Norwegian University of Life Sciences
Faculty of Environmental Science and Technology
Department of Mathematical Sciences and Technology

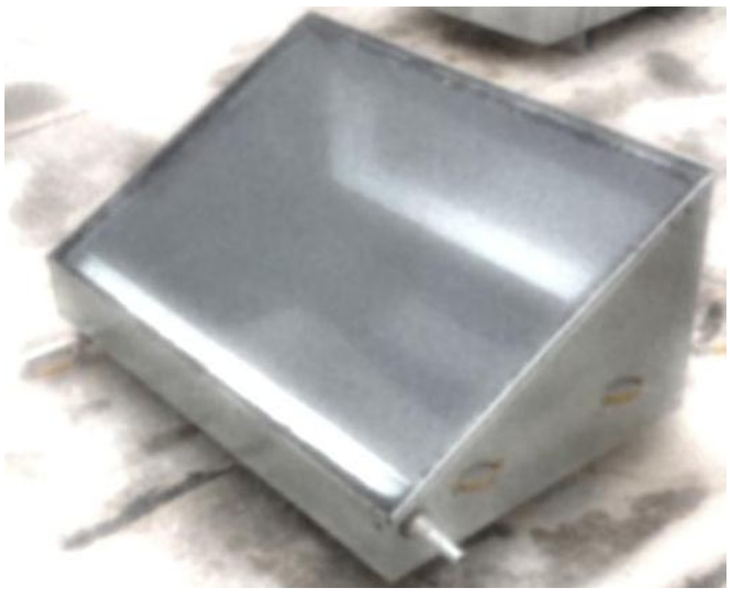
Master Thesis 2015
30 credits

Design, prototyping and field testing of solar stills in remote areas in Afghanistan

Halvard Hirsch Kopperdal

Design, prototyping and field testing of solar stills in remote areas in Afghanistan

Halvard Hirsch Kopperdal



Master thesis at Norwegian university of Life Sciences
Department of Mathematical Sciences and Technology,
Spring term 2015.

PREFACE

This master project is the final step in my degree Master of Technology at the Norwegian University of Life Sciences. This project work has been carried out at the Department of Mathematical Sciences and Technology in close collaboration with Norwegian Church Aid and Norplan.

I wanted to use my master thesis to work on a practical project and use my engineering knowledge to develop and implement sustainable solutions in development countries. Therefore I initiated contact with different aid organizations autumn 2104 and received quickly response from the Water, Sanitation and Hygiene department in Norwegian Church Aid, NCA. They were then a part of a Norwegian TV telethon related to drinking water in the third world. At this time I was choosing my project topic for a product development course, “TIP300 Concept and Product Realization”, and it was agreed that I could continue on the work that MSc. student from NMBU, Cecilie Kolstad, performed during spring 2014. The field work that Cecilie Kolstad experienced in Kabul seemed interesting and challenging from both a technical and cultural perspective and inspired me to continue working on this project. This work was a joint project between NCA and Norplan regarding the development and implementation of drinking water to a low cost in Afghanistan.

This master thesis is a continuation of that work and aims to provide poor people in the Faryab province in the north west of Afghanistan with safe drinking water through a sustainable and low technology solution.

I would like to thank Liv Steinmoeggen and Eng. Manfred Arlt at NCA and Dr. Svein Stoveland at Norplan for providing me this opportunity to connect my engineering education to develop technology and knowledge in Afghanistan. In addition, they and Eng. Cecilie Kolstad have provided me with help and support during the preparations and visit in Kabul. I am grateful for the help and effort Eng. Mohammad Yasir and Eng. Abrar Naqib at NCA Afghanistan and Ministry of Rural Rehabilitation and Development, MRRD, have put into this project related to material research and testing.

At NMBU I have received advises and help from Associate Professor Johan Andersen, Senior Engineer Bjørn Brenna and Professor Petter Jensen regarding material selection and water quality. In addition, I would like to acknowledge my supervisors Associate Professor Jan Kåre Bøe and Professor Tor Anders Nygård for guidance and help during the project.

Ås

15.05.2015

Halvard Hirsch Kopperdal

ABSTRACT

The groundwater in the Faryab province in Afghanistan is the main source of drinking water for the local people and is of low quality. They are currently drinking water with high concentrations of salt and contamination, which can be a severe health risk [6]. Due to fragmented strategies and policies in Afghanistan it is reason to believe that problems related to drinking water access and quality will increase for the future generations.

This study is based on the master thesis "Desalination of groundwater by solar stills - field trials in Afghanistan" conducted by Cecile Kolstad spring 2014 and a pre project during autumn 2014. Throughout the current study of low cost solar stills for households in the Faryab province, a design, prototype and testing is carried out in collaboration with NCA Afghanistan and Norplan.

To develop knowledge and technology that is unfamiliar for the afghan people is challenging related to technicalities such as material selection and manufacturing methods. In addition, challenges regarding social acceptance, cultural differences and safety issues make the technology implementation even more complex.

A product development process to optimize a single basin solar still with respect to design and cost has been performed. This included an extensive introduction to solar still principles and thermodynamics, with a following product development process where important design parameters, local materials and manufacturing methods were included and resulted in a preliminary design. Then, a prototype was manufactured and tested during a three week field trip to Kabul, Afghanistan.

The prototype structure is made of galvanized iron sheets, insulated with expanded polystyrene and a basin material of 1 [m^2] glass. The prototype cost is 158 [USD] and an estimated series production cost for 50 units brings the cost down to 90 [USD], which is below the product cost requirement set by NCA and Norplan.

Testing has been performed in good conditions at the NCA office in Kabul for three days and preliminary results shows a yield of approximately 1.9 [L/m^2/day] which is nearly 2 [L] lower than expected. More tests must be performed to be able to conclude and obtain statistical safety in the test results. The low production rate may be a consequence of air leakages or the low solar absorptivity of the glass basin. On the other hand, a yield of 1.9 [L/m^2/day] would provide one person with approximately 400 [L] of safe drinking water throughout the spring, summer and autumn.

There is concern regarding the choice of basin material and the low correlation between manufactured design and provided drawings, which may have resulted in a reduced still efficiency. In addition, no water quality analyses have been performed to verify the quality of the distillated water, which must be done when there is certainty in the production rates.

SAMMENDRAG

I Faryab-provinsen i Afghanistan er grunnvannet hovedkilde til drikkevann for lokalbefolkningen. Dette er av dårlig kvalitet, og inneholder høye konsentrasjoner av salt og forurensninger, noe som kan være svært helseskadelig [6]. På grunn av uforutsigbare reguleringer og en urolig politisk situasjon er det grunnlag for å tro at problemer tilknyttet kvalitet og tilgang på drikkevann vil øke for kommende generasjoner i Afghanistan.

Dette prosjektet er basert på masteroppgaven "Desalination of groundwater by solar stills - field trials in Afghanistan" av Cecile Kolstad våren 2014, og et forprosjekt høsten 2014. Denne oppgaven omhandler utviklingen av rimelige solar stills for avsalting av drikkevann til privathusholdninger i Faryab-provinsen, og design, prototype og tester er utført i samarbeid med Kirkens Nødhjelp og Norplan.

Å drive teknologisk utvikling og kunnskapsformidling i Afghanistan er utfordrende teknisk, i forhold til for eksempel materialvalg og fabrikasjon. I tillegg gjør kulturforskjell, sosial aksept og sikkerhetssituasjonen teknologi-implementeringen enda mer komplisert.

Det er utført en optimalisering av en solar still med ett basseng, med hensyn til design og kostnadsreduksjon. Prosessen startet med studier av varmeoverføring innad og utad i enheten. En påfølgende produktutviklingsprosess, hvor viktige design-parametere, lokale materialer og fabrikasjonsmetoder ble inkludert, resulterte i et design. Deretter ble en prototype fabrikkert under et tre uker langt feltarbeid i Kabul, Afghanistan.

Rammen i prototypen er laget i galvaniserte stålplater og er isolert med isopor. Bassenget er på 1 [m^2] og av 6 [mm] glass. Prototypen kostet 158 [USD] og estimert kostnad ved serieproduksjon av 50 enheter senker prisen til 90 [USD], noe som er lavere enn kostnadskravet til produktet satt av Kirkens Nødhjelp og Norplan.

Testing er utført i tre dager ved kontoret til Kirkens Nødhjelp i Kabul, og de foreløpige resultatene viser en produksjon på 1.9 [L/m^2/dag], noe som er ca. 2 [L] lavere enn forventet. Det må foretas flere tester før en kan konkludere og ha statistisk sikkerhet i resultatene. Den lave produksjonen kan være en konsekvens av lekkasjer eller at glassbassenget har lav evne til å absorbere solenergi. Likevel kan en produksjonskapasitet på 1.9 [L/m^2/dag] livnære en person med trygt drikkevann, omtrent 400 [L], gjennom våren, sommeren og høsten.

Den lave virkningsgraden kan skyldes valg av bassengmateriale og de store avvikene mellom tekniske tegninger og fabrikkert design. Det er ikke utført vannprøver for å verifisere kvaliteten av det destillerte vannet. Dette må gjøres etter at flere tester av produksjonskapasitet er utført og det er oppnådd pålitelige resultater.

ABBREVIATIONS

Table 1: Abbreviations used in the report.

Abbreviation	Definition
AFN	Afghani, Afghan currency
DACAAR	Danish Committee for Aid to Afghan Refugees
EC	Electrical Conductivity or Salinity
ENG	Engineer
EPDM	Ethylene Propylene Diene Monomer Rubber
NA	Not Applicable/Available
NCA	Norwegian Church Aid
EPO	European Patent Office
DIY	Do It Yourself
IPD	Integrated Product Development
NMBU	Norwegian University of Life Science
NTU	Nephelometric Turbidity Unit
MRRD	Ministry of Rural Rehabilitation and Development
®	Registered trademark symbol
SI	System unit International
TM	Trademark
USD	United States Dollar
WHO	World Health Organization
WIPO	World Intellectual Property Organization

CONTENTS

Page

Page

1 INTRODUCTION

The Norwegian Church Aid and Norplan are trying to reach out to the poor people that live in remote areas in the Faryab province in Afghanistan. They work to provide the local people with secure access to safe drinking water through sustainable technical solutions to a low cost. This thesis covers an extensive solar still product development process towards prototyping and field testing.

1.1 Background

Fresh drinking water is the core in human life and worldwide over 748 million people lack access to improved drinking water. Consequently, over 3.4 million people die every year related to water, sanitation and hygiene. World Health Organization, WHO, reports that investment in these sectors lower the death rate, is socioeconomically beneficial and increase quality of life [38, 44, 45].

More than two thirds of the earth's surface is covered with water, but only 1 [%] is fresh water available for humans [17]. This amount is believed to be sufficient to maintain life and vegetation on earth, and nature itself offers most of this essential fresh water through the large scale solar distillation process called the hydrological cycle. However, chemicals and harmful organisms can contaminate the water and it will therefore often require purification methods before consumption.

Afghanistan has a turbulent history with invasions, wars, terror and corruption. Because of this the people in the provinces are suffering and lack access to water, sanitation, hygiene and electricity. The population is growing and the search for new sources of groundwater is more intense, frequent and unsustainable. These factors combined with unstable strategies and policies will create a lower quality and quantity of the afghan groundwater resources. This again will cause a severe lack of drinking water for future generations [35].

1.2 History of solar desalination and solar stills

Aristotle described a process to evaporate contaminated water and condense it for drinking already in the fourth century B.C. Later on, the Arab alchemists in the 16th century documented this and Della Porta used wide earthen pots to heat up and evaporate water with use of solar radiation in 1589, see Figure 1, [17].

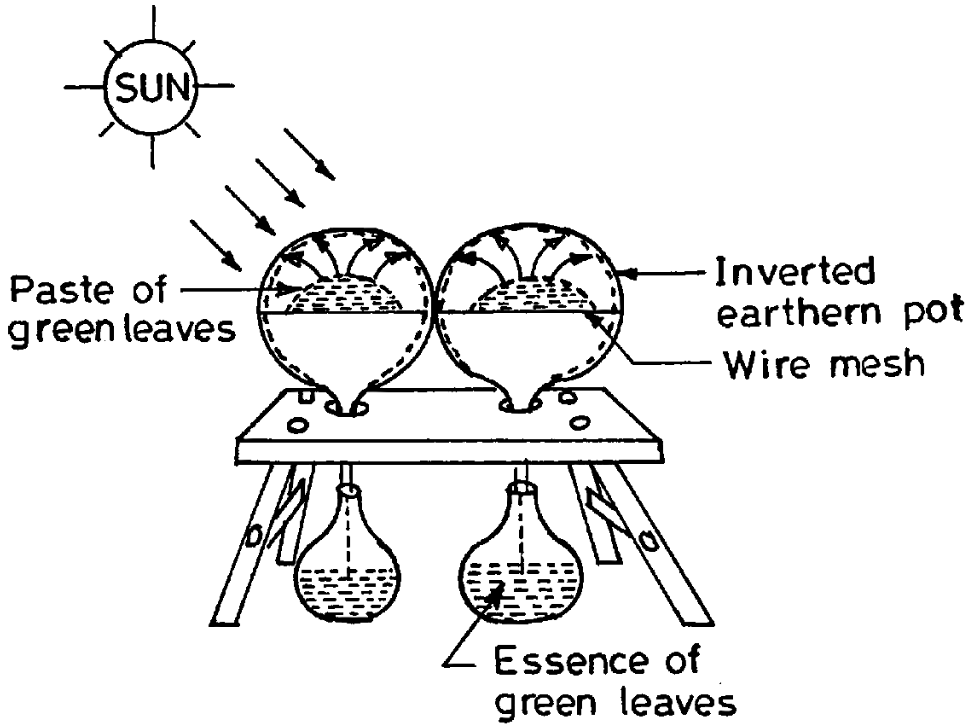


Figure 1: Solar distillation by Della Porta in 1589 [17].

In 1872 a Swedish engineer made the first large scale solar desalination plant in Las Salinas, Chile, to provide thirsty railway- and mine workers. It was made of wood and glass and had a water surface of 4459 [m^2] and a daily production of 22.7 [m^3], [18].

The interest for simple distillation methods increased during the Second World War as many soldiers were stationed in remote areas without access to safe water and consequently saved many lives. This and the establishment of the US Office of Saline Water in 1953 resulted in the foundation of many solar stills programs and development.

During the recent years the attention for small scale desalination plants for households and villages is increasing [18]. For the past two decades solar stills for households have been in use in several colonies on the US - Mexico border as a result of a joint project between El Paso Solar Energy Association, New Mexico University and SolAqua [33].

1.3 Local conditions and water quality in Faryab

The Faryab province is located in the north-western part of Afghanistan, see Figure 2, with over 800 000 inhabitants where 89 [%] of the population live in rural areas. Each household consist of an average of 7 people and 77 [%] of the families lack access to safe drinking water.

Groundwater is the primary source for drinking water in Faryab and it suffers from insufficient monitoring and is of variable quality. Around one fifth of the families have to travel up to one hour to access drinking water and over 10 [%] has to travel from 1-6 hours for the same purpose [36]. The winter climate in the Faryab province is cold and moist and people are melting snow to provide drinking water. On the other hand, the spring, summer and autumn are dry, warm and sunny which indicates good conditions for solar desalination [40, 41].

Figure 2: Map of Afghanistan and the Faryab province in the north- western part of Afghanistan. The area is mountainous and has poor infrastructure, electricity and sanitation [46].

Afghanistan's rainfall is highly irregular when it comes to location and time. The amount of surface water is therefore affected and the accessibility becomes limited. A small network of rivers and streams is another water source which covers Afghanistan. However, they are merely flowing for 3-4 months during the rainy season and then dry out for the rest of the year. For these reasons the groundwater in Afghanistan is the main source for drinking water, but the resources are finite. The groundwater is in addition very sensitive and vulnerable for contamination and over-exploitation [35].

Salt is naturally occurring in the soil, but the concentration increases in areas with high ground water table, as in Faryab, due to evaporation and irrigation. Therefore, salinity in the groundwater is one of the main concerns with respect to water quality in Faryab.

The concentration of salt is measured in electrical conductivity, EC, which measure the amount of dissolved solids in the water. WHO rate concentrations above 1800 [µS/cm] as undesirable. However, values up to 3000 [µS/cm] is accepted in Afghanistan due to limited access of acceptable drinking water [37, 6].

The Danish Committee for Aid to Afghan Refugees, DACAAR, collected water samples from over 23 000 places in Afghanistan between 2004 and 2011. The results showed that 30 [%] of the samples had EC values above 1500 [µS/cm] and the highest levels were measured in the Shirin Tagab district in Faryab with an EC of 52 100 [µS/cm]. In addition, the results revealed high concentrations of chloride, sulphate, magnesium, sodium arsenic and bacterial contamination which indicate polluted water [6].

Additionally, inadequate waste disposal, lack of sanitation and over-exploitation of groundwater combined with natural occurrence of metal elements in the soil are other reasons which contribute to poor water quality and can result in diarrhea, birth defects and cancer [35, 6].

1.4 Basic principles of solar still desalination

The basic principles of solar still desalination replicates the method our nature purifies water in the hydrological cycle. In a solar still groundwater is heated up by solar energy through a transparent enclosed cover in an airtight unit. The water heats up until it evaporates, then the vapor rises towards the sloping transparent cover. When the vapor meets the glass surface it will condense and water droplets will slide along the slope. In the end of the slope there is a channel collecting the droplets and guiding them to a storage vessel before drinking, see Figure 3.

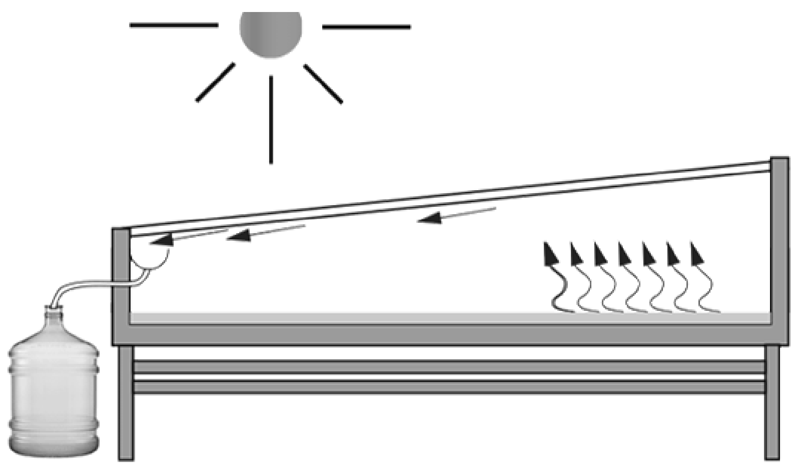


Figure 3: The distillation process in a solar still trough evaporation and condensation [34].

The rather slow distillation process secures that only water evaporates and leaves particles and contamination behind in the basin. In addition, a relatively high temperature will occur inside the still and bacteria's will therefore die and result in high quality drinking water. After the water evaporates, sludge will form in the basin and daily maintenance and cleaning is therefore necessary [7].

To evaporate 1.0 [kg] with water at a temperature of 30 [℃] the energy required is about 2400 [kJ] or 0.67 [kWh], [5]. With an average insolation of 350 [W/m^2] per 24-hour, based on Kolstad's radiation measurements in Kabul May 2014, the solar energy could evaporate around 12.5 [L/m^2/24-hour]. With an assumed still efficiency of 30 - 40 [%], which corresponds to the state-of-art solar stills today, a production rate between 4 - 5 [L/m^2/24-hour] can be expected [3,7].

1.5 Pre study project

During spring 2014 MSc. student from NMBU, Cecilie Kolstad, wrote her thesis "Desalination of groundwater by solar stills - field trials in Afghanistan" were she designed, built and tested six different solar stills in Kabul [3]. A continuation of this work resulted in a pre-study project fall 2014 in the course "TIP300 Concept and Product Realization".

"TIP 300" is divided in two sections, the first part is lessons in product development methods, design strategies and prototyping, and the second part is a product development project of approximately 370 hours [28]. Throughout that project, some knowledge and understanding of solar still design and physics were studied, but focus were on development strategies, methods and models.

The product development work was related to functional alternatives regarding design, cover slope angle, maintenance and manufacturing. The project resulted in a solar still product for remote areas named "Pure Water", see Figure 4, with the following specifications [4]:

- Assumed production rate of 6 [L/day].
- Prototype cost of 670 [USD].
- Made of a rubber basin, glass cover, brick legs and a wood structure.
- Outer still dimensions: 1532 x 932 x 950 [mm], (Length x Width x Height).
- Weight: 40 [kg].

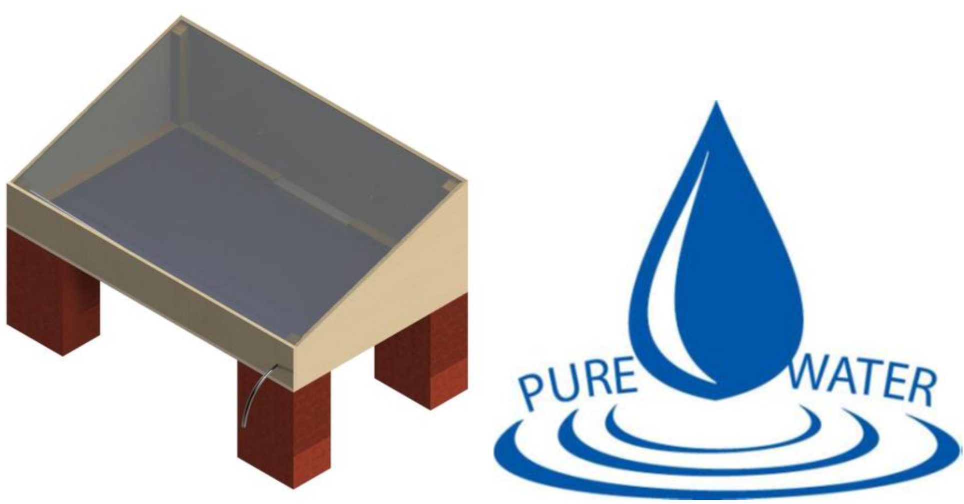


Figure 4: The developed solar still product and logo during the course "TIP300 Concept and Product Realization" [4].

Through the pre-project a lot of knowledge and experience were adapted, such as the necessity of a proper basin material and avoidance of air leakages. However, the development was performed without essential information regarding local conditions, requirements and materials. Consequently, information regarding this has now been some of the essential input parameters for a more realistic product development. The current study is a continuation of both Cecilie Kolstad's MSc. and the pre-project with a more realistic focus on design optimization and cost reduction.

2 EXISTING SOLAR STILL TECHNOLOGY

There exist several different products for desalination and filtering of water in the market. However, many of them relay on membranes, filters, electricity or frequent maintenance. Such solutions are according to NCA not sustainable in this context, and they have earlier tried to improve the quality of drinking water in Faryab with reverse osmosis units which filter the water through a membrane. Unfortunately, the membrane costs above 10 000 [USD] and needs replacement and maintenance after some years of use. This is not a viable solution for either local people in Faryab or NCA, and consequently solutions that only rely on solar energy, simple technology and construction are considered in the following section.

2.1 Main concepts

It can be differentiated between different types of solar stills which all have the interest in increasing the efficiency:

a) Single basin stills
b) Multi effect stills
c) Hybrid stills

A single basin solar still is made of one basin filled with water and enclosed with a transparent cover. The cover can have multiple shapes to ensure high insolation.

The multi-effect still consists of several basins stacked on top of each other and uses the latent heat of condensation in the lower basin to heat the water in the upper basin, see Figure 5, [10].

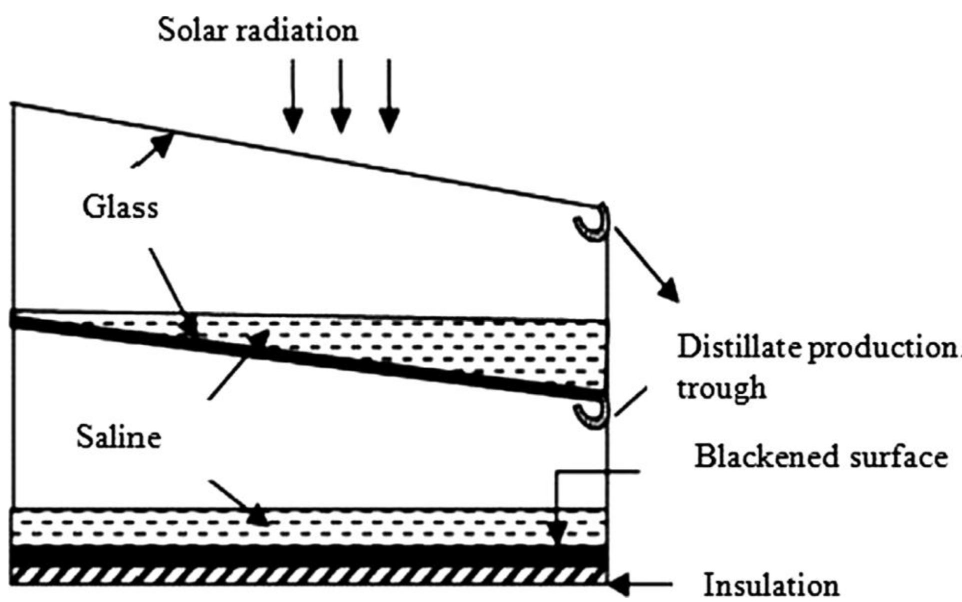


Figure 5: Illustration of a cross section for a double basin solar still [10].

The hybrid solar still uses external sources to improve the distillation process. One example is to use solar collectors to run a heat exchanger that heats up the basin water and then increasing the evaporation rate, see Figure 6, [10].

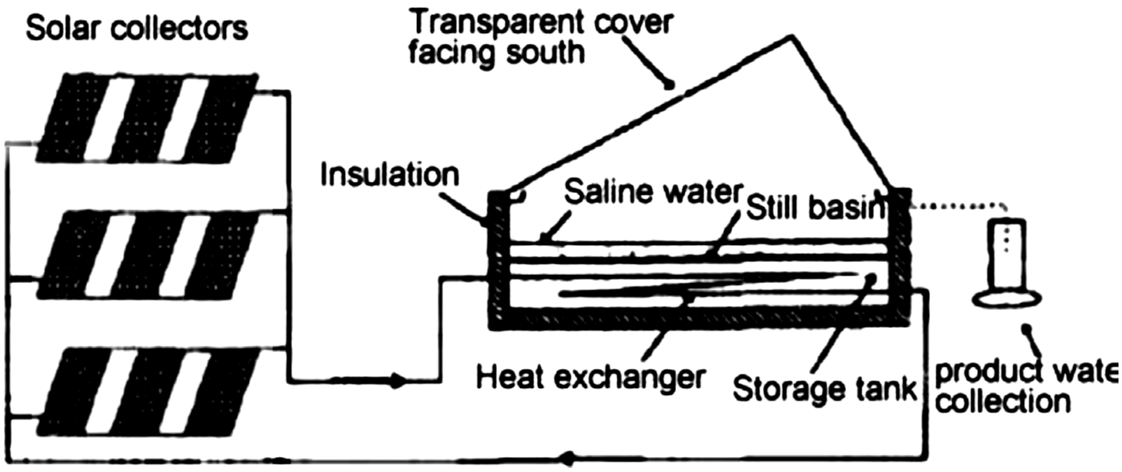


Figure 6: Schematics of a hybrid solar still system with a heat exchanger [10].

However, currently there is only the passive single basin solar still that is available on the market and the other types mentioned are mainly developed through research projects to increase efficiency. Consequently, only passive single basin solar still will be looked further into in this study and relevant products and models that exist on the market or have been prototyped are described in Table 2.

Table 2: Overview over passive single basin solar stills that have been prototyped or are for sale.

Picture of existing product	Description of existing product
	**Eliodomestico [47]** Solar distillation apparatus made in ceramic. Water is evaporating from the top and the vapor is pushed down through a nozzle in the bottom due the vapor pressure, before condensing. Not in production. Price: Estimated to be 50 [USD] Yield: 5 [L/m^2/day] Basin Area: N/A Patent: Not patented

Table 2: Continues.

Picture of existing product	Description of existing product
	**Watercone® [30]** A conic shaped solar still in transparent poly carbonate and a black basin. With a diameter of 700 [mm] it yields up to 1.7 [L/day]. Not in production. Price: Estimated to be 25 [USD] Yield: 8.8 [L/m^2/day] Basin Area: ~0.3 [m^2] Patent: US 20050098423
	**Rainmaker™ 550 [29]** A robust and single slope solar still with more advanced materials. Rainmaker has a molded plastic basin liner covered with insulation and glass fiber. During summer Rainmaker yields up to 6 [L/day]. Price: 489 [USD] Yield: 6.5 [L/ m^2/day] Basin Area: 0.93 [m^2] Patent: US 6767433 B2
	**Rainkit™ 990 [29]** From the same company as Raimaker, but Raintkit is a simpler and cheaper version developed for DIY users. The kit includes drawings and key materials that is not "off the shelf". The Rainkit model yields up to 11 [L/day] during summer. Price: 245 [USD] Yield: 6.8 [L/m^2/day] Basin Area: 1.7 [m^2] Patent: N/A, based on Rainmaker™ 550

Table 2: Continues.

Picture of existing product	**Description of existing product**
	**Plywood double sloped [3]** Double sloped solar still made in Kabul spring 2014 by MSc. student Cecilie Kolstad and local carpenters. It is made of local plywood, glass and a black painted plywood basin. Price: 110 [USD] Yield: 4.9 [L/m^2/day] Basin Area: 1 [m^2] Patent: Not patented
	**Sheet metal pyramid [27]** A pyramid shaped solar still made of sheet metal and covered with insulation. Made in Sindh, Pakistan, and is currently under testing. Price: N/A Yield: 3.7 [L/m^2/day] Basin Area: 1.5 [m^2] Patent: Not patented
	**Brick double sloped [27]** A double sloped solar still made of bricks and concrete. Made in Sindh, Pakistan, and is currently under testing. Price: 114 [USD] Yield: 4.4 [L/m^2/day] Basin Area: 2.5 [m^2] Patent: Not patented

2.2 Evaluation of existing products

Both Eliodomestico and Watercone are innovative solar still designs that have received design awards and good feedback in user tests [32]. However, they have been tested and developed for many years without entering the market. This is an indication of that the market potential is missing. Rainmaker and Rainkit are the only two solar still designs evaluated that are for sale. The water quality has been tested and approved, and they produce enough to support a small family [19]. The patents belonging to these designs are still valid, but there is no concern regarding this due to multiple work around solutions and designs. Kolstad developed six designs, but the plywood double sloped had one of the highest yields to a low cost. Unfortunately, the basin plywood fractured after short time of use and will hence shorten the design life. The two designs made in Pakistan are made of simple materials and have good production rates. Yet, no water quality tests have been performed to verify the distilled water.

2.3 Market and market potential

There has not been performed any type of local market research to ensure that the Faryab people are interested in using solar stills, or how much they are able and willing to pay for clean and safe water. For a still with 1 [m^2] basin area approximately 10 [L] of groundwater is needed every day to safely obtain 4 - 5 [L] of distilled water. The current water sources are hand pumps located in the province and the locals have to carry the groundwater themselves before refilling the still, meaning that operating the still is quite demanding. On the contrary, they are currently drinking saline and dangerous water and NCA are willing to subsidize the stills in the initial phase. However, there is a goal to lower the product cost and adapt the still design to local manufacturing in Faryab and eventually stimulate a local market.

2.4 Project framework and bottlenecks

The thesis description is defined together with NCA and Norplan and can together with the assumed technological and cultural challenges be read in the following sections.

2.4.1 Mission statements and challenges

Lack of clean drinking water is among the leading water related problems in Afghanistan, especially in form of salinity. As an attempt to find sustainable solutions, low cost solar stills are to be designed in Norway and in collaboration with local engineers in Kabul. The project will end with a field trip to Kabul where the selected design will be prototyped with local materials and by local craftsmanship. If time permits, production rates, water quality and local operability will then be tested before further manufacturing continues in Kabul or decentralized to a provincial level.

2.4.2 Technological bottlenecks

The assumed main technological challenges for this project are listed below:

Material access: It will be challenging to find necessary materials with correct quality, corresponding data sheet and specifications in Kabul.

Methods of manufacturing: Low technology facilities requires simple and well know manufacturing methods.

Water quality: Lack of safe materials and hence use of available materials, can cause outgassing of toxic gases and harm the distillated water.

Cost: The low cost requirement from NCA and Norplan will affect materials, design, manufacturing and yield towards a shortened the design life.

2.4.3 Cultural challenges

Collaboration and communication between engineers, craftsmen and staff in Kabul and personnel in Norway may be cultural demanding and the main cultural challenges for this project are listed below:

Culture: Big cultural differences can challenge the communication and collaboration.

Trust: Build up trust for solar still technology and water quality for staff in Kabul and local people in the Faryab province.

Cost: Can the users afford to pay for solar stills and are they willing to?

Market: Are the users willing to walk long distances to get groundwater for solar desalination?

3 PROJECT PLAN

To plan the project work throughout the process well defined and verifiable goals, objectives and milestones are to be made to ensure project delivery according to the time limit and can be read in the following sections.

3.1 Main goal

The following main goal is defined for the project work:

The main goal for this thesis is to design, build, install and if time permits, test a solar still for desalination of water for remote areas in Afghanistan. The final design will be presented with production directions and technical drawings. The solar still are to be built with local materials, facilities and staff.

3.2 Part goals

The following part goal activities are included in the project work to fulfill the main goal:

- To develop concept specifications and lay ground for technical development of the still concept.
- To design a module based on the developed concept.
- Perform cost evaluations and estimates of manufacturing, materials and components for both prototyping and series productions.
- Perform local manufacturing of prototype.
- Perform prototype testing.
- Follow up steps in the development process by writing report including results and final presentation of the performed work.

3.3 Work plan with milestones

Table 3 shows the work plan and the milestones are labeled with an “X”. There is planned for a week margin due to uncertainties in the project work.

Table 3: Time and work plan with milestones.

Task	Hours	Week																	
Phase I: Product development		3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Product spesification	38																		
Develop concept	40																		
Determine relevant local materials	15																		
Choose concept	-				X														
Design module	50																		
Modularization	20																		
Choose materials	-						X												
Method of production	20																		
Cost evaluation	15																		
Re-design and design variations	60								X										
Phase II: Prototyping in Kabul																			
Build prototype	113																		
Design presentation	8												X						
Follow up field tests	10																		
Phase III: Reporting																			
Report	150																	X	
Presentation	20																	X	
Planned hours pr week		38	35	45	38	30	43	30		38	38	45		41	41	41	58		
Total planned hours	558																		
Total amount of hours avalible	600																		
Margin in hours	43																		

A 30 credits master thesis have approximately 900 hours available and an assumed work efficiency of 60 [%] is included in the work plan above.

3.4 Project limitations

Due to limited resources and time the following actions and objectives must be left out of this study:

- Investigations of multiple basin and hybrid solar stills are left out. Only passive single basin solar stills are investigated.

- Alternatives enhancing the efficiency when operating the solar still is not investigated.

- A detailed heat transfer model to predict production rates and thermal performance is not developed and implemented.

- Operating guidelines for daily use are not described.

- Water quality analysis, such as salinity, pH and against WHO requirements are not performed.

4 METHODOLOGY

The terminology, tools and work process used in this product development process is described in Table 4, Figure 7, Table 5 and Table 6 the following sections.

4.1 Terminology

4.1.1 Definitions

Table 4: Overview over the main components in a solar still.

Main components in the solar still	
Nr from Figure 7	**Description**
1	Distilled storage vessel
2	Distillate production trough
3	Transparent glazing cover
4	Airtight chamber
5	Basin
6	Legs

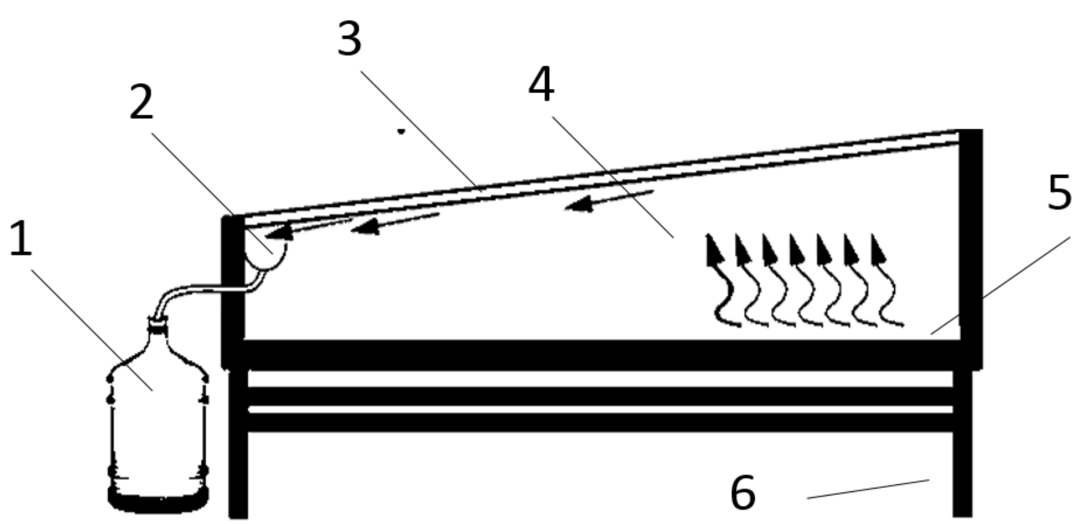


Figure 7: Overview over the main components in a solar still. The figure is modified after [34, 4].

4.1.2 Symbols and units

Table 5: Overview over relevant symbols.

Symbols		
Notation	**Description**	**Units [SI]**
A	Area	[m^2]
$E_{absorbed}$	Absorbed energy	[W/m^2]
EC	Electric conductivity	[µS/cm]
$E_{emitted}$	Emitted energy	[W/m^2]
G_D	Direct solar radiation	[W/m^2]
G_d	Diffuse solar radiation	[W/m^2]
G_{solar}	Total solar irradiance	[W/m^2]
h_{cw}	Heat loss coefficient by convection from water surface	[W/m^{2}K]
h_{rw}	Heat loss coefficient by radiation from water surface	[W/m^{2}K]
h_{ew}	Heat loss coefficient by evaporation from water surface	[W/m^{2}K]
h_{tw}	Total heat transfer loss coefficient from water surface	[W/m^{2}K]
h_{cg}	Heat loss coefficient by convection from glass cover	[W/m^{2}K]
h_{rg}	Heat loss coefficient by radiation from glass cover	[W/m^{2}K]
J	Energy, Joule	[J]
k	Thermal conductivity	[W/mK]
K	Temperature, Kelvin	[K]
L	Length	[m]
m	Weight	[Kg]
P	Production rate, Litre	[L]
P_g	Glass saturated partial pressure	[N/m^2]
P_w	Water saturated partial pressure	[N/m^2]
$\dot{q}_{cg}$	Rate of energy lost from the glass surface by convection	[W/m^2]
$\dot{q}_{cw}$	Rate of energy lost from the water surface by convection	[W/m^2]
$\dot{q}_{ew}$	Rate of energy lost from the water surface by evaporation	[W/m^2]
$\dot{q}_g$	Rate of energy lost from the glass cover	[W/m^2]
$\dot{q}_{net,radiation}$	Net radiation heat transfer rate	[W/m^2]
$\dot{q}_{rg}$	Rate of energy lost from the glass surface by radiation	[W/m^2]

Table 5: Continues.

Symbols		
Notation	**Description**	**Units [SI]**
$\dot{q}_{rw}$	Rate of energy lost from the water surface by radiation	[W/m^2]
R	Thermal resistivity	[m^{2}K/W]
S	Siemens, electrical conductance	[S]
t	Material thickness	[mm]
T	Temperature, Celsius	[℃]
T_g	Inside cover glass temperature	[K]
T_s	Surface temperature	[K]
T_{sky}	Effective sky temperature	[K]
T_w	Basin water temperature	[K]
V	Volume, cubic metre	[m^3]
v	Wind speed	[m/s]
W	Heat transfer rate, W	[W]
α_s	Solar Absorptivity	-
ε	Emissivity	-
ε_w	Water emissivity	-
ε_g	Glass emissivity	-
τ_s	Solar transmissivity	-
ρ	Surface reflectivity	-
θ	Angle of incidence of direct solar radiation	[degree ^{o}]
σ	Stefan Boltzmann constant, 5.67 x 10^{-8}	[W/m^{2}K^4]

4.1.3 Formulas and equations

Table 6: Overview over equations used.

Equations		
Notation	**Equation nr.**	**Equation**
R	4.1.4	$R = \frac{L_1}{k_1 A}$
R_{total}	4.1.5	$R_{total} = \frac{L_1}{k_1 A} + \frac{L_2}{k_2 A} + \frac{L_3}{k_3 A}$

Table 6: Continues.

Equations		
Notation	**Equation nr.**	**Equation**
G_{solar}	4.1.6	$G_{solar} = G_D \cos\theta + G_d$
$\dot{q}_{net,radiation}$	4.1.7	$\dot{q}_{net,radiation} = \sum E_{absorbed} - \sum E_{emitted}$
$\dot{q}_{cw}$	4.1.8	$\dot{q}_{cw} = h_{cw} \left(T_w - T_g\right)$
$\dot{q}_{rw}$	4.1.9	$\dot{q}_{rw} = h_{rw} \left(T_w - T_g\right)$
$\dot{q}_{ew}$	4.1.10	$\dot{q}_{ew} = h_{ew} \left(T_w - T_g\right)$
h_{tw}	4.1.11	$h_{tw} = h_{cw} + h_{rw} + h_{ew}$
$\dot{q}_g$	4.1.12	$\dot{q}_g = \dot{q}_{rg} + \dot{q}_{cg}$
$\dot{q}_b$	4.1.13	$\dot{q}_b = \frac{(T_w - T_a)}{R_{total}}$

4.2 Development methods and tools

The product development work and methods are based on strategies and knowledge obtained from the course “Product development and product design with 3D Concept” and “Product Realization”, [1, 2], at NMBU and some of the methods are described below.

4.2.1 Product development methods

IPD- Integrated Product Development

IPD is a method used to increase project efficiency and gain a better understanding of the product development project. Through IPD the development is seen from other angles than the traditional engineering and economical perspective. Mainly there are four different perspectives implemented in the process: functional development, manufacturing development, cost estimations and environmental documentation. The method can be described as a systematic guideline that must be followed in a consecutive order [2].

Pughs method

Stuart Pugh was a well-known design engineer and has written many books related to product development. He has developed a quantitative technique to ensure objective and good design choices in a product development process. Pughs method rank options on a multidimensional level against pre-defined requirements. This method can be combined with weighted criterions to account for specific product needs or requirements [31].

4.2.2 Literature review

To ensure up to date and essential background literature on solar desalination a literature research has been performed based on Kolstad’s thorough literature review [3]. In addition a patent search has been conducted on European Patent Office, EPO, and World Intellectual Property Organization, WIPO, with the following search words: Solar still, Solar desalination, SolAqua, Watercone, Eliodomestico and Single basin.

4.2.3 Graphic and design tools

The following software tools were used in the process of product development:

- Siemens NX 8.5, 2012: 3D-deisgn and technical drawings.
- Microsoft Office Professional Plus 2010: Reporting, calculations and graphics.

4.3 Development process

Figure 8 illustrates the workflow and the different stages in the product development. The loop in the middle of the process illustrates the iterative design process. A more detailed description of the development process is listed in Table 7.

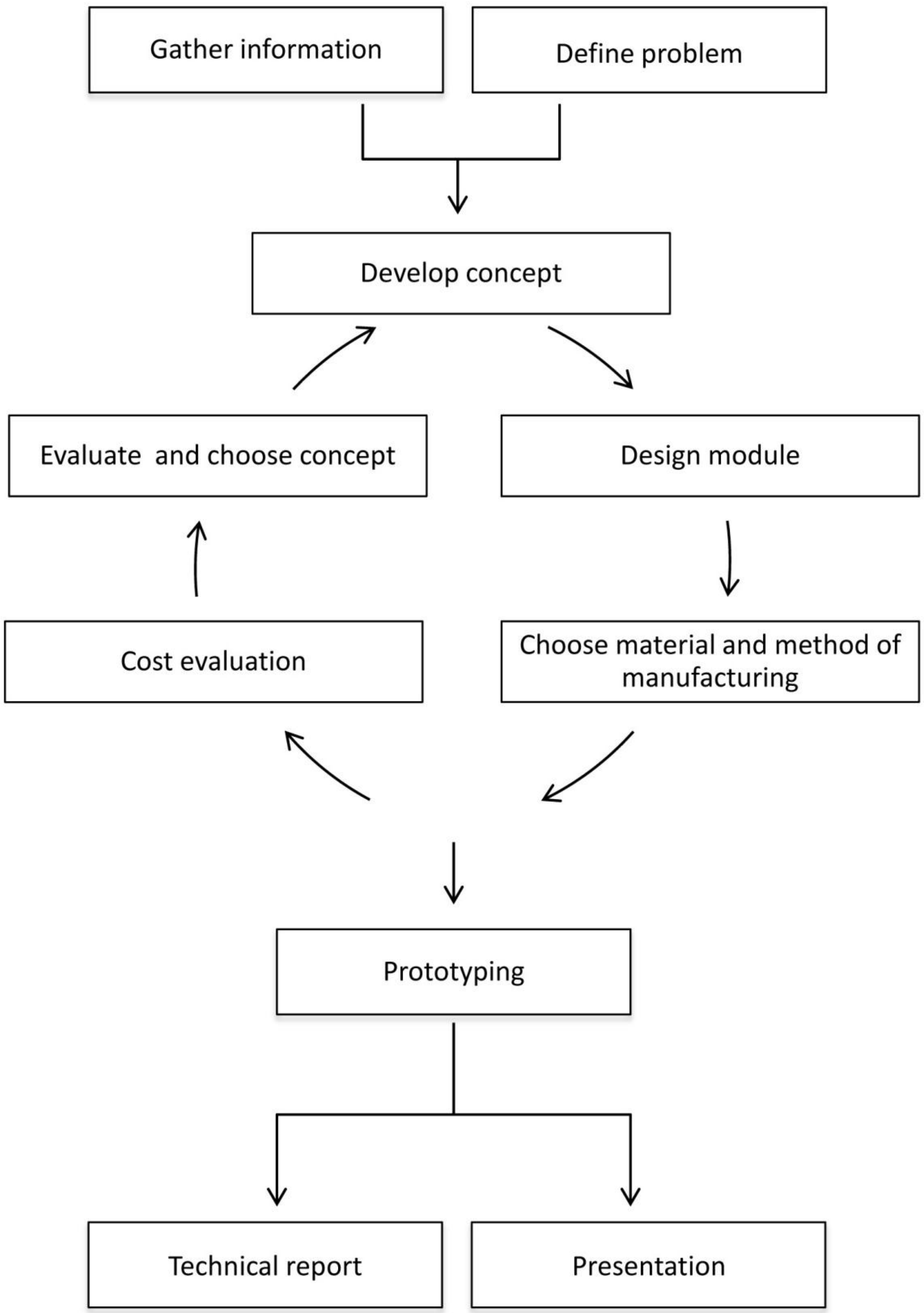


Figure 8: The process stages in the product development. The figure is modified after [4].

Table 7: Detailed overview of each stage in the process and its content. The table is modified after [4].

Process stages	Detailed content
Product specification	Define problem. Search for competitive solutions. Search for challenges and bottlenecks associated with desalination of water. Define prioritized product features. Define product specification.
Develop concept	Learn thermal heat transfer and relevant physics. Estimates of metrical specification. Functional analyses. Develop functional alternatives. Develop design alternatives. Consider relevant materials. Consider relevant methods of manufacturing.
Choose concept	Create selection criteria's for Pughs matrix. Accomplish selection of concept.
Design module	Assembly methods. Design basin. Include functionality, robustness, maintenance and production rates. Design all components. Assembly.
Modularization	Simplifications of assembly and method of manufacturing.
Materials	Choose material based on price, durability, method of manufacturing and water quality.
Method of manufacturing	Search for methods and price of manufacturing. Determine best method of manufacturing.
Cost evaluation	Calculate cost related to prototyping and series production.
Re-design	Examine if chosen design can be produced with chosen materials, method and price.
Build prototype	Present design for craftsmen. Purchase all components. Build solar still in collaboration with craftsmen. Present design and prototype for local staff and engineers. Start and follow up field tests, for production rates and water quality.
Closure	Reporting. Presentation.

5 BASIC THEORY

To evaporate water energy is needed. In solar stills the sun provides energy through solar radiation. The transparent cover transmits most of this energy and is hence absorbed by the basin material and transferred to the water. As the solar still is air tight and often insulated, the water temperature is increasing and eventually the water will evaporate. Consequently, the vapor rises to the transparent cover before condensing on the glass surface. The water droplets will then slide down the sloped cover for collection.

This process results in water cleaner than rain and destroys microbiological organisms. In addition, it removes salt, contamination and heavy metals. Badran, Abu-Khader and Mazen developed a mathematical model described in the paper, “Evaluating thermal performance of a single slope solar still”, [7], to predict the thermal performance for a single slope solar still and then compared it with experimental data. The results correlated well and hence some of the equations is extracted and presented below.

5.1 Solar Radiation

The solar energy is the earth’s primary source of energy and is reaching us in the form of electromagnetic waves. This energy consists of direct and diffuse solar radiation. Direct solar radiation, G_D, is not scattered or absorbed by the atmosphere, but the diffuse solar radiation, G_d, is scattered and assumed to reach the earth from all directions. On a clear day a surface can receive approximately 1000 [W/m^2], but much less on cloudy or smoggy days. For a specific surface on earth the latitude of this surface determines the amount of direct solar radiation the surface will receive. Consequently, setting the sloping angle on the solar still equal to its locational latitude will result sun rays normal of the surface throughout the year. The total solar energy incident, G_{solar}, for a horizontal surface on earth is then given by equation [4.1.6] from [5], and here θ is defined as the angle the sun rays make with the normal of the surface.

$$G_{solar} = G_D \cos\theta \, + \, G_d \qquad [4.1.6]$$

5.2 Solar radiative properties

When sun rays strikes the transparent cover plate not all of the energy is transmitted, and some is reflected and absorbed by the cover material. For a 6 [mm] thick glass only 80 [%] is transmitted, and in general the solar transmittance values for glass, τ_s, are increasing with decreasing cover thickness. When the sun rays have entered the still the basin material should absorb as much of the transmitted radiation as possible and hence have high solar absorptivity values, α_s, and is characterized by black surfaces absorbing the sun rays. In addition, a surface will also emit some of its energy through radiation and a suitable basin material should hence have low emissivity values, ε, in order to minimize the emission of radiation. For a surface exposed to solar radiation, the net radiation heat transfer rate is given by an energy balance based on equation [4.1.7] from [5].

$$\dot{q}_{net,radiation} = \sum E_{absorbed} - \sum E_{emitted} \quad [4.1.7]$$

$$= E_{solar,\ absorbed} + E_{sky,\ absorbed} - E_{emitted} \quad [4.1.7a]$$

$$= \alpha_s G_{solar} + \varepsilon\sigma\left(T_{sky}^4 - T_s^4\right) \quad [4.1.7b]$$

The net heat transfer rate in [W/m^2] for a solar still basin is therefore depending on the solar absorptivity of the surface, α_s, total solar energy incident, G_{solar}, the surface emissivity, ε, Stefan Boltzmann constant, σ, the effective sky temperature, T_{sky}, and the basin surface temperature, T_s.

5.3 Internal heat transfer

The heat transfer within the solar still consists mainly of convection, radiation and evaporation that occur between the water surface in the basin and the glass over. As the water is being heated and the air inside the still is not saturated there will be a difference in the concentration of water vapor in the water surface and the air. This concentration difference drives the water into the air. Before this can happen the water must absorb the latent heat of vaporization and hence vaporize.

5.3.1 Internal convective heat transfer

The vapor that rises through the air is driven by the temperature difference between water surface temperature, T_w, and glass temperature, T_g. This convective heat transfer rate can be given by equation [4.1.8] from [7]:

$$\dot{q}_{cw} = h_{cw}\left(T_w - T_g\right) \quad [4.1.8]$$

Where the convective heat loss coefficient, h_{cw}, can be obtained from the following empirical expression:

$$h_{cw} = 0.884\left[T_w - T_g + \frac{(P_w - P_g)(T_w)}{268.9 \times 10^3 - P_w}\right]^{1/3} \quad [4.1.8a]$$

Where P_w and P_g is the vapor pressure at the water and glass surface and can be expressed by the following equations:

$$P_g = e^{\left(25.317 - \frac{5144}{T_g}\right)} \quad [4.1.8b]$$

$$P_w = e^{\left(25.317 - \frac{5144}{T_w}\right)} \quad [4.1.8c]$$

5.3.2 Internal radiative heat transfer

Radiation occurs between two bodies where there is any temperature difference and in this case it will be between the basin water surface and the glass cover. The radiation heat transfer rate can be given by equation [4.1.9] from [7]:

$$\dot{q}_{rw} = h_{rw} \left(T_w - T_g\right) \quad [4.1.9]$$

$$= \varepsilon_{eff}\sigma \left[\left[T_w^2 + T_g^2\right]\left(T_w + T_g\right)\right] \quad [4.1.9a]$$

Where the effective emittance between the glass cover surface, ε_g, and basin water surface, ε_w, is given by:

$$\varepsilon_{eff} = \frac{1}{\left(\frac{1}{\varepsilon_w} + \frac{1}{\varepsilon_g} - 1\right)} \quad [4.1.9b]$$

5.3.3 Internal evaporative heat transfer

Because of the rising vapor from the water surface heat is lost through evaporation and the rate of evaporative heat transfer can be expressed by the following empirical equation [4.1.10] from [7]:

$$\dot{q}_{ew} = h_{ew} \left(T_w - T_g\right) \quad [4.1.10]$$

Where the evaporative heat transfer coefficient is given by:

$$h_{ew} = 16.273 \times 10^{-3}\, h_{cw} \frac{\left(P_w - P_g\right)}{\left(T_w - T_g\right)} \quad 4.1.10a]$$

5.3.4 Total internal heat transfer

The total internal heat lost from the basin water from convection, radiation and evaporation is based on equations described above and can be expressed by equation [4.1.11] from [7]:

$$h_{tw} = h_{cw} + h_{rw} + h_{ew} \quad [4.1.11]$$

The glass temperature will in this process always be colder than the vapor saturation temperature because the solar still is air tight and heated by solar radiation. Consequently the vapor will therefore condensate when the temperature is reduced below its saturation point and form droplets that will slide down the angled cover plate due to gravitation.

5.4 Heat losses

Not all of the energy that transmits the transparent cover is used to heat up the water. Heat losses through the bottom, sides and top are expected and driven by radiation, convection and conduction. The heat losses through the bottom and side walls can be minimized by insulation to increase the resistivity and hence lower the conductive heat transfer rate. In addition, there will be a heat loss through the transparent cover to the surroundings, governed by radiation and convection.

5.4.1 Heat losses through cover

Due to a thin glass cover and following an insignificant temperature gradient the heat losses through the glass cover are mainly depending on the ambient temperature, T_a, and the surrounding wind speed, v, and can be expressed by equation [4.1.12] from [7]:

$$\dot{q}_g = \dot{q}_{rg} + \dot{q}_{cg} \qquad [4.1.12]$$

Where the rate of heat loss through the glass cover by radiation and convection is given by:

$$\dot{q}_{rg} = h_{rg} \left(T_g - T_a\right) \qquad [4.1.12a]$$

$$\dot{q}_{cg} = h_{cg} \left(T_g - T_a\right) \qquad [4.1.12b]$$

The radiative heat transfer loss coefficient and convective heat transfer loss coefficient is given by:

$$h_{rg} = \frac{\varepsilon_g \sigma \left(T_s^4 - T_{sky}^4\right)}{\left(T_g - T_a\right)} \qquad [4.1.12c]$$

$$h_{cg} = 3.8 \times v \qquad [4.1.12d]$$

5.4.2 Heat losses through bottom and sides

Heat is lost from the water and through the walls, and from the outer walls to the surroundings through convection and radiation. The outer wall temperature is assumed to be close to the surrounding temperature due to insulation. It is therefore assumed that the conductive heat transfer is governing and can be given by equation [4.1.13], [5]:

$$\dot{q}_b = \frac{(T_w - T_a)}{R_{total}} \qquad [4.1.13]$$

Where the thermal resistivity through a multiple material wall, R_{total}, is depending on the thickness, L, and the material conductivity, k, and is shown in equation [4.1.5], [5]:

$$\mathrm{R}_{total} = \frac{L_1}{k_1 A} + \frac{L_2}{k_2 A} + \frac{L_3}{k_3 A} \qquad [4.1.5]$$

5.5 Heat transfer discussion

The thermodynamics occurring inside the solar still consist of water in different phases and is rather complex. However, the essential is to absorb as much of the incoming radiation and transfer the energy to the water to let it evaporate as quickly as possible, and at the same time secure a cold glass surface to enhance the condensation rate. Regarding the heat losses there is mainly the resistivity of the walls cross section that can be included in a solar still design optimization. Therefore a focus on the following parameters will drive the product development process:

- Secure optimal incoming radiation.
- Obtain a high evaporation rate.
- Obtain a high condensation rate.
- Minimize heat losses through bottom and side walls.

6 PRODUCT SPECIFICATION

To obtain an optimal product development and prototype, product features and objectives must be defined in an early phase of the project. These definitions and specifications can be read in the following sections.

6.1 Product features

The determined main features of the product can be seen in Table 8 and are given a score between 1 and 5, were 1 is the lowest and 5 the highest. The corresponding justification can be read below.

Table 8: Ranking and score for each product feature.

Feature	Score	Description
Water production rate	5	The main goal is to produce safe drinking water.
Production cost	4	The local people in Faryab must have the money to buy their own solar stills.
Maintenance	3	The operator must manage and appreciate the benefit of daily maintenance to secure an optimal water production rate.
Usability	2	The operator must be able both to understand and manage to use the still.
Mobility	1	The solar still will be transported by truck and carried by people.

Water production rate: The amount of drinking water a human being need for daily use depends on individual psychology and climate, but WHO recommends a minimum of 2.5 [L/day], [38]. For an average Afghan family of 7 people it means a minimum of 17.5 [L/day]. Such a high production requirement will not be met by a normal size solar still of approximately 1-2 [m^2] basin area. However, the basin area is proportional with the yield and the still can be made larger or coupled in series to meet such a requirement. For this study it's a focus to increase output, but the prototype will only have a basin area of 1 [m^2].

Production cost: NCA and Norplan has defined that the unit price should be no more than 100 [USD] for series production. In an early phase stills will be subsidized by Norplan and NCA and tested by a share of the local market. If the users are convinced that this will provide them with safe drinking water, an aim is to start local manufacturing to stimulate, and create a sustainable and local solar still market in Kabul and perhaps in the Faryab province. Therefore, it must be developed solar stills to a relatively low cost to make it possible for local users to eventually buy their own stills.

Maintenance: The solar stills will be located in remote areas in the Faryab province, far away from manufacturing site and facilities. Therefore, the robustness, durability and reliability of the stills need to be high and in focus during the design phase to secure a minimum of demanding maintenance

Usability: The users will operate, maintain and secure own production and supply of drinking water every day. The operators can have a variable technical experience and understanding, so the usability must be maintained and in center.

Mobility: The units must withstand road transportation, Kabul-Faryab, on a bumpy road and to be lifted and carried by a minimum of two persons for installation and solar position adjustments throughout the year.

6.2 Water quality

The distilled water must be free of smell, taste and be compared to the groundwater that is filled into the solar still. In addition, it must fulfill these essential requirements based on WHO guidelines, [20], to ensure safe a high quality drinking water:

• Salinity below	1800	[µS/cm]
• Turbidity level below	1	[NTU]
• pH between	6.5-8.5	
• Chloride concentration below	5000	[µg/L]
• Nitrate concentration below	50 000	[µg/L]
• Fluoride below	1500	[µg/L]
• Arsenic below	10	[µg/L]

6.3 Estimated metrical specifications

To secure a relevant and optimal design phase and get a general understanding of local materials and suppliers, an early market research was performed by engineers at NCA in Kabul. This research revealed a wide selection of relevant structural materials, but unfortunately lack of suitable basin materials. Table 9 gives an overview over applicable materials, dimensions and local prices for the material found. Based on this, an early phase metrical specification was performed, see Figure 9 and Table 10.

Table 9: Overview over available local materials, dimensions and prices in Kabul.

Material	Dimensions			Price [AFN]
	Width [mm]	Length [mm]	Thickness [mm]	
Plywood	1220	2440	8,11,16	450-1900
Wood	50	6000	50	340
Wood	100	6000	50	1350
Glass	2000	2000	4,5,6,8,10	500-1500
Alloy sheet metal	1200	2200	0.7, 1.25	1200-1800
Plastic plate	1200	1800	8	3500-8000
Aluminum plate	1220	2440	5	2600-4000
Insulation	1200	1000	50	100-400

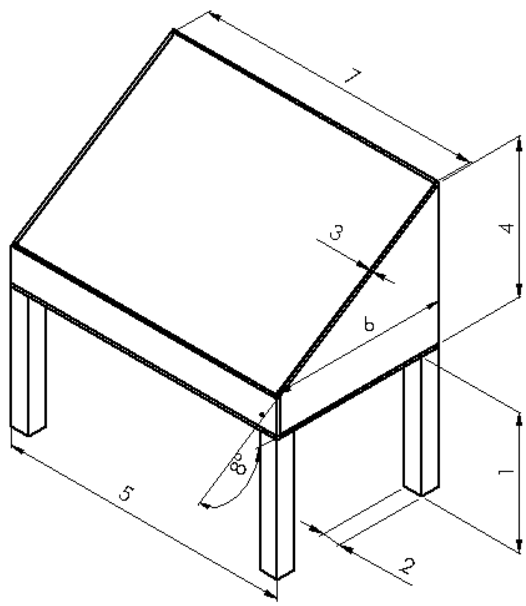


Figure 9: Illustration of estimated metrical specifications in Table 10 [4].

Table 10: Overview over estimated metrical specification for solar still [4].

Nr. from Figure 9	Definition	Unit	Min	Max
1	Height on legs	[mm]	-*	1200
2	Cross section legs	[mm^2]	-*	10 000
3	Wall thickness	[mm]	0.7	84
4	Height chamber	[mm]	50	1500
5	Length chamber	[mm]	500	2440
6	Width chamber	[mm]	500	2440
7	Glass and Basin area	[m^2]	1	2.44
8	Slope angle	[degrees°]	5	45

**Legs is not necessary*

6.4 Objectives

For the previous mentioned product features as usability and maintenance, this is features that must be designed in to the product, tested and developed through an iterative process with design and material changes combined with user tests, and is consequently difficult to measure. These features will therefore not have a defined and measurable objective other than a design focus throughout the process. However, other product features like water production rate, production cost and mobility will have clear product objectives and is listed below.

Based on the product features the solar still need to have the following specification:

- A total weight below 40 [Kg].
- Peak production rate of 4 [L/m^2/day].
- Price below 100 [USD] pr. unit.
- Produce drinking water that fulfill WHO requirements.
- Highly user friendly and intuitive.
- High durability and robustness.
- Produce only in summer, autumn and spring.
- Withstand transportation from Kabul to Faryab.

7 CONCEPT GENERATION

Based on the evaluation of existing products in chapter 2 a single basin concept is developed through a systematic functional analysis and then functional, operational and thermodynamically alternatives are developed and discussed before the final concept and design is chosen in chapter 8.

7.1 Functional analysis

The functionality of the solar still can be analyzed from two different perspectives, the user and the product itself. The main goal for the user is to secure safe drinking water. To reach this goal, several objectives needs to be fulfilled, see Figure 10.

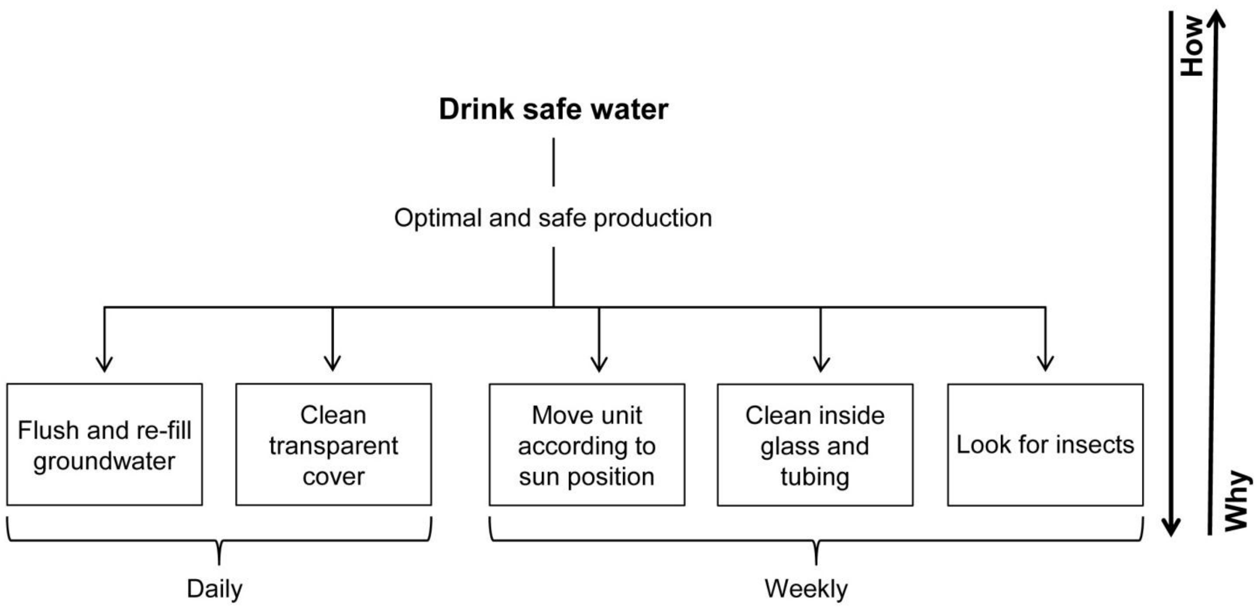


Figure 10: Functional analysis for a solar still user. The figure is modified after [4].

The daily operating processes consist of extracting distillated water and refilling saline groundwater. The basin should at the same time be flushed to avoid accumulation of salt, solids and contamination. In addition, the outer glass face should be cleaned for dust and sand. At a lower frequency a more thorough cleaning of basin, glass and hoses should be performed to avoid contamination and bacteria's. As the earth is moving relatively to the sun along the year, the solar still must occasionally be moved according to this to obtain maximum insolation. Due to the humid air inside the still during production, insects can be attracted and enter the still. This can introduce bacteria's and must be avoided.

From a product perspective, the solar still will accumulate safe and clean distilled water if functions described in Figure 11 are followed.

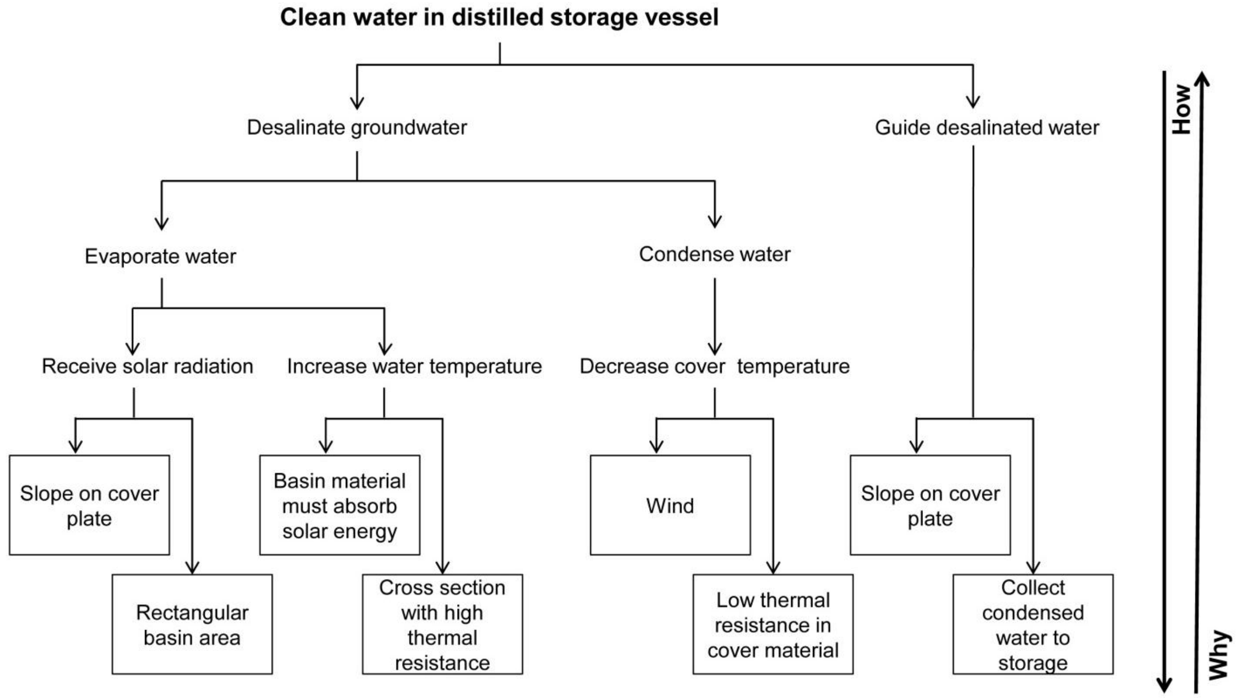


Figure 11: Functional analysis for the solar still. The figure is modified after [4].

The functions can be broken down in three sections: evaporate water, condense water and guide desalinated water. Where the evaporation of water will consist several parameters to receive solar radiation and increase the water temperature.

7.2 Functional alternatives

The functional alternatives are developed with basis in the parameters that will affect the productivity of the solar still and can be divided into climatic conditions, design conditions and operational conditions, see Figure 12.

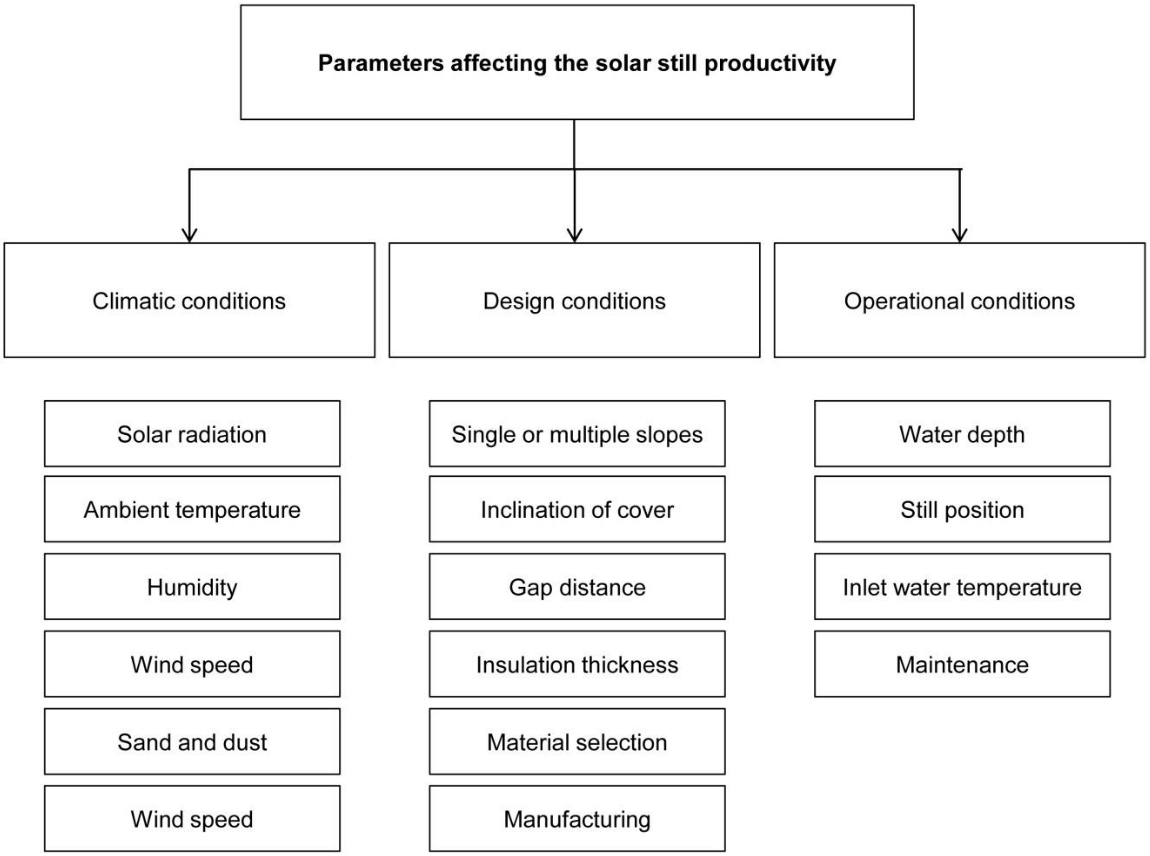


Figure 12: Parameters affecting the solar still productivity.

7.2.1 Climatic conditions

Several researchers have studied the climatic conditions and its correlation to the productivity rate in a solar still. A well supported fact is that radiation is essential and the driving energy source to the distillation process [10]. Other parameters like wind speed, humidity and ambient temperature will also affect the yield. Accumulation of sand and dust on the cover can drastically reduce the yield and the cover must hence be frequently cleaned [10].

7.2.2 Design conditions

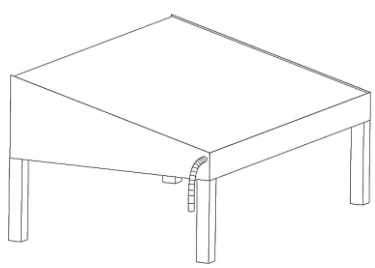
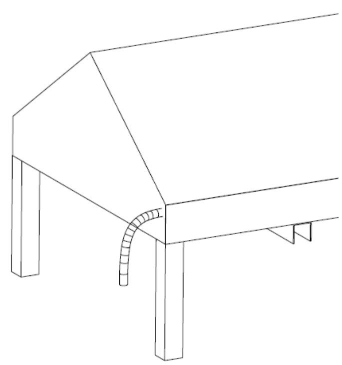
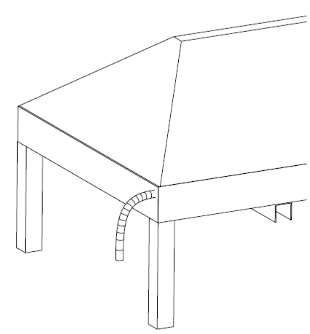
Different experiments and numerical calculations have been investigated by researchers to understand and improve the thermal performance and efficiency of solar still designs. In this study alternatives regarding cover shape, gap distance, insulation and basin design are studied and can be read below.

Cover shape

The only source of energy driving the desalination process is thermal radiation from the sun. Therefore it's a design focus to receive as much of the solar radiation as possible through the cover to secure and maintain an optimum water production throughout the design life. A single basin solar still can have several transparent covers to receive solar energy and the design of the covers determines the amount of received radiation.

During the year and day the earth changes its position and moves constantly causing the direct solar radiation to vary, which can make the design more complex if it shall be able to receive maximum direct solar radiation. As a rule of thumb the sloping angle of the cover should be the latitude + 10 [^{o}] for winter and -10 [^{o}] for summer to receive the maximum of solar radiation as possible, meaning sun rays normal to the slope surface [8, 22]. For optimal production in Faryab during summer it means a cover slope angle of 26 [^{o}]. Based on these facts and a wide design search, three different cover shape alternatives for a single basin solar still are suggested in Table 11.

Table 11: Functional alternatives around cover shapes.

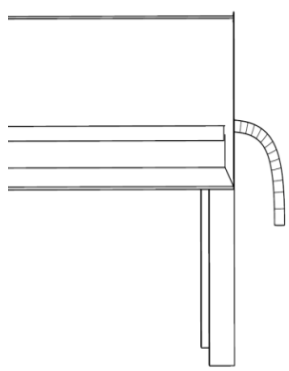
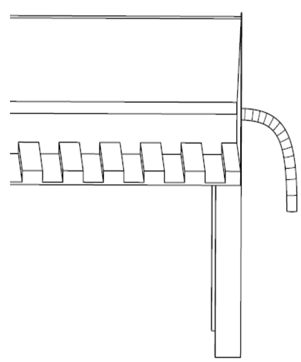
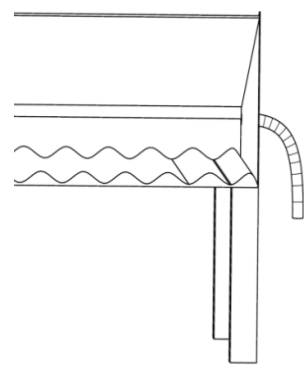
Cover shape		
Single slope	**Double slope**	**Pyramid**
		
Description: • One cover plate. • Simple construction. • Low cost. • Low solar radiation.	**Description:** • Two cover plates. • Increased insolation. • Medium cost.	**Description:** • Four cover plates. • Fragile. • Increased insolation. • High cost.

Discussion: The incoming solar radiation is assumed to increase with pyramid- and double slope shapes since there will be more transparent area facing the sun during the year. However, the cover area which is optimal for a certain sun position will be larger for a single slope still than a multiple slope still with the same basin area and will consequently receive more radiation, but requires frequently position adjustments [39]. Complex shapes can increase the manufacturing cost and are also more vulnerable for damage during operation and transportation.

Basin design

It’s important that the basin absorbs the energy that enters the still and quickly transfer it to the groundwater to be heated and subsequently evaporated. Velmuragan [9] wanted to see the impact of a fin type single basin solar still for enhancing the yield and received good match between compared theoretical analysis and experimental. The fins are increasing the surface area of the basin and consequently the temperature and production rate. Based on Velmuragans research regarding fin based basins, three different alternatives is studied to enhance the basin area, see Table 12.

Table 12: Functional alternatives around basin design.

Basin design		
Plain	**Fins**	**Wave shape**
		
Description: • Only water in the basin. • Uniform and low water depth. • Lower material and manufacturing cost. • Easy refilling.	**Description:** • Several fins in the basin. • Increased surface area. • Increased material and manufacturing cost. • Low material availability. • High production rates.	**Description:** • Wave shaped material. • Increased surface area. • High material cost. • Low material availability. • High production rates.

Discussion: Velmuragan [9] showed that the production rate increased with over 50 [%] when fins were integrated, compared to a plain basin. It is hence expected an increase in productivity for the wave shape as well. However, the bottleneck for implementing fins is the availability of suitable basin materials. The early material research in section 6.3 revealed few suitable materials that can withstand saline water, high temperatures and in this case easy manufacturability.

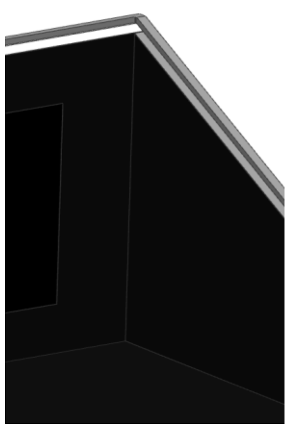
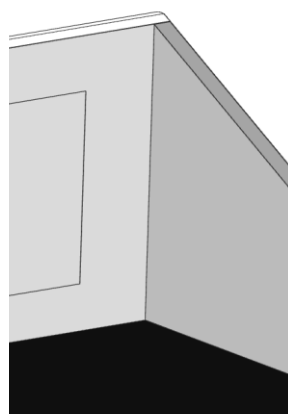
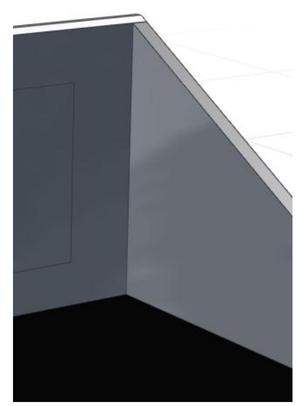
Air volume

The air volume inside the still depends on the sloping angle of the cover, the area of the basin and the gap distance, which is the height between the water surface and cover. An increase in this volume will increase conductive heat transfer through the surrounding walls due to larger wall area [39]. It will also increase the volume to be heated and consequently the material cost. The air volume inside the still should therefore be kept to its minimum to obtain the highest efficiency.

Color

The surfaces of the inside of the still will be chosen to maximize the production rate. Surfaces that are intended to absorb solar energy should have high solar absorptivity, α_s, values and low emissivity values, ε, to minimize the emission of solar radiation [5]. The inside walls can hence contribute to an increase in the production rate by either painting them black, (high solar absorptivity α_s values), with white paint (high reflectivity ρ and low emissivity values) or having reflecting mirrors on the side walls. Table 13 describes the different functional alternatives on the color of the inside wall.

Table 13: Functional alternatives on the inner side wall color.

Color of inner side wall		
Black side walls	**White side walls**	**Mirror on side walls**
		
Description: • Black paint on inner surfaces. • High solar absorptivity values. • Can outgas.	**Description:** • White paint on inner surfaces. • High reflectivity values. • Can outgas.	**Description:** • Mirrors on inner surfaces. • High reflectivity values. • No outgassing.

Discussion: Researchers agree upon a black colored basin to absorb as much of the solar energy as possible due to its high solar absorptivity, α_s, values [5]. However, there have been performed few studies on side wall colors inside the still. Pankaj [13] and

Tenthani [14] show unfortunately opposite results when they try to understand the impact of a black and white surface on the inner side walls of a solar still. Pankaj concludes that a black surface will enhance the absorption of solar energy and consequently give a higher water temperature. Tenthani states that a white inner surface will reflect the radiation into the basin and hence increase the water temperature. On the other hand, Kolstad [3] argued that paint used inside the still caused outgassing which gave a strange taste to the distillated water. Mirrors on the inner walls are another solution that can be used to reflect the solar radiation into the basin.

7.2.3 Operating conditions

The most important operating parameter that affects the efficiency of the solar still is the water depth in the basin.

Water depth

Several studies show that the water depth is inversely proportional to the production rate of the still. As the water depth increases, the heat capacity of the basin increases and therefore the water temperature decreases for a given solar radiation. When the heat capacity is decreased, due to a shallow water depth, the water will evaporate quicker and consequently increase the production rate. An optimal still will therefore secure a constant shallow water depth during production hours. H.Al-Hinai et al. [12] developed a mathematical model to predict the effect of water depth in the basin on the solar still yield, see Figure 13.

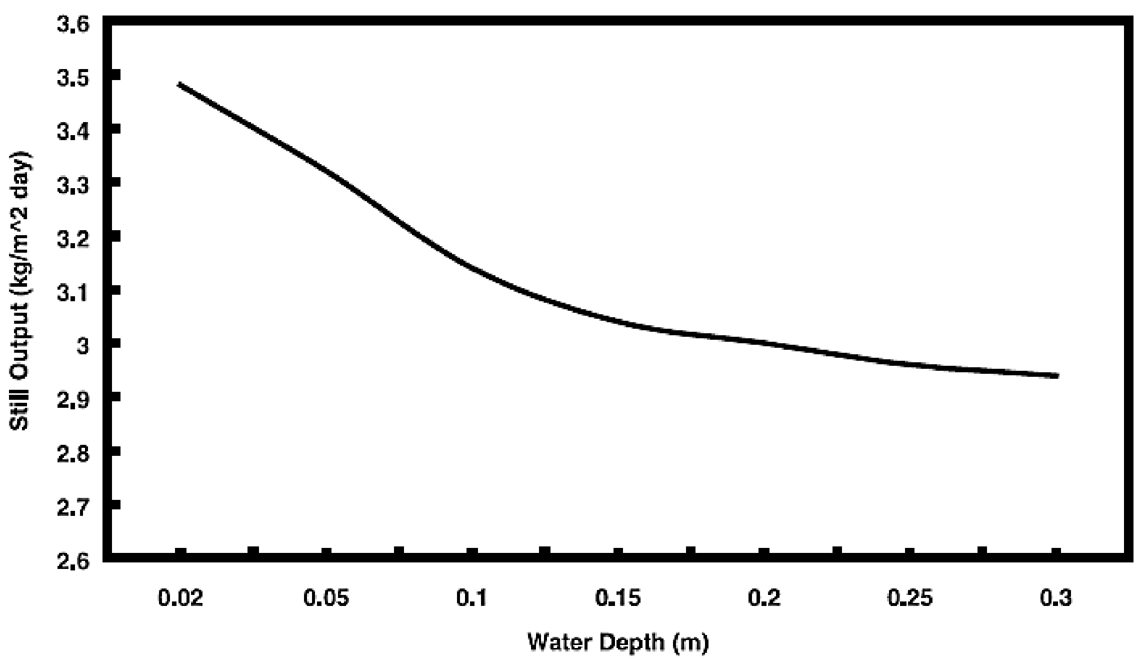


Figure 13: The effect of water depth on the yield from H.Al-Hinai et al. [12].

H.Al-Hinai et al discovered that a decrease of water depth from 100 [mm] to 5 [mm] resulted in an increase of 19.6 [%] in distilled water output. He further recommended the water depth to be in the range of 20 – 60 [mm]. To obtain this shallow water depth three functional alternatives are suggested, see Table 14.

Table 14: Functional alternatives around water depth.

Water depth		
Fixed depth	**Continuously feed**	**Floating plate**
Description: • Groundwater is applied in a batch once a day. • Marker indicates correct depth. • Slower evaporation rate. • Basin can dry out.	**Description:** • Automatic water feed to basin through a regulating system. • Secures a constant and optimal water depth. • Enhances material cost.	**Description:** • Plate floating in the basin with a thin layer of water above and larger depth below the plate. • Maintains a shallow and constant water depth above the plate.

Discussion: A state-of-the-art single basin solar still will produce approximately 5 - 10 [L/day/m^2] which corresponds to a water depth of 5 - 10 [mm/m^2] evaporated water. The water depth should be kept at is minimum to obtain optimal production, but not so low that it will go dry. This will cause outgassing of the basin material and must be avoided. A regulating input flow could manage to feed the basin with necessary water. However, this system would require a regulating unit that will increase the production cost and introduce possible unpredictability to the system. A floating plate which can absorb the heat and increase surface temperature of the water for a low cost is a simple yet effective solution and Valsaraj [11] showed that the efficiency was increased with 43 [%] with a black coated sheet floating in the basin.

Maintenance

When the water evaporates, salt and impurities are left behind and the basin will need properly and regular maintenance due to the buildup of lump salt masses. This will eventually fill the basin and decreases the efficiency and hygiene in the still. A maintenance technique must be secured and different functional alternatives can be seen in Table 15.

Table 15: Functional alternatives around maintenance.

Maintenance	
Maintenance door	**Flushing**
Description: • Inspection opening to clean and repair basin. • Easy access to basin. • More vulnerable for leakages.	**Description:** • Flush system and basin with water through a hose or valve. • No access opening to the basin. • Easier to keep air tight.

Discussion: It would be beneficial for the still to have an access opening to perform maintenance, small repairs and daily cleaning. This could secure a longer design life due to easy leakage fix and repairs. On the contrary, it will introduce a possible thermal cold spot or air leakage from the system that may decrease the efficiency. A closed system with daily flushing can prevent lump masses in the basin. It will not allow for internal repairs or maintenance which then will require a more robust design and manufacturing to prevent leakage and fractures. For both alternatives there is needed a drainage to get rid of old groundwater and contamination.

7.3 Usage and climate stresses

The solar still will be in daily use through the spring, summer and autumn in Faryab, and must consequently withstand the occurring stresses. Local weather data and usage stresses can be read it he following sections.

7.3.1 Locale environmental and climate stresses

Maimana is the capitol in the Faryab province and a weather station has been collecting data from 1958 - 1983 at an altitude of 815 [m] above sea level. The data is presented below in Figure 14 to Figure 18, [40, 41, 42]. Based on the metrological data, Maimana has hot and dry summer months with an average temperature of 25 [^{o}C] and relatively cold and moist winters. The precipitation is about half what comes down in Oslo in one year and Maimana has approximately 60 [%] more sun hours than Oslo, [40, 41, 42]. The mean monthly wind speed is relatively stable and varies from 1.8 to 2.0 [m/s] throughout the year.

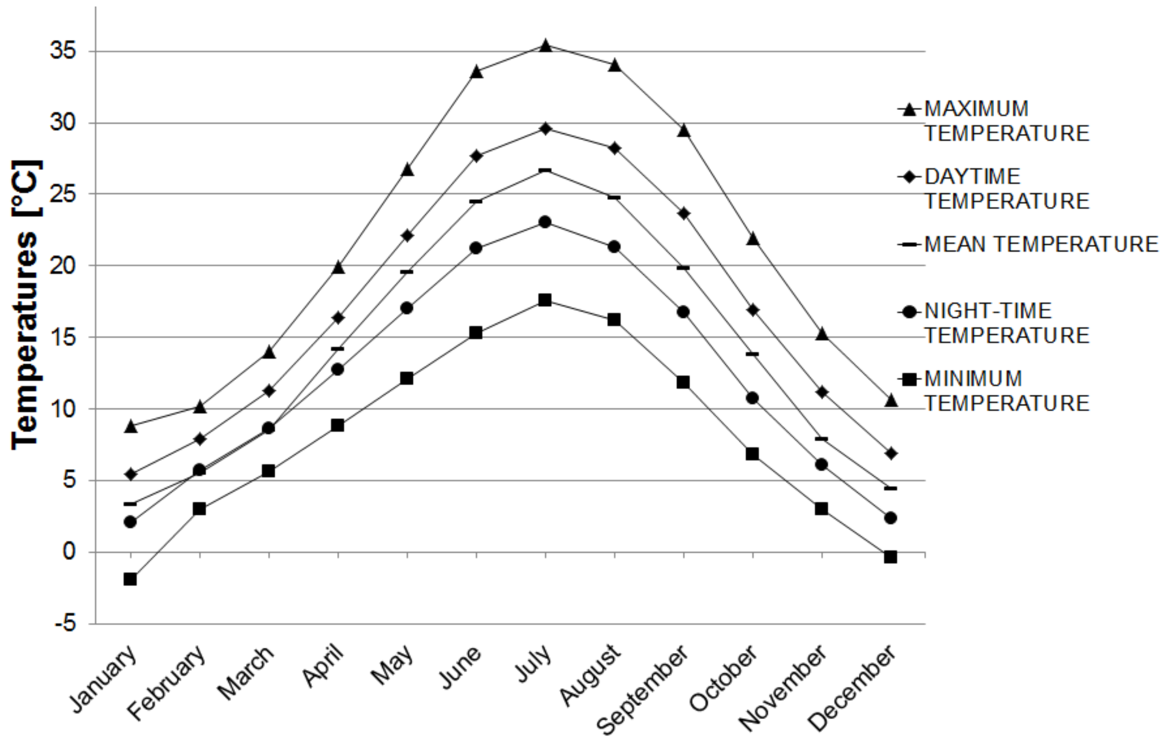


Figure 14: Mean monthly temperatures in Maimana throughout the year.

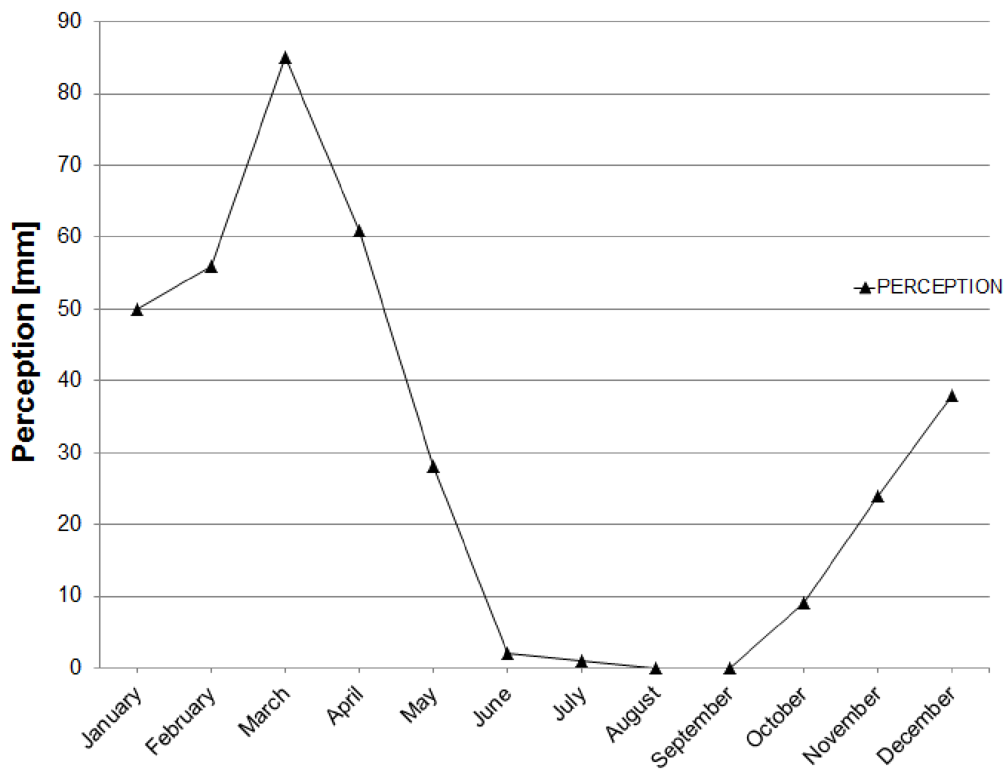


Figure 15: Mean monthly perception in Maimana.

From a technical solar still perspective, the high income of solar radiation and decrease of humidity, see Figure 16 and Figure 17, will give good conditions for the desalination process during the summer. The incoming radiation is the fuel and key parameter for the desalination and a low relative humidity will accept more vapor before the air it's saturated and consequently a higher evaporation rate is achieved.

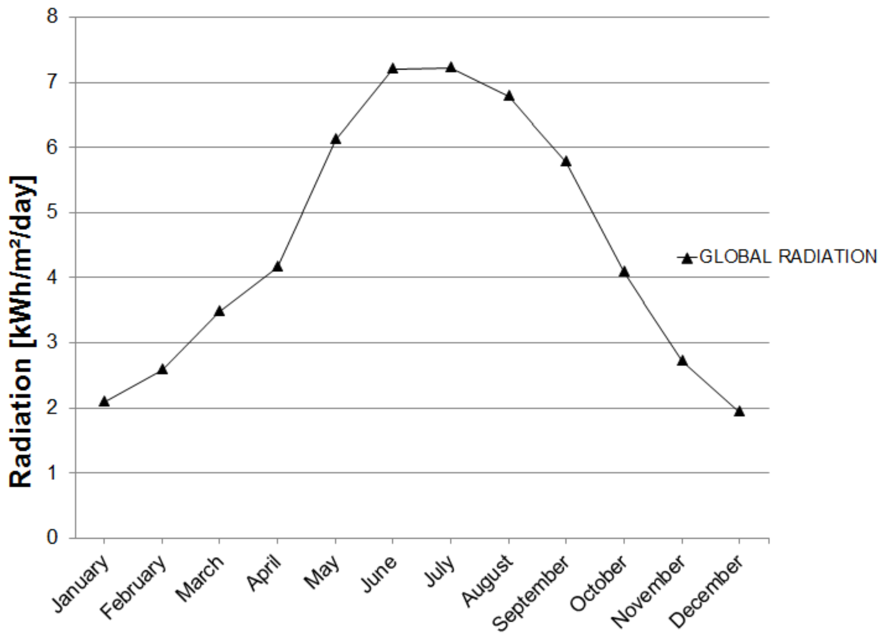


Figure 16: Mean monthly global radiation in Maimana.

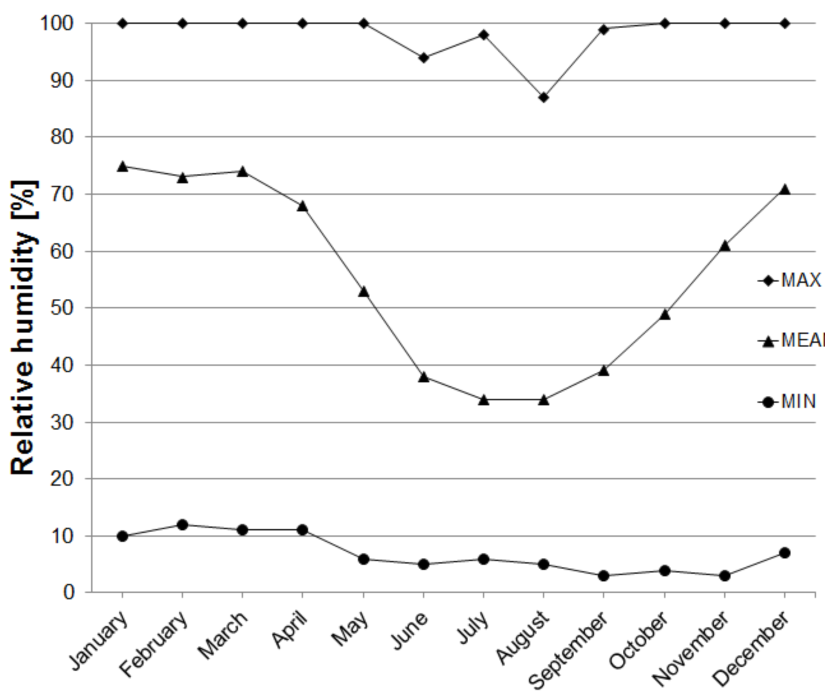


Figure 17: Mean monthly relative humidity in Maimana.

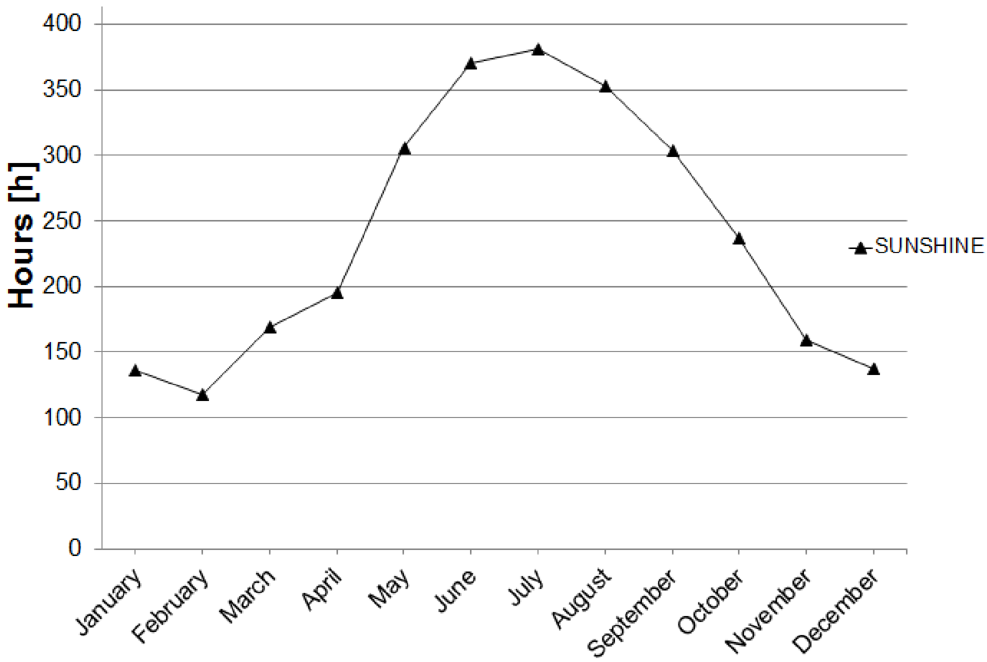


Figure 18: Mean monthly sunshine hours in Maimana.

On the other hand, the moist and cold winters with few sun hours will make it difficult to obtain acceptable production during the winter, see Figure 14, Figure 17 and Figure 18. Based on Kolstad's measurements [3], the solar still can be exposed to temperatures near 90 [^{o}C] during production. In combination with a high solar radiation the still must be able to resist these stresses and the materials must hence be chosen wisely to avoid outgassing and toxic gases inside the still that will affect the water quality.

Both the inner and outer materials must also be able to maintain its functions and shape when they are in touch with saline water, vapor, rain, ice and snow. The outer faces of the still must withstand warm summer temperatures and cold winters.

7.3.2 Daily stresses and maintenance stresses

The still will be flushed and cleaned frequently and the basin material should have high abrasion resistance to avoid fractures and cracks. In addition, the basin must sustain to be soaked in saline water with high temperatures. Tubing material must be chosen to resist fractures, high temperatures, ice and corrosion.

7.3.3 Transport stresses

The still must sustain transportation from Kabul to Faryab on bumpy roads with truck, and easily be lifted and moved by a minimum of two persons for installation, sun positioning, maintenance and winter storage.

7.4 Thermal resistivity calculations

Heat is lost out of the solar still walls trough conduction and is decreasing the output. H.Al-Hinai et al. [12] also used his mathematical model to investigate the effect of insulation thickness on the production rate and concluded that the insulation thickness increases the thermal performance proportionally until it converges and no longer pays off, see Figure 19.

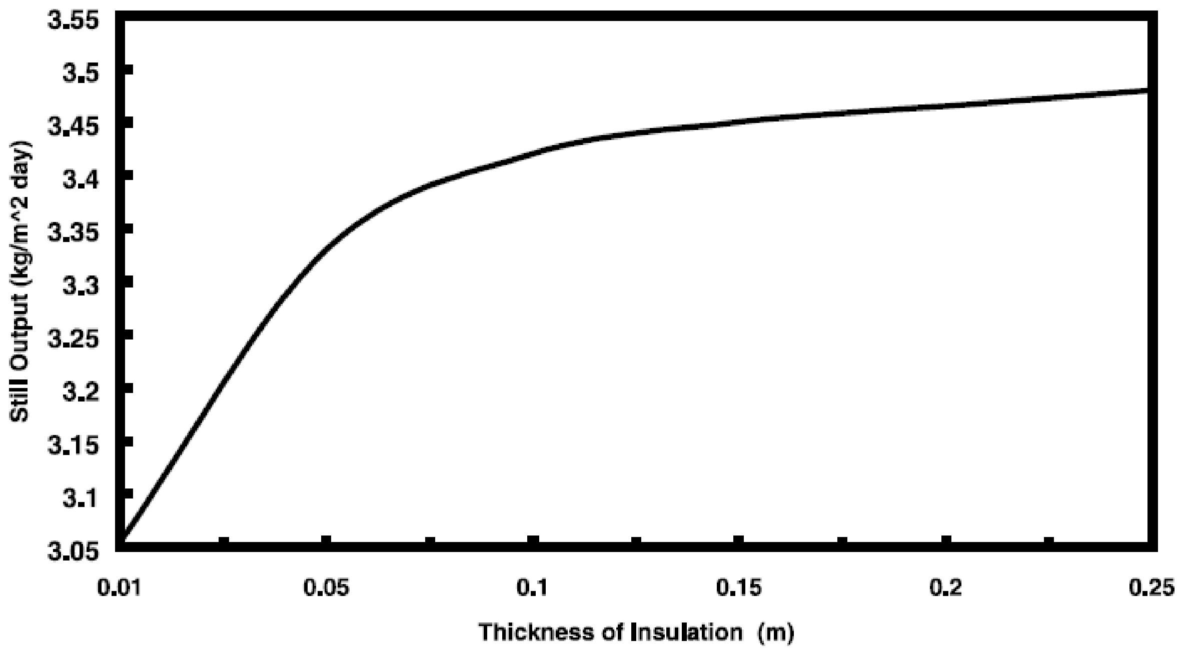


Figure 19: The effect of insulation thickness on the production rate from H.Al-Hinai et al. mathematical model [12].

Khalifa and Hamood [15] discovered that an insulation thickness of 60 [mm] resulted in an increased output of 80 [%] for their design and conditions, to a low additionally cost. Karaghouli et al [16] investigated the effect of insulating the side area of a single basin solar still and discovered that the output only increased with 2-4 [%] when compared to the same design without insulation. Therefore, thermal resistivity calculations are investigated during the design phase to reveal tradeoffs between thermal performance and cost. Multiple layers and thicknesses are investigated and their resistivity is compared against material cost, see Table 16, Table 17 and Figure 22. However, the resistivity calculations will not determine the specific impact on the output, but give input to the design and material selection.

Table 16: Calculated thermal resistivity for different materials and wall thicknesses, based on equation [4.1.4].

Material	Thermal conductivity*, k [W/m*K]	Thermal resistivity, R [m^2K/W] at wall thickness, t		
		t = 4 [mm]	t = 8 [mm]	t = 16 [mm]
Plywood	0.12	33	67	133
Galvanized Iron	20	0.2	0.4	0.8
Cement	1.4	3	6	11
Acrylic sheet	0.2	20	40	80
Glass	0.7	6	11	23
Polystyrene	0.04	100	200	400
Sawdust	0.065	62	123	246
Glass fiber	0.036	111	222	444

**Thermal conductivity at 25 [°C], [5]*

It can be seen from Table 16 that galvanized iron has the lowest thermal resistivity and will cause the biggest heat losses. On the other hand, insulation materials like polystyrene and glass fiber will insulate the system, decrease the heat losses and increase the thermal performance for the same material thickness.

To understand and compare the thermal impact different material cross sections will have on the resistivity, some relevant combinations are chosen in Table 17 and illustrated in Figure 20. Material 1 is the basin material and material 2, 3 and 4 is attached on the outside of material 1.

The following material thicknesses are used in Table 17 and based on early phase market search in section 6.3: galvanized iron 1.25 [mm], acrylic sheet 6 [mm], glass 6 [mm], plywood 16 [mm], polystyrene 50 [mm], glass fiber 50 [mm] and sawdust 50 [mm].

Table 17: Materials in different cross sections.

Cross section	Material 1	Material 2	Material 3	Material 4
A	Galvanized Iron			
B	Acrylic sheet	Plywood		
C	Acrylic sheet	Galvanized Iron	Plywood	
D	Galvanized Iron	Polystyrene	Galvanized Iron	
E	Acrylic sheet	Galvanized Iron	Glass fiber	Plywood
F	Galvanized Iron	Plywood	Sawdust	Plywood

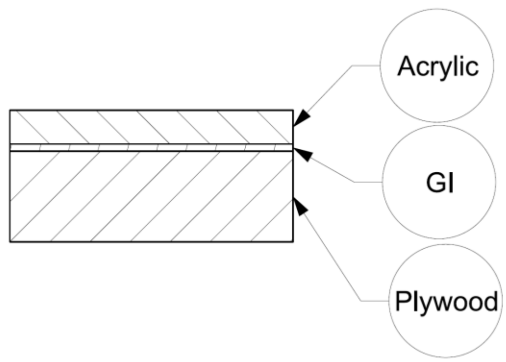


Figure 20: Illustration of cross section C, with acrylic basin and galvanized iron and plywood.

To calculate the thermal resistivity for a multiple material cross section equation [4.1.5] is used and is illustrated in Figure 21.

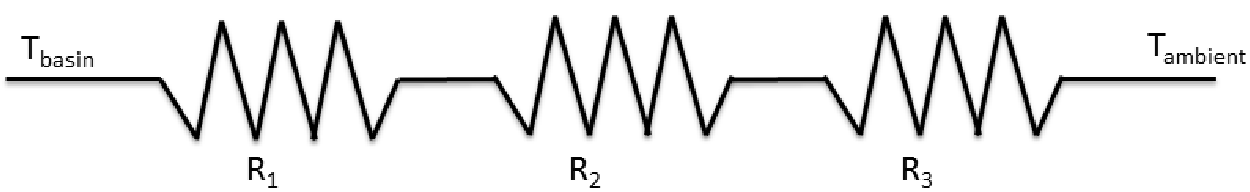
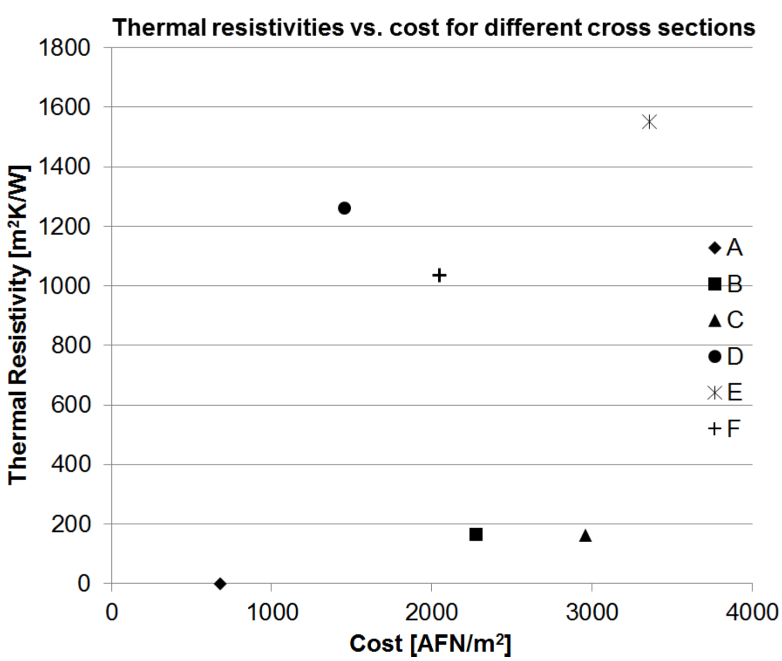


Figure 21: Resistivity schematic for a multiple material cross section.

In Figure 22 the thermal resistivity for the cross sections in Table 17 are related to its material cost and compared. This result in useful information for the design phase and links thermal performance and material cost.



Cross section A, 1.25 [mm] galvanized iron, is the cheapest, but has also the lowest resistance, 0.6 [m^2K/W]. Section E is on the opposite side with highest resistivity and cost. Below is section D with galvanized iron, expanded polystyrene and galvanized iron. This combination gives the second highest resistivity to the second lowest cost.

Figure 22: Thermal resistivity vs. cost for the different cross sections defined above.

8 SCREENING AND CONCEPT SELECTION

In chapter 7 different functions and alternatives were presented and considered. To objectively select the best suited design the product features is weighted and a selection matrix is developed in the following sections.

8.1 Weighted product features

The product features is weighted in Table 18 according to the previously defined features in section 6.1.

Table 18: Weighting of product features.

Feature	Weight [%]	Description
Water production rate	33	Main goal is to produce safe drinking water
Production cost	27	The local people in Faryab must have the money to buy their own solar stills
Maintenance	20	The operator must manage and appreciate the benefit of daily maintenance to secure an optimal water production rate
Usability	13	The operator an must be able both to understand and manage to use the still
Mobility	7	The solar still will be transported by truck and carried by people

8.2 Selection matrix

The final design is chosen based on the selection matrix in Table 19 and an early design can be seen in Figure 23.

Table 19: Selection matrix with weighted product features based on Pughs method.

Parameter	Alternatives	Product features										SUM
		Yield		Prod. cost		Maintenance		Usability		Mobility		
		Score	33 %	Score	27 %	Score	20 %	Score	13 %	Score	7 %	
Cover shape	Single slope	3,0	4,0	5,0	6,4	5,0	6,0	5,0	5,7	5,0	5,4	**50**
	Double slope	4,0	5,3	4,0	5,1	4,0	4,8	4,0	4,5	4,0	4,3	44
	Pyramid	5,0	6,7	3,0	3,8	2,0	2,4	2,0	2,3	2,0	2,1	31
Basin deisgn	Plain	1,0	1,3	5,0	6,4	5,0	6,0	5,0	5,7	5,0	5,4	**46**
	Fins	5,0	6,7	2,0	2,5	2,0	2,4	4,0	5,0	5,0	5,4	40
	Wave shape	3,0	4,0	3,0	3,8	3,0	3,6	4,0	4,5	5,0	5,4	39
Color	Black	5,0	6,7	5,0	6,4	5,0	6,0	5,0	5,7	5,0	5,4	**55**
	White	5,0	6,7	3,0	3,8	5,0	6,0	5,0	5,7	4,0	4,3	48
	Mirror	5,0	6,7	1,0	1,3	2,0	2,4	2,0	2,3	5,0	5,4	33
Water depth	Fixed depth	2,0	2,7	5,0	6,4	5,0	6,0	5,0	5,7	5,0	5,4	**48**
	Continuously	5,0	6,7	1,0	1,3	3,0	3,6	4,0	4,5	3,0	3,2	35
	Floating plate	4,0	5,3	3,0	3,8	4,0	4,8	2,0	2,3	4,0	4,3	37
Maintainance	Door	4,0	5,3	3,0	3,8	5,0	6,0	5,0	5,7	3,0	3,2	**44**
	Flushing	5,0	6,7	5,0	6,4	2,0	2,4	4,0	4,5	3,0	3,2	42
Cross section	Cross section A	1,0	1,3	5,0	6,4	2,0	2,4	2,0	2,3	2,0	2,1	26
	Cross section D	4,0	5,3	3,0	3,8	4,0	4,8	3,0	3,4	4,0	4,3	**40**
	Cross section E	5,0	6,7	1,0	1,3	4,0	4,8	3,0	3,4	4,0	4,3	37

8.3 Selected design

Based on Table 19 different parameter alternatives were chosen and resulted in a preliminary design that can be seen in Figure 23.

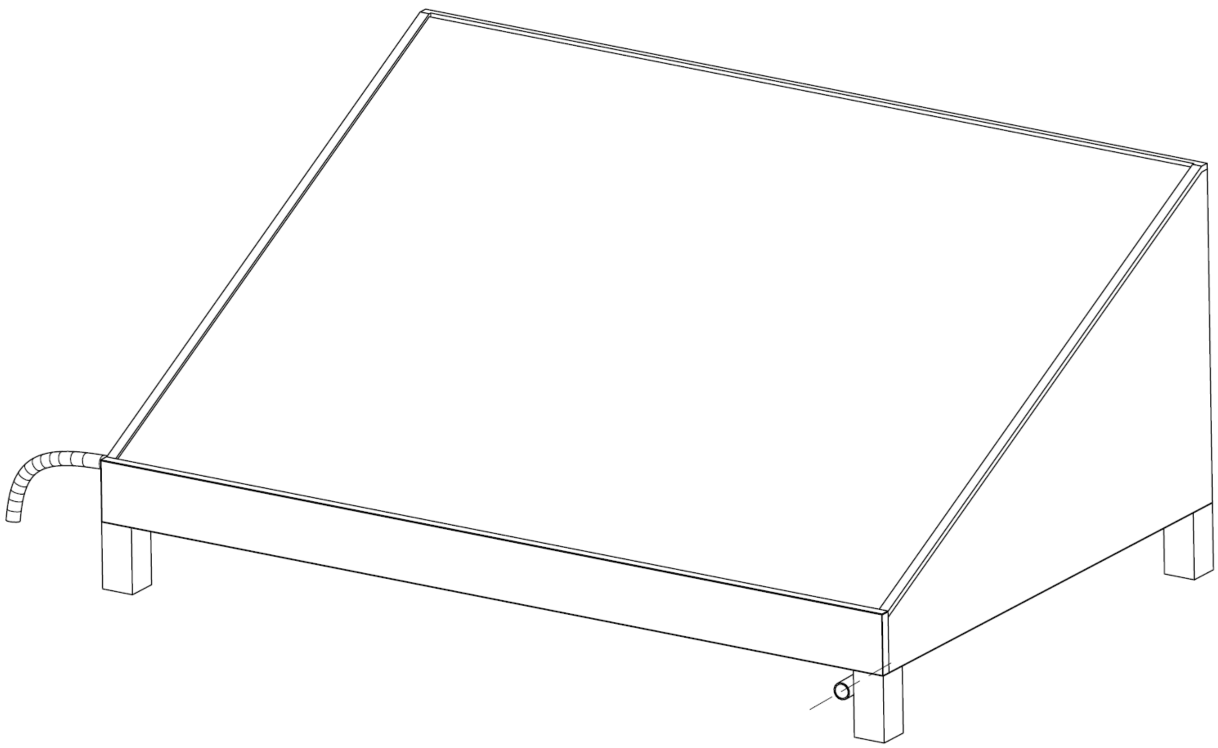


Figure 23: Preliminary design before material selection.

9 MATERIALS AND DURABILITY

Even though a local material search has been performed in an early phase to reveal local availability of relevant materials there is uncertainty to the quality and availability of a proper basin and hose material. The final decision must therefore be performed after a new market search has been performed during prototyping in Kabul. The quality and availability of the rest of the materials is meeting requirements and is described below.

9.1 Material selection

9.1.1 Cover plate

The cover plate must allow transmittance of solar radiation and allow water droplets to form and slide down in the distillate production trough without falling back in the basin. Heat transfer through the cover plate increases when the thickness decreases and allowing more vapor to condensate. A.L. Ghoneyem, [21], showed that the production increased with decreasing glass thickness. Glass in 4 [mm] thickness is chosen as a cover plate material due to higher solar transmittance for various angles compared to plastic or thicker glass. Glass has high local availability, low price and can give a long operating life.

9.1.2 Basin material

The basin material will absorb the solar radiation that enters the still and must hence have high absorptivity values, withstand high temperatures and saline water without outgassing or harm the water quality. Galvanized iron covered with black paint will absorb the solar energy and right quality paint will not outgas.

9.1.3 Insulation

The insulation material in the bottom and side walls of the still is chosen to be expanded polystyrene in 50 [mm] due to low thermal conductivity, low price and high local availability.

9.1.4 Walls

The walls will enclose the still, maintain robustness and a long operating life and is hence chosen to be galvanized iron sheets in 1.25 [mm]. Galvanized iron is resistant to saline water and will secure a stiff solar still.

9.1.5 Legs

Since the walls are chosen to be of galvanized iron sheets it will ease the manufacturing and lower the cost to have legs with the same material. The legs will therefore also be of galvanized iron.

9.1.6 Distillate production trough and hoses

The distillate production trough is chosen to be in galvanized iron, which will lower the cost and not affect the distillated water. The hoses in the still will transport both the saline and distilled water and must therefore not corrode or contaminate the water. Hoses are chosen to be in stain less steel or 316 steel.

9.2 External material analysis

9.2.1 Analysis objectives

It is important to secure good quality of the distilled water and minimize the presence of organic compounds and toxic. The materials used in the still must fulfil the requirements described in section 7.3.1. It has been difficult to obtain material properties, data sheets and information about local materials in the design phase due to local availability and challenging communication. To ensure that the correct materials are chosen for the still a group of experts is contacted in Norway to discuss relevant materials.

9.2.2 Team of experts

The experts contacted from NMBU for this survey is chosen due to their expertise and knowledge in materials, manufacturing and water quality related challenges:

Name	Position	Field of expertise
Johan Andersen	Associate Professor	Material science
Bjørn Brenna	Senior Engineer	Workshop/Manufacturing
Petter Jensen	Professor	Water and sanitation

9.2.3 Survey

An e-mail was sent to the chosen experts to initiate contact, see appendix 17.1 for survey set-up. The questions asked to the experts could be answered both from a structural and water quality point of view and were:

A. What are the key material properties to withstand high temperatures in a saline and moist environment?
B. Which materials are suitable for this to a low cost?
C. What will happen to the materials over time and how will it affect the solar still?

9.2.4 Results and discussion

A telephone meeting with Professor Johan Andersen was held 02.03.2015 [25]. Andersen confirmed that galvanized iron sheets are a durable solution, but it would then need proper surface treatment. He suggested that the still could be painted with epoxy and polyurethane to get proper adhesive and enhance the life time for the solar still. This surface treatment will obtain a high resistance to solar rays during the life time and prevent the saline water to corrode the iron sheets. Andersen also suggests some alternatives to galvanized iron sheets. Aluminum plates and stainless steel plates will be well suited, but this will increase the price and can be difficult to find in Kabul. Hence, galvanized iron sheets covered with polyurethane paint is Andersen’s suggestion.

A meeting with senior engineer Bjørn Brenna 05.03.2015 [26] was arranged to discuss suitable materials. Brenna had many ideas and stated that galvanized iron sheets, stainless steel plates or color coated steel plates would be the preferred alternatives. Stainless steel would have a safe and long operating life, but is expected to be expensive and difficult to find. Color coated steel plates are galvanized on one side and applied plastic on the other side. This combination could be a good solution, but the local availability is expected to be low. Brenna believed galvanized steel plates with proper surface treatment can be used if paint with correct quality is found.

Professor Petter Jensen was one of Kolstad`s supervisors during her thesis, but he did not reply on this survey. A long skype meeting was held in an early phase of the study to reveal parameters that would affect the water quality and to get a better overview over status, challenges and requirements to the water related difficulties. The answers from that meeting, [24], are therefore included in this section. He suggested that the distilled water should be tested for pH, electrical conductivity and a bacteria analysis for E.coli. On the other hand, he thought it will be difficult to verify the organic compounds from paint, plastic etc. in the distilled water and the materials must therefore be chosen wisely.

Consequently, a high focus during the field trip in Kabul should be to search for a suitable material for the basin and a polyurethane paint that can withstand temperatures over 90 [^{o}C]. The selected paint must not outgas and cause a strange smell and taste from the water which Kolstad [3] stated in her experiments.

10 PRODUCT ARCHITECTURE AND CONCEPT DESIGN

A solar still concept and design is developed according to requirements and local conditions in the Faryab province. The design will be prototyped and tested in Kabul during the field trip in March 2015. Design and parts are presented in the following sections in addition to a brief summary of both requirements and specifications.

10.1 Overall concept description

An overview over the design, main components and essential dimensions in [mm] can be seen in Figure 24.

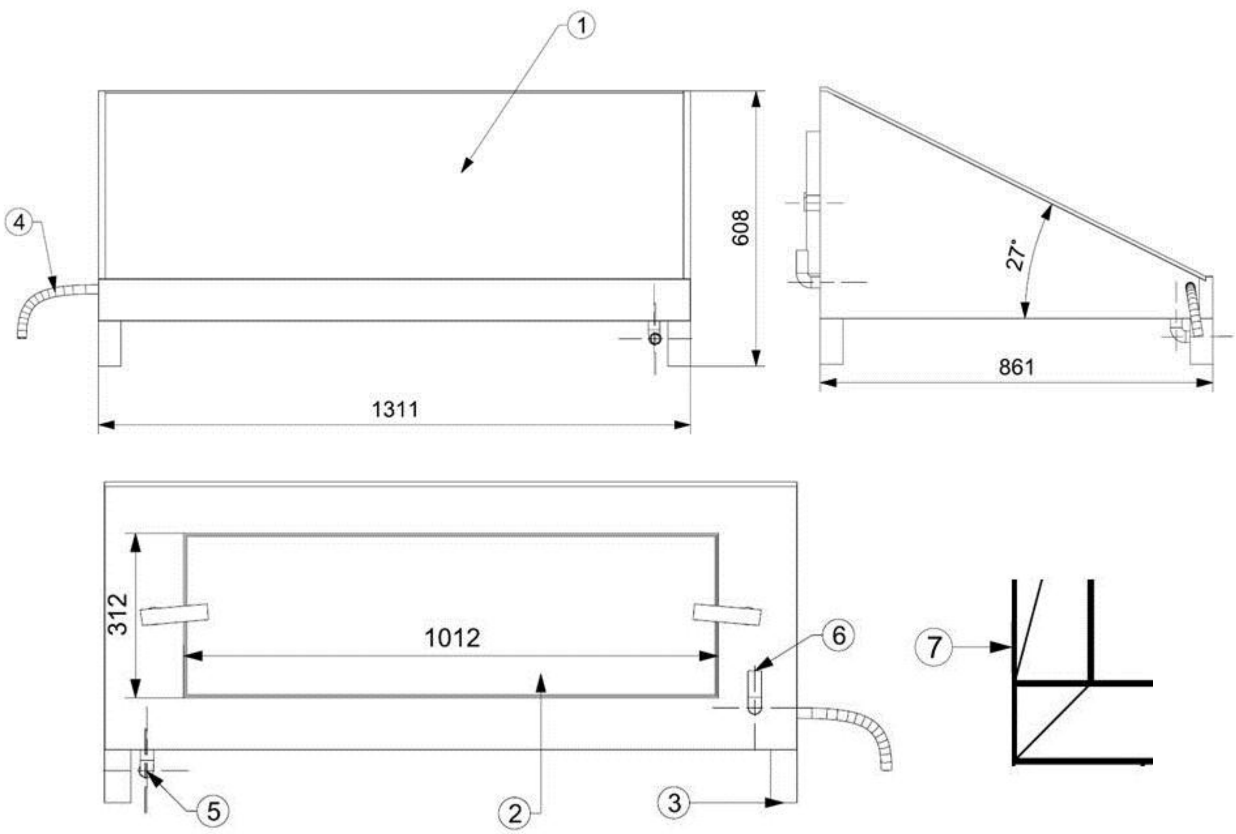


Figure 24: Overview over design, dimensions and components. 1: Glass cover, 2: Maintenance door, 3: Legs, 4: Output hose, 5: Flushing hose, 6: Re-fil opening, 7: Cross section of the wall with galvanized iron, expanded polystyrene insulation and galvanized iron.

10.2 Design and specification presentation

The requirements and specification for the developed solar still is listed below:

Requirements:

- Price below 100 [USD] per unit.
- Peak production rate above 4 [L/m^2/day].
- Produce safe and healthy drinking water.
- Highly user friendly and intuitive.
- High durability and robustness.
- Withstand transportation from Kabul to Faryab.

Specifications:

- Made with galvanized iron sheets to secure durability and robustness.
- Painted with epoxy and polyurethane to avoid corrosion and obtain high quality distilled water.
- Basin area of 1 [m^2].
- Optimal cover slope angle of 27^o.
- Expanded polystyrene bottom and side insulation layer to minimize heat loss.

There is uncertainty related to both method of manufacturing and materials available in Kabul, but a preliminary design and understanding of solar still principles is developed during design phase in Norway. Therefore, the final design, materials and manufacturing must be determined on site in Kabul.

10.3 Assemblies

Pictures of the designed solar still can be seen in Figure 25 - Figure 28.

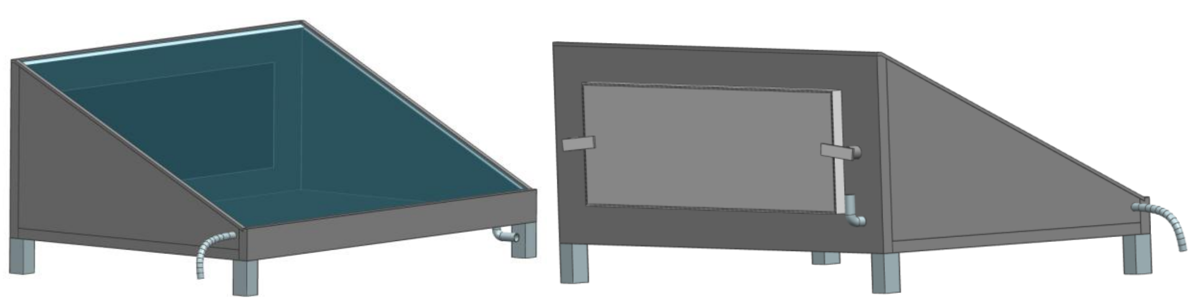


Figure 25: Left: Front isometric view of the glass cover. Right: Back view of door.

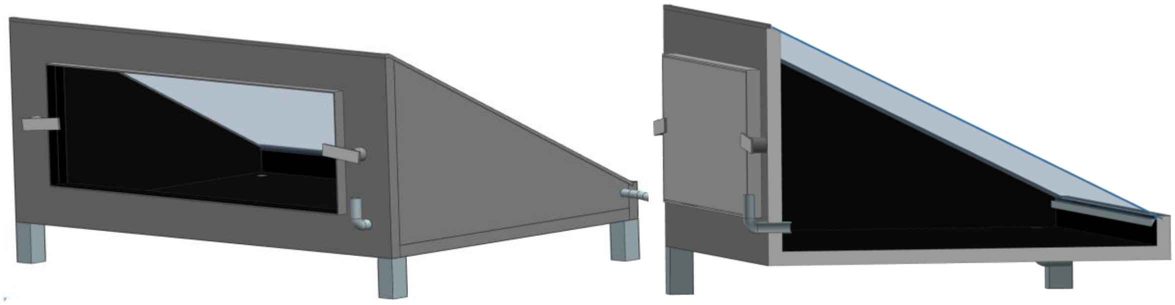


Figure 26: Left: Back view without door. Right: Side view of the cross section.

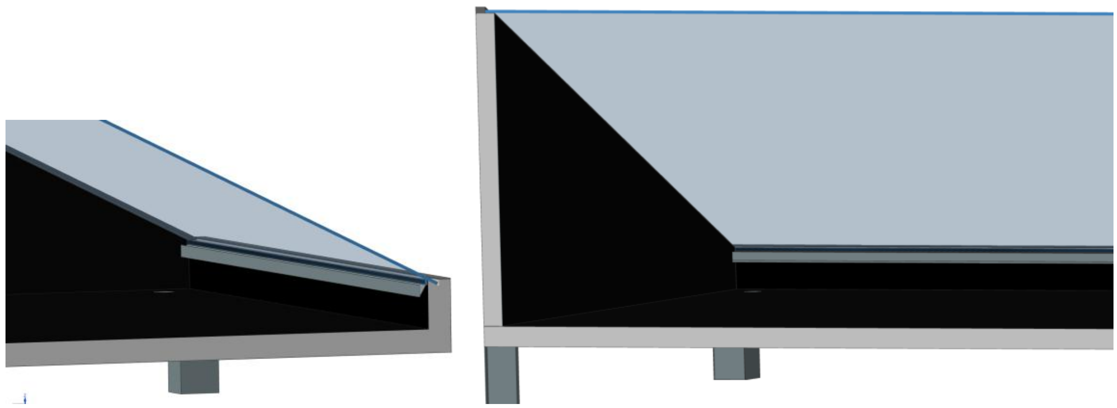


Figure 27: Left: Detailed side view without wall. Right: Back view without wall.

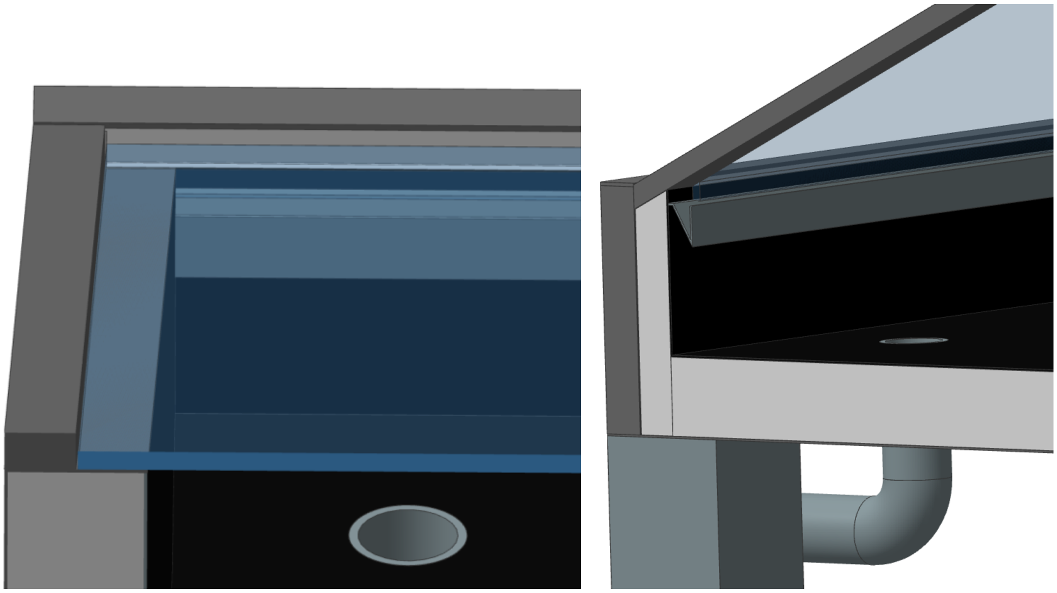
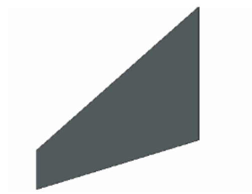
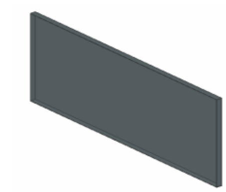
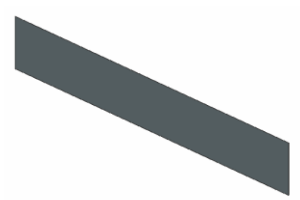
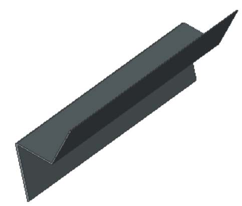
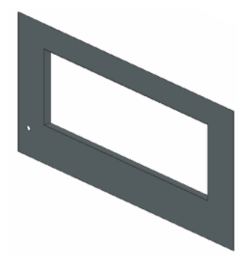
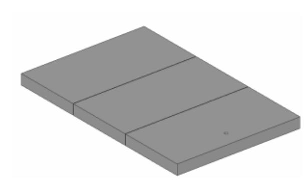
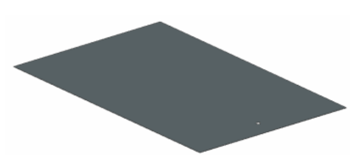
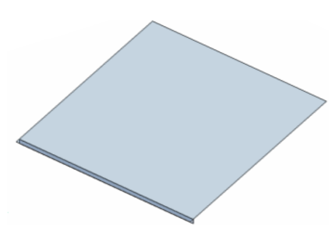


Figure 28: Left: Detailed side view of glass- wall interface. Right: Side view without wall showing the distillation channel in the middle.

10.4 Design of main components

The main components in the designed still are shown in Table 20.

Table 20: Left: Design of main components. Right: Design of small components.

Component name	Component	Component name	Component
Side wall		Door	
Front wall		Water channel	
Back wall		Insulation	
Basin		Legs	
Cover		Hoses	

11 PROTOTYPING IN KABUL

A field trip to the NCA office in Kabul, Afghanistan, was conducted between 10.03.2015 - 28.03.2015 to present concept, design, assist with prototyping and establish a test procedure. A presentation in the end of the trip was held for local staff to discuss important parameters, present know-how and suggest a plan forward.

Kabul is the capital and largest city in Afghanistan. It consists of approximately 4 million inhabitants and is in a rapid growth. The city lies in the end of a valley and is surrounded by high alpine mountains, see Figure 29. This is the national center for business and politics. The people want to reestablish and gain wealth and success after a long and turbulent history. There are shops, sellers and activity in the streets from early morning until the evening. Unfortunately, due to frequent suicide bombings and safety issues that strike the city, people are also scared and take precautions when travelling outside.

Figure 29: Morning view of the city and surrounding mountains from the roof at the NCA office in Kabul.

11.1 Field trip - working progress

Most of the work was done at the NCA Afghanistan office in Kabul, together with Eng. Yasir. He has been working on this project since autumn 2014. Eng. Abrar at Norplan in Kabul has also been assisting on the project. The first week was used to perform material research and modify the developed design to locally available materials and manufacturing methods. Further on, several other designs were prototyped and tested during the field trip and can be seen in appendix 17.3. The last days was used to discuss important design parameters, know-how and material selection to secure knowledge transfer and understanding.

11.2 Manufacturing

A new material research was executed in Kabul to find the materials selected in section 9 and 9.2, see Figure 30. However, it was difficult to obtain the right quality of polyurethane paint that would withstand the required temperatures. Consequently, telephone calls to Jotun paint expert, engineer Jan Henrik Treidene [23], was performed and it was decided to use another absorber material in the basin.

Figure 30: Searching for materials in the streets of Kabul.

Due to few local basin materials available, 6 [mm] glass with one black painted surface were chosen as basin material on top of the galvanized iron. Transparent glass has very low absorption values and very high transmissivity, but the black color is expected to increase the absorption. However, the production rate will decrease significantly compared to galvanized iron with black paint due to the low absorbance. On the other hand, glass has great high temperature properties and will therefore not contaminate the distilled water.

Due to local availability, manufacturing and cost, some thicknesses in the selected materials in section 9.2 were changed:

- The galvanized iron in walls and basin were changed from 1.25 to 0.7 [mm].
- The expanded polystyrene insulation was changed from 50 to 29 [mm].

During the design phase different methods of local manufacturing were considered and investigated. Kolstad manufactured solar stills with galvanized iron sheets in Kabul spring 2014 and contacts in NCA Afghanistan confirmed that there were several good tinsmiths available in whole Afghanistan. Bjørn Brenna also commented on the manufacturing methods during the external material analysis, see section 9.2.4. He suggested that bending, riveting and grouting of thin steel sheets could be a proper and local available method of assemble the still. Welding of thin sheets is expected to be difficult in the local workshops and it can therefore be hard to obtain the solar still air tight.

The manufacturer was chosen because he had recently made a solar still design engineer Abrar and Yasir, and therefore he already had some experience. Figure 31 shows the manufacturing workshop. The method of production is chosen to be bending and riveting, and hence the material selection of 0.7 [mm] galvanized iron sheets. Technical drawings and materials, see appendix 17.2, were presented to manufacturer and inspections of progress, comments and feedback were performed as often as possible during manufacturing.

It was experienced a low correlation between drawings and manufactured design in an early stage of the process and hence the main objective for the inspections was to ensure that there will be no leakage in the still. It was difficult to communicate with the manufacturer and explain technicalities due to use of translator. The manufacturer was not provided an assembly- or manufacturing guide, but instead given the opportunity to use local techniques and obtain understanding of the manufacturing of the still. The craftsman was asked to use silicone between the metal sheets in all slivers to avoid leaking.

Figure 31: Local manufacturing site were the solar still were produced.

The detailed technical drawings in appendix 17.2 are meant as a guideline for the tinsmiths to optimize design and manufacturing after local conditions. Consequently, the manufacturing technique and the final method of assembly would increase the local expertise and bring the costs down.

Figure 32 – Figure 35 shows the manufacturing process and final prototype.

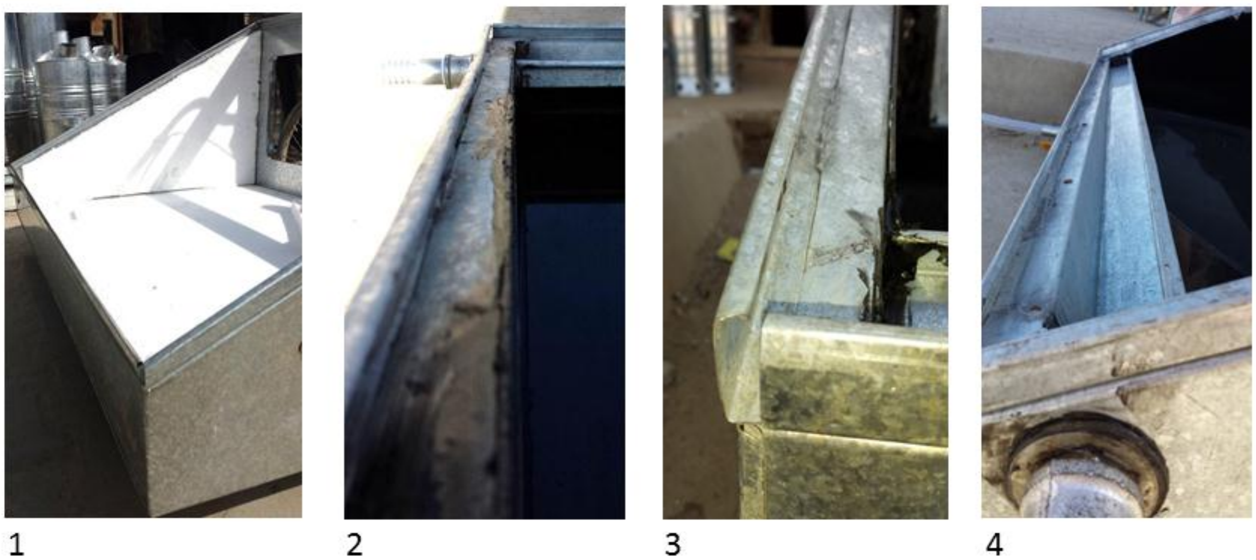


Figure 32: 1: The outer layer of galvanized iron is filled with expanded polystyrene. 2 and 3: Bracket and edge were the glass cover shall be placed. 4: Distillate trough to collect the condensed water.

Figure 33: Left: Front view of sloped glass cover and the flushing port can be seen down left. Down to the right comes the distillate output. Right: Back view with the inlet valve to the left and maintenance door in the middle.

Figure 34: Left: Side view of the distillate output without hose attached. Right: Isometric view from behind.

1 2 3 4

Figure 35: 1: Detailed picture of the door and sealing. 2: 1 inch inlet valve with open maintenance door. 3: Grouting along the outer glass surface. 4: Bending method used by the craftsman.

11.3 Material properties

The essential material properties for the selected materials can be read in Table 21. However, It has been difficult to find the exact properties for the local materials and some values have been retrieved from general sources, [5, 43], but the uncertainty in thermal conductivity will not impact the final design and discrepancy is therefore allowed. The maximum operating temperature for the used silicone has not been found and it's expected that that the distilled water will taste silicone during the first weeks of production.

Table 21: Material properties of materials used in the solar still.

Material	Thermal conductivity [W/m*K][1]	Max operating temperature [^{o}C]	Abrasion resistance[4]
Galvanized Iron	20	420[2]	Medium
Glass	0.7	1000[1]	High
Polystyrene	0.04	100[3]	Low
Silicone	~0.5	NA	High

[1]Thermal conductivities/maximum operating temperature retrieved from [5]. [2]Melting point zinc [5]. [3]Recommended maximum temperature to obtain original shape [43]. [4]Abrasion resistance retrieved from [2].

From a water quality point of view the silicone is the critical material for outgassing and the rest of the materials should withstand both the environmental and operating conditions.

11.4 Surface treatment

The materials selected for the solar still are low cost materials that rely on a high quality surface treatment to obtain robustness and a long service life. Consequently, a proper surface treatment will enhance the life time for the solar still and should be applied before field testing. A white color on the outer surfaces would reflect some of the radiation from the sun and maintain a relatively low surface temperature.

The sun will over time damage the outer silicone around the glass cover and aluminum tape can therefore be used to cover and maintain the original properties of the silicone. Unfortunately, no surface treatment was performed during prototyping due to limited time.

11.5 Maintenance

To avoid contamination of the water, proper cleaning and disinfection with chlorine compounds is necessary before use. After the still is installed a few table spoons of laundry bleach can be added to the saline water and the still will clean itself [39].

Flying insects may be another threat, as they are attracted by the humid air inside the solar still. Precaution should therefore be taken to avoid dead insects in the distillate output trough and it should hence be regularly inspected.

Lump masses of salt and contamination will gather in the basin during operation. Weekly cleaning of basin, tubing and glass must therefore be performed to secure an optimal production environment.

A short maintenance procedure from the actions above with description and frequency can be seen in Table 22.

Table 22: Maintenance procedure for solar stills.

Procedure	Description	Frequency
Disinfection with chlorine	Add a few table spoons of laundry bleach to the saline water.	Yearly
Look for insects	Look inside the solar still and especially the distillate output trough for dead insect.	Weekly
Inside cleaning	Clean the basin, tubing and glass properly.	Weekly
Flushing	Flush the solar still with 10 [L] of water.	Daily
Clean outer glass	Clean the outer faces of the glass.	Daily

11.6 Recycling

There is unfortunately no organized recycling system in the Faryab province, but there is no environmental harmfully materials in the solar still that will make a threat to the local environment. Additionally, the local people are experienced in reusing and rebuilding damaged equipment, so there is no concern regarding disposal of the solar still.

12 COST

The total product cost has been one of the driving parameters in the development process, due to the low cost requirement from NCA and Norplan. In the following sections both prototype cost and estimated series production cost is described and discussed.

12.1 Prototype cost

In the prototype cost there is not included any cost related to product development. This project and MSc. thesis is however sponsored by NCA Afghanistan and Norplan, but no cost associated to this is included in the prototype cost, which can be seen in Table 23 below, and includes manufacturing, material and component cost.

Table 23: Prototype cost for solar still.

Prototyping	Thickness [mm]	Length x Width [mm]	Unit	Cost [AFN]	Sum [AFN]
Manufacturing					
Bending/cutting	-	-	3h	200	600
Riveting/Jointing	-	-	2h	200	400
Assembly	-	-	1h	200	200
Grouting	-	-	1h	200	200
Painting			0.5h	200	100
Manufacturing Cost					**1500**
Materials					
Galvanized Iron	0.7	2200 x 1200	3	1200	3600
Galvanized Iron	1.25	2200 x 1200	1	1800	1800
Glass	6	1280 x 890	2	250	500
Expanded polystyrene	29	1200 x 1000	4	120	480
Material cost					**6380**
Components					
Hoses/tubing	2	0.5 x 15	1	50	50
Black Silicon 300 [ml]	-	-	6	120	720
L-bend 1 inch	2	80 x 80	2	40	80
Valve 2 inch	-	-	2	150	300
Black paint	-	-	1	100	100
Component cost					**1250**
Total cost					**9130**

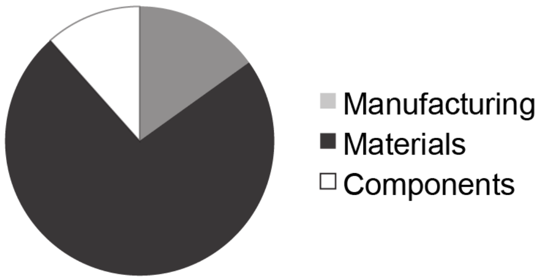


Figure 36: Overview over prototype cost divided in three shares: Manufacturing, materials and components.

It can be seen from Table 23 and Figure 36 that the material cost has the main share. Some of the materials must be bought by sheet size and hence more material than needed is bought. The 1.25 [mm] galvanized iron is the most expensive material per [m^2], and is used for the maintenance opening. The manufacturing cost is already relatively low and an effort to bring the cost down should be on the material side.

12.2 Cost estimate for series production

After the final design is chosen, some pilot solar stills shall be tested in Faryab, before adjustments from user feedback and further up scaling of more units. The first batch of solar stills will be on approximately 50 units. It is expected that the unit cost would decrease for small scale series production, due to lower manufacturing cost, more efficient materials usage and lower material/ component cost, see Table 24.

Table 24: Cost estimate for series production for 50 solar still units.

Series production of 50 units	Thickness [mm]	Length x Width [mm]	Unit	Cost [AFN]	Sum [AFN]
Manufacturing					
Bending/cutting	-	-	2h	200	400
Riveting/Jointing	-	-	1h	200	200
Assembly	-	-	0.5h	200	100
Grouting	-	-	0.5h	200	100
Painting			0.5h	200	100
Manufacturing Cost					**900**
Materials					
Galvanized Iron	0.7	2200 x 1200	3	800	2400
Glass	4	1280 x 890	2	250	500
Expanded polystyrene	29	1200 x 1000	4	100	400
Material cost					**3300**
Components					
Hoses/tubing	2	0.5 x 15	1	50	50
Black Silicon 300 [ml]			5	100	500
L-bend 1 inch	2	80 x 80	2	40	80
Valve 2 inch			2	150	300
Component cost					**930**
Total cost					**5130**

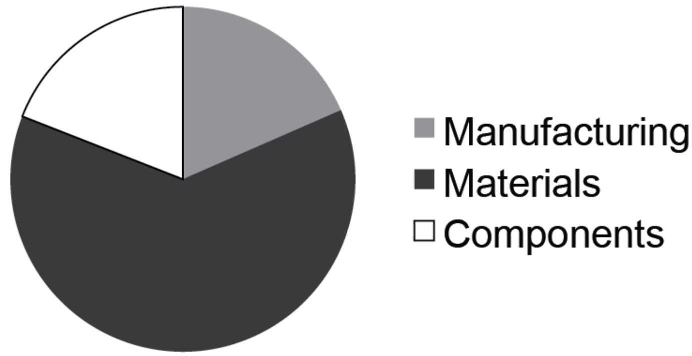


Figure 37: Overview over estimated series production cost for 50 units divided in three shares: Manufacturing, materials and components.

It can be seen from Table 24 and Figure 37 that material cost still has the main share, but the total material cost is expected to be halved due to more efficient material use and lower prices. Both costs related to manufacturing and components are also expected to be lower than for prototyping, but not in the same range.

12.3 Cost discussion

The energy source for desalination of groundwater is the sun, which is free, and the cost of the distilled water from the stills depends therefore only on the cost of materials, manufacturing and maintenance. Thus, the main part of the share is here the material cost.

The yield of a solar still is proportional to the basin and condensation area of the still, which consequently means that the cost per area is nearly constant regardless of the still size. For other desalination methods it is a trend that the product cost decreases with increased capacity, which means that a solar still will be cheaper and more beneficial in small sizes than other desalination methods [17].

A total unit price of 5130 [AFN] corresponds to approximately 90 [USD], which fulfills the low cost requirement of a unit price below 100 [USD] set by NCA and Norplan. There is not included any form of margins or additional cost related to development, testing, marketing or transportation, due to the already pre-defined unit cost requirement.

A comparison to existing products in the market shows that Kolstad's plywood double sloped design and Rainkit can be possible competitors, but they have both a higher price. A more extensive comparison can be done when both, production testing and water quality tests have been performed.

13 LOCAL FIELD TESTING

After prototyping, the solar still was tested at the roof of the NCA office in Kabul towards the end of the field trip. Radiation, temperatures and yield was some of the parameters tested. Although the presences of solar radiation were rather low at this time, experience and understanding of both testing procedure and impact parameters were obtained, discussed and shared. Engineer Yasir continued the testing during April and Mai.

13.1 Test objectives

The main goal for the testing is to ensure that the still will meet the requirements defined in section 6.4 and yield an acceptable amount of water with safe and high quality. Subsequently, the test results can give a greater understanding of the solar still performance for different boundary conditions and be compared against other designs that have been developed at NCA in Kabul.

13.2 Experimental set up

The solar still was positioned with the glazing faced north-south to ensure maximum insolation throughout the day and the basin were leveled horizontally to secure uniform water depth for optimal evaporation. The solar still was filled with water in the morning up to a water depth of 20 [mm] and at the same time dust was removed from the outer glazing cover. Thereafter hourly measurements of ambient temperature, incoming solar radiation, basin water temperature, vapor temperature, inside glass temperature, distillate water output and wind/weather observations were extracted, see Table 25 for equipment pictures and Table 26 for measurements equipment details.

Table 25: Pictures of measurement equipment used in the testing.

Incoming solar radiation	Distillate water output	Temperature			
		Ambient	Basin water	Vapor	Inside glass
					

Table 26: Measurement equipment details and specifications.

Parameter	Notation	Location	Equipment	Equipment specifications
Ambient temperature	[℃]	Outside shade	Basic thermometer	Uncertainty: NA Resolution: NA Range: NA
Incoming solar radiation	[W/m^2]	On the inclined glass surface	HT204 solar power meter	Uncertainty: $\pm$ 10 [W/m^2] Resolution: 1 [W/m^2] Range:1- 1999 [W/m^2]
Basin water temperature	[℃]	Between water surface and basin	Elma 718 datalogger thermometer	Uncertainty: $\pm$1 [℃] Resolution: 0.1 [℃] Range: -200-200 [℃]
Vapor temperature	[℃]	Between water surface and glass cover		
Inside glass temperature	[℃]	On the inside of the glass surface		
Distillate water output	[ml]	Distillated water	Graduated cylinder	Uncertainty: $\pm$2 [ml] Resolution: 2 [ml] Range: 24-250 [ml]
Wind and weather	-	Sky and air	NA	Observations of weather and wind done manually

The temperature probes inside the still were attached to a constructed tower to obtain similar probe positions during the testing. The probe wires were approximately 1000 [mm] long and was leaded out through the maintenance wall and sealed with tape to avoid leaking.

13.3 Possible sources of measurement errors

There was only one probe per location and only one location per parameter. This will not give a full picture of the overall heat transfer inside and outside the still. The measurements values are therefore linked to the specific location and discrepancies will therefore occur in water, vapor and glass if other probe locations are chosen. There is neither performed equipment calibration to ensure correct measurement values, due to lack of necessary software equipment. However, all the temperature probes were compared in room temperature and gave the same result $\pm$ 0.5 [℃].

13.4 Test results

Preliminary test results indicate that the solar still is working as planned. The still have been tested for three days on the roof at the NCA office in Kabul by Eng. Yasir. The testing was performed in April/May 2015 under sunny weather conditions. The still is yielding between 1.2 - 1.9 [L/ m^2/day]. The results shown in Figure 38 are based on the first day of testing in early April, with a yield of 1.2 [L/m^2/day].

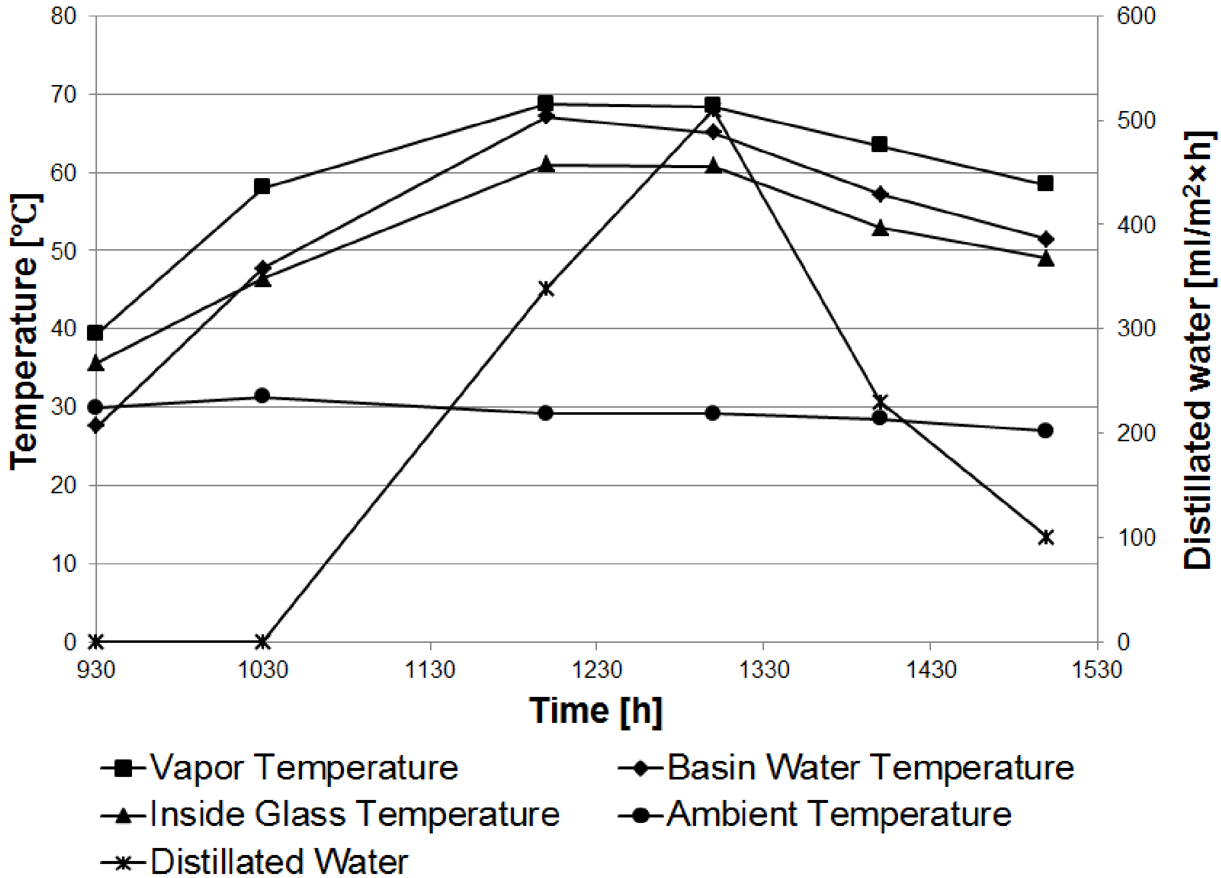


Figure 38: Hourly measurements of temperatures, left, and the amount of distillated water, right, for the solar still in early April 2015.

Inside the still, the vapor has the highest temperature and glass the lowest, as expected. The water temperature is increasing slower than vapor due to the high heat capacity of water and it takes time before the latent heat of evaporation is obtained and output can be measured, see Figure 38.

The pictures in Figure 39 show the condensed water on the glass surface and measurements of solar radiation, water, vapor and glass temperature inside the still.

Figure 39: Left: Testing of the solar still and measuring the incoming radiation on the glass surface. The glass surface is covered with condensed water. Right: The data logger on the ground is measuring water, vapor and glass temperature inside the still.

13.5 Test discussion

Initial testing has been performed and the solar still is working. The test conditions were good and a test procedure was followed to ensure correct testing and results. The best initial test result was a yield of 1.9 [L/m^2/day] and is approximately 2 [L] lower than expected, but due to the low amount of data there is no statistical safety in the results. The low production rate can be a consequence of an air leakage or the glass basin, but more testing must be performed before concluding regarding the solar still thermal perfo-rmance. It must be ensured that that the testing is being performed on the design and not on the manufacturing work. Unfortunately, no water quality tests have been perfo-rmed to verify the distilled water, due to time limitations. This should be done when there is certainty in the production rate results.

14 PROCESS EVALUATION AND DISCUSSION

From the initial “TIP 300” project autumn 2014 to product development and field testing in Kabul spring 2015 the project has been through many phases. A lot of work has been done and successfully implemented, although many things would have been done differently if they were performed again. The following sections wrap up the lessons learned during the last years project work.

14.1 Product development and prototyping- lessons learned

- A clearer and more defined product specification should have been developed together with NCA and Norplan before starting the project. This would have improved the product development process and made it easier to define the design space.

- It was essential and important to perform an early phase material research to reveal the local materials available in Kabul. However, more focus should have been put into finding a proper basin material from the beginning to obtain an efficient solar still that can produce high quality distilled water.

- An optimal single basin solar still for local conditions has been designed according to specifications and a modified prototype has been manufactured in Kabul by local craftsmen. The technical drawings brought to the manufacturer resulted in mismatch between drawings and prototype. A small scale model could instead have been brought to reduce the discrepancy.

- Test procedures have been developed and knowledge regarding testing is transferred to local engineers.

- It was chosen to approach the local NCA staff with focus on solar still knowledge transfer. This approach will ensure that the know-how and experience is transferred to the people that will continue the solar still work and not only benefit this thesis. The knowledge transfer focused on the activities below:

  - Material properties and material selection.

  - Climate-, design- and operating parameters.

  - High quality solutions.

  - Manufacturing parameters.

  - Test method and approach.

14.2 Design and cost review

- The extensive research and obtained knowledge regarding the solar still thermodynamics has been a huge benefit during the product development. Resulting in know-how and understanding related to material properties, design, cost, durability and water quality.

- Another basin material should have been used in the still. If not black sheets in silicone, polyethylene, butyl, EPDM or polyurethane paint is found in Kabul, it should be imported.

- A detailed comparison of Kolstad's designs and new developed designs should have been performed. This would reveal the best design with respect to yield and price.

15 CONCLUSION

The groundwater in Faryab have poor quality and due to fragmented strategies and policies it is reason to believe that this will cause problems related to drinking water access and quality for the future generations. Throughout this study, development of low cost solar stills for remote areas in the Faryab province, a design, prototype and testing is carried out in collaboration with NCA Afghanistan and Norplan.

15.1 Results and recommendations

A product development is performed based on specifications and requirements, resulting in an optimal single basin solar still design for local conditions in Faryab. The design is adapted to manufacturing in Kabul and a prototype has been made in collaboration with local craftsmen with the following specifications:

- The structure is made with galvanized iron sheets in 0.7 [mm] thickness to secure durability and robustness.
- A layer of expanded polystyrene at the bottom and sides to minimize heat loss.
- Basin of 6 [mm] glass with the backside painted black.
- Outer still dimensions of 1280 x 860 x 600 [mm], (Length x Width x Height).
- Basin area of 1 [m^2].
- Optimal cover slope angle of 27 [^{o}].
- Inlet and outlet ball valves for easy operability.

The prototype cost is 9130 [AFN] which corresponds to 158 [USD], and the material cost and galvanized iron takes the main share. Estimates for a small scale series production of 50 units shows that the cost can be reduced to approximately 90 [USD], which is below the cost requirement set by NCA and Norplan.

There is concern related to the manufacturing process and choice of basin material. The manufacturer was not able to replicate the given drawings, which resulted in a considerably different design than originally planned. Regarding the basin material, glass is not able to absorb as much heat as other and more appropriate basin material like liners from rubber, silicone etc. and will hence lower the yield and efficiency.

The still have been tested for three days and resulted in a yield of 1.9 [L/m^2/day] which is approximately 2 [L] lower than expected, but due to the low amount of data there is no statistical safety in the results and more tests must be performed to conclude regarding this.

On the other hand, a yield of 1.9 [L/m^2/day] would result in approximately 400 [L] throughout the spring, summer and autumn, which almost can provide one person with safe drinking water. As the yield is directly proportional to the basin area of the still, it could be increased to desired size if a higher production rate is wanted.

15.2 Further work

Some work is remaining before solar stills can be transported for pilot testing in the Faryab province:

- Ensure that the still is air tight and perform more testing of the design to get a full picture of the solar still thermal performance.

- Search for suitable black basin materials and liners in silicone, polyethylene, butyl, EPDM or polyurethane paint in Pakistan that could be imported.

- SolAqua, the manufacturer of RainKit and Rainmaker, uses a silicone membrane that is tested and approved for solar desalination. Initiate contact and obtain information about their basin material.

- Perform water quality analysis with respect to the requirements in section 6.2.

- Arrange a meeting with other manufactures and discuss details, specifications and solutions related to cost reduction of the manufacturing and material selection. Then invite them to manufacture the prototype at the NCA office to easily follow up the manufacturing.

- Arrange a field trip to Faryab to search for materials and methods of manufacturing.

- Compare all the solar still designs with respect to yield, cost and manufacturing. Then choose the optimal design and manufacturer before pilot testing in Faryab.

16 LITERATURE REFERENCES

16.1 Books, papers, and written sources

1. Jan Kåre Bøe, Produktutvikling og Produktdesign, UMB, Ås, 2013, PP. 218.

2. Jan Kåre Bøe, Konsept og produktrealisering, NMBU, Ås, 2014, PP. 215.

3. Cecile Kolstad, Master thesis: "Desalination of groundwater by solar stills – field trials in Afghanistan", NMBU, Ås, 2014, PP. 92.

4. Halvard Hirsch Kopperdal, TIP 300 project, "Pure Water", NMBU, Ås, 2014, PP. 66.

5. Cengel and Ghajar, Heat and mass transfer, Mc Graw Hill, USA, 2013, ISBN-10: 0077366646, PP. 891.

6. Hassan Saffi, M., Jawid Kohistani A., (2013). Water Resources Potential, Quality Problems, Challenges and Solutions in Afghanistan, PP.274.

7. Badran, Omar O. Abu-Khader, Mazen M., (2007). Journal Article, Heat and Mass Transfer, Evaluating thermal performance of a single slope solar still, PP. 985-995

8. G.N. Tiwari, J.M. Thomas, Emran Khan, Optimisation of glass cover inclination for maximum yield in a solar still, Heat Recov. Sys. CHP 14 (1994) PP.447–455.

9. V. Velmurugan, C.K. Deenadayalan, H. Vinod, K. Srithar, Desalination of effluent using fin type solar still, Energy 33 (2008) PP.1719–1727.

10. Ali.F.Muftahetal. Factors affecting basin type solar still productivity: A detailed review. Renewable and Sustainable Energy Reviews 32 (2014) PP.430–447

11. Valsaraj P. An experimental study on solar distillation in a single slope basin still by surface heating the water mass. Renew Energy 2002, PP.607–12.

12. H. Al-Hinai et al. Effect of climatic, design and operational parameters on the yield of a simple solar still. Energy Conversion and Management 43 (2002) PP.1639–1650

13. Pankaj K. Srivastava, S. K. Agrawal. Experimental Investigation of some Design and Operating Parameters of Basin Type Solar Still. International Journal of Emerging Technology and Advanced Engineering Volume 2, Issue 5, May 2012, PP.225-230

14. C. Tenthani, A. Madhlopa and C.Z. Kimambo, Improved Solar Still for Water Purification. Journal of Sustainable Energy & Environment 3 (2012) PP.111-113.

15. Khalifa Abdul Jabbar N, Hamood Ahmad M.On the verification of the effect of water depth on the performance of basin type solar stills. SolEnergy 2009, PP. 1312–21.

16. A.A. Al-Karaghouli, W.E. Alnaser, Performances of single and double basin solar-stills, Applied Energy, Volume 78, Issue 3, July 2004, PP. 347-354.

17. G.N. Tiwari *, H.N. Singh, Rajesh Tripathi, Present status of solar distillation, Solar Energy 75 (2003) PP.367–373.

18. Delyannis, E. Historic background of desalination and renewable energies. Solar Energy, 75(5), (2003). PP 357-366.

19. SolAqua solar still construction and operating manual, (attached to the purchase of RainKit), PP. 28.

20. Guidelines for drinking-water quality, fourth edition World Health Organization 2011, ISBN: 978 92 4 154815 1, PP. 564.

21. A.L. Ghoneyem, A. Ileri, Software to analyze solar stills and an experimental study on the effects of the cover, Desalination 114 (1997) PP.37–44.

22. A.K. Singw, G.N. Tiwari, P.B. Sharma, Emran Khan, Optimization of orientation for higher yield of solar still for a given location, Ener. Convers. Manag. 36 ,1995, PP.175–187.

16.2 Personal references

23. Jotun Paint expert, Jan Henrik Treidene
Telephone call to Jotun paint in Sandefjord, Norway, regarding proper paint for basin material. (Date of contact 20.3.15)

24. Professor Petter Jensen
Skype meeting with Professor Petter Jensen at NMBU regarding water quality challenges related to solar distillation. (Date of contact 20.1.15)

25. Associate Professor Johan Andersen
Telephone Meeting with Associate Professor Johan Andersen at NMBU regarding the material selection. (Date of contact 02.3.15)

26. Senior Engineer Bjørn Brenna
Meeting with Senior Engineer Bjørn Brenna at NMBU regarding the material selection. (Date of contact 05.3.15)

27. WASH Manager Ammar Orakzai
Oxfam solar still project report, received by e-mail. (Date of contact 01.02.15)

16.3 Web sources:

28. TIP300 Emneside.
    http://www.nmbu.no/emne/TIP300. (Date of visit 23.11.14)

29. Rainmaker
    www.solaqua.com. (Date of visit 20.10.14)

30. Watercone
    www.watercone.com. (Date of visit 20.10.14)

31. Decision-matrix method
    http://en.wikipedia.org/wiki/Decision-matrix_method. (Date of visit 12.10.14)

32. Care user test
    www.watercone.com. (Date of visit 20.10.14)

33. Solar distillation- Research Project
    http://solar.nmsu.edu/publications/1437ISESpaper05.pdf. (Date of visit 15.10.14)

34. Norplan
    www.norplan.af. (Date of visit: 27.11.14)

35. DAACAR
    National Groundwater Monitoring Wells Network activities in Afghanistan, pdf, www.dacaar.org. (Date of visit: 14.01.15)

36. Food security atlas
    www.foodsecurityatlas.org. (Date of visit: 14.01.15)

37. WHO Guidelines for drinking water
    Total dissolved solids in Drinking-water. Background document for development of WHO Guidelines for Drinking-water Quality. www.who.int. (Date of visit: 14.01.15)

38. WHO
    How much water is needed in emergencies. Technical notes on drinking-water, sanitation and hygiene in emergencies. www.who.int. (Date of visit: 23.01.15)

39. Understanding solar stills
    www.builditsolar.com. (Date of visit: 09.02.15)

40. Afghanistan long-term average climatic data
    www.aizon.org. (Date of visit: 16.02.15)

41. Statistical weather data, Maimane, txt.file
www.ftp.atdd.noaa.gov. (Date of visit: 16.02.15)

42. Climate data Oslo, Norway
www.climatedata.eu/. (Date of visit: 16.02.15)

43. Maximum operating temperature of expanded polystyrene
www.wind-lock.com. (Date of visit: 12.03.15)

44. UN-water global analysis and assessment of sanitation and drinking-water (GLAAS) 2014 - main findings.pdf. www.who.int. (Date of visit: 13.04.15)

45. WHO report: Water for Health - Taking charge. pdf
www.who.int. (Date of visit: 13.04.15)

46. Afghanistan map
www.afghanistan.blogs.cnn.com. (Date of visit: 14.04.15)

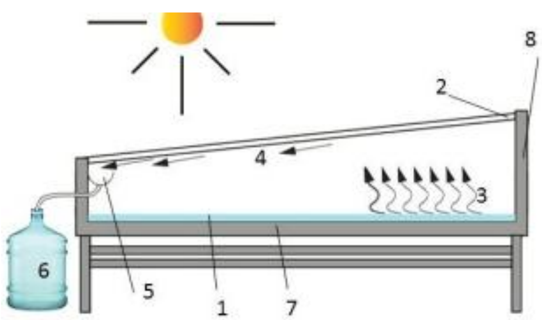
47. Eliodomestico
www.gabrielediamanti.com. (Date of visit: 14.04.15)

17 APPENDIX

The following information can be found in the appendix:

17.1 External material survey for MSc on solar desalination in Afghanistan

Solar stills are used to desalinate saline groundwater in Afghanistan through solar radiation. The basic principle of solar still distillation replicates the method our nature purifies water, see figure below. Groundwater (1) is heated up by solar energy trough a transparent enclosed cover (2). The water heats up until it evaporates (3) and then the vapor rises towards the sloping transparent cover. When the vapor meets the glass it will condense and water droplets(4) will slide along the slope and be collected in a channel(5) and ready for drinking(6). The rather slow distillation process should secure that only water evaporates and leave particles and contamination in the basin (7). In addition a relatively high water temperature will occur in the basin and bacteria's will therefore die and result in high quality drinking water.



1. Saline groundwater
2. Glass cover
3. Evaporated water
4. Water droplets
5. Channel for water droplets
6. Distilled water storage
7. Basin
8. Wall

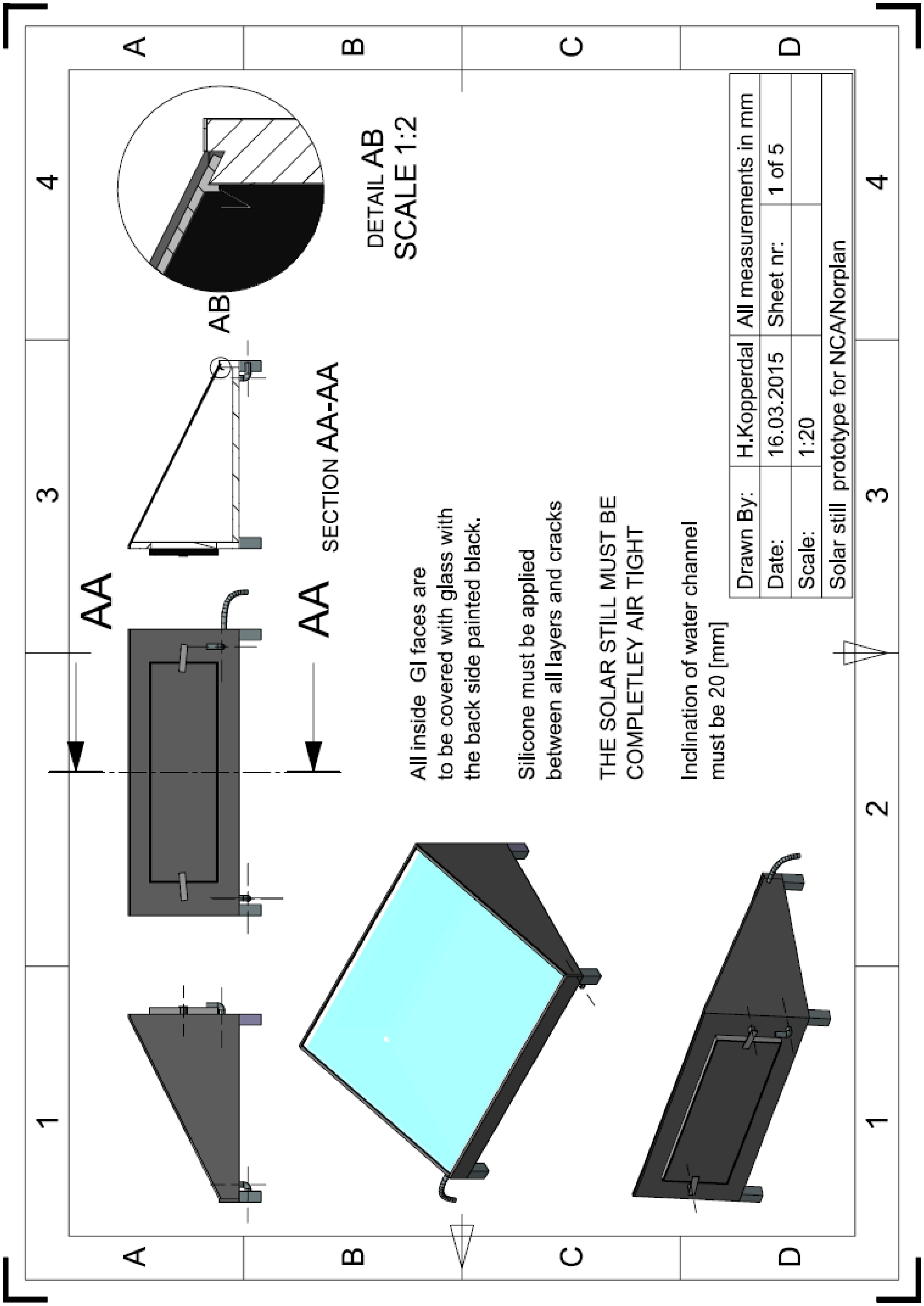
Currently the solar still walls(8) will be in galvanized sheet metal and have acrylic plastic sheet in the basin(7). Other possibilities can be plywood, paint, rubber sheets etc. Due to limitation of locally available materials and low cost requirements it has been difficult to find suitable materials that can withstand the requirements:

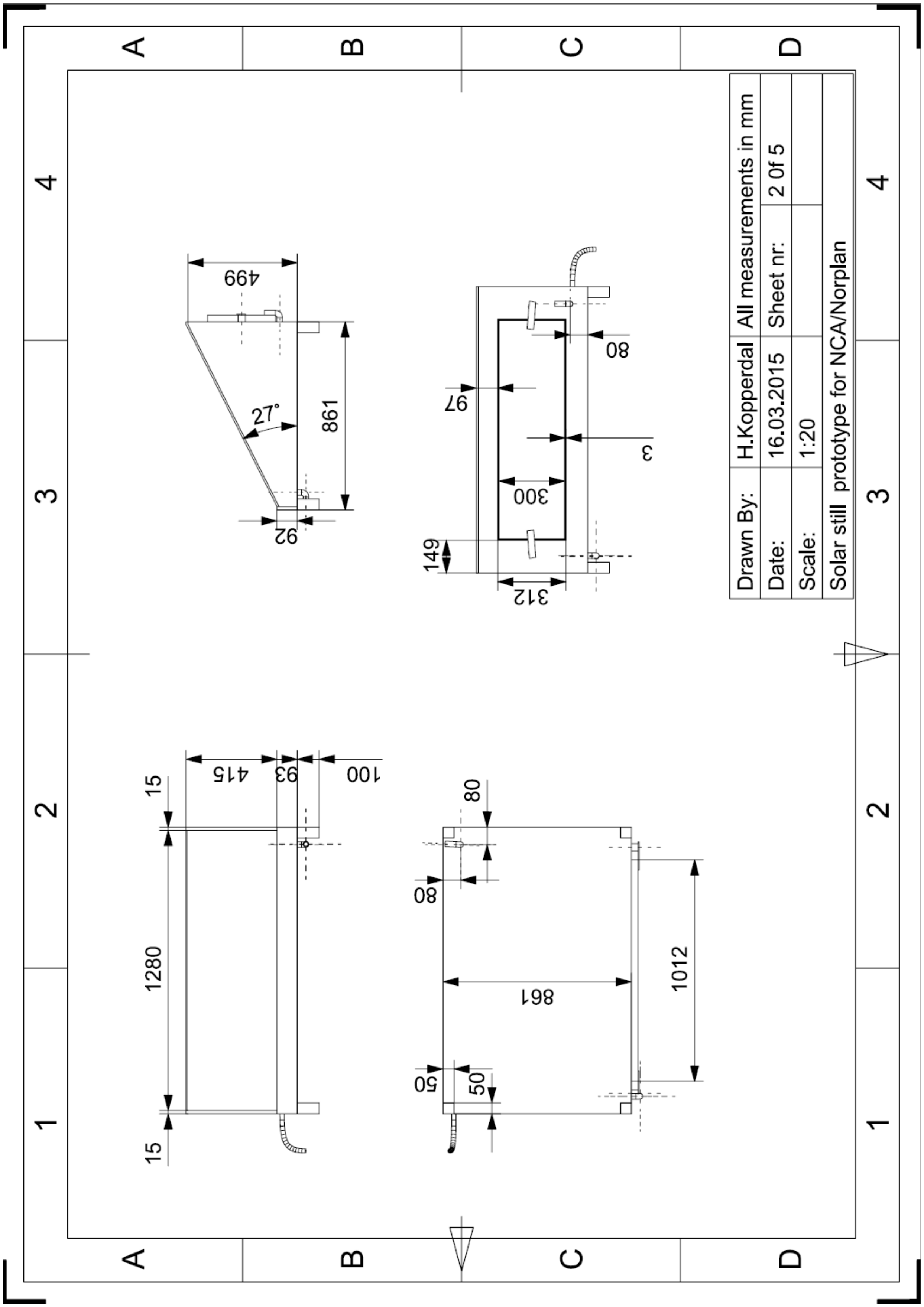
- Temperatures up to 90 [^{o}C]
- Saline water and moist conditions
- Materials must not off gas toxic or contaminate the distilled water

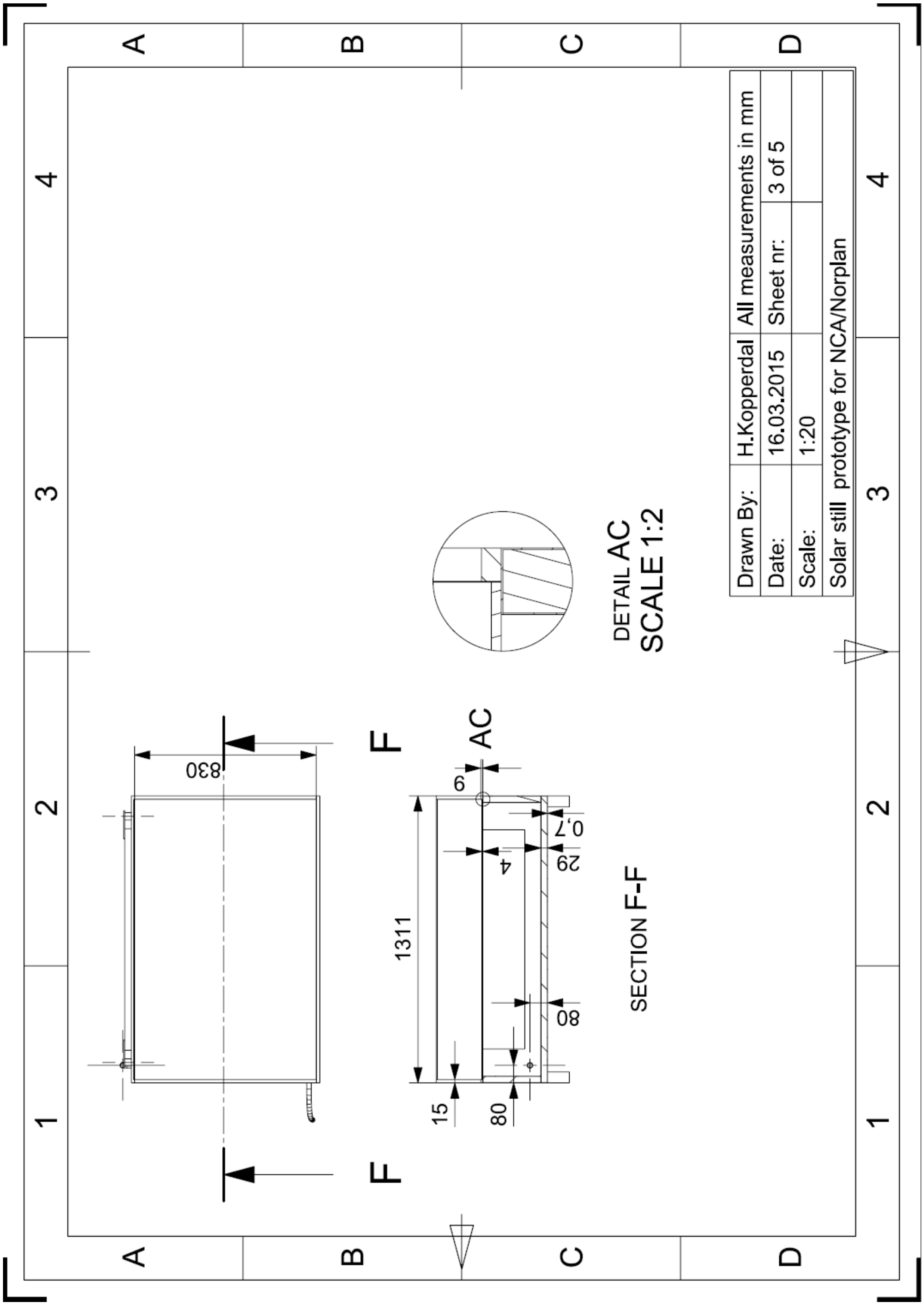
From a structural and water quality point of view I would appreciate if you have time to answer these questions:

A. What are the key material properties to withstand high temperatures in a saline and moist environment?
B. Which materials are suitable for this to a low cost?
C. What will happen to the materials over time and how will it affect the solar still?

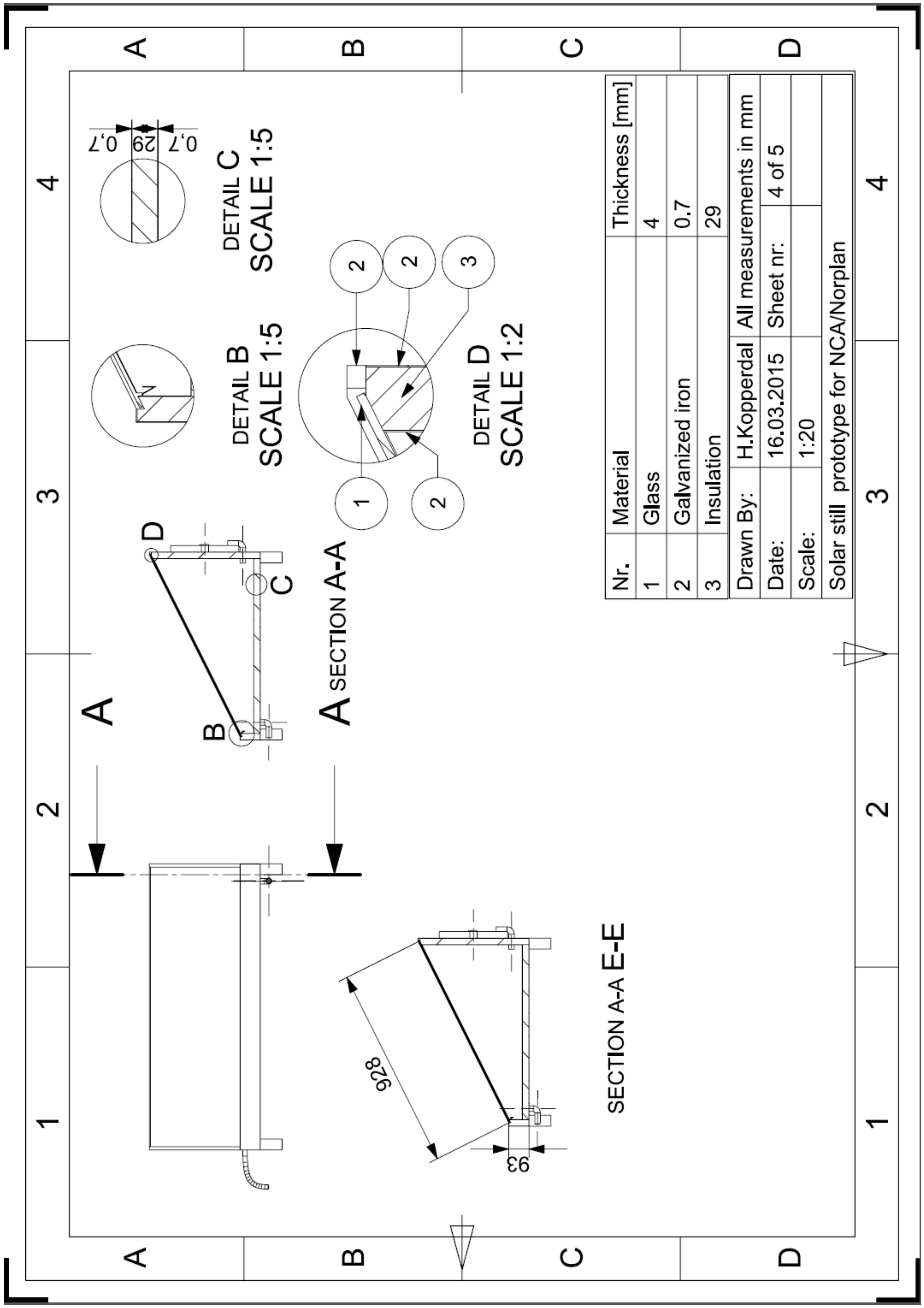
17.2 Technical drawings for prototype for local manufacture in Kabul

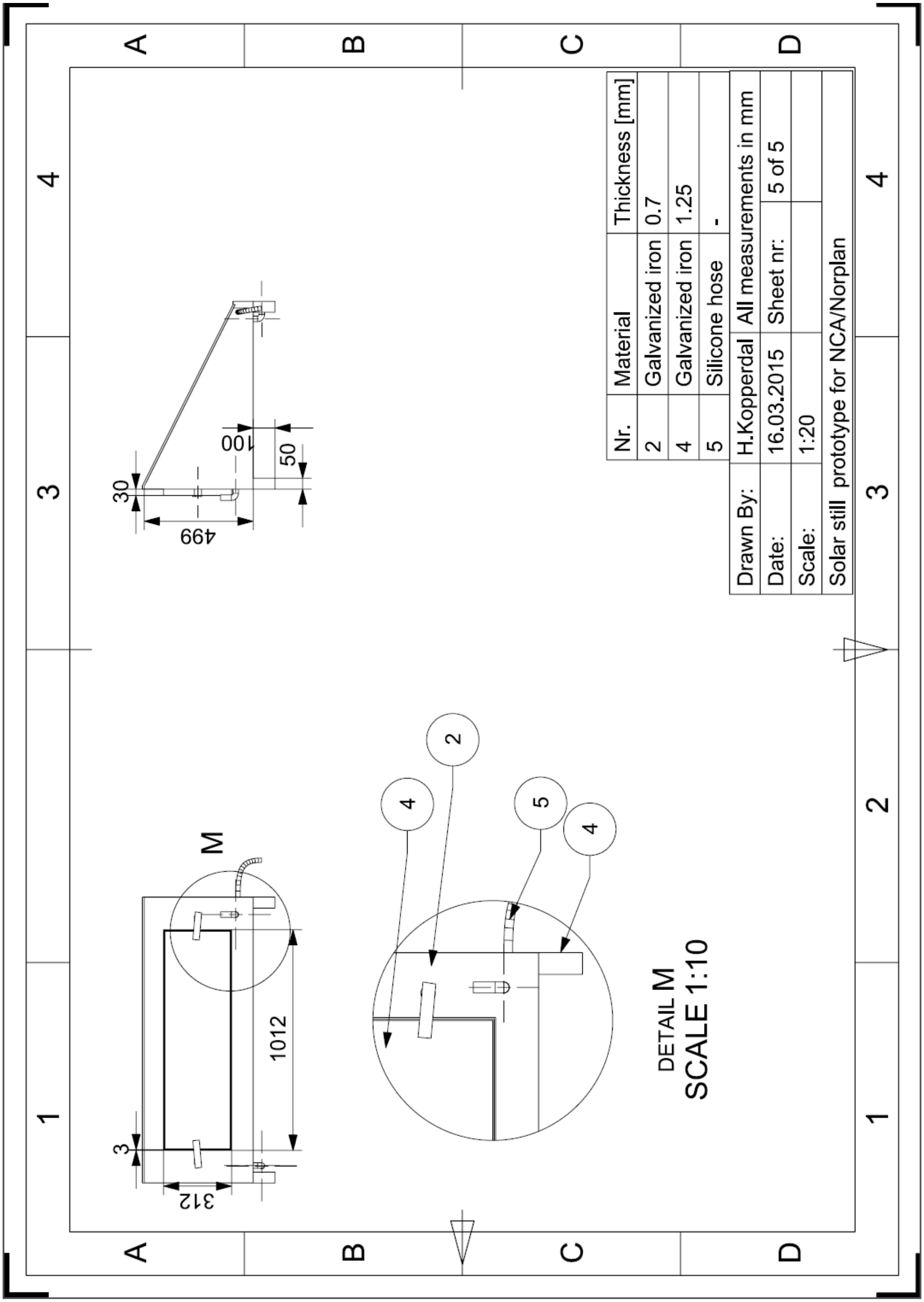



Drawn By: H.Kopperdal
All measurements in mm
Date: 16.03.2015
Sheet nr: 2 0f 5
Scale: 1:20
Solar still prototype for NCA/Norplan



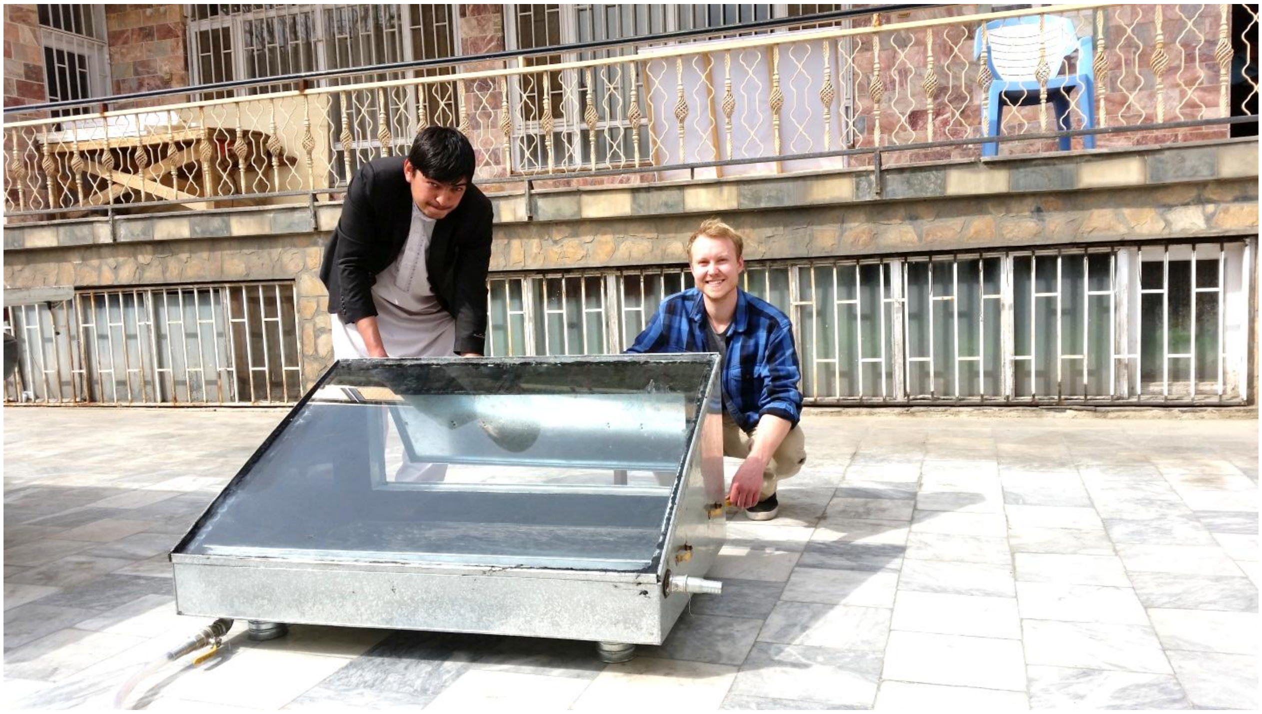
F
F
AC
830
1311
15
80
9
0,7
4
29
80
SECTION F-F
DETAIL AC
SCALE 1:2
Drawn By: H.Kopperdal
All measurements in mm
Date: 16.03.2015
Sheet nr: 3 of 5
Scale: 1:20
Solar still prototype for NCA/Norplan


DETAIL B
SCALE 1:5
DETAIL C
SCALE 1:5
0,7
29
0,7
DETAIL D
SCALE 1:2
SECTION A-A
SECTION A-A E-E
928
93
Nr.
Material
Thickness [mm]
1
Glass
4
2
Galvanized iron
0.7
3
Insulation
29
Drawn By:
H.Kopperdal
All measurements in mm
Date:
16.03.2015
Sheet nr:
4 of 5
Scale:
1:20
Solar still prototype for NCA/Norplan

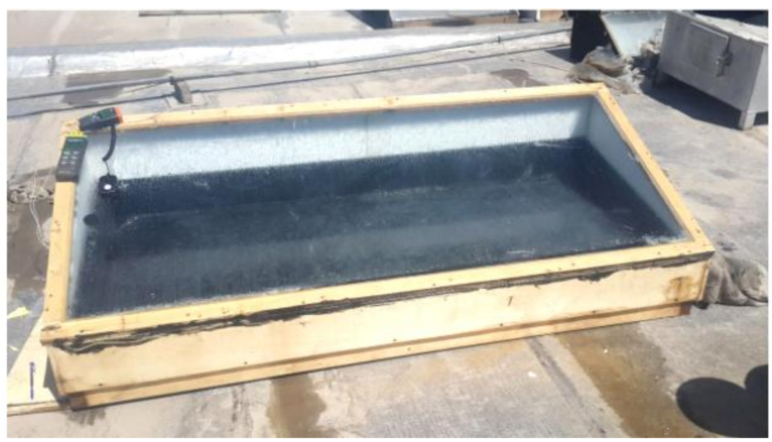

Nr. | Material | Thickness [mm]
2 | Galvanized iron | 0.7
4 | Galvanized iron | 1.25
5 | Silicone hose | -
Drawn By: H.Kopperdal
All measurements in mm
Date: 16.03.2015
Sheet nr: 5 of 5
Scale: 1:20
Solar still prototype for NCA/Norplan
DETAIL M
SCALE 1:10
M
499
30
100
50
312
3
1012

17.3 Various pictures from the trip

Figure 40: 1: Carpenters at the NCA office, 2: Halvard Hirsch Kopperdal is testing, 3: Eng. Yasir is inspecting his solar still, 4: View of a small village in Kabul, 5: Street view in Kabul, 6: Eng. Yasir is preparing for testing.



7



8 9

Figure 41: 7: Eng. Yasir to the left and Halvard Hirsch Kopperdal to the right, showing the manufactured prototype. 8: Solar still made by Eng. Yasir and Eng. Abrar. 9: Testing of the imported solar still from US, DIY Rainkit.

Norwegian University
of Life Sciences

Postboks 5003
NO-1432 Ås, Norway
+47 67 23 00 00
www.nmbu.no