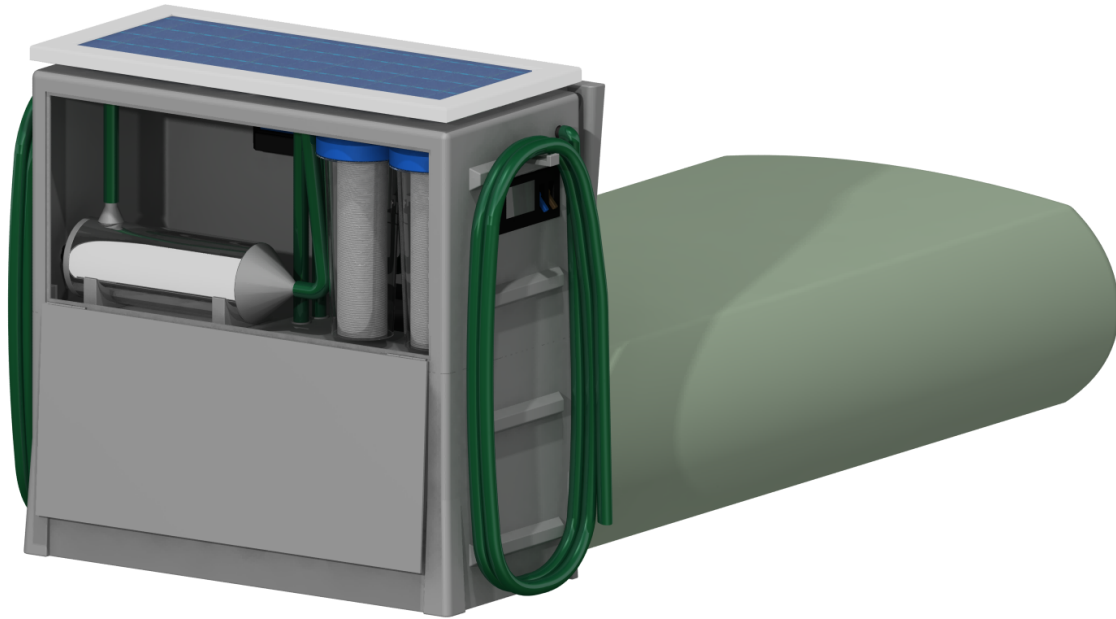




CHALMERS
UNIVERSITY OF TECHNOLOGY



The development of a solar driven water purifier for emergency use

Master's thesis in Product Development

Pontus Dackhammar
Edvin Hansson

MASTER'S THESIS

**The development of a solar driven water purifier
for emergency use**

PONTUS DACKHAMMAR
EDVIN HANSSON



CHALMERS
UNIVERSITY OF TECHNOLOGY

Department of Industrial and Materials science
Division of Product Development
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2020

Product Development Master's thesis
PONTUS DACKHAMMAR AND EDVIN HANSSON

© PONTUS DACKHAMMAR AND EDVIN HANSSON, 2020.

Supervisor: Pär Wallin, ESSIQ AB
Examiner: Erik Hulthén, Department of Industrial and Materials science

Master's Thesis
Department of Industrial and Materials science
Division of Product Development
Chalmers University of Technology
SE-412 96 Gothenburg
Telephone +46 31 772 1000

Cover: A solar driven water purification system.

Typeset in L^AT_EX
Gothenburg, Sweden 2020

Product Development Master's thesis
PONTUS DACKHAMMAR AND EDVIN HANSSON
Department of Industrial and Materials Science
Division of Product Development
Chalmers University of Technology

Abstract

Natural disasters are a growing global problem, which often negatively affect the availability of clean water and sanitation by polluting water sources and damaging water infrastructure. From the year 1995 to 2005, 90% of all disasters were caused as a consequence of weather-related events. Out of these disasters, flooding and storms accounted for approximately three quarters all of events. The aim of this thesis work was therefore to develop a solar driven water purifier, to be used in an emergency setting by providing 100 persons with clean water every day. The work involved a pre-study, generation and screening of multiple concepts, detailed design and calculations as well as a commercial analysis.

The final product is a stackable, robust, and compact system, designed to reduce the costs related to transportation. The purification process consists of a pre-filtration system and an ultraviolet disinfection unit, that reduces microbiological contaminants by a factor of 10^4 . The system receives power via solar cells and has a battery that can provide the system with power up to 3 days without any solar radiation. There is a flexible clean water tank with a capacity of 250 liters attached to the body of the system.

The analytical result, in particular for the UV-unit, needs physical testing to be validated. Therefore is it essential to build a prototype, preferably using the drawings provided in the report, to verify the product's performance. There is also a need for more detailed design regarding the electrical system before a potential commercial launch.

The estimated production cost for the system is 3369 SEK and given a unit margin of 50%, this translates to a competitive theoretical listing price compared to similar products on the market. By comparing the estimated total cost, including expected maintenance, the results indicates that I would take approximately 7 months of usage for the final product to have a significantly lower total cost than the LifeSaver Jerry Can, identified as one of the main competitors.

Keywords: water, purification, ultraviolet, emergency, natural disaster

Acknowledgements

The authors would like to sincerely thank Erik Hulthén for providing support throughout the work as well as for being the examiner for this thesis. Another acknowledgement shall be given to ESSIQ AB, and in particular Pär Wallin, for laying the basis for this thesis as well as for providing support and valuable knowledge.

The authors would also like to thank all the interviewees who participated in the customer needs identification process and to Pär Falk, who led the study visit at Alelyckan's water purification plant.

Edvin Hansson and Pontus Dackhammar, Gothenburg, June 2020

Contents

1	Introduction	1
1.1	Background	1
1.2	Aim and research questions	1
1.3	Scope	2
2	Pre-study	3
2.1	Searching for a market opportunity	3
2.1.1	Water pollution trends	3
2.1.2	Target market	5
2.1.3	Case study - 2010 Haiti earthquake	7
2.2	Customer needs identification	8
2.3	Water contaminants	10
2.4	Technology analysis	12
2.4.1	Pre-filtration	12
2.4.2	Membrane filtration	12
2.4.3	Disinfection	13
2.4.4	Other methods	14
2.5	Competitor analysis	15
2.5.1	Patented products	15
2.5.2	Non-patented products	15
2.6	Mission statement	17
3	Concept development	19
3.1	Requirements specification	19
3.2	Concept generation	19
3.2.1	Function tree	20
3.2.2	Idea generation	20
3.2.3	Morphological matrix	20
3.2.4	Elimination of sub-function ideas	20
3.3	Concept selection	26
3.3.1	Concept 1: SODIS	26
3.3.2	Concept 2 & 4: Ultrafiltration	27
3.3.3	Concept 3 & 5: Electric UV disinfection	28
3.3.4	Comparison between concepts	29
4	Further development	33

4.1	System layout	33
4.2	System capacity	34
4.3	Design of the purification system	35
4.3.1	Pre-filter design	35
4.3.2	Pump design	37
4.3.3	UV-system design	38
4.4	Dimensioning and design of power supply	45
4.4.1	Battery sizing	45
4.4.2	Solar panel sizing	46
4.4.3	Solar charge controller	48
4.4.4	Body and clean water tank	48
5	Manufacturing processes and materials selection	51
5.1	Clean water tank	51
5.2	UV-lamp housing	54
5.3	UV-lamp adapters	56
5.4	Body	57
6	Final concept	59
6.1	Final design	59
6.2	Assembly and usage	63
7	Commercial assessment	65
7.1	Estimated total production cost	65
7.2	Benchmarking against the Lifesaver Jerry Can	66
8	Discussion	69
8.1	Water source quality	69
8.2	Pre-filters	69
8.3	Water pumps	70
8.4	UV-lamp	70
8.5	Battery	71
8.6	Body and clean water tank	71
8.7	Fulfillment of requirements	71
8.8	Estimated Production cost	72
8.9	Development Process	72
9	Conclusion	73
	References	75
A	Appendices	I
A.1	Study visit at Alelyckan drinking water purification plant	I
A.2	Patents & solutions	II
A.3	World risk map	VIII
A.4	Requirements specification	IX
A.5	Morphological matrix	X
A.6	Pugh matrix	XI

B	Calculations	XIII
B.1	Pump Calculations	XIII
B.2	UV-calculations	XVII
B.2.1	Optimization.m	XVII
B.2.2	fun.m	XIX

1

Introduction

This report covers a master's thesis that was carried out between January to June, year 2020. The thesis was a collaboration between Chalmers University of Technology and ESSIQ AB and performed by two Chalmers students who have a background within mechanical engineering and product development.

1.1 Background

ESSIQ AB is a consultancy firm, who operates in many different branches such as automotive-, medical- and information technology. ESSIQ is owned by the investment company Fourwise AB, who also partly owns the startup company Solros AB. Solros develops a product that brings real sunlight into dark rooms through fiber-optic cables, by using a large lens that follows the sun throughout the day and concentrates the solar energy into the fibers.

With inspiration from this product, the management team at ESSIQ wanted to see if solar energy could be used to purify water, since the lack of safe drinking water is a huge global problem that causes the death of millions of humans every year. This Master's thesis was therefore initiated to investigate the possibility to design a product that purifies contaminated water by using solar energy, possibly in combination with Solros existing solution. By using solar power instead of traditional fossil fuels, it is possible to make the product emission free and environmentally sustainable. This also makes it possible for the product to be used without any dependency on external energy, such as diesel or electrical grids, which will make the product versatile in remote areas with high solar density.

1.2 Aim and research questions

The aim of the thesis is to develop a solar driven water purifier. The following research questions needs to be answered to fulfill the aim.

- Which markets hold the biggest potential for a solar driven water purifier?
- Who are the main stakeholders and what demands do they have?

- What existing water purification technologies exist and what types of contaminants do they remove?
- How should such a product be designed to fulfill the demands of the potential customers?
- How well does the final product stand against the main competitors?
- What is the production cost of the final product and what listing price is needed to achieve a financially stable product?

1.3 Scope

The product will be delimited to involve solar energy to some extent. For this reason, the solution will be most suitable for markets that are exposed to a high amount of solar energy. However, the solution may be combined with other non-solar driven purification methods, such as for example pre-filtration. It is assumed that contaminated water will be available in the areas in which the system will be utilized, thus the project will not consider the aspects of collecting water.

The thesis is expected to deliver detailed CAD-models but is delimited to not produce a physical prototype. The project is limited in terms of time, ranging from the start of the project, the 20th of January 2020, until the end of the project at the 5th of June 2020.

2

Pre-study

A pre-study was performed to gain knowledge regarding the market opportunities and needs, types of water contamination, existing water purification methods as well as patented products and other competitors.

2.1 Searching for a market opportunity

Given that the development team had little knowledge regarding the need for a solar driven water purifier, the thesis started with a search for a market opportunity for such a product.

2.1.1 Water pollution trends

One of the World's 17 goals for a better world by year 2030, is clean water and sanitation for all human beings (Project Everyone, 2015). According to the World Health Organization, at least two billion people are drinking contaminated water on a regular basis. These people are risking many serious diseases such as diarrhoea, cholera, dysentery, typhoid and polio. Almost half a million people are estimated to die each year from drinking contaminated water by getting diarrhoea, which happens mainly in developing countries with the majority of the victims being children under 5 years of age.(United Nations, 2014) (WHO, 2019)

There have been many efforts to improve the availability of clean, safe drinking water in the world. According to the report *Progress on Sanitation and Drinking Water* by UNICEF and WHO, one example of such effort is the Millennium Development Goal 7 (MDG 7), signed by the United States of America. One of the goals of this agreement was to half the proportion of the World's population who do not have access to safe water, from year 1990 until year 2015. The overall goal of the MDG 7 was met and the proportion of people who have access to safe drinking water increased from 76% in 1990 to 91% in 2015, well above the goal of 88%.(WHO & UNICEF, 2015) These numbers are very positive and indicates that the trend is going in the right direction.

However, there is another type of water pollution that has been progressively increasing in frequency, caused by sudden water pollution. These accidents are hard

to predict and involves much uncertainty, both when it comes to where the accident will occur but also its magnitude.(Cheng, Wang, & Lu, 2018)

According to *The Human Cost of Weather-Related Disasters (2015)*, 90% of the disasters between 1995 and 2015 were caused as a consequence of weather-related events. Over this period nearly 6500 weather-related disasters were documented. Between 2005 and 2014 there were an average of 335 water related disasters documented per year, which was an increase of 14 % from the period between 1995 and 2005 and almost the double of what was documented between 1985 and 1994. These statistics indicates that weather related disasters are a growing problem and will affect even more people as our population is growing. Out of the nearly 6500 weather-related disasters the majority of these were caused by flooding and storms, accounting for 47% and 28% of the disasters respectively. The other documented disaster types are earthquakes, extreme temperatures, landslide, drought, wildfire and volcanic activities. These disaster types account for 8%, 6%, 5%, 5%, 4% and 2% of the disasters respectively. (CRED & UNISDR, 2015)

There is a strong link between a country's economy and its access to clean water. Therefore are surface water pollution accidents (SWPA), caused by for example natural disasters, heavily destructive for a country's economic growth, especially in the case for developing countries. (SIWI, 2005) According to a report by Yao, You and Liu (2016), the amount of SWPA in China have been growing in the recent years. The report studied how SWPA affects the economy and found that there are serious economic losses related to SWPA. The authors classified the potential economical damages into eighth different categories; damages to human health, water supply suspension, damages to fisheries, damages to recreational functions, damages to biological diversity, damages to environmental properties, damages to pollution sources as well as other indirect damages.

The report also looked at a previous serious water pollution caused by an explosion at a biphenyl production workshop in 2006, which polluted the Songhuajiang river in China. The authors used mathematical models to estimate the economic losses of that specific accident, by using scaled data from 2006, one year after the accident. The result indicated a total loss of 2263 billion CNY (324 BUSD), whereof 5.3 billion CNY (0.76 BUSD) was related to direct economic losses. (Yao, You, & Liu, 2016)

2.1.2 Target market

In order to identify potential target markets for a water purifier that is driven by solar energy, a screening process were done which is illustrated in a process flow chart in figure 2.1.

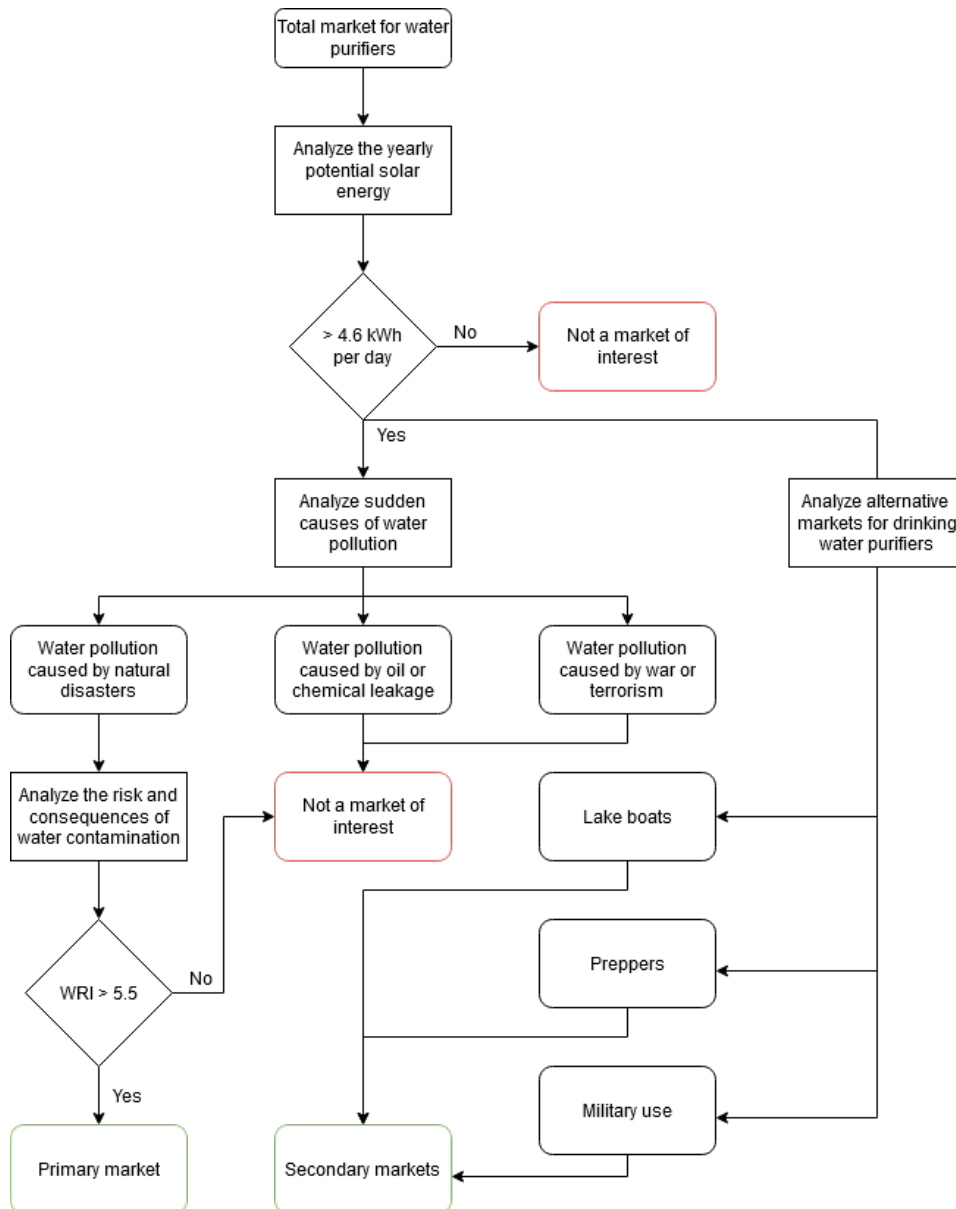


Figure 2.1: Process flow chart visualizing screening of markets.

Since solar energy will be used as the main power source, it was of interest to search for regions with high solar density. The global horizontal irradiance (GHI) was chosen as an appropriate unit for examining the solar power potential, since this unit is the sum of the direct sun radiation and the diffuse solar irradiance, perpendicular to the earth. Figure 2.2 visualises how the GHI is distributed over the world. The map indicates a higher potential for countries near the equator and

2. Pre-study

in the southern hemisphere. Figure 2.2 was used as reference when narrowing the regions, eliminating regions with a daily total below 4.6 kWh/m² as potential target markets.

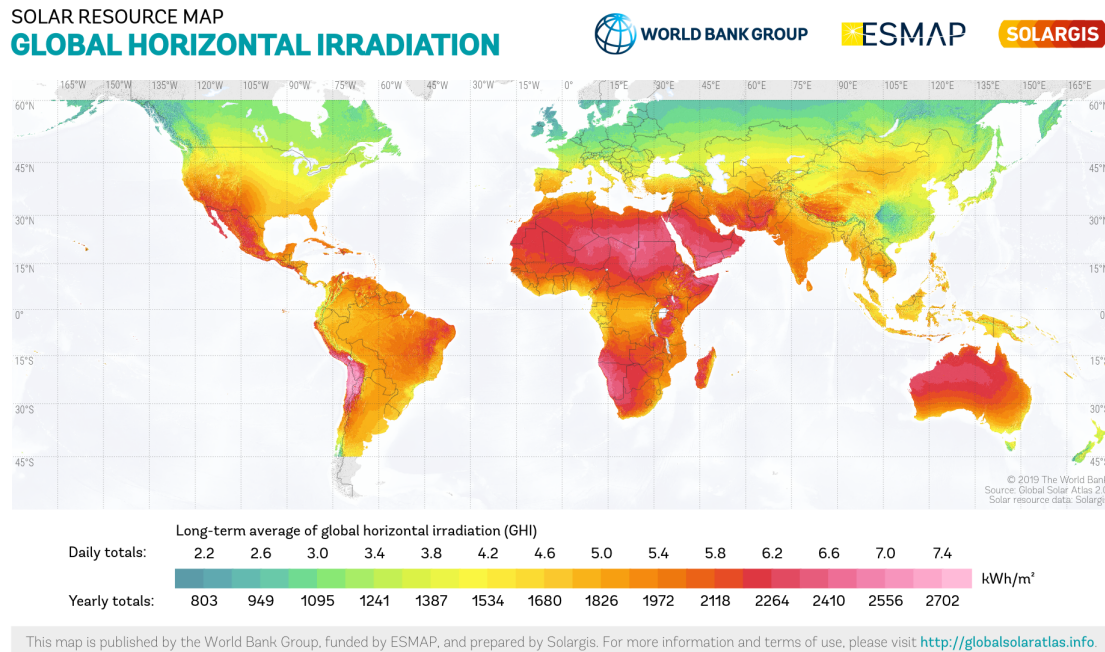


Figure 2.2: Global horizontal irradiance (Solargis, 2020)

The market was then analyzed in terms of the risk for sudden water pollution. Three major different causes of sudden water pollution accidents were identified; natural disasters, chemical or oil leakage and war or terrorism. Based on the increasing weather-related natural disasters, as discussed in section 2.1.1, it was decided that natural disasters would be the primary cause of concern in this project.

The remaining markets were then narrowed down by eliminating regions with a low risk for natural disasters. The private aid organization Bündnis Entwicklung Hilft, in cooperation with the United Nations University in Bonn, have developed World Risk Index (WRI) that quantifies the risk of water contamination and shortage during a natural disaster. The index is based on four different factors; the exposure to disasters, susceptibility and the ability to cope and to adopt to disasters. Regions with a WRI below 5.5 was categorized to have a low to very-low risk and were eliminated, see appendix A.7.(Day et al., 2019)

By combining the GHI and WRI maps, the regions of interest turned out to be the majority of Africa, Southeast Asia, southern parts of North America and western parts of South America. It is expected that the level of technicality and knowledge of the available resources will be relatively low, thus a solution requiring minimal maintenance is of importance.

To expand the potential markets, alternative markets with similar needs as the pri-

mary market were considered. This resulted in three secondary, alternative markets, that can be of interest; lake boats, preppers and military use.

2.1.3 Case study - 2010 Haiti earthquake

To provide a more detailed description regarding the need of innovative water purifiers, a case study from the Haiti earthquake in 2010 was analyzed. Haiti is a typical target market that both has a high solar irradiance as well as a high risk to be heavily affected by natural disasters.

Haiti is an island in the Caribbean and is one of the poorest countries in the world. In January 2010, a massive earthquake with magnitude 7.0 on the Richter scale hit Haiti, damaging infrastructure and killing approximately 230 000 persons and injuring another 300 000. The disaster made over 1 million internally displaced persons (IDP) to take shelter in one of the emergency settlements in the capital and its surrounding areas. Relatively fast portable water was transported to the IDP camps by tankers, organized by DINEPA, international organizations and local agencies. However, there were big differences over the country; in 2010, 85 % of the people living in urban areas had access to improved water, but for the rural population this number was only 51 %. (Gelting, Bliss, Patrick, Lockhart, & Handzel, 2013) In October the same year, an epidemic of cholera broke out, according to Tappero and Tauxe (2011). The main cause of this outbreak was contaminated water sources, used by the local people. The authorities told the people to either boil or chlorinate their water, but many lacked sufficient means to be able to do so. (Tappero & Tauxe, 2011)

As a consequence of the earthquake and cholera outbreak, many water points were installed around Haiti to provide the inhabitants with fresh water. In March 2013, a study by Widmer et al (2014) identified 377 water points in the area around the cities Leogane and Gressier, and collected data for these regarding the constructor as well as its management strategy, see table 2.1 (Widmer et al., 2014)

Table 2.1: Data from Widmer et al (2014)

Construction information	Count	Percentage
Number constructed pre-earthquake	3	0.8%
Number constructed post-earthquake	374	99.2%
Total constructed post-earthquake	377	100.0%
Constructed and marked by IO/NON	213	56.5%
Constructed with no sign of sponsor	132	35.0%
Constructed by community	13	3.4%
Privately constructed	16	4.2%

As seen above, the majority (56.5%) as all the water points were constructed and marked by either International Organizations or Non-Governmental Organizations. The second biggest group (35.0 %) of water points had no sign of a sponsor, meaning

that it could be set up by IO/NGOs, as well as any other organization. Only a small percentage of all the water points were constructed by the community or by private persons.

Out of the total 377 water points identified, 263 of these were improved sources and 82 unimproved. Out of the improved water sources, the average Fecal coliforms were 18.7 CFU/100 ml, well above the recommended value by Sphere, see chapter 2.3 for more detailed information regarding CFU and the Sphere standards. However, the standard deviation was high and main contributors to the high average were a few water points which had very high concentrations of Fecal coliforms. Approximately 85 % of all improved water points had Fecal coliform below 10 CFU/100 ml, meaning that a few of the water points had very high values of Fecal coliforms. (Widmer et al., 2014)

The case-study indicates that IO/NGO's are the main contractor of water points, hence these will be seen as the main potential customer for water purifiers. The study also indicates that some of the improved water sources significantly exceeded the recommended value by Sphere standard, indicating that there is a need for better improved water points.

Another important take away from the study is that a natural disaster can affect societies for a long time after the actual event. In the case of Haiti, this manifests in the lack of clean water and sanitation many years after the earthquake. The conclusion from this is that a water purifier for disaster relief needs to have a relatively long life-length, for the society to have time to repair its infrastructure.

2.2 Customer needs identification

In order for the product to fill a clear market gap, it was important to recognize the needs for the potential customers. There are many non-governmental organizations who are working with water purification towards distressed areas. These organizations are of high interest in our case, since they both have technical knowledge regarding different products and techniques, as well as real-life experience of working in disaster areas.

Four semi-structured interviews were carried out with persons with varied backgrounds from Oxfam, The Red Cross, Engineers Without Borders and Doctors Without Borders. The interviews started with a brief description of the project, followed by a set of questions regarding their and their organizations role during crises, their existing solutions, challenges during emergencies, important parameters and properties for water purification, the distribution process and more. The interviews were held either face to face or through Skype and lasted approximately one hour. The different interviewees and their role are:

- Sophie Mack-Smith. Communication coordinator, Oxfam.
- Malin Denninger. Water, sanitation and hygiene (WASH) advisor, The Red

Cross.

- Mårten Skogh. Head of Internal Coordination and Innovation, Engineers without borders.
- Mikael Mangold. Field water engineer, Doctors without borders.

Table 2.2 provides a summary and the takeaways from the interviews. All of the interviewees stated that it is the microbiological contaminants in the water that are the main concern after a natural disaster. The contaminants will be further discussed in section 2.3. They were all, to some extent, using the Sphere Handbook (Sphere Association et al., 2018), as a set of standards during their humanitarian responses. Other standards used are the WHO- drinking water guidelines, specific regional standards or their own standards. However, all the standards concerning the water quality and quantity are of similar nature.

Being able to desalinate the water is not considered a necessity as freshwater seldom is unavailable and having desalination would increase the cost a lot. The production capacity was discussed with the interviewees and a capacity of providing 100 persons with drinking water was suggested by the development team. Only Malin from The Red Cross expressed an uncertainty for the need of a system providing around 100 people with water, with the argument that she thinks that smaller household water treatment systems can be used effectively to handle that quantity.

The most important properties for an emergency water purifier are robustness, simplicity and cost, as collected from the interviews. The system must be able to withstand the various environmental conditions which prevails after natural disasters and it should not have any parts that has a high risk of malfunction. As for the simplicity, it is vital that the product is easy to use and has a intuitive design. If the product is intended to be used by local people, a short tutorial should be sufficient for people to understand how to operate the system.

The cost is always of importance during humanitarian response as the resources is limited and being efficient is a must. During the interviews, the distribution process for emergency goods were discussed. It was mentioned that the air shipment of resources constitutes a large part of all the expenses during responses. The final part of the distribution chain is often uncertain and there is not always functioning roads where vehicles can drive, thus it is beneficial if the product can be carried by hand. Below follows a table of customer desires that were interpreted out of the interviews.

Table 2.2: S.M.S - Sophie Mack Smith at Oxfam UK, M.D - Malin Danninger at Red Cross, M.M Mikael Mangold, Doctors without borders

No.	Customer desires	S.M.S	M.D	M.M
1.	Ability to adjust for different contaminants	X		
2.	Possibility to carry by hand	X		
3.	Easy to operate	X	X	X
4.	Ability to purify surface- and grond water	X		
5.	The water should taste good	X		
6.	Possibility to operate without external energy	X		
7.	High robustness	X	X	X
8.	Low environmental footprint		X	
9.	Scalable for diffrent production rates		X	
10.	Quick assembly		X	
11.	High level of guessability		X	
12.	Low cost	X	X	X

2.3 Water contaminants

The first step to better understand the science behind water purification is to identify which contaminants that are the most common and where they occur. According to the Environmental Protection Agency (EPA), water contaminants can be categorized into four general groups. The first one is physical contaminants, which mainly affect the appearance, such as the transparency, or the physical properties of water. The amount of physical contaminants can be determined by measuring the turbidity of a water sample. Example of physical contaminants are particles of rust, dirt, sand or sediments. It can also be organic matter coming from decaying plants and animals. Physical contaminants themselves do often not pose a health threat for humans. However, they make the process of removing other disease-causing contaminants harder. In addition, physical contaminants may foster the regrowth of certain harmful contaminants.

Chemical contaminants on the other hand could consist of for example salts, heavy metals, pharmaceuticals and pesticides. These materials are both naturally occurring but also man-made. People that consume high levels of chemical contaminants in drinking water risk acute and in some cases life-threatening illnesses. Chemical contaminants are often dissolved in the water and can be energy demanding to remove.

Radiological contaminants, also known as radionuclides, are substances such as uranium and radium. Radionuclides exists naturally in the ground water in some areas but also originates from man-made activities such as mining, medical facilities and nuclear power plants. Drinking water consisting of radionuclides is known to increase the risk of cancer and kidney diseases.

Biological contaminants, also known as microbiological contaminants or pathogens,

are disease-causing microorganisms such as bacteria, viruses, protozoa, parasites, worms and fungi. Pathogens exist everywhere on our planet but end up in our water mainly from human and animal faeces due to insufficient or non-existent sewage systems. Cholera, diarrhoea, dysentery, hepatitis A, typhoid and polio are some of the waterborne diseases caused by pathogens. (Environmental Protection Agency 1, n.d.) (Environmental Protection Agency 2, n.d.)

To encourage healthy living and prevent diseases, there are guidelines for drinking water-quality. These guidelines can vary between countries and regions but the most recognized and widely used guideline is the World Health Organization's (WHO) guidelines.

In the case of emergencies however, chemical and radiological contaminants are often given a lower priority than microbiological contaminants, since the negative health effects caused by the chemical and radiological contaminants generally is a result of a prolonged exposure. The effects caused by microbiological contaminants on the other hand, often have an immediate impact (Thompson et al., 2007). According to WHO it is of higher priority to be able to supply water during an emergency even though it significantly exceeds their guideline values for chemical and radiological values to water, in order to reduce the risk of waterborne disease outbreaks. This provided that the microbiological contaminants are reduced and that the water can be supplied quickly. Out of that reason, it is not uncommon that emergency water treatment guidelines, which deviate from the WHO-guidelines, are used in crisis situations.

Sphere is a global movement which aims to improve the quality of humanitarian assistance during disaster response. The Sphere handbook has a well-known set of minimum standards that is often used during humanitarian response to natural disasters. Their standards regarding the quality of the drinking water are compiled in the list below. (Sphere Association et al., 2018)

- < 10 CFU/100 ml of faecal coliforms at point of delivery for unchlorinated water. CFU stands for colony-forming unit and is a means of measuring the microbiological cells in a sample.
- ≥ 0.2 – 0.5 mg/litre FRC at point of delivery of delivery for chlorinated water. FRC stands for free residual chlorine and is a way of preventing re-contamination of the treated water.
- Turbidity < 5 NTU. NTU stands for Nephelometric Turbidity Unit is a means of measuring the turbidity of a sample.

A case-study from a serious flooding in Beijing year 2012 by Sun et al. examined the effects of water pollution 6 days after a flooding on 9 different sites close to Beijing, commonly used as drinking water sources. The results from the samples indicated that all of the samples sites contained water that were unsuitable as drinking water, as measured from 9 commonly used drinking water quality parameters.(Sun et al., 2016). The mean values of contaminants from the 9 different sites were within the

allowed maximum limits with the exception for the turbidity and the total bacterial count, which greatly exceeded the maximum limit allowed.

The conclusion is that it is first and foremost physical and microbiological contaminants that is of importance during disasters. The microbiological contaminants is the cause of the majority of the harmful diseases during crises and the physical contaminants protects and fosters regrowth for the microbiological contaminants.

2.4 Technology analysis

Water purification is the process of removing or inactivating undesirable contaminants from water. For the purification of drinking water, there are many proven methods, more or less effective. The technology analysis started with a study visit to Alelyckans drinking water purification plant in Gothenburg, to gain an insight in different methods for water purification - see appendix A.1 for a summary of the visit. The following sections will describe the most commonly used drinking water purification methods.

2.4.1 Pre-filtration

Most purification methods require pre-filtration in order to sort out large particles that otherwise can damage the system or make the purification process ineffective.

Disposable filters is a very cost-effective and simple pre-filtration method. Common disposable filters are cartridge filters and bag filters. The water is pushed through these filters, trapping unwanted particulates whilst allowing water to pass through. Eventually the filters will get filled to a point where the pressure drop over the filter, caused by the trapped particulates, is too high and causes the water to flow too slow. At that point, the filters need to be replaced.

Sedimentation is a filtration process, mainly used in larger purification plants, which is using gravity to let large particles slowly fall to the bottom of the sedimentation tank where they can be removed from the water. A coagulant can be added into the water to gather and bind these particles together, forming so called flocs. Flocs are heavier than the water molecules and will therefore sink to the bottom of the sedimentation tank where they can be removed. (Brooks, 2015)

Sand filtration consist of a sand bed, which filters the water as it passes through. It is a very cost-effective but rather slow process. Eventually the bed of sand will get clogged and require backwashing or replacement to continue functioning.

2.4.2 Membrane filtration

A common water purification method is to use membranes to filter the water by creating a pressure difference between the membrane for the water to pass through. The membrane exists in many different shapes and sizes and can be used as a standalone purification method or in combinations with other methods.

Reverse osmosis is a process which uses a semi-permeable membrane, which only allows particles with a size less than $0.0001\mu m$ in diameter to pass. In the natural occurring osmosis process, water with a lower concentration of for example salt naturally will flow through the membrane, allowing water molecules to pass through but not the salt, until it is of the same concentration as the water with a higher concentration. This happens due to the difference of water potential for the two solutions and the water with the higher potential will therefore move to even out the potential difference between the solutions. In reverse osmosis an external pressure is added to reverse the natural flow. This will force the water molecules from the higher concentrated water solution into the weaker, leaving purified water on one side of the membrane and contaminated water on the other side. The contaminated water will be flushed away as new raw water is added to the tank. Reverse osmosis removes the majority of all contaminants, including dissolved substances such as salt, but also removes beneficial minerals such as calcium and magnesium. (Bergsrud, Seelig, & Derickson, 1992)

Ultrafiltration is another membrane filtration process utilizing a pressure gradient to force water through the membrane. The difference between reverse osmosis and ultrafiltration is that ultrafiltration has larger pore sizes and requires a lower pressure to function. However, this also means that it will not remove certain contaminants such as for example salts.

2.4.3 Disinfection

UV-disinfection is a common disinfection method. The light that is visible and can be perceived to the human eye constitutes a small part of the electromagnetic spectrum with a wavelength ranging from 340-760nm. Ultraviolet light is of a lower wavelength than the visible light ($<340\text{nm}$) and thus is not visible for the human eye. The ultraviolet light in turn can be divided into four segments with different wavelengths.

- UV-A (315-340nm)
- UV-B (280-315nm)
- UV-C (150-280nm)
- Vacuum UV (10-150nm)

UV-light disinfection of water is primarily done in the UV-C section and to some extent in the UV-B section. It can be done either directly from the sun or by using UV-lamps, which usually emits their light at a wavelength of around 254 nm. The UV-light penetrates the cell of the microorganism removing their capabilities of reproduction. UV-light is very effective in destroying microorganisms but does not remove other contaminants such as chemicals, heavy metals or unwanted minerals.

The UV-dose is the amount of energy the water is exposed to and is typically measured in J/m^2 . A parameter that is central to UV disinfection is the transparency for

UV-light of the water. This is often measured in UV-transmittance, which specifies how much of the UV-light that passes through the water. Therefore, pre-filtration of the water often is a necessity to ensure the water has a high transmittance for the UV-disinfection to be effective. (Svenskt Vatten, 2009)

Solar water disinfection (SODIS), is a method of UV-light disinfection that is commonly used in rural areas in developing countries. The principle behind this method is to have a transparent plastic container which allows the sun's UV-light to pass through. The water is then disinfected after 6-48 hours depending on the cloudiness. (CDC, n.d.)

A study by G.K. Rijal and R.S. Fujioka investigated the differences of disinfecting contaminated water with heat compared to heat together with UV-radiation, by using a product called Family Sol*Saver. In the first case the product had a two-layer non-UV transmittable cover sheet and in the second case the sheet was replaced with one layer UV transmittable sheet. The result showed that there is a synergistic effect between UV-radiation and heat and that there was no significant growth of microorganisms from the end of the experiment. (Rijal & Fujioka, 2001)

Chlorine disinfection is done by adding chlorine to the water which will inactivate most microbiological agents. It is one of the most used disinfectants for water disinfection. It is cheap and effective but correct dosage can be tricky and affects the taste of the water negatively. (Environmental Protection Agency 3, n.d.)

Ozone Disinfection. Ozone is added to the water in which it diffuses into bubbles and mixes with the water and reacts with pathogens inactivating them in the process. It is very effective but is a relatively costly method and toxic to handle. (Solomon, Casey, Mackne, & Lake, 1998)

Activated carbon filtering is another process which is common both for household treatment but also in WTPs. It uses a bed of activated carbon, which is carbon that has been processed to have a high surface area and a microporous structure, enhancing its adsorption properties. The activated carbon will trap contaminants in their pores as water flows through it, removing them along with taste and odor from the water (Bansal & Goyal, 2005).

2.4.4 Other methods

Pasteurization of water is done by heating water and maintaining that temperature for a certain amount of time depending on the temperature. A typical process is to heat the water to 75 °C for 10 minutes. Pasteurization is a substitute to boiling and will kill all pathogens of concern regardless of the turbidity and other parameters that might influence other methods. (Burch & Thomas, 1998)

Electrolysis decomposes the water by allowing an electric current to pass through it causing a reduction at the cathode and an oxidation at the anode destroying contaminants in the process. (Reimanis, Mezule, Ozolins, Malers, & Juhna, 2013)

Distillation of water is the procedure where water is being heated into boiling point where it vaporises. The heat is kept at a constant temperature maintaining the water vaporization while prohibiting undesirable elements from vaporizing, separating it from unwanted contaminants. This since water has a relatively low boiling point, lower than most of the contaminants found in water, thus leaving them behind in the process.

2.5 Competitor analysis

The purpose of the competitor analysis was to investigate the freedom of operation, as well as to gain inspiration for the concept generation.

2.5.1 Patented products

To search for already existing solutions and investigate the freedom of operation, patent searches on Espacenet were carried out. By using different combinations of different keywords, the phrases were changed until a manageable number of results were found, leaving 27 patents. The patents search is shown in detail in appendix A.1.

A quick screening of the remaining patents were done in order to sort out patents that were clearly not of relevance or that had drawings that were unreadable, which reduced the number of results from 27 to 16.

The remaining 16 patents were then categorized into groups depending on similarities in purification methodologies and techniques. The patent deemed most promising in each of the groups were then kept, discarding the rest of the patents. In this assessment the perceived performance and complexity of each solution were taken into consideration. This left 5 concepts that will be described in detail and with explanatory pictures in appendix A.2.

These patents do not provide sufficient information to perform a benchmarking between the solutions in regards to parameters such as cost, energy consumption, capacity, flow rates, lifespan or level of contamination reduction. Instead it will only give an indication of the freedom of operation and act as a basis throughout the idea generation.

2.5.2 Non-patented products

During the interviews with the NGOs it was mentioned that products that they develop themselves usually do not get patented since they do not want to hinder other organizations from utilizing a good product and potentially saving lives. Out of this reason, web searches were made to find additional relevant solutions. One product that stands out is **The Livesaver Jerry Can**.

The Livesaver Jerry Can is a portable 18.5-liter plastic container utilizing a ultrafilter to purify the water. It is not powered by solar energy but instead through a manual

2. Pre-study

pump which pressurizes the container and forces the water through the filter. It is developed by lifesaver in collaboration with the NGO, Oxfam, and is handed out to people in need during humanitarian response. The Lifesaver Jerry Can costs roughly 825 SEK and last for approximately 15000 liters before filter exchange is needed. It provides a bacterial 6-log reduction which corresponds to removing 99.9999% of the microbes. (Oxfam, 2020)

The Lifesaver will in addition to acting as a basis of the idea generation, which the patents do, act as a framework in the bench-marking processes.

2.6 Mission statement

To summarize the chapter and to provide an interface between the pre-study and the concept generation, a mission statement was set up, see table 2.3.

Table 2.3: Mission statement

Project description	The mission is to develop a solar driven water purifier to be used in emergencies, with primary focus on water contamination caused by natural disasters. The system is expected to provide 100 persons with 7.5 liters of clean water each day, according to the Sphere standards.
Benefit proposition	A system that has a lower cost per liter of produced water and is more robust than smaller scale purifiers, as well as being more modular and faster to install than larger scale purification plants.
Key business goals	To produce a system that is more profitable compared to household water treatments, by lowering the cost per liters of produced water.
Primary markets	IOs & NGOs operating in regions with a high risk of natural disasters with an average daily horizontal irradiance over 4.6 kWh/m ² &day
Secondary markets	Lake boats, preppers and military.
Assumptions & constraints	It is assumed that the people using the purifier will be having water containers to fill, as well as the contaminated water will be available nearby.
Stakeholders	IO/NGOs Local inhabitants ESSIQ AB Chalmers University of Technology

3

Concept development

The following chapter discloses the concept generation process and how concepts were compared against each other to choose the concept with the highest potential.

3.1 Requirements specification

The information from the pre-study was used to set up a requirements specification for an emergency water purification system. The requirements were however also updated continuously throughout the project as more knowledge were acquired and includes both demands and wishes from the potential customers found in the pre-study, along with requirements set by the development team in collaboration with ESSIQ. Some of the requirements are based directly on standards for emergencies as well as drinking water standards in general, set by recognized organizations such as WHO, Sphere and UNICEF. See figure 3.1 for a preview of the requirement specification.

All	Requirements/Desires	R/D	Justification	Verification/Evaluation	Weighting (1-3)	Note
1	Water quality					
1.1	Faecal coliforms < 10 CFU / 100 ml	R	Sphere Handbook	Water test		
1.2	Faecal coliforms < 1 CFU / 100 ml	D	WHO drinking-water guidelines	Water test	2	
1.3	Chemical contaminants < WHO guidelines	D	WHO drinking-water guidelines	Water test	1	
1.4	Radiological contaminants < WHO guidelines	D	WHO drinking-water guidelines	Water test	1	
1.5	Turbidity < 5 NTU	R	Sphere Handbook / WHO	Water test		
2	Capacity					
2.1	Should provide 100 persons with 7.5 liters drinking water daily	R	Interviews / Sphere Handbook	Calculations		
2.2	Should be able to store 1000 liters	D	Requirements from ESSIQ	Calculations	3	

Figure 3.1: Requirement specification

The desires are weighted as a means to imply its relative importance, between 1-3, with 3 being the most important on the scale. The weighting is based on the information gathered in the interviews. The final iteration of the requirement specification can be found in appendix A.4.

3.2 Concept generation

Based on the pre-study and the requirements specification, a concept generation process was carried out.

3.2.1 Function tree

To ease the idea generation process, a breakdown of the main functions was made with the help of a function tree. The function tree can be seen below in figure 3.2. Out of the three main functions, "Handle raw water input", "Purify water" and "Handle output", seven sub-functions were generated.

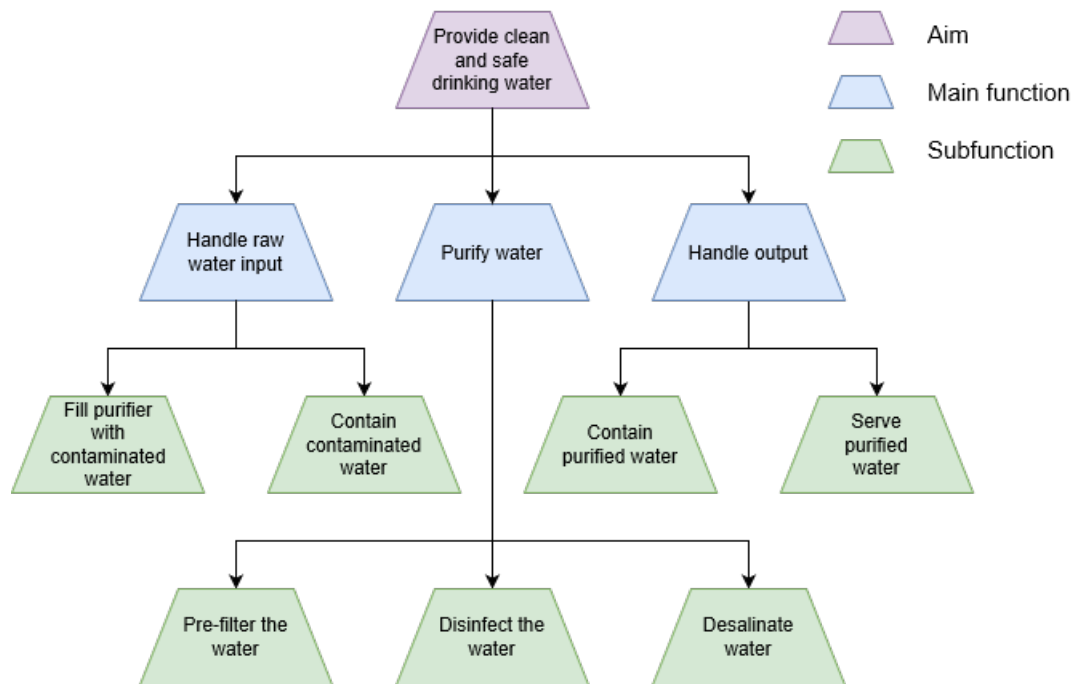


Figure 3.2: Function tree

3.2.2 Idea generation

In order to generate solutions for the different sub-functions classified in the function tree, several brainstorming sessions were held, with multiple ideas for each sub-function. The ideas were then put into a morphological matrix, to be used in the next stage of the concept generation process.

3.2.3 Morphological matrix

The morphological matrix, see appendix A.5, was used to combine the solutions into system concepts. This resulted theoretically in thousands of different combinations. In order to reduce the amount, a screening of the solutions was needed in order to make the amount of concepts manageable.

3.2.4 Elimination of sub-function ideas

Starting with one of the main functions, *Handle raw water input*, two sub-solutions for filling the system with contaminated water were eliminated. The idea to scoop

water using a bucket was considered to be a too slow and time-consuming process for the intended capacity of the system. The idea to put the purifier under water to fill it was considered to be ungainly as the system might be heavy as well as the water source might not be deep enough. The screening of solutions for handling raw water input is shown in figure 3.3.

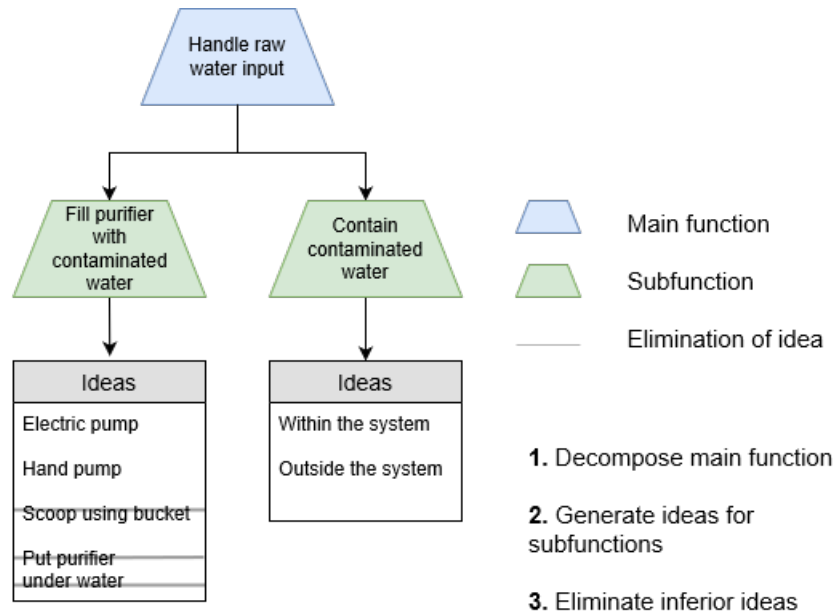


Figure 3.3: Subfunctions and solutions for handling raw water input

Regarding the main function *Purify water*, several purification methods were removed. Starting with the sub-function, *Pre-filter the water*, sedimentation, sand filtration and distillation were removed as realistic alternatives. All three of these methods are slow processes and sedimentation often relies on adding coagulants to the water which makes the system more difficult to operate and monitor. Furthermore, distillation was removed in the other branches as well for the same reason.

For the sub-function *Disinfect the water*, solar radiance, chlorine disinfection, ozone disinfection and activated carbon were removed. Solar radiance is a slow process and not very effective when the water is not heated. However, the combination of solar radiance and water pasteurization was kept as a solution, because of its synergistic properties, as described in 2.4.3.

Chlorine disinfection is a method that easily could go wrong without proper education and training. According to Sophie Mack Smith, not even chlorine tablets are distributed to people in emergencies without first giving them proper user-instructions, which highlights the complexity of chemical additives.

3. Concept development

Ozone disinfection is a very costly and unproven method, as well as the gas produced is heavily toxic. Activated carbon was removed as it is not particularly effective in removing microbiological contaminants but rather chemicals, taste and odor.

Regarding the branch *Desalinate water*, all of the methods are relatively expensive and consumes high levels of energy. Since the ability to desalinate water was not a specific desire from the potential customers interviewed during the pre-study, all methods for desalination were removed. The trade-off between cost and performance was considered too unfavorable, and the project will henceforth not focus on desalination. The screening of solutions for purifying water is shown in figure 3.4.

This left a total of four possible combinations for the "Purify water" function.

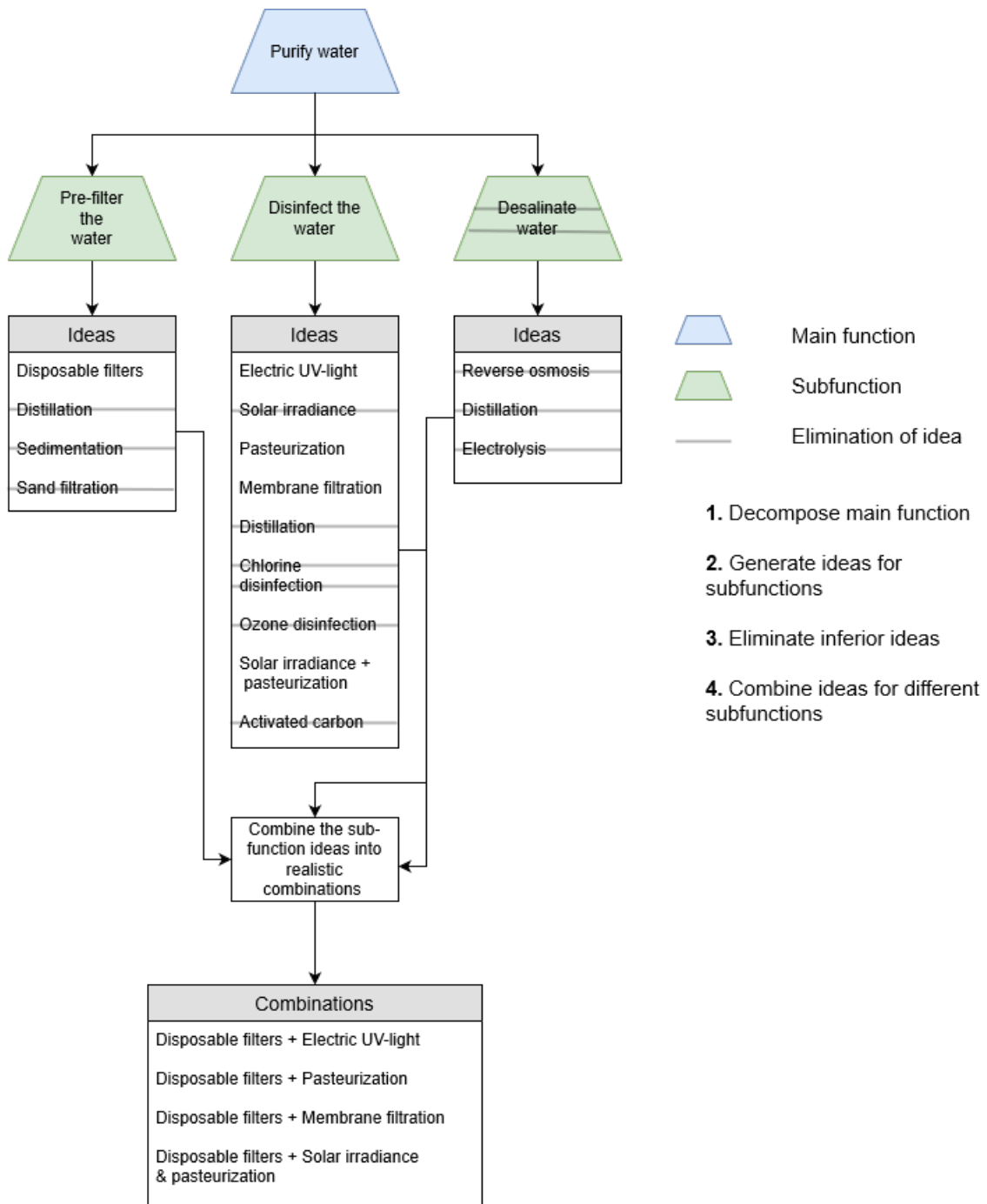


Figure 3.4: Subfunctions and solutions for purifying water

In figure 3.5 subfunctions and solutions for handling the output is visualized. All solutions for handling the output were kept at this stage, leaving 96 potential concepts by combining the different solutions for each subfunction.

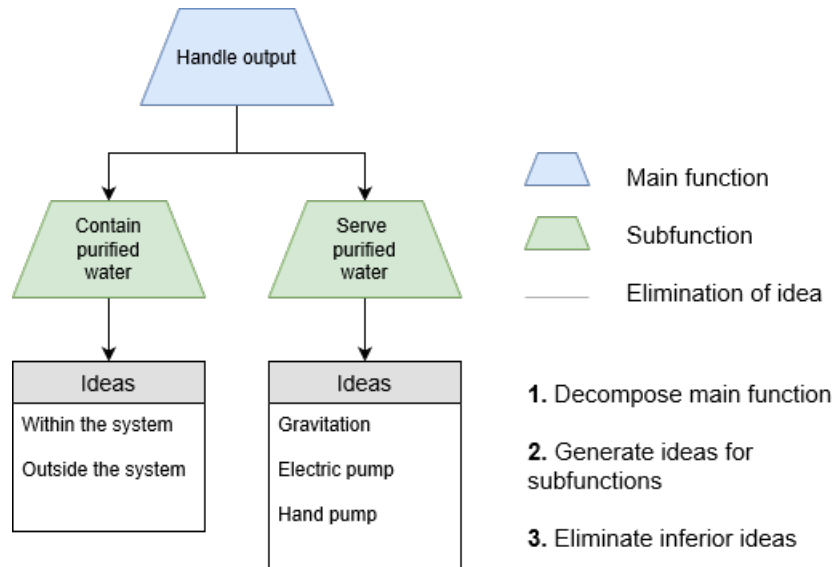


Figure 3.5: Subfunctions and solutions for handling the output.

From the remaining 96 potential concepts, the development team took the decision to not distinguish between the solutions for *Serve purified water* at this early stage of the design, since either of these solutions significantly limits the design. The same argument was used for pasteurization with or without solar irradiance.

To further reduce the number of concepts, all concepts with an electrical purifier were only combined with electrical pumps and vice versa for the mechanical solution as a means of filling the purifier with contaminated water. This decision was supported by doing power calculations for electric pumps, intended for a system pumping around 750 liters daily, which showed low energy consumption for such pumps, see appendix B.1 for details. The cost for implementing electrical pumps in concepts where electricity would be needed anyways, such as for the electrical UV-light and membrane filtration, is therefore assumed to be relatively low.

Because of this, concepts with hand pumps together with electricity driven purification methods could be removed as potential solutions. The same arguments was used the other way around as well - there is not a good idea to have an electrical pump when the purification methods do not need any electricity. Taken this into account, the number of possible concepts were reduced to 12.

From these 12 concepts, two concepts seemed unrealistic, consisting of a combination of pasteurization + solar irradiance and containing contaminated water outside of the system. This will probably not be a realistic combination since the water will be needed to be stored somewhere in order to absorb the energy from the solar radiance.

Out of the ten remaining concepts, two concepts utilize pasteurization in combination with solar irradiance disinfection, four concepts utilize electric UV and the remaining four concepts utilize membrane filtration as disinfection method. The difference between the concepts with the same purification technology is whether the contaminated water and clean water is stored within or outside of the system. To avoid developing duplicate solutions half of these ten remaining concepts were decided to proceed development with, leaving five concepts, perceived by the development team to have the most potential. The combinations of the remaining five concepts can be seen in table 3.1-3.5 below.

Table 3.1: Concept 1

Concept 1	
Handle raw water input	Hand pump + within the system
Purify water	Coarse filter + solar irradiance & pasteurization
Handle output	Outside of the system

Table 3.2: Concept 2

Concept 2	
Handle raw water input	Electrical pump + within the system
Purify water	Coarse filter + membrane filtration
Handle output	Within the system

Table 3.3: Concept 3

Concept 3	
Handle raw water input	Electrical pump + outside of the system
Purify water	Coarse filter + Electric UV-light
Handle output	Within the system

Table 3.4: Concept 4

Concept 4	
Handle raw water input	Electrical pump + outside of the system
Purify water	Coarse filter + membrane filtration
Handle output	Outside of the system

Table 3.5: Concept 5

Concept 5	
Handle raw water input	Electrical pump + outside of the system
Purify water	Coarse filter + Electric UV-light
Handle output	Outside of the system

3.3 Concept selection

The previous section resulted in five different concepts, that were further developed and designed. This section is intended to present these concepts along with a comparison, in order for a decision to be made regarding which concept that has the highest potential.

3.3.1 Concept 1: SODIS

The first concept consists of a covered pool, a hand pump with a integrated coarse filter, as well as a parabolic trough collector. The water will get pre-heated in the pool to around 50-60 degrees Celsius, and then pumped and filtered up to the parabolic trough where the water gets heated to just above 70 degrees Celsius, where the water will get disinfected. Concept 1 can be seen in figure 3.6

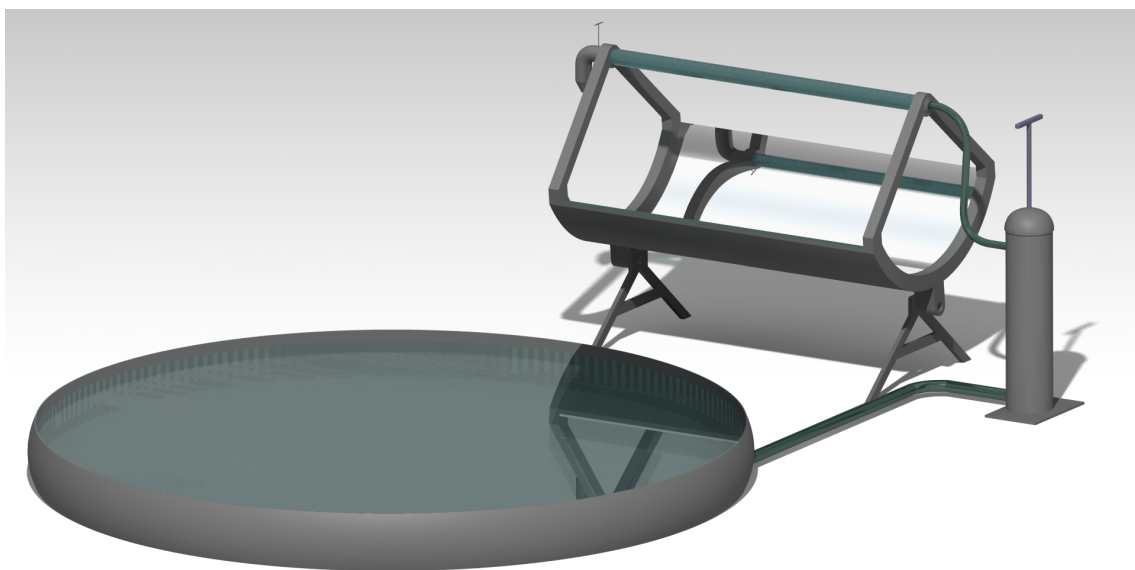


Figure 3.6: Concept 1

3.3.2 Concept 2 & 4: Ultrafiltration

Concept 2 and 4 both use electrical pressurized ultrafiltration and will be powered using solar cells.

Concept 2 consists of three different boxes. The solar panel is attached to the top box, in which all the necessary electronic parts are located, such as battery, pump, connections and cables. The middle box is intended for the contaminated water and can be filled either through a hose which can be connected to an inlet for the pump in the top box, or manually through a lid on the middle box. There is a cutout in the top box to allow for the lid and inlet arrangement. In the bottom of the middle box is another pump connected to the bottom box and an ultrafilter. The second pump forces water through the ultrafilter, leaving clean water in the bottom box. The bottom box will act as storage for the clean water providing a buffer of water. A water tap is mounted in the bottom section of the bottom box. For explanatory pictures, see figure 3.7.

The idea of having boxes is to make the distribution process more efficient since it constitutes a large part of the cost during humanitarian responses as discussed in 2.2. The boxes are shaped with an incline which allows them to fit within each other and enables stacking of multiple units, significantly reducing the area consumption whilst disassembled.

To empty the clean water tank, the user simply opens the water tap. If the bottom box is out of clean water the user purifies the water by either putting the hose in the water source and starting the first pump, or manually filling the system with water through the lid. Then the user starts the second pump filling the bottom box with clean water.

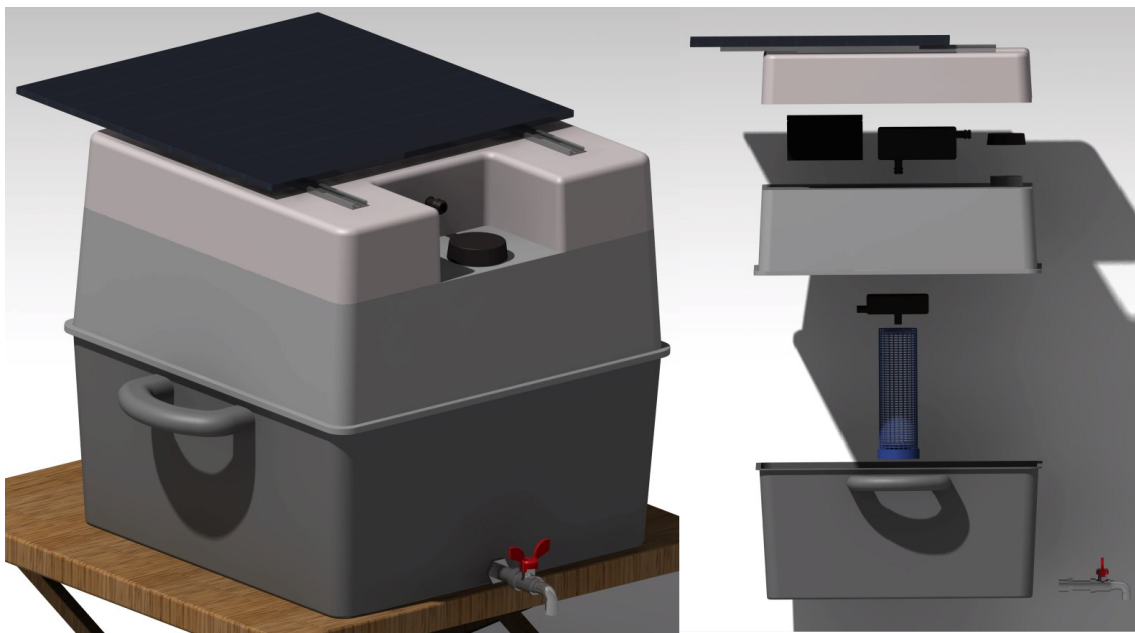


Figure 3.7: Concept 2 - Ultrafiltration with water storage

Concept 4 has no water storage and consists of the electronic and purification parts, designed to minimize its total volume. Prior to the ultrafilter, pre-filters will be placed to prolong the life-length of the ultrafilter. The cylindrical shape is chosen because the filters were assumed to also be of circular shape. The water is pumped through the system using an electrical pump, which is placed between the pre-filters and the ultrafilter. The solar panel for this concept is flexible and is bent around the cylinder whilst attached, to minimize space consumption during distribution. The solar panel can easily be detached and placed next to the purifier during operation. A water tap is placed on the end of the cylinder after the ultrafilter. Concept 4 is shown in figure 3.8.

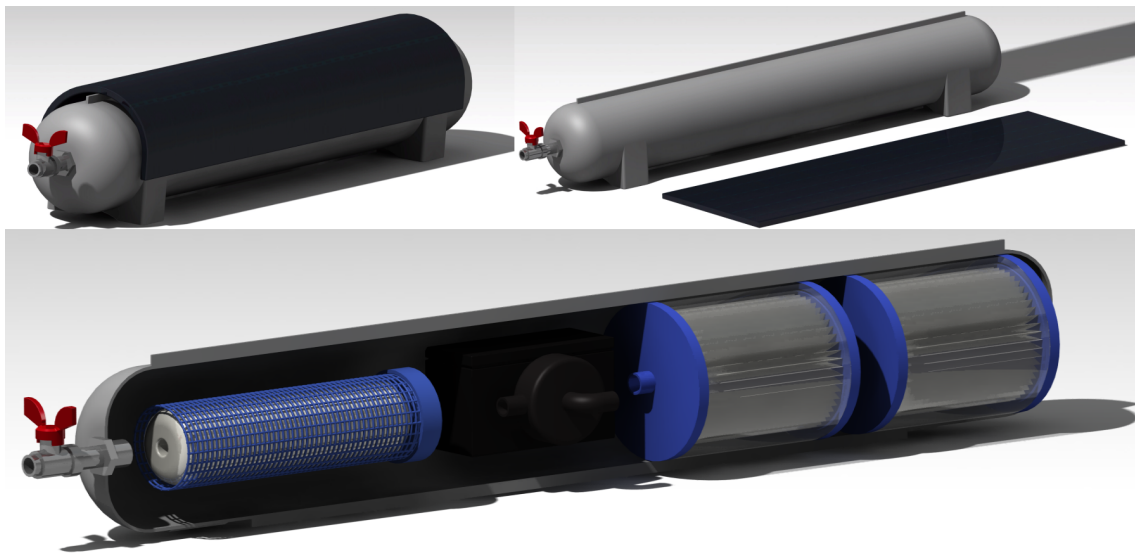


Figure 3.8: Concept 4 - Ultrafiltration with flexible solar panel

3.3.3 Concept 3 & 5: Electric UV disinfection

Concept 3 and 5 both use UV-disinfection as their purification method and solar panels will provide the systems with power. Both concepts have pre-filters prior to the UV-lamps, in order to decrease the turbidity of the water and ensure that the transmittance of the water is high enough for the UV-lamp to be efficient.

Concept 3 consists of two different boxes. The top box consists of all electronic parts along with the pre-filters and the UV-lamp. The bottom box will act as storage for the clean water providing a buffer of water. A water tap is mounted in the bottom section of the bottom box. The system is filled with water through the pump inlet, on which a hose can be connected. The water is then pumped through the pre-filters and UV-lamp into the bottom box. The design is similar to concept 2 with inclined boxes to make the distribution more efficient. Concept 3 is shown in figure 3.9.

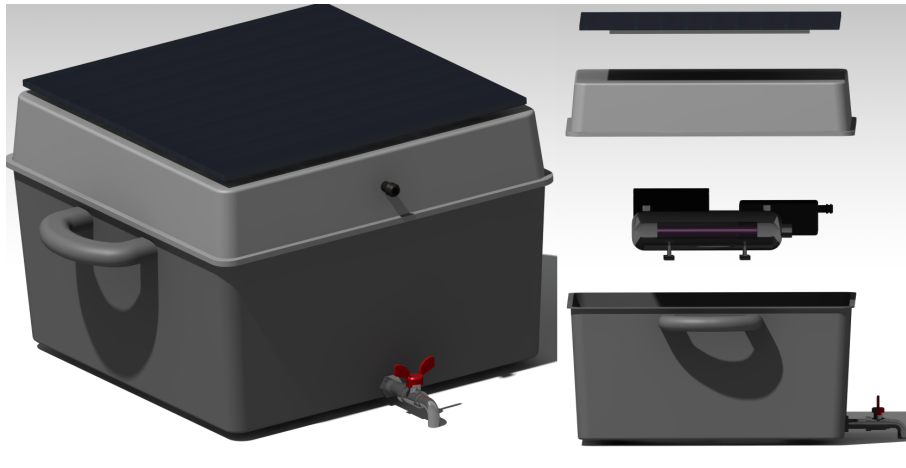


Figure 3.9: Concept 3 - UV-lamp disinfection with water storage

Concept 5 is similar to concept 4 with the difference of having a UV-lamp instead a ultrafilter. The concept also has pre-filters with smaller pore-sizes than concept 4, to increase the transmittance of the water. Concept 5 is shown in figure 3.10.

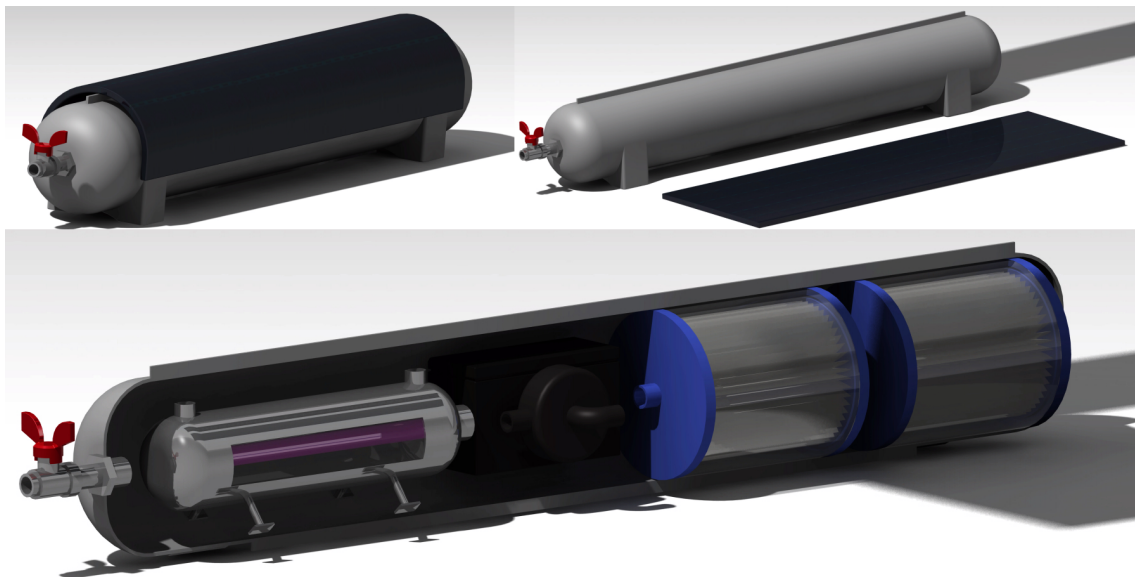


Figure 3.10: Concept 2 - UV-lamp disinfection with flexible solar panel

3.3.4 Comparison between concepts

The five remaining concepts were then evaluated using Pugh-matrices, based on a set of criterion, see table 3.6.

Table 3.6: Criteria used in the Pugh-matrix

No	Criterion
1.	Manufacturing cost
2.	Safety
3.	Distribution cost
4.	Assembly complexity
5.	Robustness to varying solar radiance
6.	User-friendliness
7.	Maintenance

The Pugh-matrices were iterated three times in total, with different concepts used as reference each time, to get a precise result. After the three iterations, a decision was made to proceed the development with Concept 3 and eliminate all other inferior concepts. The Pugh-matrices are located in appendix A.6.

Concept 1 was found to be inferior in comparison to the other concepts in all aspects except the production cost. The usage of a parabolic through which concentrates the solar energy will result in extremely high temperatures on certain areas of the product which can cause injuries to the user if not used correctly. The water pool, used in the concept, is foldable and together with the pump arrangement does not occupy much space. However, the parabolic mirror cannot be collapsed to reduce size. The concept will not function on days with low solar irradiance as the concept is powered completely by direct solar energy. In addition, concept 1 is fully mechanic and requires someone to operate the valves and pumps making it less user-friendly than the other concepts.

Concept 2 is very similar to concept 3 with the difference being the contaminated water storage and that it uses ultrafiltration as purification method instead of UV-lamp disinfection. During the comparison it was concluded that having a contaminated water tank is unnecessary. This since the reason of having a contaminated water tank was to be able fill the purifier at a water source and then carry the purifier to another location, to enable some sort of gravitational pre-filtration. However, it is not reasonable to carry a filled purifier due to its weight as well as the gravitational pre-filtration methods is as previously discussed relatively slow.

According to a comparative study by Gómez, Plaza, Garralón, Pérez and Gómez (2007), the installation cost for a physico-chemical-UV system was significantly less than for macrofiltration-ultrafiltration system in the case of a large wastewater treatment plant. (Gómez, Plaza, Garralón, Pérez, & Gómez, 2007) Based on this, a decision was made that UV-disinfection as a purification method is preferred. For this reason, it was decided that no further development would be made for concept 2 and concept 4.

Concept 5 and concept 3 both uses UV-disinfection as purification method, with the difference being the body design and that concept 3 has clean water storage.

Having clean water storage leads to the possibility of having the pump, battery and solar panels smaller and thus cheaper, since the purification rate can be slower. The system can work continuously by filling the water storage, whereas it otherwise only operates when someone fills their water container, which will require a higher flow rate. It also means that it will have an increased robustness against weather changes, as the clean water storage will continue to provide water for a while if the batteries run out of power. Concept 5 on the other hand will be slightly better regarding assembly complexity and transportation aspects as it will be more compact and come fully assembled. However, concept 3 was superior overall and was therefore chosen as the concept to proceed the development with.

3. Concept development

4

Further development

This chapter covers the design of the system layout for concept 3, changes in the system capacity as well as more detailed design of the components in concept 3.

4.1 System layout

To identify the main components for concept 3, a schematic diagram over the electronic layout and the purification units was created, see figure 4.1. The dashed rectangle illustrates the system boundary, separating components that will be inside the product from the outside. The red and black lines represent the positive and negative electronic cables whereas the blue lines represents the water from raw water to purified water.

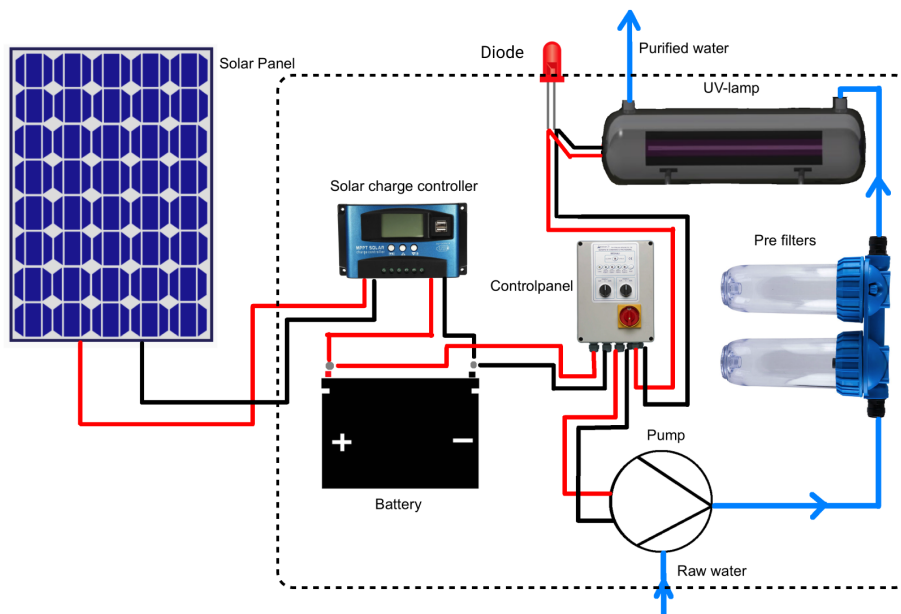


Figure 4.1: Preliminary system layout of concept 3

The solar panel will provide the system with power by charging a battery which

in turn will power the pump and the UV-lamp. The reason for not powering the pump and UV-lamp directly from the solar panel is to be able to run the system throughout the whole day and not just during sun-hours. Having a battery will also provide a buffer against days when the solar irradiance is low, caused by for example high cloudiness.

A solar charge controller is a regulator which controls the charging of the battery to keep the battery from overcharging. It will control the voltage and current going from the solar panel to the battery. A solar charge controller is needed because the output voltage and current values from the solar panel varies with the solar density. For example, a 12 V solar panel typically has a voltage output up to 16-20 V. The reason for that being that if the panels strictly had an output of 12 V it would only provide that during perfect conditions, something which is not always the case in many areas. (Abdul Rahman et al., 2020)

The pump and UV-lamp are then powered from the battery through a control panel. The control panel connects the wiring and has a switch for the system. The user can manually start and turn off the system from the control panel. A diode is connected between the control panel and the UV-lamp indicating if the system is running.

4.2 System capacity

To design the water pumps, the UV lamp and the pre-filters, one needs to know the maximum production capacity for the system. To illustrate how the system is expected to be used, a graph illustrating a typical day of usage was created, based on requirements regarding the capacity from the Sphere standards. The minimum limit for quantity in the Sphere standards is 7.5 liters/person&day, which translates to a daily water production capacity of 750 liters for 100 persons. In table 4.1 the distribution of the minimum water quantity per person is illustrated. The clean water tank was designed to provide enough water for one day of survival, in order to have a buffer against unexpected failures of the system. Given that people need 2.5 liters of clean water per day to survive, this resulted in a clean water tank of 250 liters.

Table 4.1: Minimum quantity needs

Needs	Quantity (litres/person&day)
Survival: water intake	2.5
Hygiene	2
Basic cooking	3
Total	7.5

Given that the system has a 250 liters clean water tank, the tank needs to be filled and emptied three times a day to produce a total of 750 liters. From the Sphere standards the minimum flowrate of a system for 100 persons is 3 liters per minute, thus it will take roughly 83 minutes to fill and empty the tank respectively.

At this stage of the development, a new clean the water tank was designed. To minimize the space consumption of the system, an inflatable bag was decided to be used instead. When the bag is empty it can be collapsed by furling it up, enabling storage within the body of system during distribution. The new water tank will be further discussed in section 4.4.4.

With the new shape of the clean water tank came a realization regarding the intended water tap. In order for a tap to function it would have to be positioned in the bottom of the inflatable bag. That would make it difficult to fill water containers. In addition, as the bag gets emptied the flow-rate using a tap will decrease as the pressure gets lower and it was concluded that with a water tap requirement 2.3 regarding the flow-rate of the system would not be realizable. Instead it was decided to use a second water pump to serve the purified drinking water.

4.3 Design of the purification system

Based on the flow rate of 3 liters per minute, a process of designing all the necessary water purification components for the system were initiated.

4.3.1 Pre-filter design

In order for the UV-lamp to work efficiently, the transmittance of the water needs to be relatively high, which will be discussed further in 4.3.3. Since the transmittance of the raw water is assumed be low, pre-filters with pores down to 5-micron meters in diameter is needed to increase the transmittance of the source water, based on recommendations from UV-lamp manufacturers. The life-length of the 5-micron filter can be greatly prolonged by having a coarser filter connected in series, as the coarser filter will catch larger particles leaving the finer filtration to the 5 micron filter.

In the case of emergency water purification, cartridge filters are suitable since they are compact, do not require back-washing and can run on low flow rates (Goh, 2011). The cartridges are designed in standard sizes which are placed in standardized housings that protects the cartridge.

There are a variety of different types of cartridge filters. Depth-filters is a specific type of cartridge filter that generally remove and hold more particles without losing pressure than other cartridge filters, leading to longer intervals between maintenance and/or replacement. The depth filters are also best suited when there is a variety of different particle sizes. This type of filter was decided to be used in the pre-treatment, as keeping the maintenance to a minimum is preferred and the water treated is expected to consist of highly varied particle sizes. More specifically a string-wound filter cartridge, which is a type of depth-filter that is relatively cheap and extensively used for pre-filtration were chosen (Kanade & Bhattacharya, 2016).

A 50-micron string-wound cartridge filter will be used followed by a 5 micron string-

4. Further development

wound cartridge filter prior to the UV-lamp. The size chosen for the pre-filters is 2.5 inches in diameter and 10 inches long, which translates to 6.35 x 25.4 cm. This size is suitable in terms of space occupation. Another reason for using a common size is that it will make it easier to get hold of eventual reserve filters. Based on these arguments, the pre-filters and their associated attachments were designed, see fig 4.2

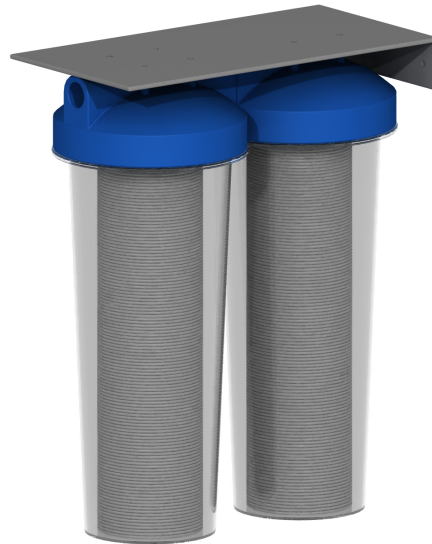


Figure 4.2: Filter cartridges with attachments

The filters will cause friction to the water and will result in a pressure drop over the filter. Manufacturers provide pressure drop data for their cartridges (Hutten, n.d.). Pressure drop tables from three different manufacturers, Fieder filter systems, Delta Pure and Lenntech measuring the pressure drop for different flow rates and filter fineness's for 9.75/10-inch string wound filters were studied. It was found that for a flowrate of 3l/min a 50-micron and a 5-micron filter will cause a combined initial pressure drop of no more than 1 PSI (0.07 bar). The pressure drop over the filter can be converted in to pump head by using the formula (EngineeringToolBox, 2004):

$$h_k = \frac{p \times SG}{0.0981} = \frac{0.07 \times 1}{0.0981} = 0.714\text{m}$$

where

h_k = Filter pump head (m)

p = pressure (bar)

SG = specific gravity of fluid (1 for water)

Over time particles will fill the pre-filters leading to an increased pressure drop, and eventually the filters will need to be replaced. To handle the increased pressure drop

it is beneficial to over-dimension the pump. In the technical data sheet of Lenntechs string-wound cartridges the capacity for a 10x2.5" filter is 80000 L, a number that is highly dependent on the source water quality (Lenntech, 2016). The source water quality where the product is intended to be used is expected to be low and thus the estimated capacity of the filters is 40000 L. In order to treat 750 L daily over a year, 7 filters are required.

4.3.2 Pump design

Given the flowrate of the system and the friction losses caused by the filters and pipes, calculations to estimate the power needed by the pump could be made. Assumptions regarding needed pump elevation, pump efficiency, hose length and the shape and material of the hose were made and follows below:

- Pump elevation, $z_{outlet} - z_{inlet} = 5\text{m}$
- Pump efficiency, $\eta_{pump} = 60\%$, small water pumps usually has a efficiency between 50-70. (Evans, 2012)
- Hose length = 20m
- Hose diameter: 0.015875m (which is a standard garden hose diameter 5/8 inches)
- Hose material = PVC, which gives a relative roughness of 0.0001

With these pre-requisites, the total pump head could be calculated, which is needed when calculating the pump power. The pump head, H_p , is calculated with Bernoulli's equation:

$$\frac{p_{inlet}}{\rho_{water} \times g} + \frac{v_{inlet}^2}{2 \times g} + z_{inlet} + H_p = \frac{p_{outlet}}{\rho_{water} \times g} + \frac{v_{outlet}^2}{2 \times g} + z_{outlet} + h_f + h_k$$

By using H_p , the total pump power was calculated. See B.1 for in depth calculations.

$$P_{pump} = \frac{Q \times H_p \times \rho_{water} \times g}{\eta_{pump}} = 4.81\text{W}$$

In the calculations, the friction caused by fittings were ignored and the increased pressure drop over the pre-filters, as they get filled up, were not considered. With this taken into consideration and wanting to avoid the pump running at max capacity to increase life-length it was decided to over-dimension the pump with a factor of 2, leading to a pump power need of roughly 10 Watts.

Commercial pumps with these specifications were studied to get approximate dimensions of the needed pump. This resulted in an approximate size of 100x65x50 mm, which will be used henceforth. Based on these dimension a pump were designed, see figure 4.3.

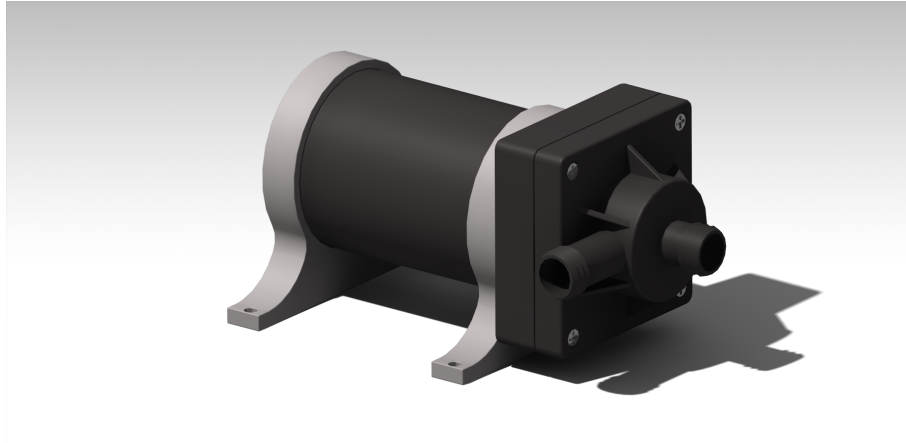


Figure 4.3: Water pump

As mentioned in section 4.2, a second pump will be used to serve the purified water. The same calculations were made for the second pump, with different assumptions regarding the pump elevation, hose length and without filter pump head, h_k . For an elevation of 2 m and a hose length of 5 m,

$$P_{pump2} = \frac{Q \times H_p \times \rho_{water} \times g}{\eta_{pump}} = 1.7W$$

By adding a safety factor, the outlet water pump was rated to 4W.

4.3.3 UV-system design

The goal of this section is to design the UV-lamp with respect to the requirements for the water quality, as well as to minimize its power consumption with respect to the radius of the UV-lamp cover. The following calculations will mostly be based on the article *Analysis of the radiation dose in uv-disinfection flow reactors* (Artichowicz, Luczkiewicz, & Sawicki, 2020). The article is providing a framework for estimating the radiation dose for a UV-disinfection system with simple geometries, see figure 4.4. In the case of this report, the UV-system is expected to have a similar design, with the exception that the outlet will be placed with a 90 degrees angle to the lamp, see figure 4.5. The reason for this design is to ensure that the entire UV-chamber is always water filled during operation, to ensure that the water velocity is low enough for it to receive a sufficient UV-dose.

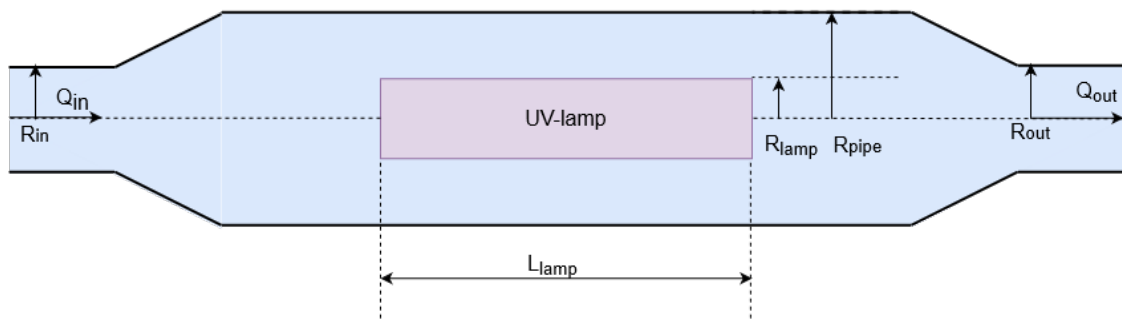


Figure 4.4: Theoretical UV-system setup, first iteration

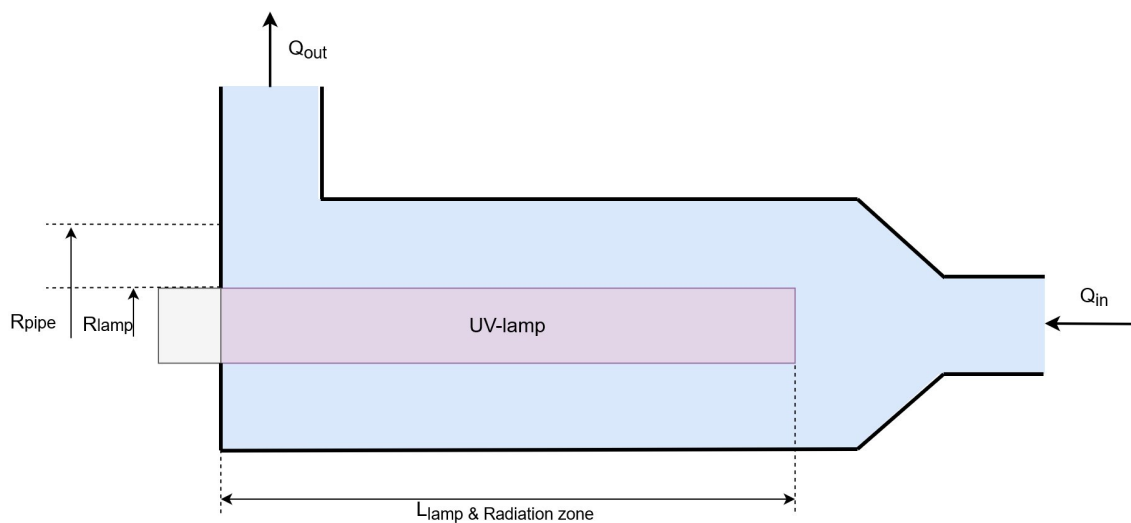


Figure 4.5: UV-system setup in practice, second iteration

In the following calculations, the UV-system will be treated as if it was designed like figure 4.4, even though its actual design will be as in figure 4.5. This assumption was made since this will simplify the calculations and on same time provide a result that is expected to be similar to the real case. To compensate for eventual differences in velocity profiles due to asymmetry, a safety factor will be added to the result.

In addition to this, several constraints and assumptions needs to be made in order to proceed to the calculations.

- Both the water pipe and the UV-lamp have a circular shape.
- All sections of the system are expected to have turbulent flow.
- The UV lamp will only radiate in a vertical direction.

Another very important assumption that needs to be made is the level of transmittance for the pre-filtered water. The transmittance is the most important water quality factor that affects the received UV-dose and depends on both the pre-filtration,

but also on the composition on the contaminants in the water. According to EPA (2006), the transmittance is a function of the absorbance, and is measured as a percentage of how much UV-light that passes through a media at a specific wavelength and path length. The absorbance should generally be determined by collecting samples of the UV-light intensity at fixed distances from the UV-source. However, in the case of this report, this is considered to be out of the scope and historical data for transmittance will be used instead. In the city of Winnipeg, the design of a UV-disinfection unit for raw water estimated the transmittance of the water to be 75%, given 1 NTU in average turbidity, between year 1989 and 1994. To estimate the pre-filtered water to have the same turbidity as raw water in Winnipeg is a conservative approach, but given the uncertainty of the turbidity in the areas where the system is intended to be used, this is assumed to be a relevant approximation. (Environmental Protection Agency 4, 2006)

The UV-dose (UVD) absorbed by the water is calculated in Eq (1), where I is the UV-intensity and t is the time under radiation.

$$UVD = I * t_R \quad (1)$$

The intensity varies as a function of the vertical distance from the lamp (r) and α , which is a function of the transmittance (T), of the water and (h), which usually equals to 10 mm.

$$I(x) = I_0 * exp(-\alpha * x) \quad (2)$$

$$\alpha = -\frac{1}{h} * \ln T \quad (3)$$

The flow around the lamp is expected to be turbulent. The velocity profile is described by the Hagen-Poiseuille equation for turbulent flow.

$$u_x(r) = -\frac{\Delta p}{4 * \mu * L_{lamp}} * r^2 + C_{T_1} * \ln r + C_{T,2} \quad (4)$$

C_L is an auxiliary variable and can be calculated using the Hagen-Poiseuille equation for laminar flow.

$$C_L = \frac{\Delta P}{4 * \mu * L_{lamp}} \quad (5)$$

The pressure drop for an annular section can according to Wilson C. Chin (2012) be calculated as follows. (Chin, 2012)

$$\Delta p = \frac{8 * Q_{in} * \mu_{water} * L_{lamp}}{\pi * R_{pipe}^4 * (1 - \kappa_{lamp}^4 - \frac{(1 - \kappa_{lamp}^2)^2}{\log \frac{1}{\kappa_{lamp}}})} \quad (6)$$

where

$$\kappa_{lamp} = \frac{R_{lamp}}{R_{pipe}} \quad (7)$$

Combining equations (5) and (6), yield the following.

$$C_L = \frac{2 * Q_{in}}{\pi * R_{pipe}^4 * (1 - \kappa_{lamp}^4 - \frac{(1 - \kappa_{lamp}^2)^2}{\log \frac{1}{\kappa_{lamp}}})} \quad (8)$$

Adjusting C_L for turbulent flow.

$$C_{T,1} = \frac{C_L * (R_{pipe}^2 - R_{lamp}^2)}{\ln \frac{R_{pipe}}{R_{lamp}}} \quad (9)$$

$$C_{T,2} = C_L * R_{pipe}^2 - C_{T,1} * \ln R_{pipe} \quad (10)$$

Introducing boundary conditions; the velocity is estimated to be zero at the lamp surface as well as on the outer pipe surface.

$$u_x(r = R_{lamp}) = 0, u_x(r = R_{pipe}) = 0 \quad (11)$$

By using the boundary conditions, $C_{T,2}$ can be substituted.

$$u_x(r) = C_L * (R_{pipe}^2 - r^2) + C_{T,1} * \log\left(\frac{r}{R_{pipe}}\right) \quad (12)$$

Introducing relative radius, where r goes from R_{lamp} to R_{pipe} .

$$R_R = \frac{r}{R_{pipe}} \quad (13)$$

The intensity $[W/m^2]$ decreases with the distance from the lamp source intensity I_0 .

$$I(R_R) = I_0 * R_{pipe}^2 * (1 - R_R^2) + C_{T,1} * \log(R_R) \quad (14)$$

The time under radiation depends on the velocity profile and the length of the lamp.

$$t_r = \frac{L_{lamp}}{u_x(R_R)} \quad (15)$$

4. Further development

Finally, the UV-dose can be calculated by multiplying the time under radiation with the intensity.

$$UVD(R_R) = t_r(R_R) * I(R_R) \quad (16)$$

By using MATLAB's optimization function *fmincon* with a boundaries for R_{pipe} ranging from $[R_{lamp}, 0.05]$, the optimal radius with respect to the lowest UVD turned out to be 0.05 m. Even though it was decided that 0.05 m will be the highest possible radius due to design constraints, the boundaries was changed in order to find the real maximum for the radius, which resulted in a theoretical optimum radius of 0.0992 m.

In order to calculate which lamp intensity (I_0) that corresponds to a reduction which yields a contamination level of less than 10 faecal coliforms per 100ml of water, one needs to make an assumption on the level of water contamination. Faecal coliforms is a bacterial group, mainly (>99 %) consisting of a coliforming group named E.coli (Sphere Association et al., 2018). In the book *Detection of Pathogenic Bacteria in Flood Water* (Basri, Othman, & Wahid, 2015) the quality of flood water from three different sampling sites in Malaysia is measured. An average of 67100 CFU/100ml of E.coli were measured for the three different sampling sites. The highest concentration measured were 115000 CFU/100ml of E.coli. By taking a conservative approach, the highest concentration was used when determining the needed fluence.

With these values, the needed log-reduction to pass requirement 1.1 regarding the microbiological contaminants not surpassing 10 CFU/100ml of faecal coliforms can be calculated.

$$\frac{CFU_{after}}{CFU_{before}} = \frac{10}{115000} = 0.00009 \approx 10^{-4}$$

The level of contamination approximately corresponds to a log-4 reduction. This value was then checked against a table over the needed fluences for different log reductions for various bacteria presented in the paper: *Fluence (UV Dose) Required to Achieve Incremental Log inactivation of Bacteria, Protozoa, viruses and Algae* (Malayeri et al., 2016). To achieve a log-4 reduction of the faecal coliforms, a UV-dose of 22 mJ/cm² is required.

By re-arranging equation (1), I_0 can be calculated.

$$I_0 = \frac{UV_{dose,4log} * u_{x,r}(k)}{L_{lamp} * exp(-\alpha * R_{pipe} * (R_{rz}(k) - \frac{R_{lamp}}{R_{pipe,opt}}))} \quad (17)$$

By using I_0 and the R_{opt} , previously calculated, the following relationship between the relative radius and the intensity as well as velocity was plotted in figure 4.6.

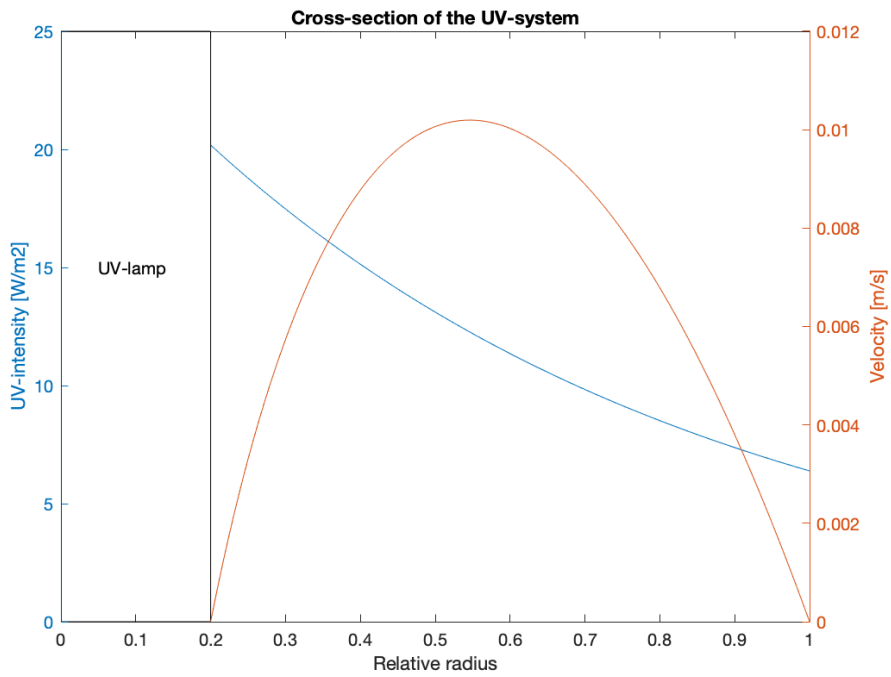


Figure 4.6: The velocity and intensity as a function of the relative radius

The UV-dose as a function of the relative radius varies as in figure 4.7

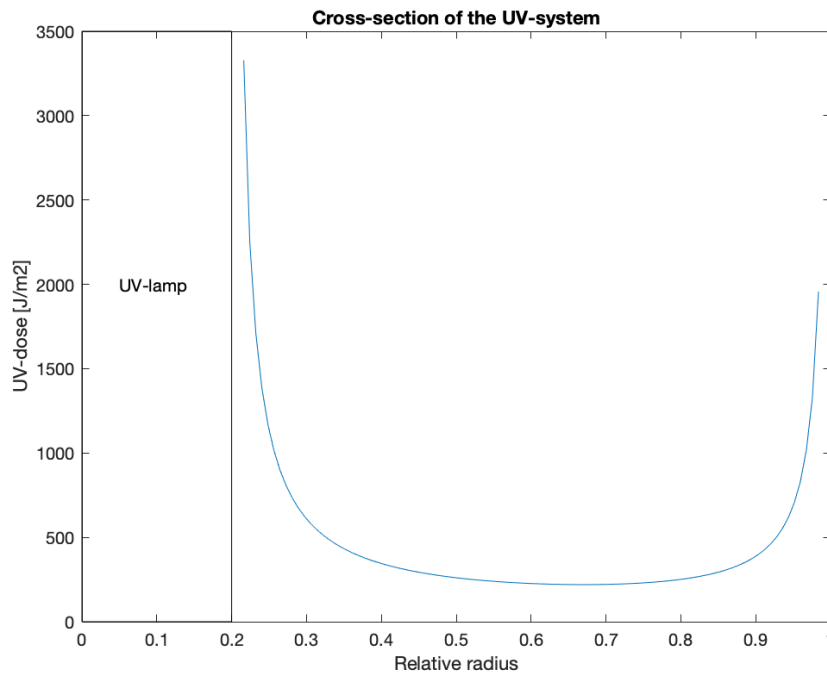


Figure 4.7: UV-dose as a function of the relative radius

4. Further development

I_0 is the intensity of the UV-lamp at a specific wavelength of 254 nm. To calculate the total flux φ from the lamp, the formula from H.Keitz(1971) is used. By looping through all distances a , the maximum total flux was calculated.

$$\varphi_{max} = E * 2 * \pi * a * L_{lamp} = 0.4324W \quad (18)$$

where E is the irradiance at a point P at the perpendicular distance a from the UV-lamp.

The last step was to adjust for the electrical to germicidal efficiency and the aging- and fouling factor. For the Winnipeg plant described earlier regarding the transmittance, the same values for the aging and fouling factor will be used, since this factor is estimated using the same transmittance as used earlier. In this case, the fouling and aging will then be approximated to 70%. For the electrical to germicidal efficiency, EPA (2006) states that this efficiency generally is between 30% and 35%. Taking a conservative approach, 30% was used in the calculations. Finally, a safety factor of 1.5 was added to compensate for the eventual differences between the theoretical set-up and the real design

Given that the UV-lamp is monochromatic and only radiates at 254 nm, the total power for the UV-lamp can be calculated.

$$P_{lamp} = \frac{\varphi}{\eta_{aging,fouling} * \eta_{lamp}} * \eta_{safety} = 4.11W \quad (19)$$

Based on the result above, the UV-system was designed with a 225 mm long UV-lamp. The cylindrical part was made of a reflective material and the other parts were designed in plastics. The complete design of the UV-system can be seen in 4.8.

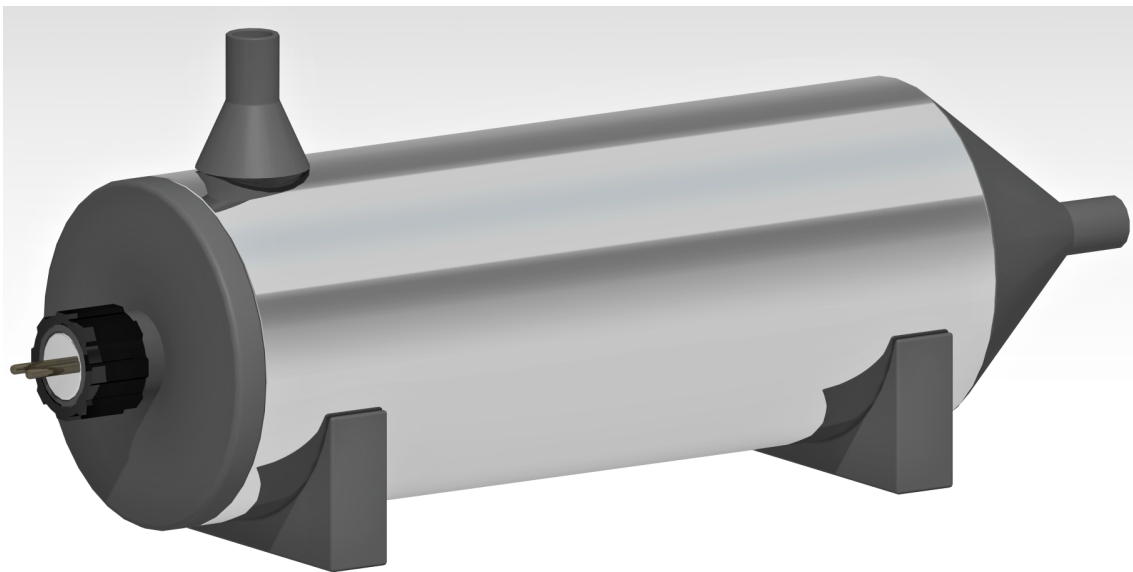


Figure 4.8: The UV-system

4.4 Dimensioning and design of power supply

Based on the power consumption of the water purification components, calculations to estimate the sizing of the power supply components could be made.

4.4.1 Battery sizing

The current capacity of the battery was calculated using the following equation:

$$C_{bat} = \frac{E_{load} \times N_a}{DoD \times U \times \eta_{bat}}$$

Where,

E_{load} is the daily energy need of the system.

N_a is the number of autonomy days (days the battery can power the system without charging).

DoD is the recommended maximum depth of discharge, set by the manufacturer. Exceeding the DoD will lower the life-length of the battery (Depth of discharge is the percentage of the total capacity of the battery that is discharged).

U is the rated voltage of the battery.

η_{bat} is the efficiency of the battery, how much of the electrical input that can be retrieved from the battery.

The daily energy consumption for the system, E_{load} , can be calculated by multiplying the system power times the hours of daily usage. The hours of daily usage can be calculated knowing the flow rate, for a 3 L/min flow rate filling 750 L will take 250 minutes, which equals 4.2 hours. In table 4.2 the power, the daily time and energy need is illustrated.

Table 4.2: Power consumption of appliances, daily time and energy need

	Power (W)	Time (h)	Energy (Wh)
Pump 1	10	4.2	42
Pump 2	4	4.2	16.8
UV-Lamp	4	4.2	16.8
Total:			75.6

$$E_{load} = 75.6\text{Wh/day}$$

According to *Off grid PV power systems* (Global Sustainable Energy Solutions, 2019), which is a design guide for off-grid photovoltaic systems, the PV systems battery voltages usually are 12,24 or 48V. For loads lower than 1kWh daily a 12V battery is recommended and will be used in this project. To keep the system running during days with lower irradiance, the days of autonomy were set to 3 which is the

minimum amount recommended for remote site PV systems. The DoD varies from battery to battery but as a recommended measure it should not be discharged more than 80% of its rated output (Deambi, 2016). Lead-acid batteries are common for solar systems as they are reliable and cost-effective. The efficiency of a lead-acid battery approximately ranges between 80-90%, $\eta_{bat} = 0,85$ (Pinnangudi, Kuykendal, & Bhadra, 2017).

$$C_{bat} \approx 28Ah$$

Commercial batteries with 12V and 28Ah were studied to get approximate dimensions of the needed battery. This resulted in an approximate size of 180x130x170 mm, which will be used henceforth.

4.4.2 Solar panel sizing

The size of the solar panel was calculated using the Peak Sun Hour (PSH) method as described in *Standalone Photovoltaic System Sizing using Peak Sun Hour Method and Evaluation by TRNSYS Simulation* (Al Riza & Gilani, 2014). Peak sun hours are a way of measuring how much solar energy that is available for an area throughout a typical day. One PSH equals an hour during which the solar irradiance is 1000 W/m². The performance of solar panels is measured and rated by manufacturers according to standard test conditions (STC), which is the industry standard for the conditions under which a solar panel are tested. The STCs are a solar cell temperature of 25°C and a solar irradiance of 1000 W/m². The following formula was used to calculate the needed area of the solar panel:

$$A_{solarpanel} = \frac{E_{load}}{P_{output} \times PSH} \quad (1)$$

Where,

$A_{solarpanel}$ is the required area of the solar panel,

E_{load} is the daily energy consumption of the system,

P_{output} is the amount of power per area the solar panel can convert to electricity,

In this project the target markets are limited to areas with a daily global horizontal irradiance above 4.6 kWh/m². Thus, the minimum amount of peak sun hours for our regions of interest, with a solar irradiance of 1000 W/m², will be:

$$PSH = \frac{4600}{1000} = 4.6h$$

P_{output} can be calculated with:

$$P_{output} = P_{solar} \times \eta_{conversion} \times \eta_{system} \quad (2)$$

Where,

P_{solar} is the solar irradiance and equals to 1000 W/m^2 ,

$\eta_{conversion}$ is the conversion efficiency of the solar cells. Crystalline solar cells are the most common commercially used solar cells. There are two types of crystalline solar cells, mono-crystalline and poly-crystalline. Poly-crystalline solar cells have a lower efficiency but is cheaper and will be used in this project. The conversion efficiency of poly-crystalline cells is around 20%, $\eta_{conversion} = 0.2$ (OFFICE of ENERGY EFFICIENCY & RENEWABLE ENERGY, 2020) and η_{system} is the system efficiency.

The system efficiency, η_{system} , is dependent on several factors, which are taken from the off-grid photovoltaic system design guide. (Global Sustainable Energy Solutions, 2019)

- Temperature. During use the solar cells will heat up and exceed the STC value of 25°C , as the temperature exceed 25°C the output decreases. For a daytime ambient temperature of 30°C the solar cells temperature will be around 55°C which will lead to an approximate loss of 11% of its rated output, $\eta_T = 0.89$
- Manufacturers Output Tolerance, usually is $\pm 3\%$ which means a potential loss of up to 3% of its rated output, $\eta_{tol} = 0.97$.
- Dirt and dust. For most rural off-grid areas the loss due to dirt and dust does not exceed 5% of its rated output, $\eta_{dd} = 0.95$
- Mismatch and wiring losses. The output of the solar panel will in most cases be less than the sum of the maximum output of the individual solar cells, in addition there will be losses due to resistance in the system wiring. This factor is set to 5%, $\eta_{mw} = 0.95$

$$\eta_{system} = \eta_T \times \eta_{tol} \times \eta_{dd} \times \eta_{mw} = 0.779$$

Putting these values into equation (2) gives:

$$P_{output} = 155.8 \text{ W/m}^2$$

Which put in equation (1) gives:

$$A_{solarpanel} = 0.105 \text{ m}^2$$

By knowing the area of the solar panel to meet the daily energy demand, the case where the battery has been discharged following days with less solar irradiance needs to be considered. In order to charge the battery in addition to meeting the daily energy demand, the solar panel needs to be over-sized. The design guide recommends an oversize factor, $O_{discharge}$ of 1.2. Thus,

$$A_{solarpanel} = 0.105 \times O_{discharge} = 0.126 \text{ m}^2$$

The cost of solar panels is usually measured as a cost/watt and thus the rated output for the solar panel needs to be calculated. This can be done with:

$$P_{rated} = A_{solarpanel} \times P_{solar} \times \eta_{conversion} = 25.2W$$

4.4.3 Solar charge controller

The dimensioning of the solar charge controller means getting a controller that can handle the amount of power and current produced in the PV system. To account for temporary increased current levels due to for example light-reflection a safety factor of 1.25 for the needed current is usually used, which gives:

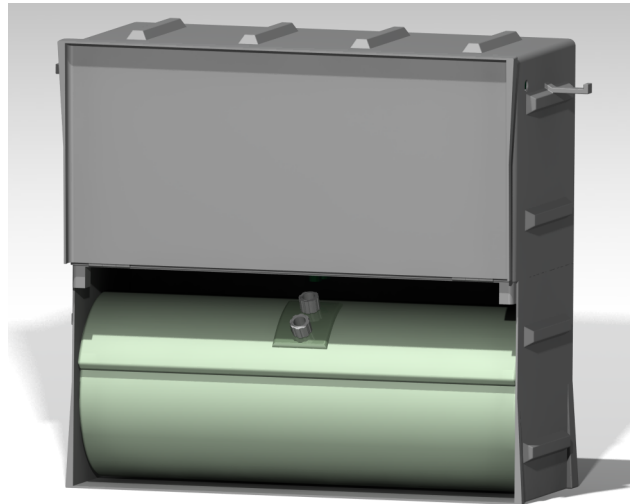
$$\frac{P_{rated}}{U} \times 1.25 = 2.64A$$

4.4.4 Body and clean water tank

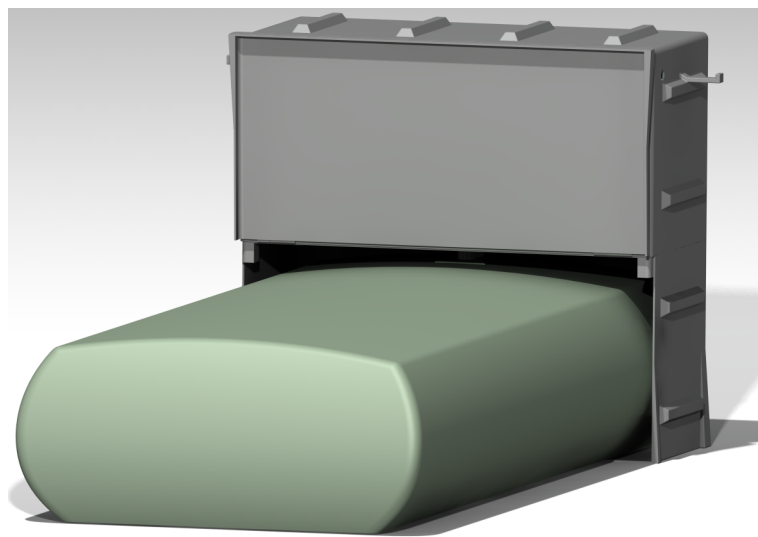
Based on the size and positioning of the components within the system boundary in figure 4.1, the system body could be designed. In terms of positioning of the components, there were constraints on the direction in which the filters and UV-lamp were placed. To utilize the whole cartridge of the filter they need to be placed vertically with the lid of the housing being on top of the cartridge. If the filters were to be placed horizontally the gravity would make the water go through one side of the cartridge more than the other, reducing the life length. Placed vertically the filters have a length of 294 mm. In order to enable replacement of cartridges the top box's height were set to 315 mm. The remaining components were positioned in a way which utilizes space efficiently and promotes stability. The dimensions of the top-box were set to 650x300x315 mm.

A matching sized box is used to store the inflatable bag, used as a clean water tank, whilst in its collapsed form. The inflatable bag needs a volume of 0.25 m³ and the dimensions were set to match the storage box. The boxes are strengthened with horizontal reinforcements which besides strengthens the boxes, also will protect the components that will be partly outside of the box, such as the pumps and the control panel, if the system should fall over. The positioning of the components is illustrated in chapter 6.

In figure 4.9 the body and clean water tank are illustrated in two different forms.



(a) Body and collapsed clean water tank



(b) Body and Filled clean water tank

Figure 4.9: The system body and the clean water tank

4. Further development

5

Manufacturing processes and materials selection

The following section will describe the selection of materials and manufacturing processes for those components, which prices cannot be estimated from off-the-shelf products. The screening and selection of materials were done in *CES Edupack 2019*, which is a software with large databases for different materials.

5.1 Clean water tank

The materials database used for this search was of level 3, containing 4010 different materials in total. (CES Edupcak 2019, Granta Design Limited, n.d.) The material constraints for the clean water tank are listed in table 5.1. The constraint for the low value for flexural modulus was added since the bladder is expected to be folded when not used and it will therefore have to be easy to bend.

Table 5.1: Material constraints for clean water tank

Constraint	Target value	No of hits
Material category	Plastics	610
Fresh water resistance	Excellent	539
Recyclable	Yes	239
UV-resistance (sunlight)	Excellent; good; fair	157
Flexural modulus	< 0.1 GPa	7
Tensile strength	> 10 MPa	5
Maximum service temperature	> 45 °C	3

From the material screening process, 3 materials passed all constraints. The remaining materials are very similar and are a type of Polyvinyl chloride (PVC). To see eventual differences in price and density, a graph containing values for density and price for the materials was plotted see fig 5.1.

5. Manufacturing processes and materials selection

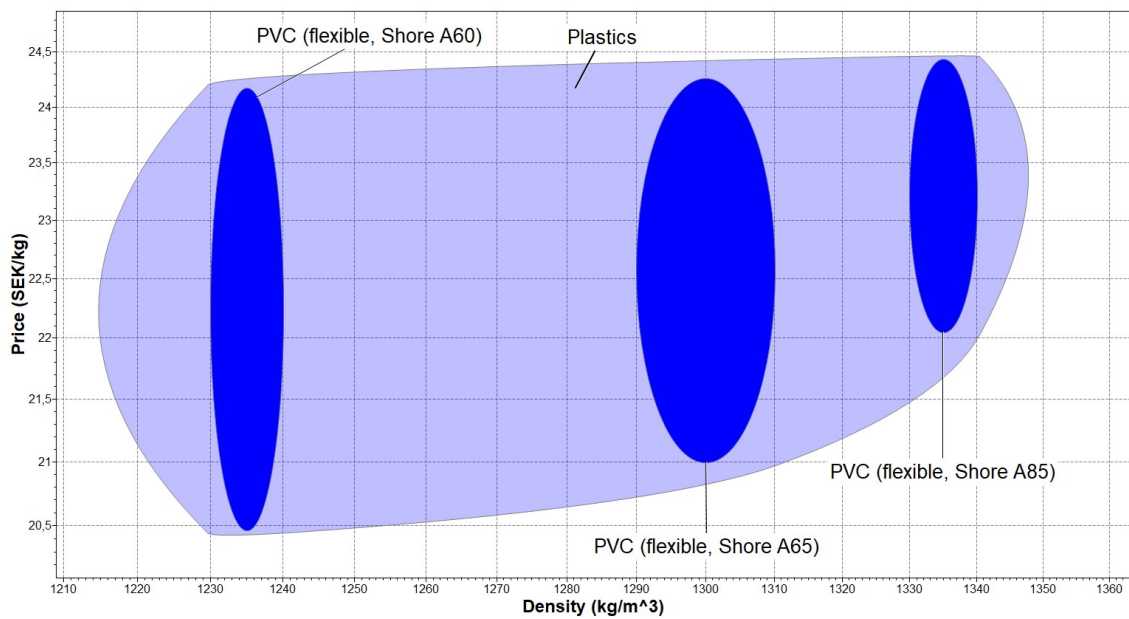


Figure 5.1: Data from CES Edupack 2019

As can be seen from above, the price and density range for the different materials are quite similar. To differentiate between the materials, the elongation was plotted against the tear strength, see fig 5.2.

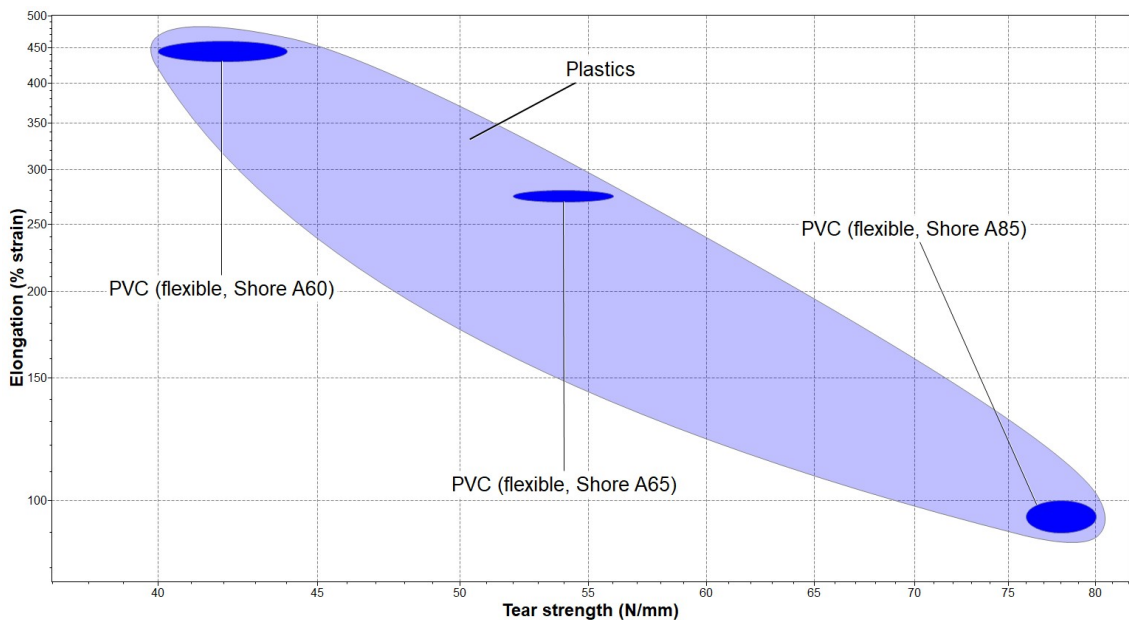


Figure 5.2: Data from CES Edupack 2019

Here it is evident that PVC (flexible, Shore A85) had a much lower elongation, which will make this material keep its shape better while filled with water, relative to the other materials. The tear strength was also significantly higher, thus this material was chosen for the clean water tank.

The next step was to choose an appropriate manufacturing process for the clean water tank. Calendaring was chosen as manufacturing process since it is capable of high production rates and works well for PVC. The manufacturing process will be to produce two sheets of PVC, which will be welded together using hot gas welding. (CES Edupcak 2019, Granta Design Limited, n.d.) The parameters, shown in table 5.2 and 5.3 was used when estimating the cost for the production of sheets to the clean water tank.

Table 5.2: Material parameters for PVC (flexible, Shope A85)

Material parameter	Value
Material area	2.739 m ²
Material thickness	3 mm
Density	1330 kg/m ³
Weight	10.93 kg
Price per kg	23.25 SEK/kg

Table 5.3: Process parameters for calendaring

Process parameter	Value
Overhead cost	1323.25 SEK/h
Discount rate	5%
Capital write off	5 years
Load factor	50%

Assuming a batch size of 100 000, the cost per unit of clean water tanks will range between 275 SEK to 379 SEK as shown in figure 5.3. However, the cost of cutting and welding is not included in this cost. Given the assumption that the cost for these two processes equals 20% of the sheet manufacturing cost, the total cost is in between the range 330 SEK to 455 SEK.

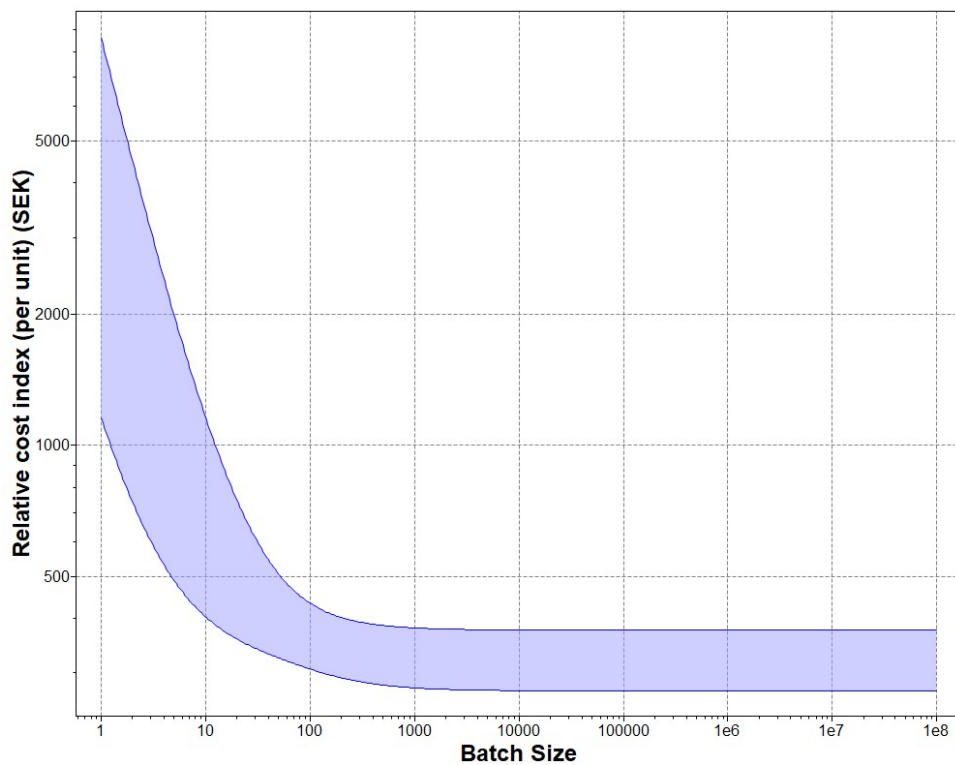


Figure 5.3: Cost per unit relative to batch size - data from CES Edupack 2019

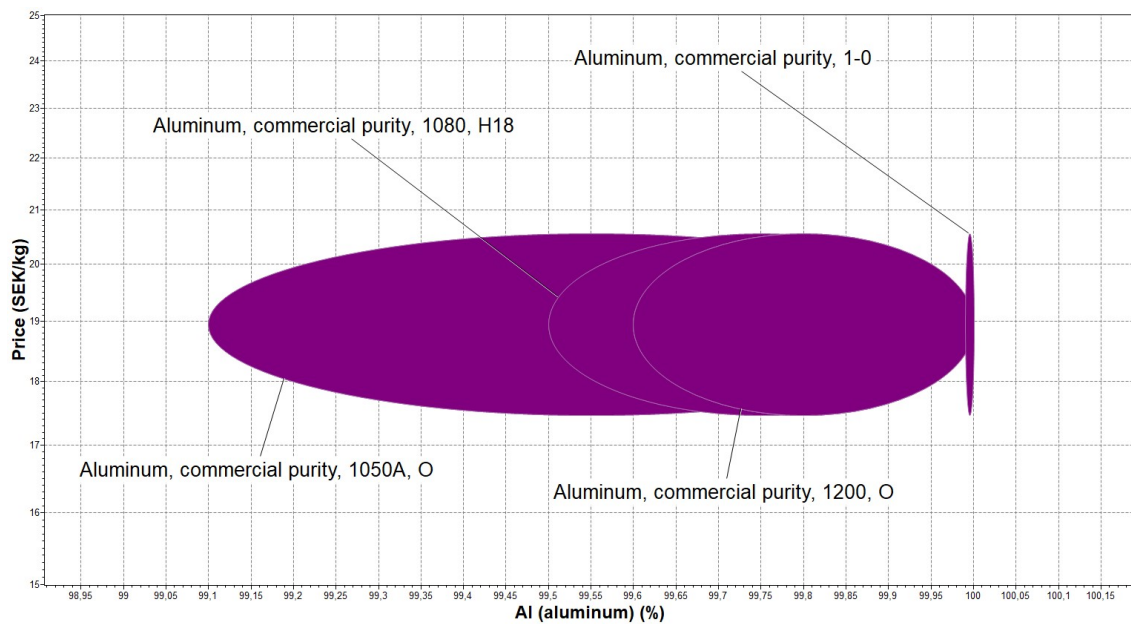
5.2 UV-lamp housing

The UV-housing should be in a reflective material, so that the remaining UV-rays which do not get absorbed by the water, can reflect back to the water and therefore increase the disinfection efficiency. Because of this desired property, this search was limited to only involve metals. Since metals could be toxic, the material database was changed to *Level 3 Bioengineering*, to be able to set constraints regarding toxicity. After the second last constraints, it was evident that aluminum was going to be used. It was therefore assumed that aluminum with high purity is more reflective than aluminum with lower purity and a constraint for the purity was therefore set. Table 5.4 illustrates the material constraints for the UV-lamp housing.

Table 5.4: Material constraints for UV-housing

Constraint	Target value	No of hits
Material category	Metals	1863
Fresh water resistance	Excellent	1376
UV-radiation (sunlight)	Excellent	1376
Recyclable	Yes	1319
RoHS compliant	Yes	1230
Food contact	Yes	715
Cost	< 20 SEK/kg	209
Density	< 5000kg/m ³	155
Metal hot forming	Excellent; good	126
Amount of aluminum	> 99.9%	8

The remaining eighth metals was all different types of aluminium. The cost per kg was therefore compared against the level of purity in figure 5.4, since cost is an important parameter and purity was assumed to be an estimation for the ability to reflect UV-light.

**Figure 5.4:** CES Edupack 2019

Since there was not a difference in price range between the different alloys of aluminum, pure aluminum (Aluminum, commercial purity 1-0) was chosen as material for the UV-lamp housing.

To avoid the costly process of TIG-welding, which is commonly used with aluminum alloys, it was decided that the inlet, outlet and lamp attachment parts of the UV-housing should be made out of a plastic material. The process for this will be covered in the next section.

The chosen manufacturing process for the aluminum profile was hot metal extrusion. In this case however, it will be more economical to make larger profiles per batch and therefore the batch size was changed to 10 000 units, where each unit will be cut into 10 different parts. The cost estimation for the aluminum parts of the UV-housing is visualised in table 5.5

Table 5.5: Cost estimation for aluminum UV-housing parts

Length	Volume (m3)	Density (kg/m3)	Weight (kg)	Cost per 257mm
2570mm	0.00164	2700	4.4	14.5-63.4 SEK

5.3 UV-lamp adapters

In these parts of the UV-lamp the reflective property of aluminum is not needed. To avoid the need of threads these parts were shaped as plugs, which is simply pressed into the aluminum pipe. The material constraints for the plastic parts of the UV-cover is listed in table 5.6.

Table 5.6: Material constraints for plastic parts of UV-housing

Constraint	Target value	No of hits
Material category	Plastics	610
Fresh water resistance	Excellent	539
Recyclable	Yes	239
UV-resistance (sunlight)	Excellent; good	57
youngs modulus	> 1 GPa	52
Price	< 30SEK/kg	12

The remaining 12 materials were plotted against the material cost, Polypropylene (impact copolymer, UV-stabilized), PP, were chosen as the material for the plastic parts of the UV-lamp housing. The manufacturing process for these components was chosen to be injection molding and the same parameters as for the clean water tank regarding overhead cost, the capital write off time, discount rate and load factor were used. For a batch size of 100 000 the cost estimation for the plastic components of the UV-lamp can be seen in table 5.7.

Table 5.7: Cost estimation for plastic UV-lamp components

Part	Volume (m3)	Density (kg/m3)	Weight (kg)	Cost range (SEK)
Lamp inlet	0.00004	904	0.0362	10.9-50.9
Lamp outlet	0.000007	904	0.0063	9.9-49.8
Lamp attachment	0.000031	904	0.0280	10.7-50-6
Total	0.000078	N/A	0.0705	31.5-151.3

Combining this with the cost of the aluminum profile gives a total cost for the UV-lamp housing of 46-214.7 SEK

5.4 Body

The body needs to be strong in order to withstand the weight of all components as well as the eventual impacts during transportation. However, it also needs to be lightweight to be able to carry. Based on this, as well on the harsh environment the system is expected to be used in, a list of constraints were set up, see table 5.8.

Table 5.8: Material constraints for body

Constraint	Target value	No of hits
Fresh water resistance	Excellent	2696
UV-radiation (sunlight)	Excellent;good	2182
Recyclable	Yes	1510
Transparency	Opaque; translucent	1467
Form	Bulk material	1323

To reduce the amount of materials further, the mass per unit of stiffness was plotted against the density in figure 5.5, for a panel in bending as the load case. This was chosen since the body will consist of panels which are likely to bend if the stiffness is too low. The index line with slope -1 was added to minimize the y-axis and x-axis.

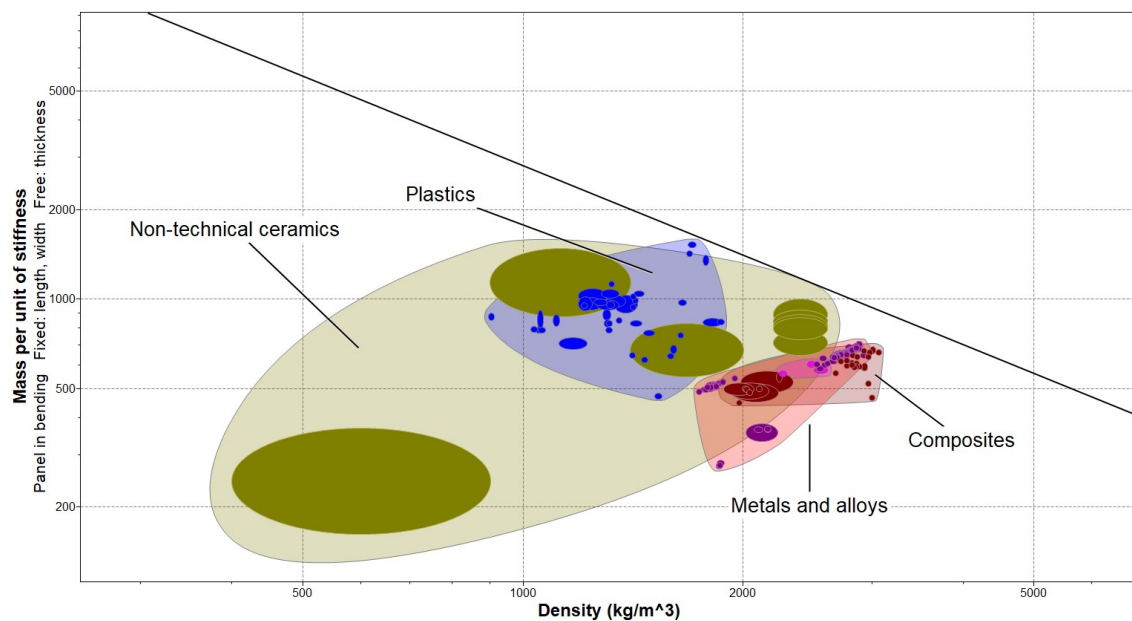


Figure 5.5: CES Edupack 2019

The minimization resulted 442 different materials. However, many of these were non-technical ceramics. These type of materials will not be suitable for the body

since they are brittle and will be hard to manufacture in the desired shape. This group of materials was therefore removed and another graph was plotted, figure 5.6, with the same load case as previous but with cost instead of mass and strength instead of stiffness. A line with slope -1 was added to minimize the index, removing all materials above the line. The line's interception point at the y-axis was moved, until only three materials remained.

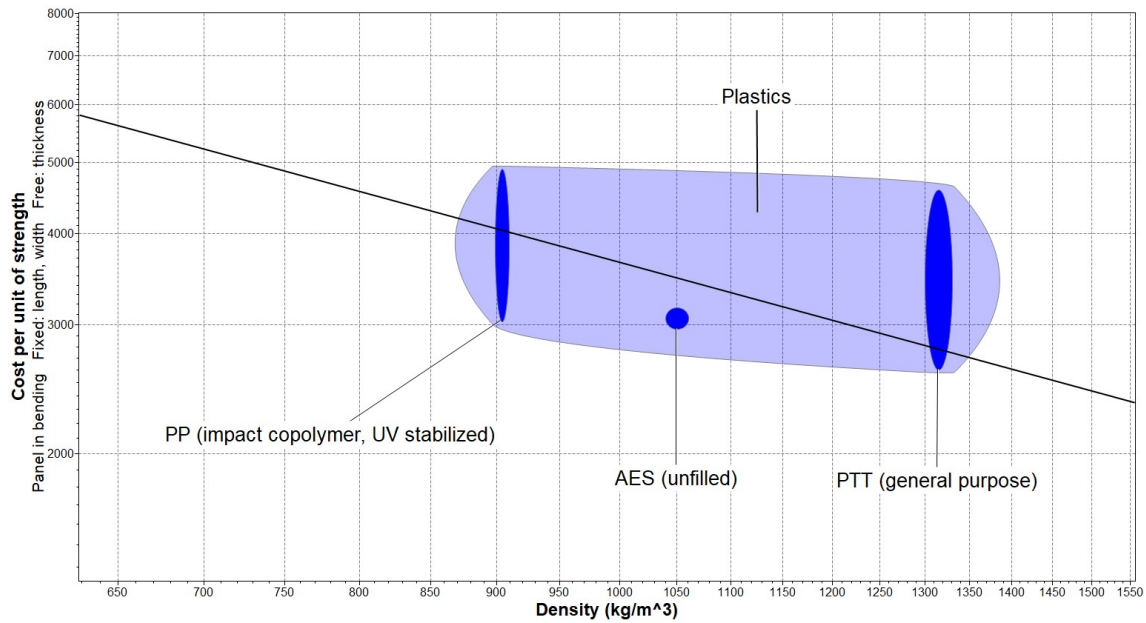


Figure 5.6: CES Edupack 2019

From these three materials, AES (unfilled) was chosen as the material for the body since it had the highest fracture toughness compared to the others, as well as excellent manufacturability for injection molding.

The body consists of five different parts; the bottom box, the top box, the middle plate and two lids. The manufacturing process for these components was chosen to injection molding and the same parameters as for the clean water tank, will be used for the overhead cost, discount rate, capital write off and load factor. The cost estimation of the body is visualised in table 5.9

Table 5.9: Cost estimation for body

Part	Volume (m ³)	Density (kg/m ³)	Weight (kg)	Cost range (SEK)
Bottom box	0.002	1040	2.288	83.6-135
Top box	0.003	1040	2.611	93.3-147
Bottom lid	0.0008952	1040	0.931	41-82.9
Top lid	0.0006469	1040	0.673	32.5-73.5
Middle plate	0.0007573	1040	0.788	36.3-77.7
Total	0.0073	N/A	7.291	286.7-516.1

6

Final concept

6.1 Final design

The final concept is named **light2pure**. The main idea with the design is to minimize space consumption during distribution, lowering the total cost per liters of purified water compared to smaller emergency water treatment products, as well as being user-friendly. Figure 6.1 - 6.4 illustrates the final design of the light2pure.

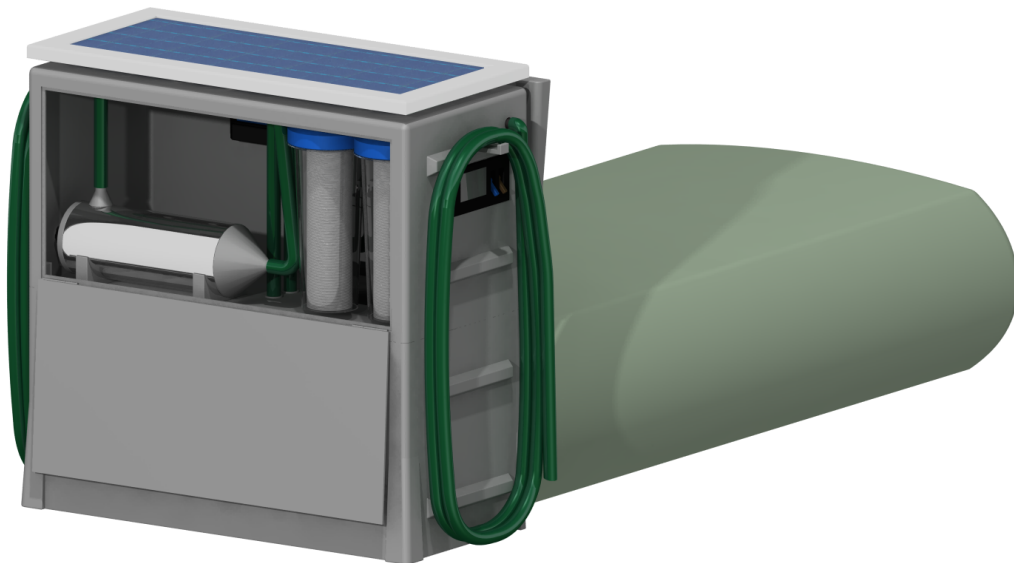


Figure 6.1: Isometric view from the front

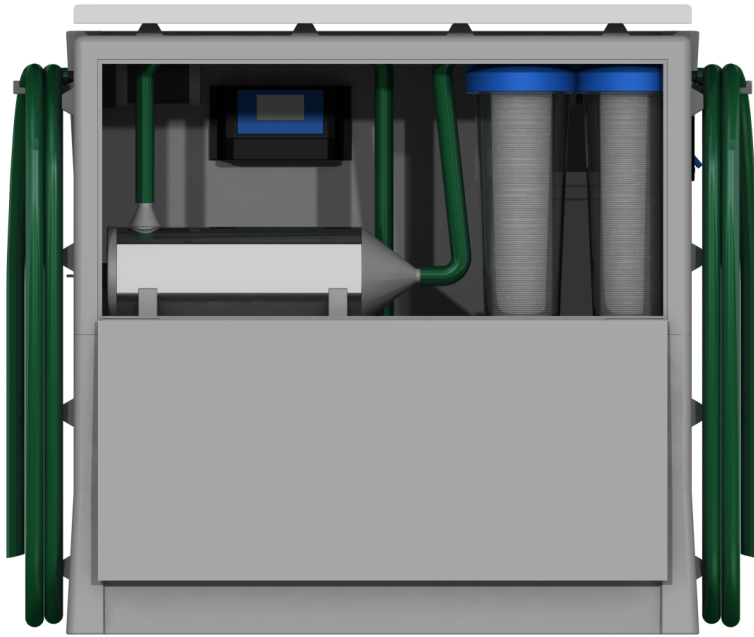


Figure 6.2: Front view of the light2pure

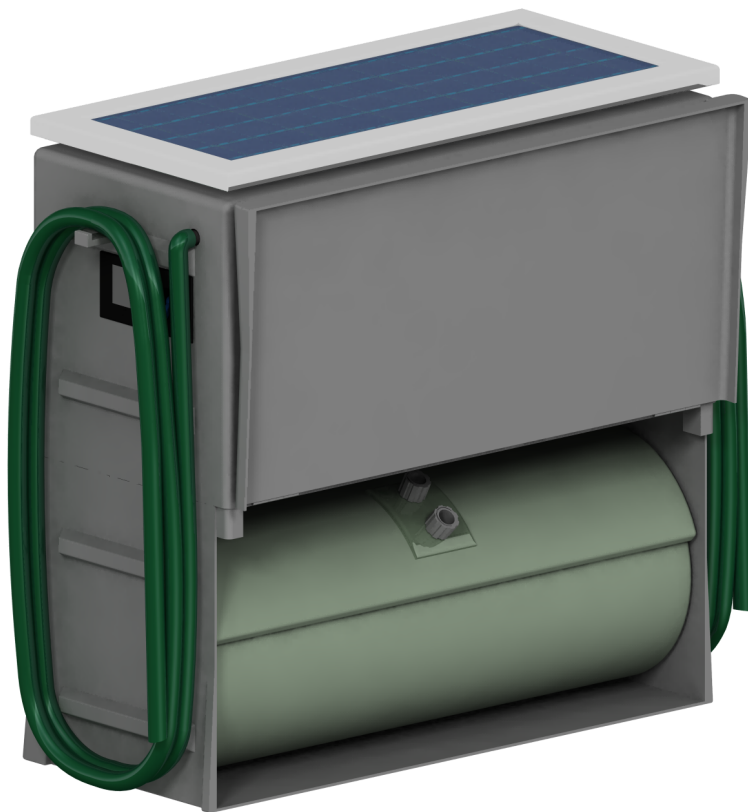


Figure 6.3: Isometric view from the back, with the water tank rolled up.



(a) Front view

(b) Back view

Figure 6.4: Transportation mode

The product consists of 13 different components, excluding fasteners, tubing, electrical cables and adapters needed by the components. The different components are visualized in figure 6.5 below.

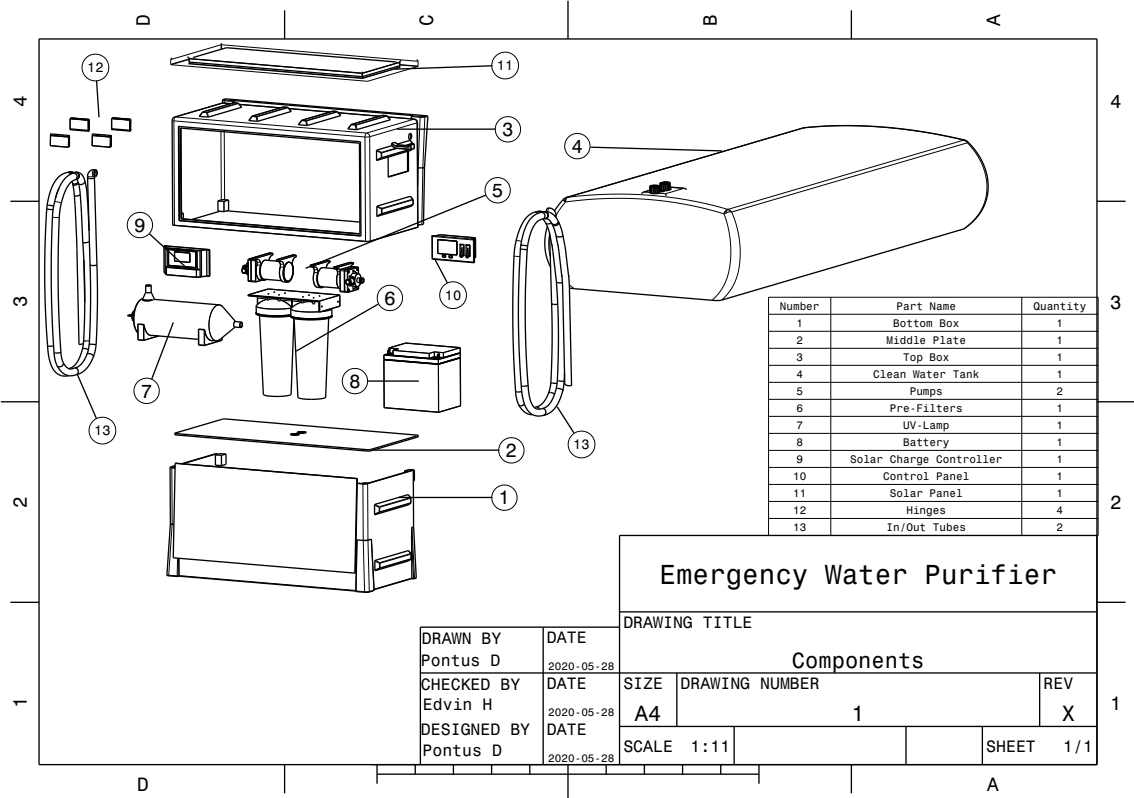


Figure 6.5: Drawing of the light2pure and its components

The bottom box is used as storage for the clean water tank during distribution. It

has a lid, which when opened, enables the clean water tank to be rolled out and filled with water. The middle plate separates the bottom box and the top box. Together with the bottom box the middle plate provides a connection between the clean water tank, purifying system and water outlet of the product. The clean water tank has one inlet and one outlet opening. The inlet is connected to the UV-lamp with a hose and enables the tank to get filled. The outlet is connected to the outlet pump with a hose and enables serving of the purified water from the clean water tank.

In the top box, the pump, the purification components along with the battery and solar charge controller is stored. The solar panel is mounted to the top of the top box. The top box has cutouts on each short side for the pump pipes. The inlet and outlet hoses are mounted on the respective pump pipe. The top box has a lid which makes the components within the top box easily accessible. On the short side of the top box where the inlet pump is placed, there is another cutout in which the control panel is attached. From the control panel the system is turned on/off and the flowrate of the system can be adjusted according to the level of water contamination. In figure 6.6 the control panel is visualized. The brown switch operates the inlet pump and UV-lamp, the blue switch operates the outlet pump. The display and associated buttons give the possibility of seeing the current flow-rate of the system and changing the flow-rate depending on contamination level (a slower flow-rate will make the UV-disinfection more efficient).

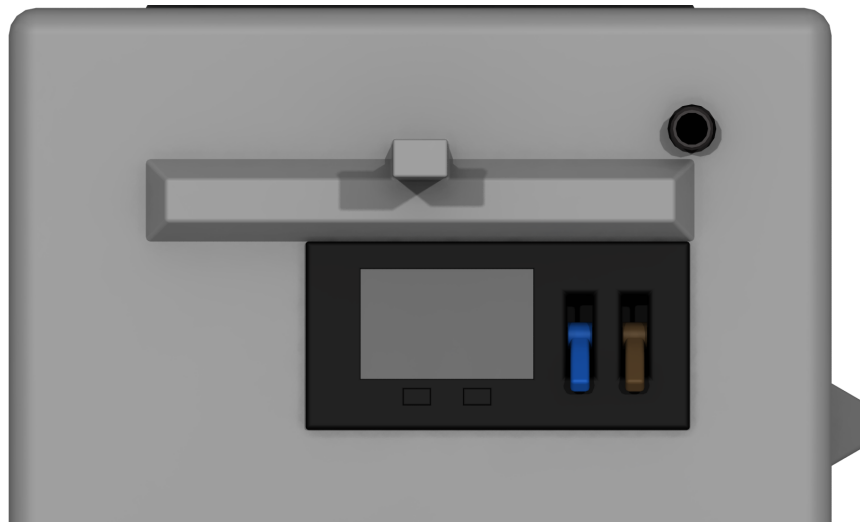


Figure 6.6: Control panel

The source water is pumped by the inlet pump through the inlet hose, then continues through the pre-filters and the UV-lamp before arriving through one of the openings in the clean water tank. The purified water is pumped out of the clean water tank by the outlet pump through the outlet hose.

6.2 Assembly and usage

Upon delivery the clean water tank is rolled up and stored in the bottom box together with the solar panel. The remaining power supply components and purification components are attached in their respective position in the top box, together with the inlet and outlet hoses. To prepare the light2pure for usage the following steps should be made:

1. Place the light2pure in a spot with limited shading, and within 20 meters of a water source.
2. Open the lid of the bottom box, take out the solar panel and roll out the clean water tank.
3. Attach the solar panel and its electrical cables to the top of the top box.
4. Open the lid of the top box, take out the inlet and outlet hose.
5. Attach the inlet and outlet hoses to their respective pump pipe on the short sides of the top box.
6. Attach the hose from the UV-Lamp and the hose from the outlet pump to the clean water tank through the holes of the middle plate.
7. Start the solar charge controller by pressing the ON-button.

The assembly process is expected to take less than 15 minutes with provided instructions. After these steps, the light2pure is ready for usage. To operate the system the following steps should be made:

1. Place the end of the inlet hose in the water source.
2. Start the purification of the contaminated water by turning the brown switch on the control panel to ON.
3. Place your water container under the outlet hose
4. Start the extraction of purified water by turning the blue switch on the control panel to ON.
5. Switch the blue switch on the control panel to OFF when done filling your container.
6. OPTIONAL: turn the brown switch to OFF to stop the purification of contaminated water

The step of turning the purification process off is optional since there will be a switch in the ceiling of the bottom box which will turn of the system as the clean water tank gets filled. The assembly process is expected to be used a few times

6. Final concept

throughout the products life-length whereas the purification process is expected to be used several times every day.

7

Commercial assessment

This chapter will provide an estimation of the production cost for the light2pure, along with benchmarking with competing products.

7.1 Estimated total production cost

To estimate the production cost, CES's built-in cost estimation tool were used for the components that underwent material selection, see section 5. For the remaining components, prices for products from resellers with similar properties were used.

List prices from Filer Filter Systems were used for the pre-filters. The price for a 10x2.5" Polypropylene string-wound cartridge when bought in a quantity of 24-pieces is 4.35£ each for micron ratings of the filters ranging from 0.5 to 150. Matching housings for the cartridge filters were found at ESP Water products at a retail price of 13.61\$ each.

When estimating the cost of the water pumps, BLDC PUMP Co, were contacted for a quote regarding pumps with similar properties regarding power, pump head and flowrate. The free on board (FOB) price for the needed inlet pump and outlet pump is 12\$/piece with a minimum order of quantity of 100.

The cost of the UV-lamp, UV-ballast, battery, solar panel and solar charge controller were estimated from commercial prices of products on Amazon. The cost of a single ended 4W UV-lamp is 14\$ and the matching ballast 35\$. The approximate cost for a lead-acid solar storage battery with 12V and around 30Ah is 60\$. A 12V 25W poly-crystalline solar panel costs roughly 35\$. The cost of a 12V 10A solar charge controller is around 12\$ (the price for a 12V 3A unit is roughly the same). In table 7.1 the estimated production cost is visualized.

Table 7.1: The estimated production cost for the different components. Exchange rates used: 1GP£=11.88SEK, 1US\$=9.65SEK

Production Cost				
Qty	Component	Cost	Cost (SEK)	Reseller
	Pre-filter			
1	String wound filter 5 μm	4.35£	52	Fileder Filter Systems
1	String wound filter 50 μm	4.35£	52	Fileder Filter Systems
2	Filter Housing	13.61\$	262	ESP Water Products
	Pumps			
1	Inlet Pump	12\$	116	BLDC PUMP Co.
1	Outlet Pump	12\$	116	BLDC PUMP Co.
	UV-lamp			
1	Lamp	14\$	136	Amazon
1	Ballast	35\$	338	Amazon
1	Housing		46-214.7	N/A
	Power-supply			
1	Battery	60\$	617	Amazon
1	Solar Panel	35\$	338	Amazon
1	Solar Charge Controller	12\$	116	Amazon
	Body			
1	Body		288.7-516.1	N/A
1	Clean water tank		330-455	N/A
	Others			
1	Tubes, cables, fasteners etc.		300	N/A
	Total Cost		3108-3629	

The cost for the smaller components such as the tubing, electrical cables, fasteners and adapters were estimated to account for around 10% of the total cost, which converts to approximately 300 SEK. The estimate total cost of the product therefore ranges between 3108 and 3629 SEK. The rather large price interval is a consequence of the estimated production cost, which is dependent on the complexity of the components produced - the lower interval being for simple geometries and the higher for complex geometries. The components that were investigated in CES are all expected to have relatively simple geometries and a production cost in the middle of the price interval, 3369 SEK, was decided to be used henceforth. To achieve requirement 6.2 regarding the manufacturing cost not exceeding 50% of the purchasing cost gives a minimum purchasing cost of 6738 SEK, which is well within the limit of 8000 SEK in requirement 6.1.

7.2 Benchmarking against the Lifesaver Jerry Can

To make the light2pure comparable with the Lifesaver Jerry Can, the products were assumed to produce equal amount of clean water per day and have a life length of at least 1 year each. Given the production rate of 750 liters per day

over a one-year period, this translates to a total production of 273750 liters of water. The filter in the Jerry Can has a life-length of 15000 liters, thus the filters must be replaced approximately 18 times, in order to produce the total amount of water. The purchasing cost of the Jerry Can is 825 SEK, including one filter, and a filter exchange is 587.5 SEK. The light2pure has a purchasing cost of 6738 SEK and requires 7 filter exchanges over the period of one year, estimated in section 4.3.1, leading to a filter exchange rate of 0.58 filters/month. The accumulated cost comparison between the light2pure and the Lifesaver Jerry can is visualized in figure 7.1.

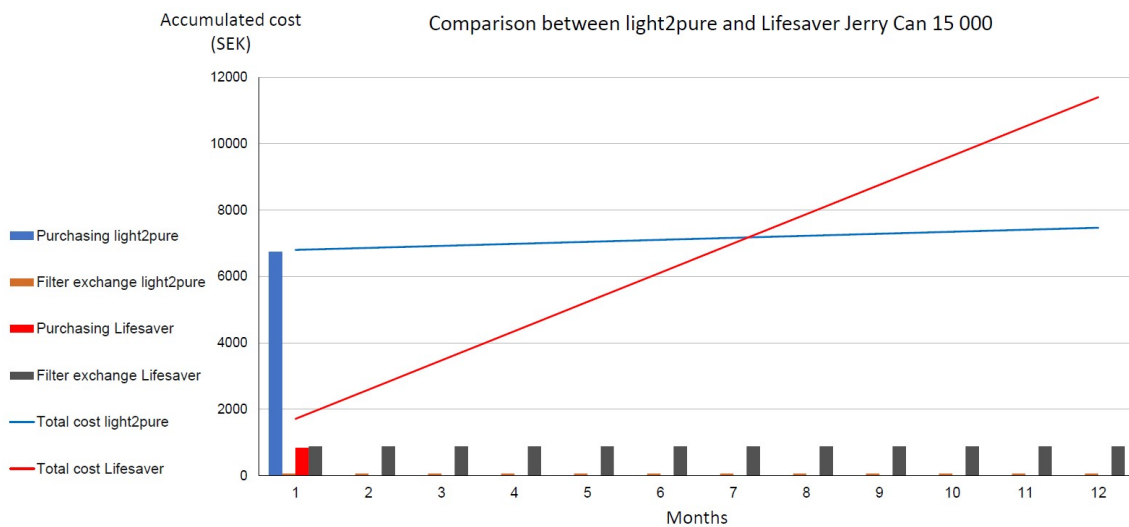


Figure 7.1: Accumulated cost comparison

Regarding the microbiological filtration efficiency, the Lifesaver provides a 6-log reduction whereas the light2pure provides a 4-log reduction. The flowrate of the two products is similar, however, the Jerry can does not account for the time spent pressurizing or filling the system. Producing 750 L with the Jerry can will require 41 cycles of pressurizing and filling. The cost per liter for the two products given the production rate and life-length used in the accumulated cost comparison is shown in table 7.2.

Table 7.2: Cost per liter comparison

Comparison	light2pure	Lifesaver Jerry Can
Cost per liter (SEK)	0.025	0.042

8

Discussion

This chapter will cover a discussion regarding the different constraints and assumptions made throughout the project and how these affect the final product. There will also be discussion regarding the how well the final product fulfilled the requirements that were set up and what needs to be done to verify the properties of the final product. Lastly there will be a discussion regarding the development process as a whole.

8.1 Water source quality

The level of contamination in the water source determines how large the microbiological log-reduction needs to be to meet the requirements regarding water quality. In this project, the water source quality was set based on a single case study of water contamination as a consequence of one flooding. The highest recorded value on the microbiological contamination out of three samples was chosen as the reference value. The required log-reduction lays the foundation for the dimensioning of the UV-lamp which in turn affects the required size of the power supply components. With more qualitative data for the water source quality after natural disasters, the design of the components could be optimized as a means of reducing size and cost whilst still guaranteeing sufficient quality, over a certain confidence interval, for the purified water.

The historical data that was used to estimate the transmittance and turbidity level for the water after the pre-filtration, is considered to be reasonable. This since several UV-lamp manufacturers recommend a 5-micron pre-filter prior to an UV-system whilst simultaneously recommending a turbidity below 1 NTU for UV-disinfection.

8.2 Pre-filters

A big uncertainty in this project is the life-length, holding capacity and the over time increasing pressure drop of the pre-filters. These parameters will affect maintenance intervals which in turn will affect the total cost for the product.

The assumption made in section 4.3.1 regarding the capacity of the pre-filters being half of the specified capacity for the source water quality during natural disasters

might not be accurate. It is not unreasonable to assume that more or less filters might be needed. The cost of the pre-filters constitutes a small part of the total cost, together the 5 μm and 50 μm pre-filters stands for 3.4% of the production cost. Thus, eventually adding or removing additional filters to maintain the life length for the product of at least one year will not significantly affect the total estimated cost.

Since the product uses cartridge filters, the increased maintenance will be minimal, as replacing cartridge filters takes a couple of minutes. To compensate for the unknown increased pressure drop, the pumps were over-dimensioned with a factor of 2 as mentioned in section 4.3.2.

With proper testing of different pre-filters and fineness's with relevant water quality, the choice of pre-filters could be optimized to reduce cost and maintenance of the product.

8.3 Water pumps

An uncertainty regarding the inlet pump is whether it has the ability of self-priming for the set pre-requisites of 5 meters elevation and 20 meters hose length. Self-priming pumps is common but for the relatively small size of the inlet pump it is a possibility that the pump needs to be combined with a manual pump or have a larger safety factor for priming.

8.4 UV-lamp

Even though the analytical solution can be useful as a first stage of determining the UV-dose, measurements of the UV-dose using UV-sensors in a complete physical system needs to be done to validate the result. The formulas used in the calculations are also based on a specific UV-setup, fully symmetric, whilst the UV-system designed in this project has a slightly different design and is asymmetric. This was compensated for by using a safety factor, because it was assumed that the flow around the UV-lamp will not be symmetric because of its asymmetric design. This in turn affects the minimum UV-dose required for all water molecules to receive enough UV-dose. However, the safety factor was only based on gut-feeling and Computational Flow Dynamics could be one approach to make a better estimate on how the flow profiles changes.

Another aspect that most probably will improve the result is to include the reflective coating in the calculations. However, since this is rather advanced to do analytically, it was chosen to completely ignore this effect. The result of doing so is a UV-lamp with slightly too much power. However, this will improve the water quality even further and the total power consumption will not be affected much.

8.5 Battery

Having a battery or not was discussed several times throughout the project. The battery is relatively costly, takes a lot of space and will weigh around 10 kg. The downsides of having a battery seems to be many. However, by having a battery the product can be used throughout the whole day and not just during sun hours. This in turn will reduce the required capacity of components as the daily production of water can be spread out over more hours. In addition to the reduced costs for less requiring components, the battery will provide a buffer towards days with less solar irradiance. This attribute is something that is invaluable when it comes to water purification as access to safe water is a matter of life and death. Having a product which will only function as intended during sunny days and only during some hours of the day is not desirable.

It could be argued that the amount of autonomy days, $N_a = 3$, in combination with the clean water tank of 250 l is a too conservative approach regarding buffer against less solar irradiance. This since the market has been narrowed to regions with exposure to high solar irradiance. By reducing the amount of autonomy days to two days the needed battery capacity can be reduced with 34% and with it the cost, weight and size. In order to make a decision regarding the nominal days it could be beneficial to make an analysis concerning how common it is with three consecutive days of for example rain. It should also be noted that even during rain and heavy cloud coverage the solar panel will produce some energy, which speaks for lowering the amount of nominal days.

8.6 Body and clean water tank

The choice of using an inflatable bag as clean water storage lowers the needed size during distribution from 0.3114 m³ to 0.1228 m³, which is a reduction by roughly 60%. This considering the previous design with a firm box as clean water storage. However, this is not completely accurate as the previous design intended the boxes to be stacked. Nevertheless, it can be concluded that using an inflatable bag as clean water storage saves valuable space during distribution.

8.7 Fulfillment of requirements

Out of the 16 requirements stated in the requirement specification, see A.4, light2pure in theory fulfills 9 of them, based on the calculations and design choices made throughout the project. Some of these requirements needs to be confirmed fulfilled by testing in practice such as for example the requirements regarding water quality. The remaining six requirements either will show over time, requires user-testing or in some case needs further development to be considered fulfilled.

Requirement 3.1 and 4.4 will show over-time. Many of the components should according to manufacturers last longer than one year, such as the UV-lamp, solar

panel and battery. However, there is as previously mentioned uncertainties regarding the pre-filters. The raw water entering the inlet pump may affect the life length of the pump and needs testing. Having some sort of sintering prior to the inlet pump could solve this, but would affect the pump head. Regarding requirement 4.4 the material selection for the system body and the water tank is done to withstand rural atmosphere and bad weather but the sealing of openings needs to be tested.

Requirement 4.2, 7.1, 7.2 and 7.4 all require user-testing to be considered fulfilled. However, these requirements have been taken into consideration when designing the product. Using non language specific explanatory stickers is an option to facilitate these requirements.

Currently there is no solution in place for requirement 4.3 of having a fail-safe preventing the product from providing water when it is not purified. The calculations made for the UV-lamp with regards to flowrate and water quality will ensure that the water is purified when the lamp is working as intended. If for some reason the lamp is not operating at its intended intensity this would be jeopardized. A potential solution for this could be having a sensor measuring the intensity at the most critical point of the UV-lamp which in turn could influence the electrical circuit if the intensity is not within accepted values. This matter is something that needs further investigation in terms of feasibility and cost.

8.8 Estimated Production cost

Out of the components that did not go through a material selection stage in CES Edupack, the prices used in the estimated production cost are end-user retail prices. The actual production cost will most likely be lower by purchasing directly from manufacturers and ramping up production rates, by gaining economy of scale. Despite this, the estimated production cost gives a good indication of how much the product will cost to manufacture.

8.9 Development Process

A lot of time were spent on developing different concepts with different purification technologies. In the end, a big part of the decision to proceed with concept 3 came down to comparison between technologies in terms of cost and purification efficiency. If a proper comparison between different technologies were done in an earlier stage of the project a decision regarding which technology to use could have been made prior to the development of concept 1-5. This would have given more time to design the chosen UV-concept.

The customer needs identification was a big part of setting the requirement specification for the product and lead to many valuable insights. However, there was no feedback loop with the interviewees throughout the project. By involving the interviewees in for example the concept selection or further development processes would probably have been of valuable input.

9

Conclusion

The goal of the project was to develop a solar driven water purifier to be used when the water sources become contaminated as a consequence of natural disasters. The goal was met as such a product has been designed. The final product is well suited for the intended type of environment because of its robust design and high production capacity relative to its size. From the case-study it was also evident that water contamination is not a transiently problem, but a long-term issue that can affect people's access to water for a long time. The product is therefore designed to have a long life length and to not require much maintenance. The product can be used anywhere on the earth, where there is a high solar irradiance, and has an energy buffer for up to 3 days, making it robust to alternating weather. Regarding the potential customers it was clear from the pre-study that this type of product can be used in many different branches, although International Organizations and Non-Governmental Organizations is considered to be the largest stakeholder. One of the most important demands from these group of customers, according the customer interview, was that the product should be easy to transport. Because of this, the body of the product have a simple geometry in order for it to be able to stack.

Regarding the performance of the product, the results indicates that the product will be able to purify the water according to the Sphere standard. However, in the case of the UV-disinfection there need to be more testing done in order to validate the theoretical results. Out of the 16 requirements set for the product, 9 of them is considered to be fulfilled at the end of this project. The remaining 6 requirements needs further testing to ensure fulfilment. The key business goal was to lower the cost per liter of produced water compared to household water treatment products. The cost per liter of the light2pure is 40.5 % lower than a widely used household water treatment product known as the Lifesaver Jerry Can.

All together the development team is satisfied with the light2pure and the results indicate that the system could potentially be a successful product, even though further work is required to verify that the purifier functions as intended.

References

- Abdul Rahman, N. . . ., Mat Saat, E. . . ., Ilham, N. . . ., Hussin, M. . . ., Yusrina, Y. . . ., & Omar, A. . . . (2020). Design and development of three stages maximum power tracking solar charge controller. *Indonesian Journal of Electrical Engineering and Computer Science*, 18(3), 1270-1278. Retrieved from <http://search.ebscohost.com/login.aspx?direct=true&AuthType=sso&db=edselc&AN=edselc.2-52.0-85079168368&site=eds-live&scope=site&custid=s3911979&authtype=sso&group=main&profile=eds>
- Al Riza, D. F., & Gilani, S. I.-H. (2014). Standalone photovoltaic system sizing using peak sun hour method and evaluation by trnsys simulation. *International Journal of Renewable Energy Research (IJRER)*, 4(1), 109–114.
- Artichowicz, W., Luczkiewicz, A., & Sawicki, J. M. (2020). Analysis of the radiation dose in uv-disinfection flow reactors. *Water*, 12(1), 231.
- Bansal, R. C., & Goyal, M. (2005). *Activated carbon adsorption*. CRC press.
- Basri, Z. D. M., Othman, Z., & Wahid, M. A. (2015). Detection of pathogenic bacteria in flood water. In *Isfram 2014* (pp. 185–193). Springer.
- Bergsrud, F., Seelig, B., & Derickson, R. (1992). Treatment systems for household water supplies: reverse osmosis.
- Brooks, V. A. (2015). *Understanding Water Treatment Processes*, 22–25.
- Burch, J. D., & Thomas, K. E. (1998). Water disinfection for developing countries and potential for solar thermal pasteurization. *Solar Energy*, 64(1-3), 87–97.
- CDC. (n.d.). *Solar disinfection*. Retrieved from <https://www.cdc.gov/safewater/solardisinfection.html>
- CES Edupcak 2019, Granta Design Limited. (n.d.). ([Student access])
- Cheng, T., Wang, P., & Lu, Q. (2018). Risk scenario prediction for sudden water pollution accidents based on bayesian networks. *International Journal of System Assurance Engineering and Management*, 9(5), 1165–1177.
- Chin, W. C. (2012). *Managed pressure drilling: modeling, strategy and planning*. Gulf Professional Publishing.
- CRED, & UNISDR. (2015). The human cost of weather-related disasters, 1995–2015. *United Nations, Geneva*.
- Day, S. J., et al. (2019). Worldriskreport 2019: Focus: Water supply. , 64.
- Deambi, S. (2016). *Photovoltaic system design: Procedures, tools and applications*. Crc Press.
- EngineeringToolBox. (2004). *Converting pump head to pressure and vice versa*. Re-

- rieved from https://www.engineeringtoolbox.com/pump-head-pressure-d_663.html
- Environmental Protection Agency 1. (n.d.). *Types of drinking water contaminants*. Retrieved from <https://www.epa.gov/ccl/types-drinking-water-contaminants>
- Environmental Protection Agency 2. (n.d.). *Potential well water contaminants and their impacts*. Retrieved from <https://www.epa.gov/privatewells/potential-well-water-contaminants-and-their-impacts>
- Environmental Protection Agency 3. (n.d.). *Disinfection with chlorine*. Retrieved from <https://ofmpub.epa.gov/tdb/pages/treatment/treatmentOverview.do?processId=-1118142891>
- Environmental Protection Agency 4. (2006). *Ultraviolet disinfection guidance manual for the final long term 2 enhanced surface water treatment rule*. US Environmental Protection Agency, Office of Water Washington, DC, USA.
- Evans, J. (2012). *Pump efficiency - what is efficiency?* Retrieved from <https://www.pumpsandsystems.com/pump-efficiency-what-efficiency>
- Gelting, R., Bliss, K., Patrick, M., Lockhart, G., & Handzel, T. (2013). Water, sanitation and hygiene in haiti: past, present, and future. *The American journal of tropical medicine and hygiene*, 89(4), 665–670.
- Global Sustainable Energy Solutions. (2019). *Off grid pv power systems*. Retrieved from <https://www.ppa.org.fj/wp-content/uploads/2019/08/Off-Grid-Design-Guidelines-V3.1-July-2019.pdf>
- Goh, B. (2011). *The pros and cons of cartridge filters*. Retrieved from <https://www.splashmagazine.com.au/wp-content/uploads/2011/10/Splash-October-11-pages-49-92.pdf>
- Gómez, M., Plaza, F., Garralón, G., Pérez, J., & Gómez, M. A. (2007). A comparative study of tertiary wastewater treatment by physico-chemical-uv process and macrofiltration–ultrafiltration technologies. *Desalination*, 202(1-3), 369–376.
- Hutten, I. M. (n.d.). *Handbook of nonwoven filter media*.
- Kanade, P. S., & Bhattacharya, S. S. (2016). *A guide to filtration with string wound cartridges: Influence of winding parameters on filtration behaviour of string wound filter cartridges*. Elsevier.
- Lenntech. (2016). *Polypropylene string-wound cartridges*. Retrieved from <https://www.lenntech.com/Data-sheets/Lenn-KP-series-L.pdf>
- Malayeri, A. H., Mohseni, M., Cairns, B., Bolton, J. R., Chevrefils, G., Caron, E., ... Linden, K. G. (2016). Fluence (uv dose) required to achieve incremental log inactivation of bacteria, protozoa, viruses and algae. *IUVA News*, 18(3).
- Mathew, M. (2010). The mathematics of pumping water. *The Royal Academy of Engineering*.
- OFFICE of ENERGY EFFICIENCY & RENEWABLE ENERGY. (2020). *Off grid pv power systems*. Retrieved from <https://www.energy.gov/eere/solar/crystalline-silicon-photovoltaics-research>
- Oxfam. (2020). *Filter household water, lifesaver jerry can*. Retrieved from <https://supplycentre.oxfam.org.uk/filter-household-water-lifesaver-jerry-can-682-p.asp#ptabs2>

- Pinnangudi, B., Kuykendal, M., & Bhadra, S. (2017). Smart grid energy storage. In *The power grid* (pp. 93–135). Elsevier.
- Project Everyone. (2015). *The global goals*. Retrieved from www.globalgoals.org
- Reimanis, M., Mezule, L., Ozolins, J., Malers, J., & Juhna, T. (2013, 05). Drinking water disinfection with electrolysis. *Latvian Journal of Chemistry*, *51*, 296–304. doi: 10.2478/v10161-012-0016-9
- Rijal, G., & Fujioka, R. (2001). Synergistic effect of solar radiation and solar heating to disinfect drinking water sources. *Water Science and Technology*, *43*(12), 155–162.
- SIWI. (2005). *Making water a part of economic development: The economic benefits of improved water management and services*. Retrieved from https://www.who.int/water_sanitation_health/waterandmacroecon.pdf
- Solargis. (2020). *Global solar atlas*. Retrieved from <https://globalsolaratlas.info/download/world>
- Solomon, C., Casey, P., Mackne, C., & Lake, A. (1998). *Ozone disinfection*. Retrieved from www.nesc.wvu.edu/pdf/WW/publications/eti/Ozone_Dis_gen.pdf
- Sphere Association, et al. (2018). *Sphere handbook: Humanitarian charter and minimum standards in humanitarian response*. PRACTICAL ACTION.
- Sun, R., An, D., Lu, W., Shi, Y., Wang, L., Zhang, C., ... Wang, Q. (2016). Impacts of a flash flood on drinking water quality: case study of areas most affected by the 2012 beijing flood. *Heliyon*, *2*(2), e00071.
- Svenskt Vatten. (2009). Råd och riktlinjer för uv-ljus vid vattenverk. *Publikation. Svensk bear-betning av Norsk Vann Rapport*, *164*.
- Tappero, J. W., & Tauxe, R. V. (2011). Lessons learned during public health response to cholera epidemic in haiti and the dominican republic. *Emerging infectious diseases*, *17*(11), 2087.
- Thompson, T., Fawell, J., Kunikane, S., Jackson, D., Appleyard, S., Callan, P., ... others (2007). *Chemical safety of drinking water: assessing priorities for risk management*. World Health Organization.
- United Nations. (2014). *Water stress versus water scarcity*. United Nations department of economic and social affairs. Retrieved from <https://www.un.org/waterforlifedecade/scarcity.shtml>
- WHO. (2019). *Drinking water*. World Health Organization. Retrieved from <https://www.who.int/news-room/fact-sheets/detail/drinking-water>
- WHO, & UNICEF. (2015). *Progress on sanitation and drinking water: 2015 update and mdg assessment*. World Health Organization.
- Widmer, J. M., Weppelmann, T. A., Alam, M. T., Morrissey, B. D., Redden, E., Rashid, M. H., ... others (2014). Water-related infrastructure in a region of post-earthquake haiti: High levels of fecal contamination and need for ongoing monitoring. *The American journal of tropical medicine and hygiene*, *91*(4), 790–797.
- Yao, H., You, Z., & Liu, B. (2016). Economic estimation of the losses caused by surface water pollution accidents in china from the perspective of water bodies' functions. *International journal of environmental research and public health*, *13*(2), 154.

A

Appendices

A.1 Study visit at Alelyckan drinking water purification plant

The 11th of February a study visit at Alelyckan drinking water purification (DWP) plant was carried out, with the intention of gathering more knowledge within the area of large scale DWP as well as to gain information regarding the robustness of such systems. Alelyckan DWP plant is one of two plants that provides the city of Gothenburg with fresh drinking water each day. The visit was led by plant engineer Pär Falk and started with a visit in the control room, followed by a tour around the water plant, following the water flow including the system for re-activating the coal used during the purification process.

According to Pär, the DWP plant at Alelyckan is very robust partly since they have multiple water sources to gather water from, mainly Göta Älv or Delsjön and as a third option Rådasjön. Alelyckan also has built-in clean water reservoirs as well as water towers around Gothenburg, which provides a back-up water if an emergency situation would occur and Alelyckan has to shut down. The DWP plant also has backup power generators if the electricity would go out.

Pär also told that there is a clear trend going towards more robust DWP systems, to tackle eventual water borne infections in the future. Gothenburg city has made a big investment in ultra filters in their DWP plant in Lackarebäck and there are future plants to also implement this technique in Alelyckan. The ultra filters could in theory work on its own, without any other filtration or disinfection method, even though the ultra filters in this case is intended to work together with the rest of the filtration and disinfection methods as another layer of safety.

Another interesting aspect that Pär mentioned is that the cost for the production of drinking water is very low relative to the price one pays for tap water, since the majority of the water price is connected to the transportation and the treatment and disposal of used water.

To summarize the visit, some key takeaways are listed below.

US2011198275 uses reverse osmosis as its purification method. The system is powered by either man power, in form of a foot pump or through an air compressor that is powered by a battery which in turn is powered by solar panels. The foot pump or air compressor supplies the necessary pressure on the feed water that is needed to operate the reverse osmosis membrane. The pure water is collected in a pure water storage tank whereas waste-water from the membrane is returned into the feed water tank. The system then optionally has post filtration which can be tailored for a specific contamination type.

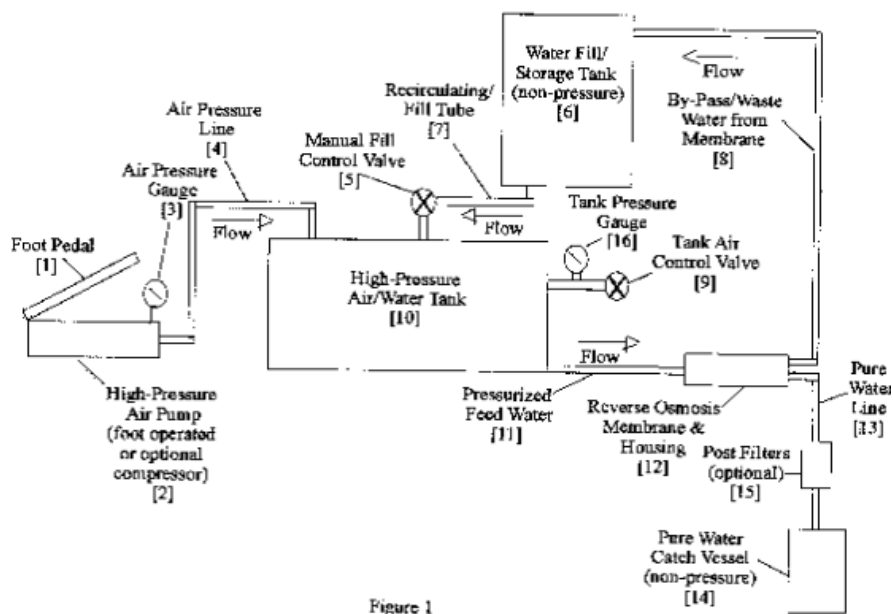


Figure 1

Figure A.2: Patent US2011198275

US8808537 is a box on wheels which has several embodiments. Primarily it uses ultra filtration as its purification methods, in addition it has a step with chemical disinfection and an optional step of UV-light disinfection. It can be powered through many different sources, such as grid electricity, batteries, gas, man-power or solar power. Although solar power is the preferred source, at least partially. Raw water is pumped into a tank in which chemical treatment can be performed, the water then passes through an under-drain before passing through a screen and being pumped into an ultra filtration unit. After the ultra filtration the water has an optional UV-light disinfection before proceeding to a water storage tank.

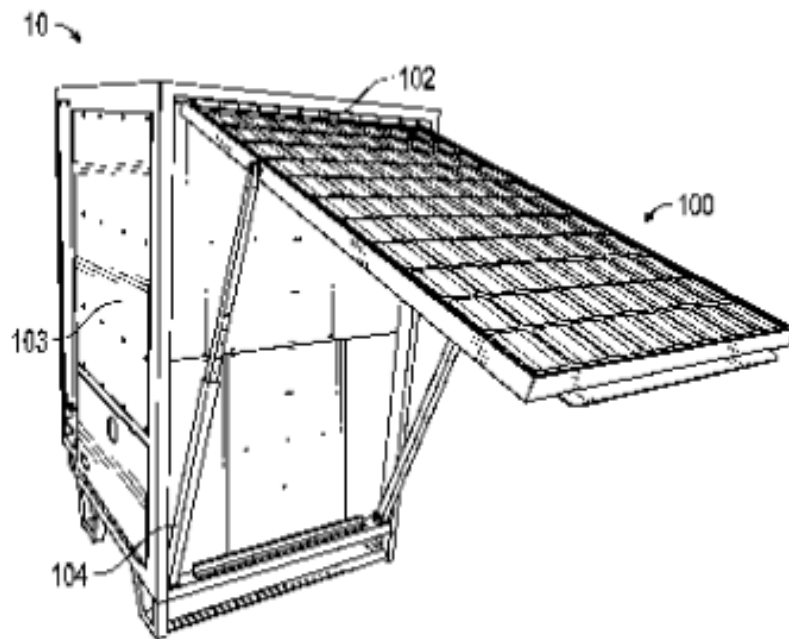


Figure A.3: Patent US8808537

WO2015116254 distills water using solar power. The system has a reservoir which stores raw water. A pre-heating system then elevates the temperature of the water and connects the reservoir into the production unit of the system. The production unit consists of a base, a transparent dome and several lenses which is self adjusting to maintain the focal point. A connector between the pre-heating system and the production unit makes sure the water depth in the base is no more than 30mm to promote evaporation of the water. The whole system is powered by solar energy.

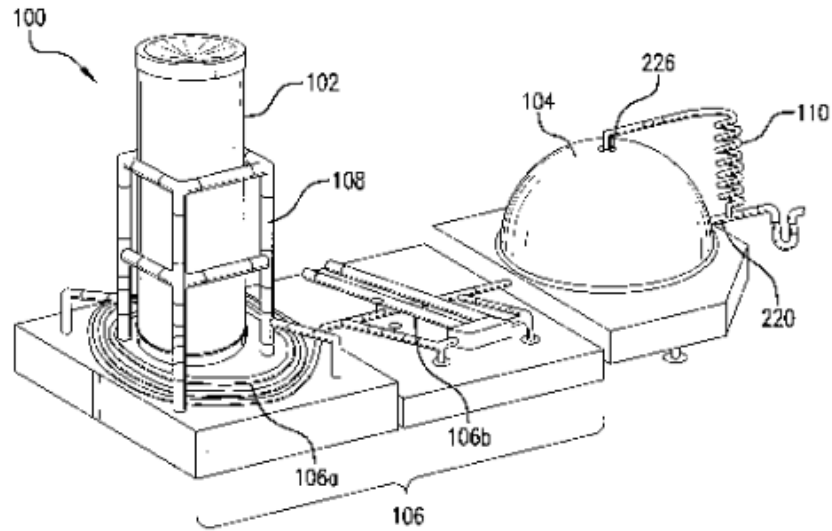


Figure A.4: Patent WO2015116254

US2004108280 is one of several systems using multiple filtration stages followed by UV-light treatment. The system is either powered through external electricity or through a battery powered by solar panels. In areas with a high irradiation dose the excessive solar energy can be used as an electrical power supply. It is a box on wheels that takes in raw water through an inlet pipe. The water then passes two pre-strainers to remove particulates. After that the water is pumped through a series of filters, allowing smaller and smaller particulates to pass through, before going across an activated carbon filter and finally the UV-light chamber. The water then proceeds to the outlet pipe.

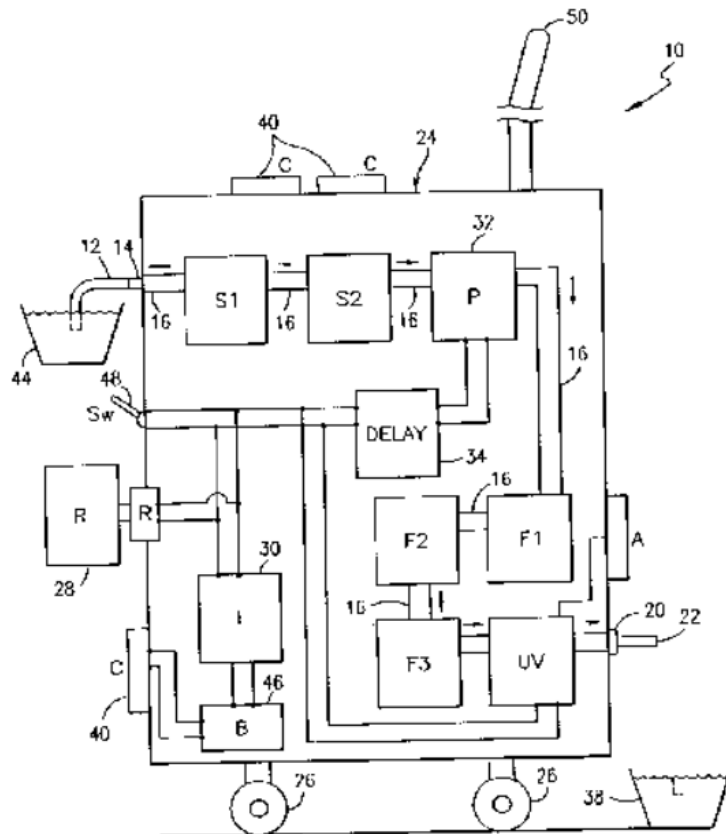


Figure A.5: Patent US2004108280

CN209522603. The water purification is done with activated carbon filtering and heat disinfection. The system has a solar heat collector which through a sun sensor is regulated to follow the sun and thus increase the efficiency. Raw water is poured into a "cold" water tank and then pumped into the activated carbon filtration. After that the water the water is pumped through a heat pipe, that is connected to the heat collector, absorbing thermal energy and thus getting heated. The heated water flows into a hot water tank in which a heating rod that is powered by a mix of solar energy and electric energy, further heats the water into boiling.

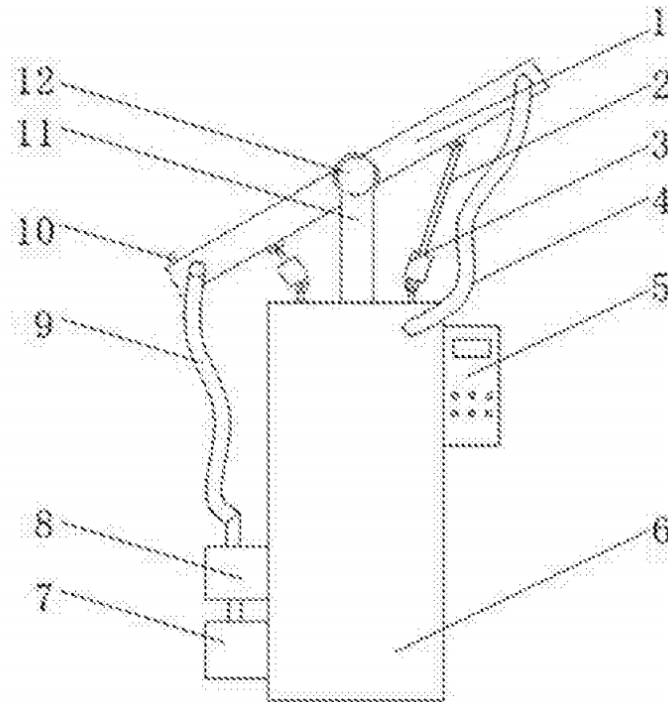


Figure A.6: Patent CN209522603

A.3 World risk map

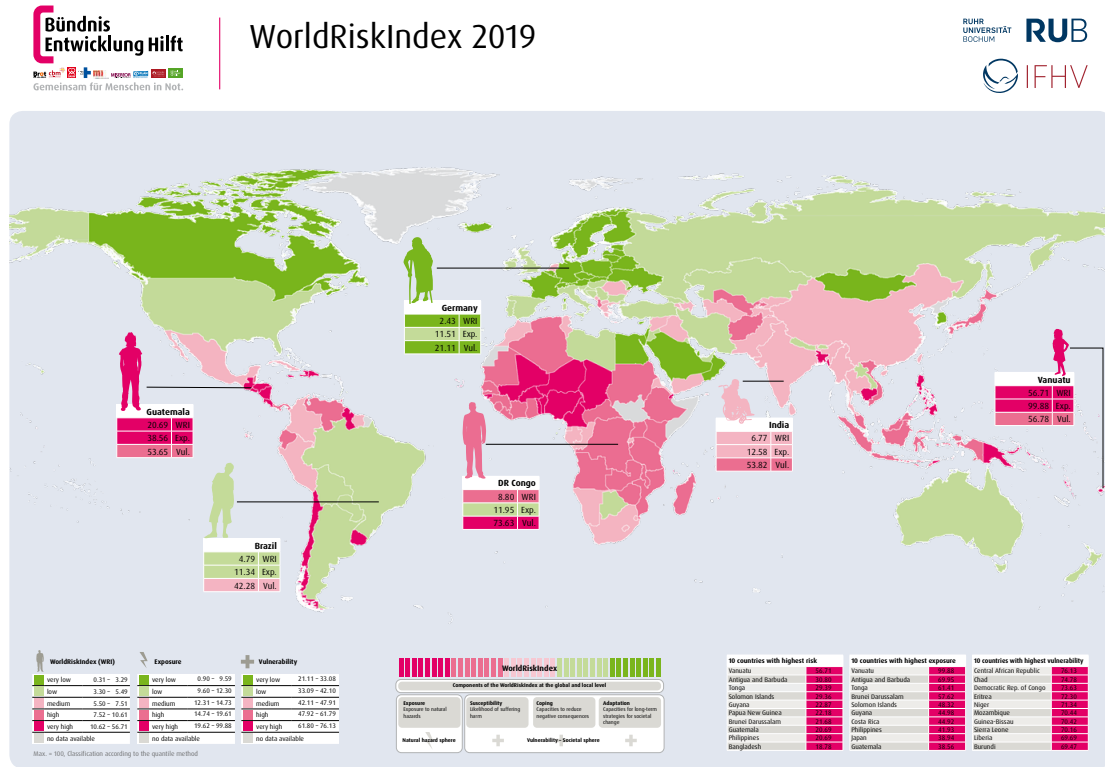


Figure A.7: Risk map

A.4 Requirements specification

All	Requirements/Desires	R/D	Justification	Verification/Evaluation	Weighting (1-3)	Note
1	Water quality					
1.1	Microbiological contaminants < 10 E. coli / 100 ml	R	Sphere Handbook	Water test		
1.2	Microbiological contaminants < 1 E. coli / 100 ml	D	WHO drinking-water guidelines	Water test	2	
1.3	Chemical contaminants < WHO guidelines	D	WHO drinking-water guidelines	Water test	1	
1.4	Radiological contaminants < WHO guidelines	D	WHO drinking-water guidelines	Water test	1	
1.5	Turbidity < 5 NTU	R	Sphere Handbook / WHO	Water test		
1.6	Total dissolved solids < 1000mg/L	R	WHO drinking-water guidelines	Water test		
2	Capacity					
2.1	Should provide 100 persons with 5 liters drinking water daily	R	Interviews	Calculations		
2.2	Purified water storage of 100 liters	D	Development team	Design	2	
3	Environmental sustainability					
3.1	Lifelength > 1 year	R	UNICEF HWTS standards, Interviews	Testing		
3.2	No loose plastic parts that can end up in the nature	D	Interviews	CES/Design	1	
3.3	50 % of product weight should be recyclable	D	Development team	Design	1	
4	Robustness					
4.1	Should not require any external electricity	R	Interviews	Design		
4.2	All end-users should be able to perform necessary maintenance	R	Development team	Prototype		
4.3	Should have a fail-safe, preventing product from providing water when it is not clean	R	UNICEF HWTS standards			
4.4	Should withstand typical emergency settings (Hard wind, heavy rain etc.)	R	UNICEF HWTS standards, interviews			
5	Packaging, Storing and Shipping					
5.1	Packages should be able to stack on each other	D	Interviews	Design	3	
5.2	Packages should come in part(s) that are possible to carry by hand	R	Interviews	Design		
6	Production and Manufacturing					
6.1	Purchasing cost should be less than 8000 SEK	R	UNICEF HWTS standards	Cost calculations		
7	Assembly					
7.1	Assemble time less than 1 day for 1 person	R	Interviews	Testing		
7.2	Instructions should be non-language specific	R	Interviews	User testing		
7.3	Assembly should be able to perform without any special tools	R	Interviews	Design		
7.4	Adults should understand how to operate the system with instructions	R	Interviews, UNICEF HWTS standards	User testing		
8	Miscellaneous					
8.1	Ability to use the same solar capturer as in Solros's solution (ESSIQ and Team)	D	ESSIQ			

Figure A.8: Requirements specification

A.6 Pugh matrix

	Concept 1	Concept 2	Concept 3	Concept 4	Concept 5
Production cost	R e f e r e n c e	-	-	-	-
Safety		+	+	+	+
Transportation		+	+	+	+
Assembly compexity		0	0	+	+
Robustnesss to cloudiness		+	+	+	+
User-friendly		+	+	+	+
Maintenance		0	0	+	+
Total +		N/A	4	4	6
Total 0	N/A	2	2	0	0
Total -	N/A	1	1	1	1
Net	0	3	3	5	5
Rank	5	3	3	1	1

Figure A.10: Pugh matrix with concept 1 as reference

	Concept 2	Concept 1	Concept 3	Concept 4	Concept 5
Production cost	R e f e r e n c e	+	+	-	+
Safety		-	0	0	0
Transportation		-	0	+	+
Assembly compexity		0	0	+	+
Robustnesss to cloudiness		-	0	0	0
User-friendly		-	0	0	0
Maintenance		0	0	-	-
Total +		N/A	1	1	2
Total 0	N/A	2	6	3	3
Total -	N/A	4	0	2	1
Net	0	-3	1	0	2
Rank	3	5	2	3	1

Figure A.11: Pugh matrix with concept 2 as reference

A. Appendices

	Concept 5	Concept 1	Concept 2	Concept 3	Concept 4
Production cost	R e f e r e n c e	+	-	+	-
Safety		-	0	0	0
Transportation		-	-	-	0
Assembly complexity		-	-	-	0
Robustness to cloudiness		-	+	+	0
User-friendly		-	0	0	0
Maintenance		-	+	+	0
Total +	N/A	1	2	3	0
Total 0	N/A	0	2	2	6
Total -	N/A	6	3	2	1
Net	0	-5	-1	1	-1
Rank	2	5	3	1	3
Futher development	NO	NO	NO	YES	NO

Figure A.12: Pugh matrix with concept 5 as reference

B

Calculations

This chapter of the appendix consist of calculations made throughout the project. The majority of the calculations is dependent upon assumed prerequisites. In order to try out different prerequisites the calculations were formated into an excel-sheet which allows for changing single variables as more information of how the system will look is acquired.

B.1 Pump Calculations

Below follows calculations made to estimate the energy needed to power the pump used in the project. The calculations are made based on assumptions of how the system will look and the paper *The mathematics of pumping water* (Mathew, 2010).

These calculations consider the pump arrangement shown in figure B.1. The pump power is given by the following formula:

$$P = \frac{Q \times H_p \times \rho \times g}{\eta} \quad (1)$$

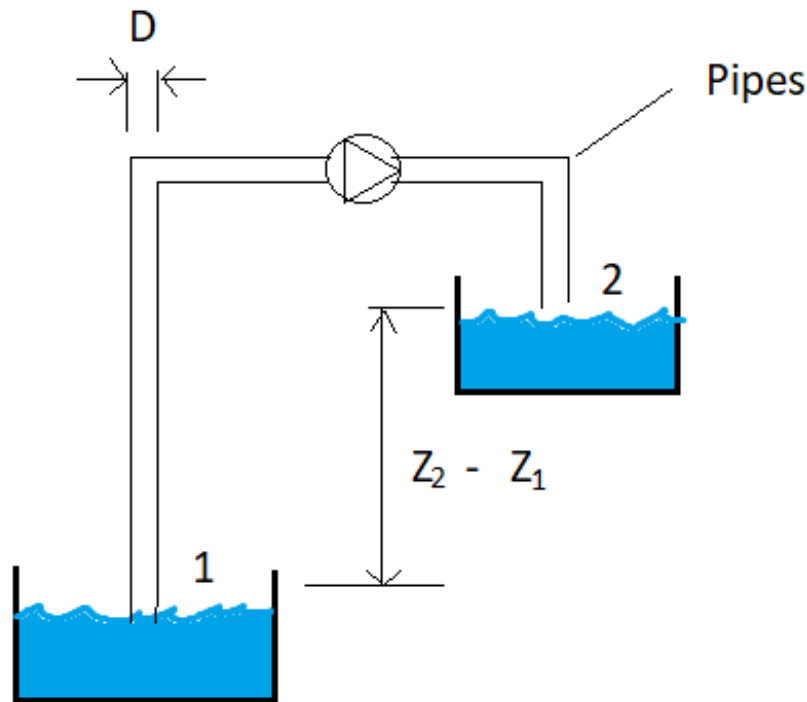


Figure B.1: Pump arrangement

Where Q = Flow rate of the liquid in the pipe (m^3/s)

H_p = Pump head which is a combination of the elevation the liquid is pumped and the friction losses that occurs in the pipes. The friction losses is made up by two elements, friction losses caused by the surface of the pipe and losses caused by filters and fittings used in the pipeworks such as bends and valves. In this case the friction losses caused by fittings is assumed to be minor and will be ignored.

ρ = density of the liquid (kg/m^3), $1000 \text{ kg}/\text{m}^3$ for water.

g = acceleration due to gravity (m/s^2), $9.81 \text{ m}/\text{s}^2$

Considering that a relatively small pump water pump is used the efficiency is usually somewhere between 50 to 70 percent (Evans, 2012) =>

$$\eta = 0.6$$

H_p can be calculated by using bernoulli's equation between the two points, 1 and 2 in figure B.1, and looks as following:

$$\frac{p_1}{\rho \times g} + \frac{v_1^2}{2 \times g} + z_1 + H_p = \frac{p_2}{\rho \times g} + \frac{v_2^2}{2 \times g} + z_2 + h_f + h_k \quad (2)$$

where

p_1 = Pressure in point 1 (Pa)

p_2 = Pressure in point 2 (Pa)

v_1 = Pressure in point 1 (m/s)
 v_2 = Pressure in point 2 (m/s)
 z_1 = Elevation in point 1 (m)
 z_2 = Elevation in point 2 (m)
 h_f = Friction losses due to surface (m)
 h_k = Friction losses caused by pressure drop over filters (m)

Considering that point 1 is at the water surface of the water source and that point 2 is just outside the pipe after the water has exited the pipe leads to the following assumptions: pressure in both points is going to be atmospheric pressure, the velocity in point 1 is going to be 0. Further the elevation in point 1 is set to 0 as what really matters is the difference in height between z_2 and z_1 .

$p_1 = p_2 = p_{atm}$
 $v_1 = 0$ m/s
 $z_1 = 0$ m

Using these values in (2) gives:

$$H_p = \frac{v_2^2}{2 \times g} + z_2 + h_f + h_k \quad (3)$$

Considering a standard garden hose made out of PVC to be used as piping with the following specifications:

Pipe diameter, $D = 5/8'' = 0.015875$ m
 \Rightarrow Area, $A = \frac{\pi \times D^2}{4} = 0.000198$ m²
 Pipe length, $L = 20$ m
 Absolute roughness, $\epsilon = 0.0015 \times 10^{-3}$ m
 \Rightarrow Relative roughness, $r = \frac{\epsilon}{D} = 0.0001$
 And a flow rate through this pipe of:
 $Q = 3$ l/min = $3/1000 \times 60 = 0.00005$ m³/s

The velocity, v_2 , can be calculated according to (4)

$$v = \frac{Q}{A} \Rightarrow v_2 = 0.256 \text{ m/s} \quad (4)$$

With these values the friction losses, h_f , can be calculated with the Darcy-Weisbach equation (5)

$$h_f = f \times \frac{L}{D} \times \frac{v_2^2}{2 \times g} \quad (5)$$

where

B. Calculations

f = Friction coefficient

The friction coefficient for turbulent flow is found through a moody chart by knowing the relative roughness, r and the reynolds number, Re . For laminar flow the friction coefficient can be calculated with:

$$f = \frac{64}{Re}$$

The reynolds number is calculated with:

$$Re = \frac{Q \times D}{\nu \times A}$$

where $\nu = 1.004 \times 10^{-6}(m^2/s)$ for water at 20 °Celsius

=> $Re = 4017$, which is within the turbulent flow regime. With the reynolds number and the relative roughness f is found by reading a moody chart:

=>

$$f = 0.04$$

From equation (5):

$$h_f = 0.04 \times \frac{20}{0.015785} \times \frac{0.256^2}{2 \times 9.81} = 0.169m$$

h_k was calculated in 4.3.1 to be 0.714 m

From equation (3), assuming that the elevation z_2 is 5m:

$$H_p = \frac{0.256^2}{2 \times 9.81} + 5 + 0.169 + 0.714 = 5.886m$$

From equation (1):

$$P = \frac{0.00005 \times 5.886 \times 1000 \times 9.81}{0.6} = 4.81W$$

Provided the prerequisites mentioned above the pump will need about 4.81 watts to function.

B.2 UV-calculations

B.2.1 Optimization.m

```

clear all
%% Calculations
% 3 liters per minute
Q_in=(3)/(60*1000); %Flow rate (m3/s)
R_in=0.015785;      % Inlet housing radius

%UV-lamp constants
R_lamp=0.010;      %Lamp radius
L_lamp=0.200;      %Lamp length

T=0.75;            %Transmittance (depending on turbidity) WINNIPEG
f_a_f=0.7;         %Fouling and aging factor
h=0.010;
alpha=(-1/h)*log(T);
I0=1;              %Intensity, for radius opt. Can be any value.

eta=0.225;         %Electrical to Germicidal UV Conversion Efficiency

%Contaminants
UV_dose=[60 90 130 220]; %Faecal coliforms (1 - 2 - 3 - 4 log) J/m2
Cont_start=115000;    %Contamination of E.coli [CFU/100ml]
Cont_end=10;

Log_red=log10(115000/10); %Log reduction

% Optimazation constants
A = [];
b = [];
Aeq = [];
beq = [];
lb=R_lamp;
ub=0.05;           %Upper limit for pipe radius

%Input vector to fun.m
X=[R_lamp, L_lamp, Q_in, alpha, UV_dose(4), I0, R_in];

%Optimize pipe radius with respect to the UVD
[R_pipe_opt]=fmincon(@(R_pipe) -fun(R_pipe,X),0.1,A,b,Aeq,beq,lb,ub);

%Use the optimum pipe radius to calculate UVD and I0
[UVD_min, UVD_min, I0_min,I_real,R_rz_r, UVD]=fun(R_pipe_opt,X);

```

B. Calculations

```
I0min_milliwattpercm2=I0_min/10;

%% Valid if  $D < 0.5 * L_{lamp}$  (IF  $L_{lamp} = 0.15 \Rightarrow D < 0.075$ )
for j=1:length(R_rz_r)
    D(j)=R_pipe_opt*(R_rz_r(j)); %Distance to I(j)
    P_UV(j)=2*I_real(j)*D(j)*L_lamp*pi;
end

P_UV_max=max(P_UV);

%Power required for the UV-lamp
P_lamp=P_UV_max/(eta*f_a_f);

%% Plots
X=[R_lamp, L_lamp, Q_in, alpha, UV_dose(4), I0_min, R_in];
[UVD_min, I0_min,I_real,R_rz_r, UVD, I, u_x_r]=fun(R_pipe_opt,X);

%I vs R_rz_r & u_x_r vs R_rz_r
figure(1)
yyaxis left
plot(R_rz_r,I)
hold on;
rectangle('Position',[0 0 R_rz_r(1), 25 ])
xlim([0,1]);
ylim([0,25]);
xlabel('Relative radius');
ylabel('UV-intensity [W/m2]');
title('Cross-section of the UV-system');
txt = {'UV-lamp'};
text(0.05,15,txt)

yyaxis right
plot(R_rz_r, u_x_r);
ylabel('Velocity [m/s]');

%UVD vs R_rz

figure(2)

plot(R_rz_r(3:98),UVD(3:98))
hold on;
rectangle('Position',[0 0 R_rz_r(1), 3500 ])
```

```

xlim([0,1]);
ylim([0,3500]);
xlabel('Relative radius');
ylabel('UV-dose [J/m2]');
title('Cross-section of the UV-system');
txt = {'UV-lamp'};
text(0.05,2000,txt)

```

B.2.2 fun.m

```

function [UVD_min,I0_min,I_real,R_rz_r,UVD,I,u_x_r]= fun(R_pipe,X)
%Input vector
% X=[R_lamp, L_lamp, Q_in, alpha(i), UV_dose(4), I0, R_in];

%Radiation zone flow area
A_rz=pi*(R_pipe^2-X(1)^2);

%Average velocity
v_avg=X(3)/A_rz;

r=linspace(X(1),R_pipe);

%Relative radius (r_lamp/r_pipe to 1)
R_rz_r=r./R_pipe;

%% Pressure drop for annular flow
C_L=2*X(3)/(pi*R_pipe^4*(1-R_rz_r(1)^4-...
((1-R_rz_r(1)^2)^2/(log(1/R_rz_r(1))))));

%Convert to turbulent flow
C_T1=(C_L*(R_pipe^2-X(1)^2))/log(R_pipe/X(1));

%Velocity vector for relative radius
u_x_r=(C_L*R_pipe^2)*(1-R_rz_r.^2)+(C_T1.*log(R_rz_r));

%Intensity
I=X(6)*exp(-X(4)*R_pipe*(R_rz_r-(X(1)/R_pipe)));

%Time under radiation
t_R=X(2)./u_x_r;

%UV-dose received
UVD=t_R.*I;

```

B. Calculations

```
%Find minimum value for UVD and its corresponding relative radius
[UVD_min,k]=min(UVD(2:99));

%Source (lamp) intensity based on input
IO_min=(X(5)*u_x_r(k))/(X(2)*exp(-X(4)*R_pipe*...
(R_rz_r(k)-(X(1)/R_pipe))));

%Intensity base on IO
I_real=IO_min*exp(-X(4)*R_pipe*(R_rz_r-(X(1)/R_pipe)));

end
```