (loading 3.0 mg/cm^2) and have a thickness of 127 μm.

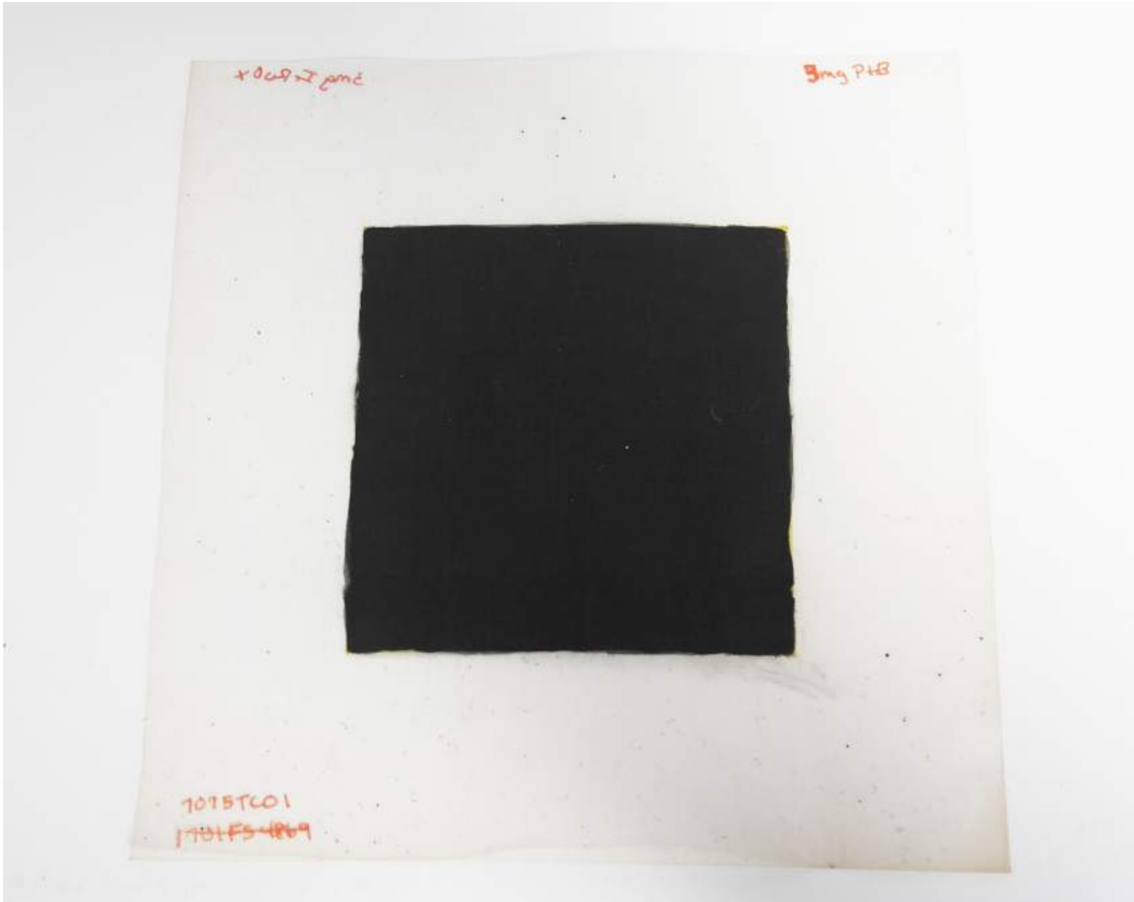

Figure 5.12: Electrolyzer MEA, electrolyzer 2.

5.2.2 Assembling the electrolyzer

Pictures in figure 5.13 show the assembling of the electrolyzer 2 with all its parts included.

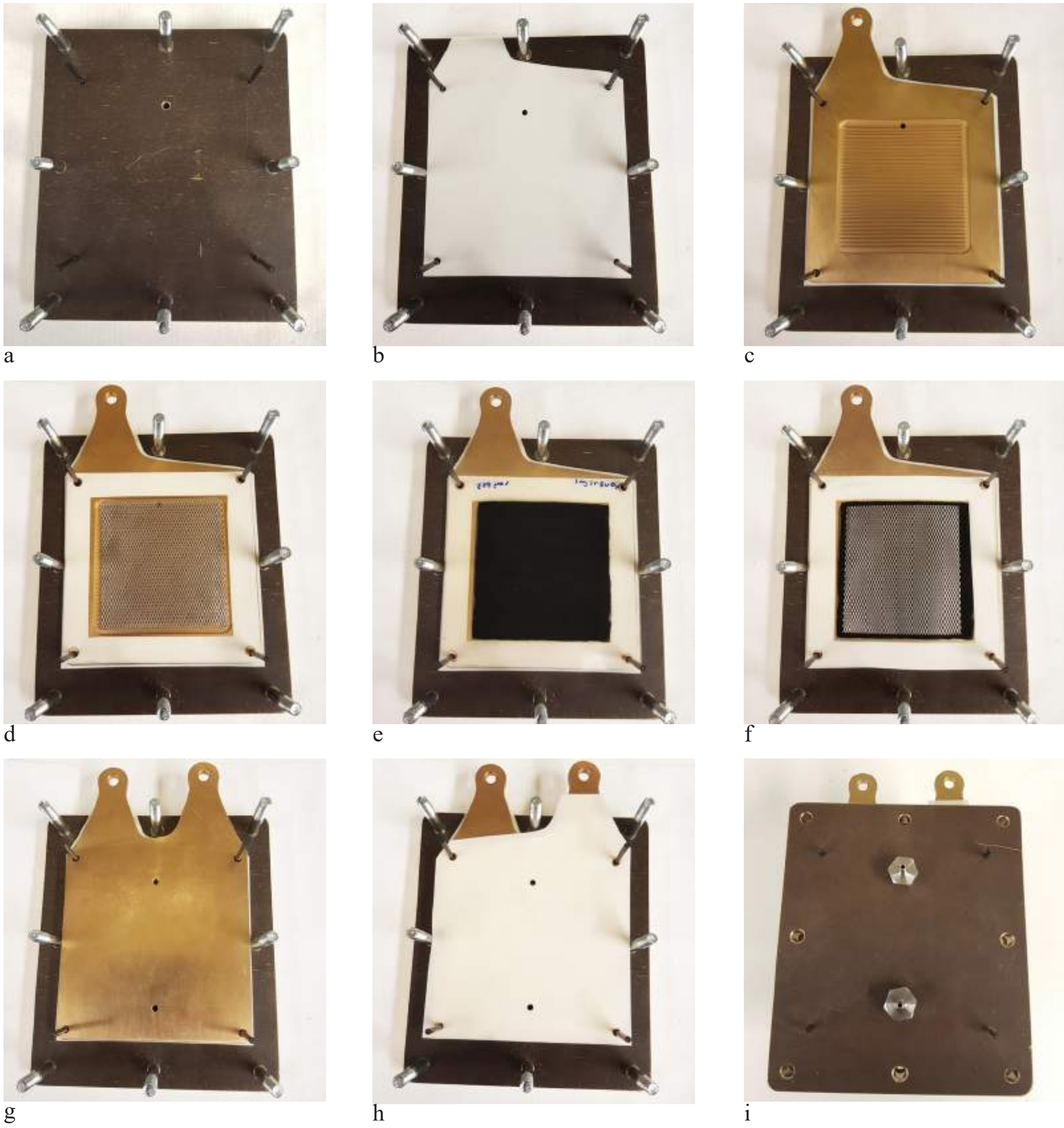

Figure 5.13: Assembling the electrolyzer step by step.

a) Cathode end plate with bolts and a hole for hydrogen to exit, b) silicon gasket on cathode end plate, c) cathode flow field plate, d) cathode silicone gasket and titanium screen, e) electrolyzer MEA, f) anode silicone gasket and titanium screen g) anode flow field plate h) silicon gasket anode flow field plate, i) anode end plate with bolts and hole for water to enter and oxygen to exit.

5.2.2.1 Amount of hydrogen produced

The amount of hydrogen generated by the electrolyzer can be calculated by the equation

$$PV = n \cdot R \cdot T \tag{5.2}$$

$$V = \frac{n \cdot R \cdot T}{P} \tag{5.3}$$

where

P is the pressure of the gas, P=101325 Pa

V is the volume of the gas

n is the number of moles of gas

R is the ideal gas constant, 8.314 $\mathrm{mol}^{-1}\mathrm{K}^{-1}$.

$$n = \frac{Q}{F} \tag{5.4}$$

where Q is the charge transported by a constant current of 1A in 1 second, unit C and F is the Faraday constant, F=96400 C/mol.

5.3 DC-DC converter

A DC-DC converter is an electric power converter that converts a source of direct current (DC) from one voltage level to another. The converter is needed to match the output voltage level from the solar panels, to the input level needed by the electrolyzer. The solar panels generate electricity with high voltage and low current, and the electrolyzer needs a low voltage level and high current. The input voltage of the chosen DC-DC converter is 160-250 V and the output level 2 V. The efficiency of the DC-DC converter is 50%.

Figure 5.14: DC-DC converter.

5.4 Weather balloon

A weather balloon is used for the storage of hydrogen. The balloon has a weight of 350 g and holds 1600 liters of gas. The flexible material allows the flow of production of gas to be seen. When the balloon is full or when hydrogen is needed, there is a tap which empties the gas from the structure. Before the hydrogen gas enters the balloon, a one-way valve prevents the hydrogen from going back into the electrolyzer.

5.5 Setup

The solar panels are glued onto a strong, flexible, transparent plastic sheet of 4x3 meters. This provides the shelter for the roof. The solar panels are connected in series and parallel with 1.5 mm^2 cables. To resist rain, the connections are glued. Roped are attached to the corners of the roof for suspension.

In the middle of the roof is a hole with a pipe connected to the electrolyzer, where the water is collected from rain and further used in the prototype. From the electrolyzer, the oxygen produced is released into the air. The hydrogen is stored in the inflatable weather balloon, from where the energy may be released by a valve. All connections and tubes is Swagelok $\frac{1}{4}''$.

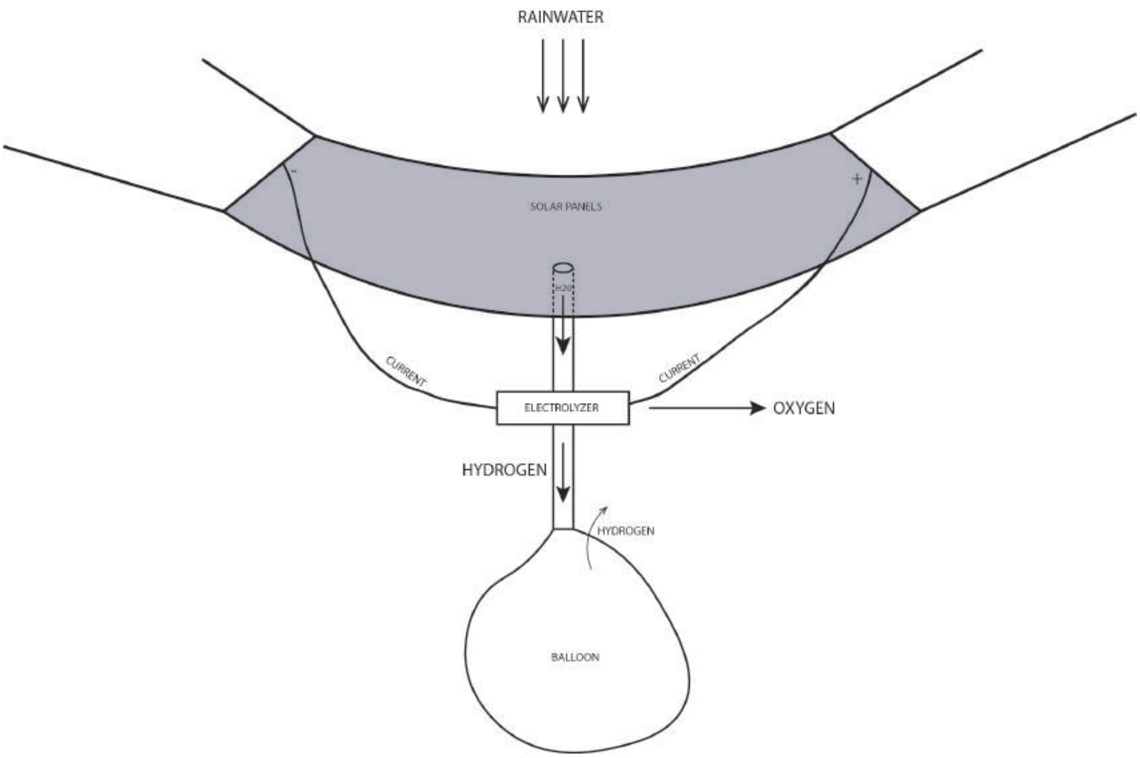

Figure 5.15: Sketch of prototype.

Figure 5.16: Prototype with all its component parts.

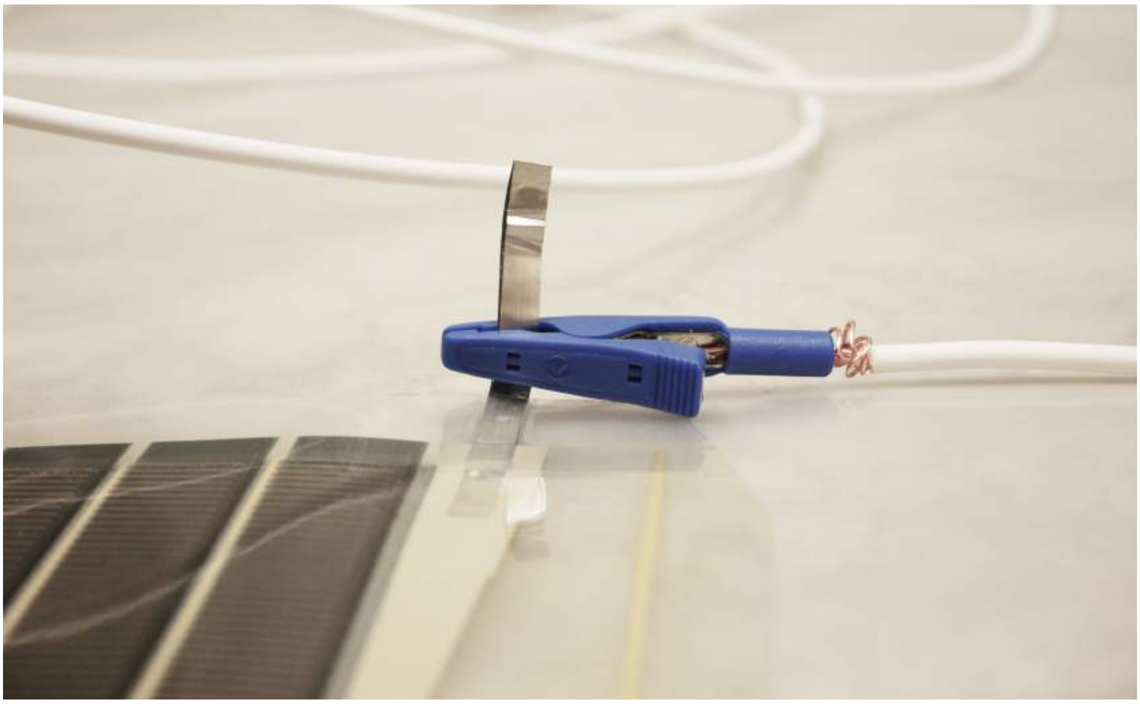

Figure 5.17: Connection between solar panel and cable.

Figure 5.18: Solar panels at the test site for the prototype.

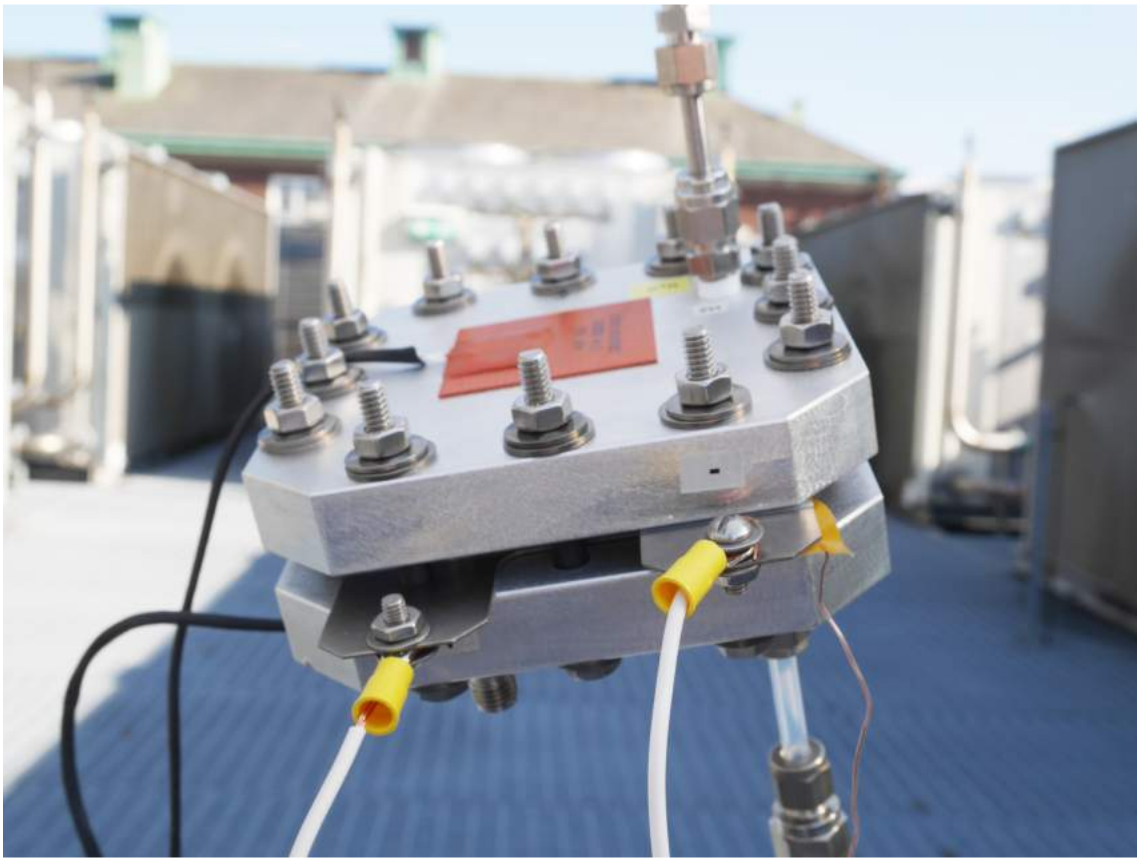

Figure 5.19: Electrolyzer at the test site for the prototype.

Figure 5.20: Electrolyzer connected to the solar roof.

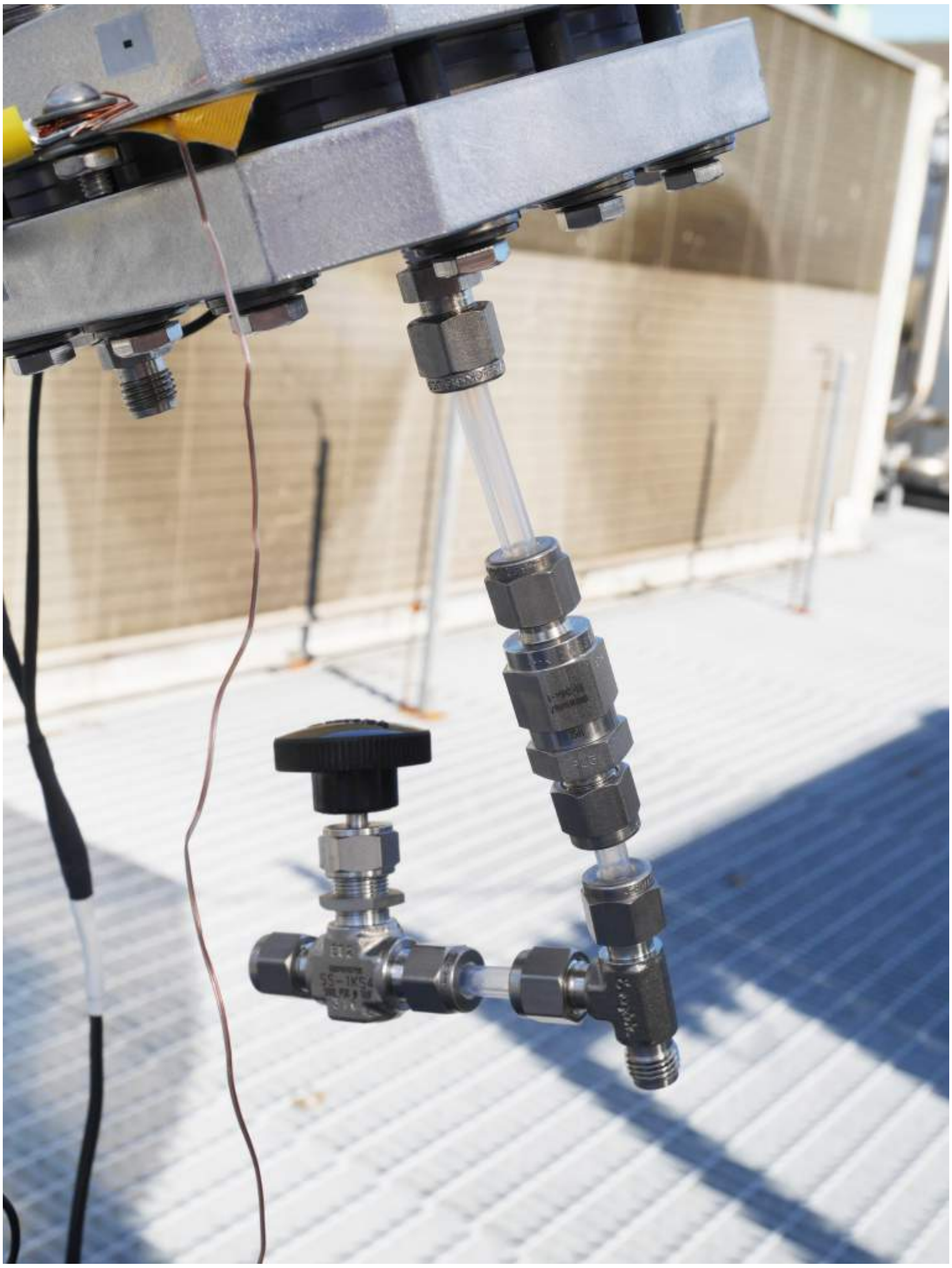

Figure 5.21: Tap for hydrogen to exit the weather balloon.

6

Results and discussion

Since the solar panels broke, the prototype could not be tested all together. The results below discuss the separate parts of the prototype and how they would function together.

6.1 Solar energy

Depending on which converter is used and its limit of input and output, other ways of connecting the solar panels would be needed. The maximum voltage is received by connecting all six panels in series which gives $V_{oc} = 864$ V and $V_{maxP} = 691.2$ V. The maximum current is received by connecting all panels in parallel, which gives $I_{sc} = 138$ mA and $I_{maxP} = 110.4$ mA. Their values are derived from the individual values of each panel stated in section 5.1.1.

6.2 Hydrogen generation

As shown in figure 6.1 the reaction of water splitting begins with a potential of 1.4 V, and then increases as the current is increased. In theory and as calculated in section 3.3.2, the reaction occurs at a potential of 1.23 V. In practice, there are some factors that need to be taken into account. Among those factors are activation energy, ion mobility (diffusion) and concentration and resistance of wire. Furthermore surface hindrance needs to be taken into account, caused by a bubble formation causing the membrane area to be blocked or other obstacles. Because of this an increased potential, an overpotential is required. In this case the overpotential is 0.17 V, resulting from all the factors mentioned and possibly more.

6.2.1 Electrolyzer 1

The electrolyzer 1 is the first constructed electrolyzer of the project. Beacuse of its aluminium frames the electrolyzer was unusable after some experiments due to oxidation at the frames.

6.2.2 Electrolyzer 2

The current connectors of the second electrolyzer were made out of brass covered with gold instead of aluminium, for better electrical contact and for a longer lasting result. Unfortunately, the gold cover was not even enough and therefore this electrolyzer also stopped working after a while. The result was much better than measured by the electrolyzer 1, since it reached a higher current.

6.2.3 Electrolyzer 3

The purchased electrolyzer (electrolyzer 3), as not to sustain damage to the carbon internal components, is able to handle a maximum voltage of 3 V. However it works best up to 2.4 V. The rest of the components in the cell are able to support a current of 70 A without problem. In figure 6.1 the current and voltage of the electrolyzer is shown. In the experiment, the cell operated at room temperature with deionized water. The maximum current of 28 A was achieved at 3 V. At 2.4 V the electrolyzer gave a current of 20 A, which corresponds to a power of 48 W.

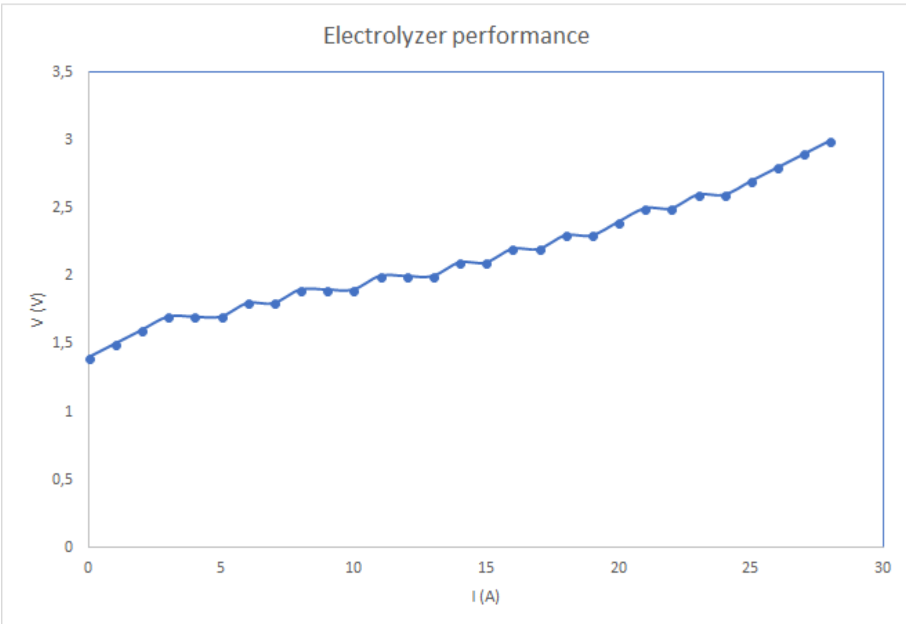

Figure 6.1: Voltage as a function of current.

When the electrolyzer is operating in the prototype together with the solar panels and DC-DC converter, it is not able to operate at its maximum since the power of the solar panels together with the DC-DC converter is limited. Since the maximum power of the solar panels is 16 W and the DC-DC converter only has an efficiency of 50%, the limit of the power is 8 W. Since the output of the DC-DC converter is 2 V, the output of the current is 4 A.

According to equation 5.3, the hydrogen generation of the electrolyzer in the prototype is $V_{H_2} = 4.99 \cdot 10^{-7}$ m^3/s when used together with the other components.

If the DC-DC converter had a higher efficiency, let's say 100%, then the hydrogen generation would be doubled $V_{H_2} = 9.97 \cdot 10^{-7}$ m^3/s. If the converter had been able to handle a higher voltage, the hydrogen production would be larger. When the electrolyzer has a voltage of 2.4 V it corresponds to a current of 20 A, which gives the volume of H_2 $V_{H_2} = 2.49 \cdot 10^{-6}$ m^3/s.

To improve the results, heated water should be used. The electrolyzer generally prefers a water temperature of 60°C but can be pushed to 80°C. Since the output value from the DC-DC converter is around 8 W, the limit was set by this value and a higher current from the electrolyzer could not be received. However, if another DC-DC converter with higher efficiency had been used, a higher generation of hydrogen would have been possible, both with and without heated water. Also, the purpose of the prototype is to use rain water, which is one of the reasons the water has not been heated up. Cold water is counterproductive to efficiently operating the cell. To be able to use rain water, a filter is needed to clean the water before it enters the electrolyzer.

Another change to improve the results of the electrolyzer is to use other catalysts of the membrane inside the cell. A lot of research is going on to optimize this.

6.3 Materials

The materials of the prototype are used for a short period of time, only around a couple of weeks for testing. If the prototype were to stand for a longer time, materials and the way it is set up would need to improve. The weather balloon works for a low generation of hydrogen. If the generation were much higher so that there was a large pressure inside the balloon, this would need to be taken into account. One way could be to make the output valve automatically switch on when there is a predetermined pressure inside the balloon. This to prevent the balloon from exploding. The hydrogen should then be stored in a pressure tank which can handle a pressure up to 700 bar and is safe for this purpose.

7

Conclusion

The main purpose of the prototype is to apply the method of producing hydrogen gas through electrolysis on architecture, which in this case is a roof. With this said, the purpose of the prototype has not been to optimize the electrolyzer, nor the other components of the prototype.

There is a large potential to optimize the overall prototype by optimizing its component parts. By choosing solar panels that generate a higher power, a DC-DC converter with higher efficiency and other catalyst material in the membrane of the electrolyzer, an overall optimization could be achieved.

To use the prototype for longer usage or in larger scale, other materials would need to be considered, both for the stabilization of the construction and also for safety reasons. The materials and the construction need to take the weather and different seasons into account. The storage of hydrogen would also need to be considered since the balloon can only handle a low pressure of gas and it can easily break due to extreme weather.

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