Design of a user centered Solar Refrigerator

Graduation Report

by Jonas Rikkert Jan Martens

"User Centred Solar Refrigeration"

Main
Market
Technique
Ideas & Concepts
Concept Bearnaked

by Jonas Rikkert Jan Martens, November 2010

I

MAIN

Introduction

In the search of a global reduction in carbon dioxide emissions, increase of mundane wealth and decreasing health risks within countries in development, current types of refrigeration form a respectable partner in doing exactly the opposite. Either refrigeration is unreliable or not available at all in large parts of the world, or the method of cooling thrives on our fossil fuels due to the large energy input that is needed to maintain its functionality. The aim of this project is to counter these problems with an affordable and adaptable type of refrigeration that is suitable in several global market segments; the world in development and the western leisure markets.

Solar energy is an overabundantly present throughout the globe, and the total solar energy absorbed by the earth's atmosphere in one hour, counts for the total energy demand of the world over a whole year. More importantly, about twice as much energy that reaches our surface can be harvested as can ever be obtained by all of earth's non-renewable resources combined (GCEP, 2010). Adding to this, large parts of the world are not connected to (mostly non-renewable) electricity grids, this phenomenon occurs especially within area's where the largest shares of the world's population are situated (i.e. Asia, Africa, and South America). These, often low income but growing markets, are therefore in need for decentralized solutions, that could most easily harvest solar energy. But, product development in a low-income market does have other implications because of the many cultural differences, and especially in terms of local empowerment; local communities have to become and feel involved with the product they are buying or selling. This thesis is an attempt to overcome and combine all of these aspects through product design.

The Problem

Within the world's countries in development, some great problems are linked to the lack of available refrigeration. Electricity is commonly unavailable within rural area's, and with current (electrical driven-) solutions, no refrigeration is one of the consequences. In India, 400 million people, or 100 million households, live without electricity (UN ETC, 2010; IEA, 2008), almost half of the population. Combining Latin America, Africa and Asia, the amount of civilians that live without electricity comes to a total of 1200 million, according to International Energy Agency in 2008. A huge problem and potential to do differently.

Without reliable refrigeration, edible food and produced goods spoil easily, and much of the earnings small entrepreneurs should be making, are lost due to breaks in the cold chain. While on the production side produced goods are spoiled due to storage and transport without cooling; On the receiver end, eating spoiled food and beverages (i.e. fish & milk) can be one of the cause for major health trauma's, responsible for millions of deaths and diseases.

These households, in the developing world, have a need for decentralized solutions, outside the electricity grids. Increasing wealth and opportunity.
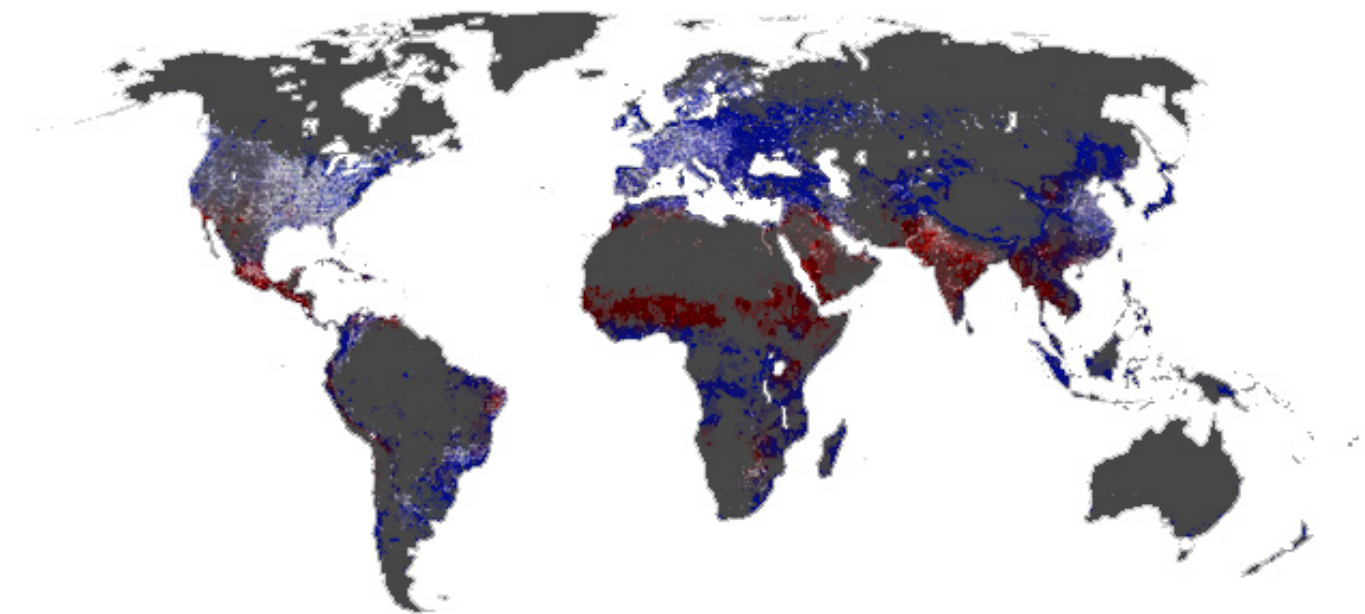
white   Electrification (NASA)
blue   Population density
red   Opportunity areas using solar irradiation map (NASA)

Figure I.1   Overlays of the world's electrification, population density and solar irradiation, using NASA pictures.

As can be seen in figure I.1, overlays of electrification, population and solar irradiation show the general areas of opportunity for a solar driven, off-grid refrigeration solution.

In western societies, refrigeration takes up a large part of our energy bill at home, let alone speak of our industries. Especially during hot summer days, refrigeration energy demand peaks out of proportion and pulls out some *extra* 150 gigawatts within the U.S. alone (Scientific American, 2008), around 120-200 times the supplying capacity of a typical Dutch coal plant like the "Amercentrale" in Geertruidenberg. In Dutch households, on average 10-20% of our electrical bill is spend on all types of refrigeration within the house (CBS, 2010). Furthermore, (higher) market segments in western societies spend time enjoying leisure activities like sailing and camping, where refrigeration either costs fuel or electricity which is commonly unavailable.

C   Project Overview

Change the world by design

C 1   Vision

There is a viable desire to increase wealth worldwide in which all parts of the hemisphere must participate. To enable equal opportunities in accordance to personal stakes, and a decrease in disease spread and death toll, sustaining solutions must

be found to counter real life problems and brighten future prospects for all. The solarbear initiative wants to offer cooling solutions by locally managing spoilage problems as strengths, using the sun as input for its refrigeration process. The world does change by proper design.

C 2   Mission

By disruptively combining existing technologies and accessible production techniques, the solarbear initiative wants to offer affordable and decentralized refrigeration to those parts of the world which are currently unreachable for electrification. Hereafter, the solarbear initiative has a main purpose of decreasing overall energy dependence by combining self-sustaining, decentralized entrepreneurial opportunities through adaptable electricity independent cooling techniques. The solarbear aims to combine realistic business with green and ethical design.

C 3   Ambition

By the end of 2011, a full validation on technical feasibility combined with a coherent market proposition of the solarbear initiative will have been executed by means of high level research, generation of business models, prototyping and pilot studies. After several sincere milestones, the solarbear initiative shall cooperatively join forces with international universities, able multinationals, similar initiatives or NGO's to ensure an increase in production numbers, facilities and distribution channels; reducing price and increasing availability worldwide.

D   Project Goals

The goals of the solarbear project, are to test viability of adsorption refrigeration technically and market wise. To come to such conclusions, technical and market analysis have to be combined, of which this graduation forms the basis of further investigational opportunities. Ultimately, the solarbear project has been set up to reach out to the people with a still viable need for refrigeration by using degraded techniques, as intended by its founders.

Derived from earlier business plans and research, two main markets are to be explored; the low income markets around the world and the western leisure markets. With a large potential ethical impact & turnover, and higher margins respectively. Both explorations are described within this thesis, and can be found in chapter II.

Eventually in 2011, a pilot study will be done proving or disproving the viability of this project, although this extends the scope of this thesis. The overall goals are:

0   Funding
1   Technical & Market viability studies
2   Working Prototype(s)
3   Intellectual Property
4   Pilot study in a chosen market segment with prototypes and user groups
5   Cocreation, learnings & new funding applications, resulting in product improvements
6   Cooperating with (a) large capable external partner(s) for first production batch and distribution
7   Commercialization of the project worldwide

E Project Strategy

Although not part of this thesis directly, choices in project strategy have been extensively made and reconsidered, mixing with the content of this thesis. The overall strategy is formulated and divided into several milestones as described earlier. Milestones 0-3 are being, or have been executed during the making of this thesis.

One of the pillars that holds the overall direction is based on knowledge transfer, and can be described as the main thread throughout the entire project. In order to achieve the first five project goals with limited funds, the overall strategy includes a cocreation within the project by closely cooperating with (international) Universities, combining readily available knowledge to get to a shared goal: success of the solarbear project. During the writing of this thesis, already much work has been done on the matter, and much is to be finalized afterwards. Several (multidisciplinary-) student teams from the Technical University of Delft have been recognized, set up and guided partly by the author and TUDelft departments. Each team focussed on different aspects surrounding the project solarbear.

Following up on the initial business plan written by the founders in 2009, several (specific) market studies were created on low income markets like Surinam and Ghana, next to intellectual property studies. Currently, solarbear student researchers are looking into the difficult technical aspects while at the same time Ghana is more deeply explored (follow our students on their very nice blog at solarbear-ghana.blogspot.com). Electives circling the solarbear project were created; Entrepreneurial Minors (EM), students entered the Sustainable Business Game (SBG), and the Design Challenge (DC). Furthermore, possible project opportunities in Southern Africa are discussed together with the Haagse Hogeschool and local African universities, as well as with the Anton de Kom University in Surinam.

But, our main knowledge partner remains the TUDelft, and the solarbear founders extensively collaborate with several departments within the University: especially the Delft Centre for Entrepreneurship (DCE), Design Engineering (DE), Design for Sustainability (DfS), Process & Energy (P&E), the Energy Club (EC), the Energy Initiative (EI), Students for Sustainability (S4S) and more. As of recently, eventual Intellectual Property is shared by half in between the founders and the TUDelft, and the Stichting Techniek en Wetenschap (STW) granted a mentionable amount of funds via the University. An overall timeline is given in figure I.2.
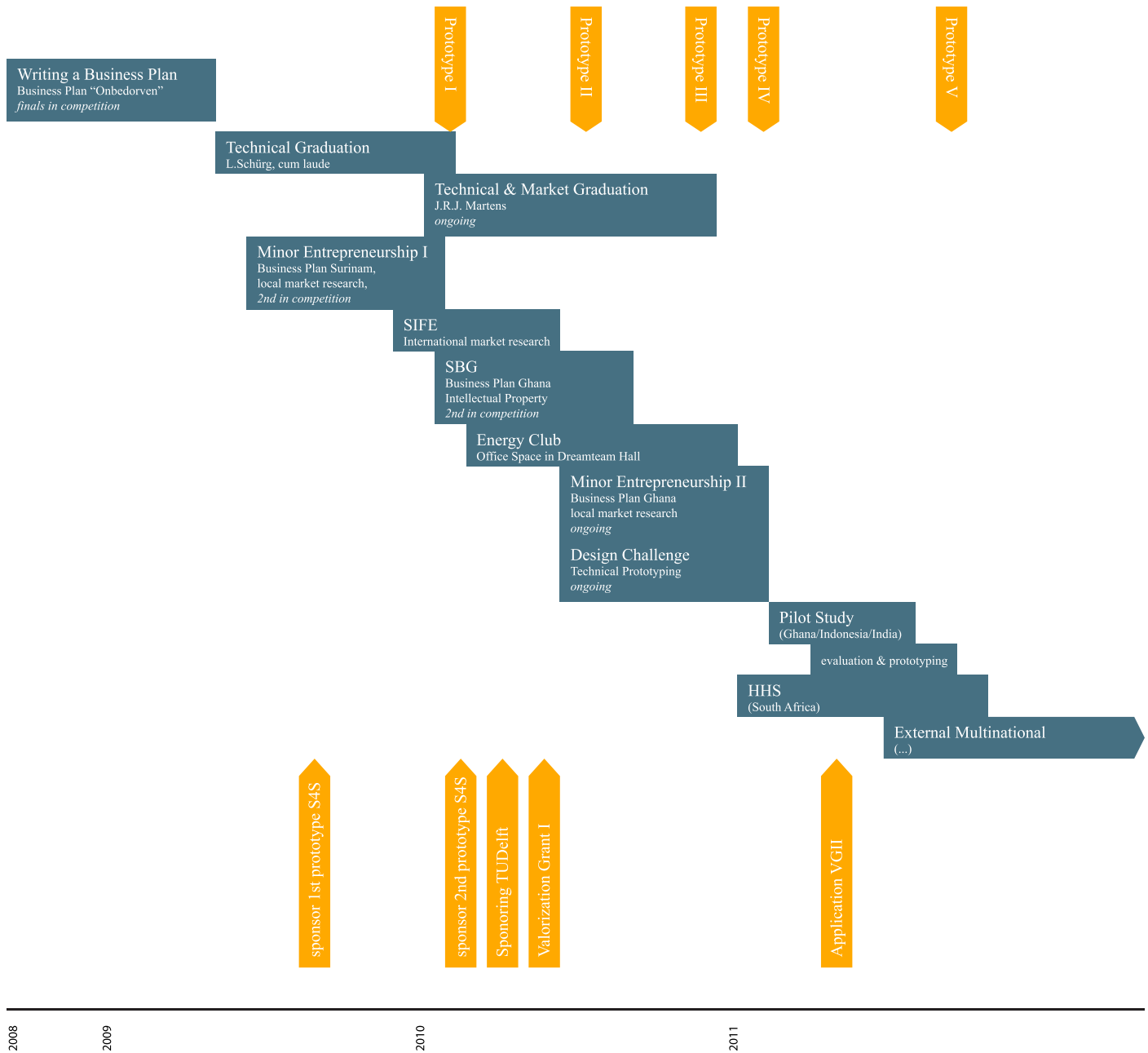
Prototype I

Prototype II

Prototype III

Prototype IV

Prototype V

Writing a Business Plan
Business Plan "Onbedorven"
finals in competition

Technical Graduation
L.Schürg, cum laude

Technical & Market Graduation
J.R.J. Martens
ongoing

Minor Entrepreneurship I
Business Plan Surinam,
local market research,
2nd in competition

SIFE
International market research

SBG
Business Plan Ghana
Intellectual Property
2nd in competition

Energy Club
Office Space in Dreamteam Hall

Minor Entrepreneurship II
Business Plan Ghana
local market research
ongoing

Design Challenge
Technical Prototyping
ongoing

Pilot Study
(Ghana/Indonesia/India)

evaluation & prototyping

HHS
(South Africa)

External Multinational
(...)

sponsor 1st prototype S4S

sponsor 2nd prototype S4S

Sponoring TUDelft

Valorization Grant I

Application VGII

2008   2009   2010   2011

Figure I.2   General Solarbear project timeline

F   Stakeholders

The solarbear project has been initiated in 2008 by Jonas R.J. Martens and Leonard Schürg, while studying at the faculty of Industrial Design Engineering at the Technical University of Delft, the Netherlands. This initiative, currently called the solarbear project, has ever since enjoyed (inter)national attention due to the high potential of the product / market combination, and due to its vision, "change the world by design". With time, project solarbear gained focus from general idea to concept, and now supplies input to different student teams within the TUDelft, co-researching technique(s) and market(s) as stated earlier. To be able to forfeit this thesis into the overall project, the stakeholders have been mapped out, as of October 2010.
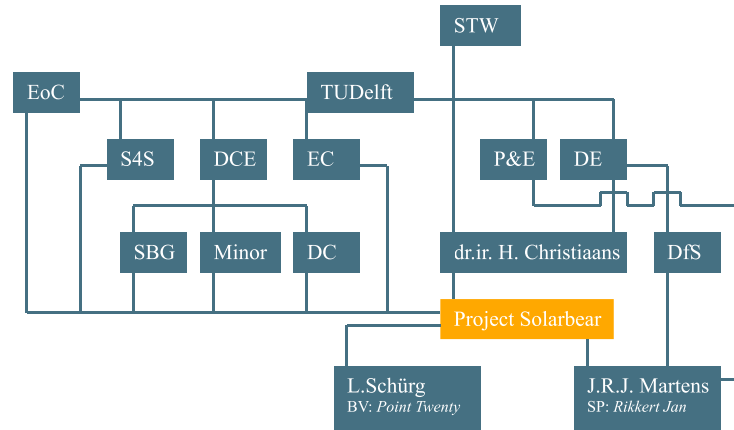

Figure I.3   Solarbear project stakeholders as of Oct 2010.

G   Graduation Assignment

"Design a user centered solar refrigeration system based on the adsorption principle"

The graduation assignment evolved during project advancement, but has remained the same in its core values; design a solar refrigeration for a suitable market. Exploring both technical restrictions in terms of i.e. efficiencies and design challenges, while at the same time exploring market needs, opportunities and threats to eventually bridge the remaining gap. The mentioned aspects are described in chapter III and II respectively, while chapter IV attempts to merge these facets into a suitable concept.

H   Methods & Approach

Overall graduation design methods used follows the prescribed rules of engagement set out by product development analysts. The design process is divided in distinct phases diverging and converging midterm conclusions and ideas; Analysis, Idea Generation, Conceptualization, Realization and Evaluation phases. Within the Analysis and Idea Generation phases, a wide scope on the project must be obtained, while within the Conceptualization phase this scope is narrowed down by incorporating choice and earlier made conclusions to reach a single product proposal that is prototyped, tested and evaluated.

The approach per subassignment (i.e. market vs. technique) varies although the eventual goal is similar; the formation of design parameters to enter the idea generation phase. For the market analysis, pre-research (or desk research) determines

the input for a close and personal conversation with the targeted user groups, by organizing focus groups and internet surveys, and eventually experiencing the chosen culture at close range. For the technical analysis, collaboration with professors and students shaped the outcome of demands, on top of what literature research could not provide. Also, many companies within specific fields have been contacted and interrogated in order to get to the most realistic design parameters, ideas and concepts.
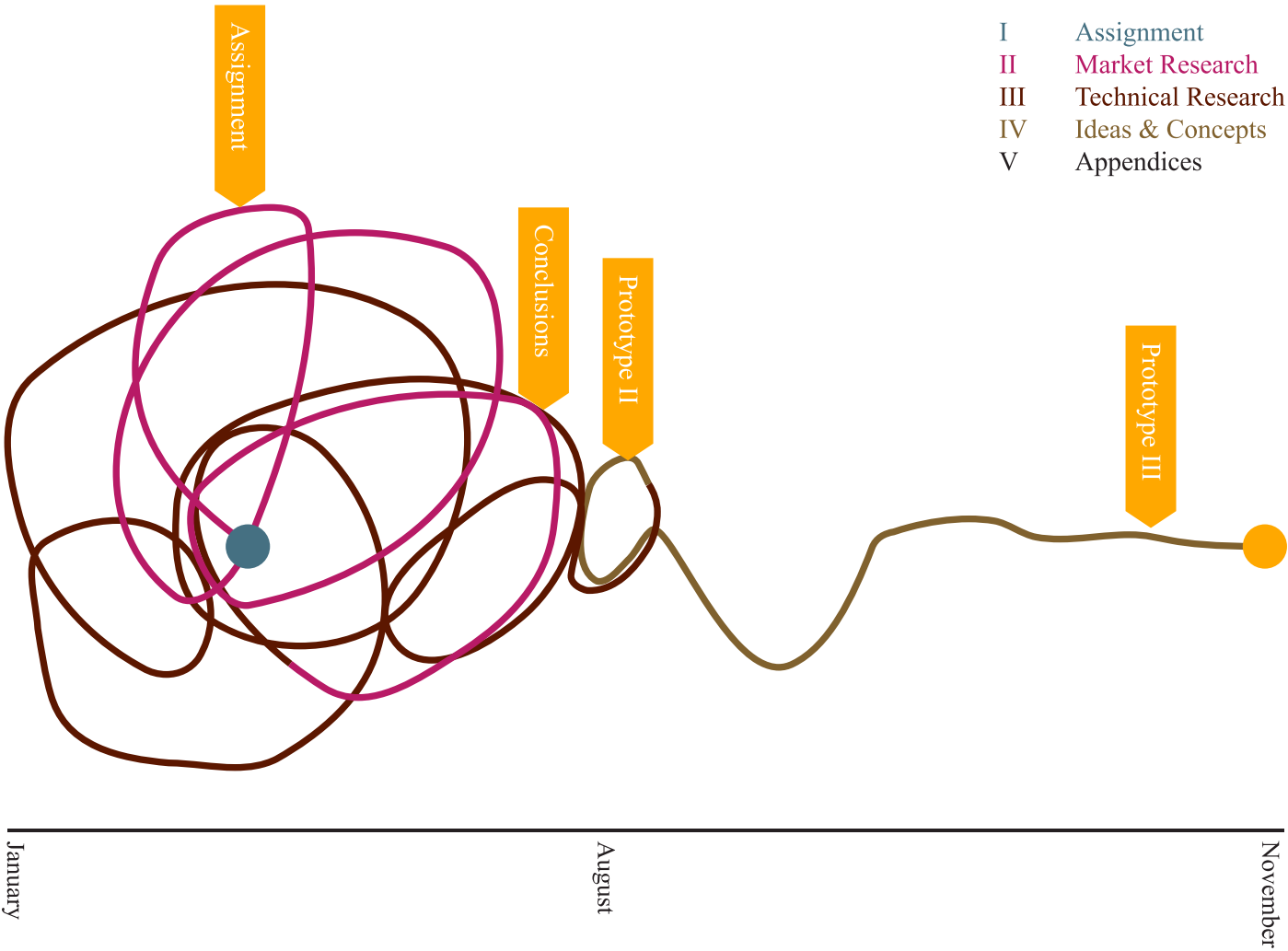

I   Assignment
II   Market Research
III   Technical Research
IV   Ideas & Concepts
V   Appendices

January

August

November

Figure I.4   Graduation Timeline.

"The developing countries and all the rest of us must cooperate by combining simpler and small-scale approaches with new technologies, which for the first time make decentralized and human-size development feasible."

- Victor Papenek 1981 - 1984.

II

MARKET

Introduction

*A*ny product design needs a combination of two important facets in order to create value; a technical solution that *properly fits market needs. In this chapter, the latter is explored, discussed and concluded, and starts it search with finding a viable need in the developing and western world. After validation, target groups are selected which form the design criteria, one of the two pillars of the eventual product proposal.*

A 1 ### Basic Psychological Needs

Every human being has basic needs, wherever they live, wherever they come from whatever historical background. Needs of survival to needs of independence and self distinguishment. Although they differ by culture, basic psychological needs are overall similar for most. According to Maslow's Hierarchy theory, these psychological needs can be separated into a varying layers of importance. The lower the needs in the hierarchy, the more fundamental they are for anyone's existence, when these are not met, the more a person tends to abandon the needs in the upper layers. A great example is, when we are ill, we care little for what other may or may not think, we just want to get well again. Within the most fundamental layer, the primal psychological needs can be found, which can be described as maintaining our health. This layer can be linked almost directly to the functionality of refrigeration, while a refrigerator itself, its form, its look & feel, belongs to one of the more upper layers of needs, a way of separation from others in our surrounding: esteem. An important difference when designing a refrigeration system for people with or without as much to spend on self-esteem as us.

Self Actualisation — achieving individual potential

Esteem — self esteem and esteem from others

Belonging — love, affection, being part of groups

Safety — shelter, removal from danger

Physiological — health, food, sleep

Figure II.1   Maslow's Psychological Needs

The market research has been split into two different overall target markets, the Developing and Western market, in both needs for off grid, solar powered refrigeration are explored. The following chapters have been divided accordingly, in "Base of the Pyramid" (BOP) and "just Below Our Absolute Top" (BOAT). In both BOP and BOAT, strategy, market segments, market choice, specific competition, are all analyzed and concluded to form design criteria that lead to chapter IV, which discusses the ideas & concepts that attempt to bridge the gap in between these markets and technique (chapter III). For my personal graduation on solar refrigeration specifically, it was intended to find corresponding and contradicting elements in the two markets (BOP vs BOAT). These conclusions have led to two extremes for product development, the low and high end product design by using the exact same technique.

"Those who live in poverty present great business opportunities for the private sector", is how the Base of the Pyramid business strategy is commonly described. This, poorer, base of the less developed world represents a new world of opportunities for entrepreneurship, market entry & growth, (sustainable) innovation and labor (Hart, 2005; London & Hart, 2004; Prahalad, 2005). Executing business in cooperation with the poor as a strategy offers opportunities for both, in which a situation is created where both parties gain financially. In order to meet financial requirements, businesses are forced to work more economically effective, and the private sector is therefore motivated to use its problem-solving capacity in an extensive matter. There are however, other conditions in which to do such business in contrary to the developed world. Cultural differences on a global and local scale, the dependance on an informal type of economy, poorer living conditions, weak legal institutions, fragmented markets and motivation are important considerations in a BOP-type business strategy. To enable production, sales, and after sales of any product in a differentiating and low income market, it is clear that business model innovation too, forms a necessity next to an innovative product solution. Neither one will work without the other.*

Despite the criticism on turning the poorest of our world into a new type of consuming industry, much is to gain for both parties when they provide a close type of cooperation; new local businesses can be formed, thriving urban economics, health issues slowly disintegrate because of new set standards, knowledge transfer by using appropriate technological solutions, and new relations are formed. Maintaining dialog (or, communication, for which us Europeans even have managers) is a key for success in every BOP business according to the protocol of Erik Simanis (2008); respect equals involvement. Prahalad (2002) suggests six, often false assumptions with respect to the poor, stated below.

1. The poor are not our target consumers because with our current cost structures, we cannot profitably compete for that market.
2. The poor cannot afford and have no use for the products and services sold in developed markets.
3. Only developed markets appreciate and will pay for new technology. The poor can use the previous generation of technology.
4. The bottom of the pyramid is not important to the long-term viability of our business. We can leave them to governments and nonprofits.
5. Managers are not excited by business challenges that have a humanitarian dimension.
6. Intellectual excitement is in developed markets. It is hard to find talented managers who want to work at the bottom of the pyramid.

Four billion people, or two out of three people in the world lived on less than €6 a day in 2005 (Hammond et al., 2007). These four billion people made around €2150 a year in 2002, and €2340 in 2005. In 2009, over 3 billion people, still live on or below the somewhat arbitrary line of less than US$2 a day (≈ €1,4), which is defined as the Base of the Pyramid by the World Bank. In 2008 the world bank concludes: around 95% of the developing world lived on less than US$10 a day (≈ €7,2) in 2008 (Ravallion et al.,2008). The complete BOP consumer market annual purchasing power accounts for nearly €1 trillion (€5 trillion when corrected for the PPP). These shocking numbers show that problems can actually become opportunities.
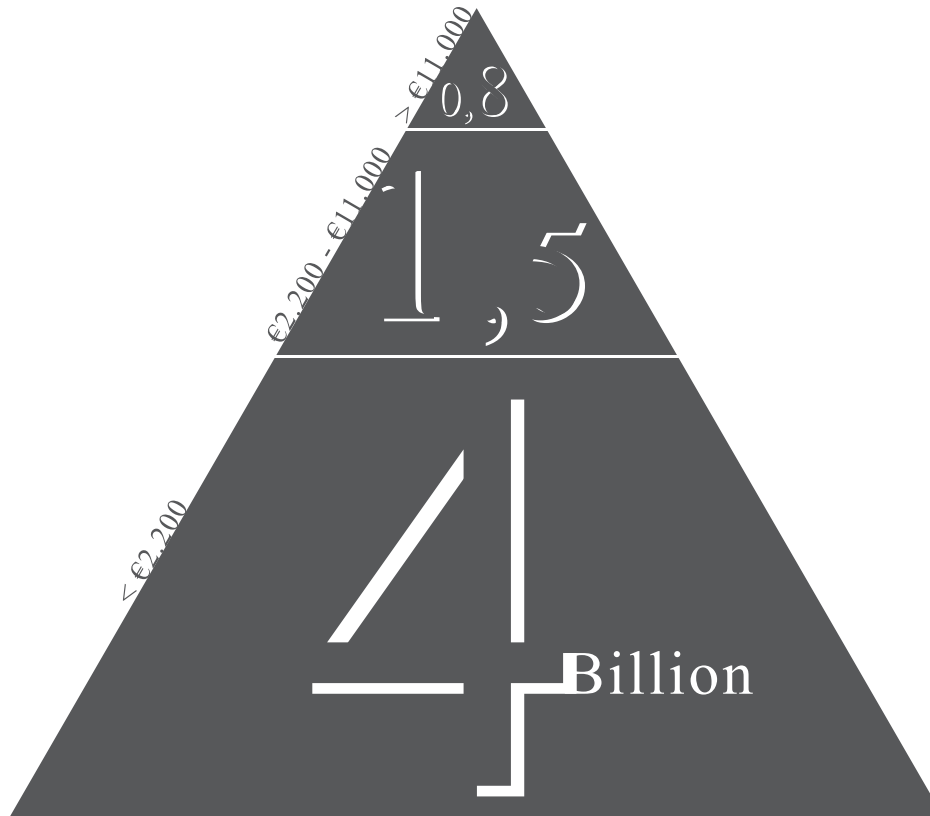
Figure II.2   World Population against income division per year (Prahalad & Hammond, 2002; Hammond et al, 2007

1.1   Insolation / BOP

When we take a look at the world map as shown in figure I.1, the division of (low-income) world population seems to have a clear overlap against unelectrified areas. Large parts of the poorer rural population within BOP countries do not have access to electricity, coincidentally, these areas have another thing in common: high intensity of solar irradiation throughout the year. The combination of these three overlapping maps pre-validate the opportunity for solar driven refrigeration, given there is an existing need in specific market segments. This need will be researched within the BOP chapter of this thesis.

2.1   Introduction

Success in BOP markets depends on both the product innovation level as well as the necessity of business model innovation in low income markets (e.g., Arnold & Quelch, 1998; Chesbrough, Ahern, Finn, & Guerraz, 2006; Dawar & Chattopadhyay, 2002; Hart, 2005; London & Hart, 2004; Seelos & Mair, 2007). A properly designed business model around a properly designed solar refrigerator determines whether the complete project will succeed. Without question, poverty is the prime key within any BOP type strategy, and thus creating value is done through social value innovation, using social structures as a strategy. Hart (1997, 2005) created a path type for any firm that wishes to improve social impact through business, as seen in figure II.3. When correctly implemented with the other complementing substrategies, a long term strategy focused on Social Vision has the highest potential impact, reach and pay off (Klein, 2008).

Short Term Focus   Long Term Focus
Exploitation   Exploitation

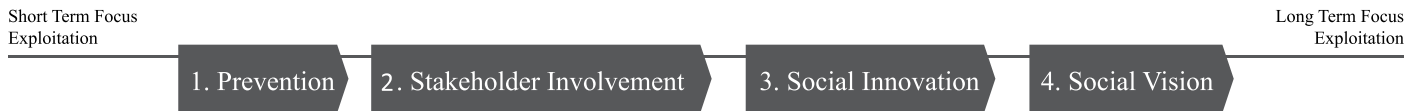| 1. Prevention | 2. Stakeholder Involvement | 3. Social Innovation | 4. Social Vision |

Figure II.3   Hart Business Models for the Developing World.

A BOP approach focuses on the development of the private sector as a crucial actor, and more specifically, places emphasis on including the poor as producers, employees, suppliers, distributors and consumers; a vital vicious circle which enables local entrepreneurial offspring around a product or service, eventually contributing to social and economical growth. Thus, in order to reach out to the poor, product price must be dealt with, and one way to accomplish that is by disruptive innovation in all of the processee before and afterwards (i.e. in distribution, education, human resources management); simplicity. A complementary approach to Disruptive Innovation (see II.2.2), with the eye on BOP specifically, would be the implementation of Appropriate Technology. Using simplified, innovative technology (II.2.3) combined with a market corresponding design in order for localities to still accept what it truly offers. Thus, meaning a product or service does not stand too far away from the locally known level of (technical) innovation; Most Advanced Yet Acceptable (MAYA). This basically means: exactly the opposite of a complicated water pump in a distant African rural area build by western technicians, so that when it does break down, no local handyman is able to fix it and all surrounding villagers go back to walking those long kilometers to the nearest well.

sum Concerning this project, a solar refrigerator type concept in a BOP type context, focus should be maintained on stakeholder involvement and social vision. Prevention is a core value of the product itself while social innovation can not be determined yet, and has its specific influences locally.
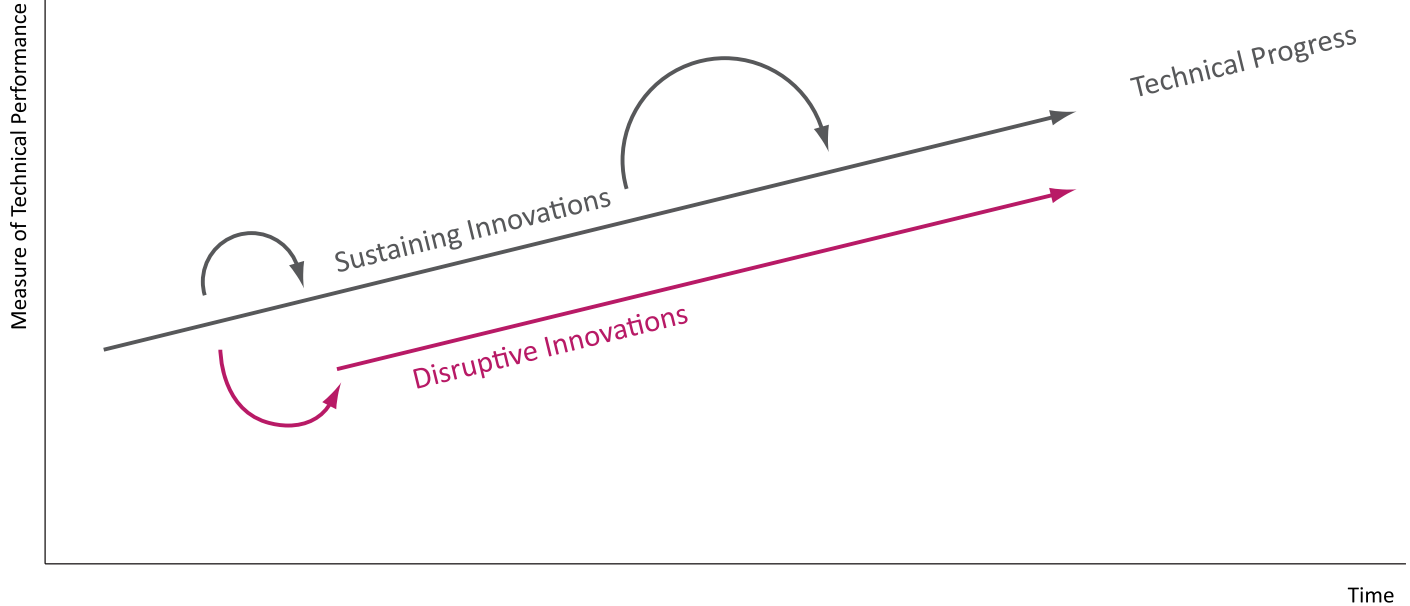
Figure II.4   Disruptive Innovations

In a BOP situation, highly complicated or new techniques are not as useful because of the lack in local resources, facilities and knowledge. Therefore, technically, it is wise to reduce complications, and use readily available, off the shelf processes and components that enable local businesses to thrive around any new type of innovative product or service, i.e. as producers, in maintenance or sales. Christensen (The Innovators Dilemma, 1997), theorized a strategic model in order to stimulate rapid growth for a company that uses straightforward technology in different market segments. Using technology which stands close to its end users in the predetermined market segment, the innovation must come from within the product itself, its use or its (social) vision. Another advantage of using disruptive innovation or technology, when developed below the umbrella of constant innovation as here in the West, knowledge, standardized parts, and many technological examples already exist, making it easier to simplify any technique, product or service. Christensen defines disruptive innovation as a product or service designed for a new type of customers.

> "*Generally, disruptive innovations were technologically straightforward, consisting of off-the-shelf components put together in a product architecture that was often simpler than prior approaches. They offered less of what customers in established markets wanted and so could rarely be initially employed there. They offered a different package of attributes valued only in emerging markets remote from, and unimportant to, the mainstream.*"

2.3   Appropriate Technology

Appropriate Technology, is the use - or the design of - technology intended for a certain community, taking environmental, ethical, cultural, social, political, and economical aspects into consideration. With appropriate technology in mind, fewer resources are used and are appropriately repairable (considering local literacy). It is the implementation of technology for

and with the local target group. Appropriate technology is to prevent waste of time and energy, on undesired solutions. Photovoltaic cells, for instance, are very difficult to repair locally and therefore difficult to maintain, apart from the fact a certain extend of knowledge is needed to use them properly. Appropriate technology, goes hand in hand with knowledge transfer in most cases, empowering local communities, similar to the saying: "Give a man a fish and you feed him for a day; teach a man to fish and you feed him for a lifetime", Appropriate Technology is about providing the means, or to basically sell him the rod in such a way that the man is able and wants to own the rod by incorporating current lifestyle and means. Criteria for Appropriate technology are the following (Darrow, 2010):

1   Requires only small amounts of capital.
2   Emphasize the use of locally available materials, in order to lower costs and reduce supply problems.
3   Are relatively labor-intensive but more productive than many traditional technologies.
4   Are small enough in scale to be affordable to individual families or small groups of families.
5   Can be understood, controlled and maintained by villagers whenever possible, without a high level of specific training.
6   Can be produced in villages or small workshops.
7   Suppose that people can and will work together to bring improvements to communities.
8   Offer opportunities for local people to become involved in the modification and innovation process.
9   Are flexible, can be adapted to different places and changing circumstances.
10 Can be used in productive ways without doing harm to the environment.

Figure II.5   Western Example of Appropriate Technology

Many examples of BoP type initiatives exist, some failed and some succeeded. The main question lies in what these success factors could have been, and equally important, what mistakes have been made. Treated here are personal conclusions on several initiatives, for more information on these examples please refer to appendix B.BOP.1.

Figure II.6   Celtel in Congo "Have more time for love", and Hindustan Lever Ltd in India.

A clear overlap exists in between succeeded initiatives, the informal service system around a certain product. The service system extends those who offer mere advice or repairments, it is the complete (financial) involvement of locals that forms its fundamentals. Local businessmen are involved within the company as a soul proprietor, buying products from the establishment and selling these products or its intended service informally, using their own language, by means of their own culture. Not only is this is an excellent way to get to the local inhabitants, it provides an immediate feedback system as these entrepreneurs return to base. Furthermore, these entrepreneurs are commonly educated on sales, using the technology, finance (depending on the type of project), and do transfer this knowledge to their own direct environment. Hindustan Lever Ltd. (Unilever) in India, uses female self help groups in a combination with micro-finance, to expand its reach to rural area's. These, mostly hygienic products, are purchased by this self help women called 'Shakti' dealers, which in their turn sell these products to remote rural villagers. Apart from making an honest living, more than many others in these regions, illiterate Shakti dealers are constantly educated on sales and hygiene, while HLL profits economically, in distribution terms and in respect by the poor. The same goes for Celtel, another Dutch initiative, who struggled to set up mobile phone networks in Congo, during the civil war in 2000. It formed its company vision around the country's rebuild, expressing the need for local scattered civilians to reconnect to each other, and build its business model with prepaid cards (avoiding debts), shared-access (sharing phones in families) and local distribution. And, micro entrepreneurs are offered to rent a handset from Celtel to start a local kiosk in order to earn a living, while at the same time Celtel offers to paint its walls in their distinct color scheme. Also Philips has tried to set up a Shakti like dealership for their woodstove in India, concerning educational

II.8

transfer it worked properly, but they made an early mistake in culture (and later on technical failures), they supposedly did not involve the end user as much as they should within the early stages of development. As an initial strategy, the woodstove would come to the market in two different types, one which was of shiny stainless steel, and a more affordable version made out of thermoresistant plastic. As it turned out, close to none of targeted low income consumers would purchase the plastic woodstove, although it was the only one seemingly fitting those hard to meet requirements. People from India did not want to be perceived as poor, and therefore rather save money to buy the more expensive version. A similar mistake happened with the Lifestraw, a tube type waterfilter for the poorest, where people are supposed to drink from polluted lakes like a straw, they gave many away but only few would actually use it because of the forced perception it would bring upon the people drinking from a strange straw out of a river. Another mistake, concerning technical and education levels, was made with the adjustable reading glasses for Ghana. Although the ingenious application of Disruptive Technology, locals are commonly unaware they even have a sight problem, and when they do, readjusting glasses when shared in a family for instance, proved to be a job for an optician instead of a child or uneducated father, taking aside the risk of further damaging the eyes. One thing that these last mentioned projects have in common is the absence of locals in distribution, service and sales. Locals are not expected to make a living by it, therefore decreasing the perceived (social) value of the product.

`sum`   Thus, by integrating local entrepreneurs in the BOP business scheme, the return value is more than promotion itself, but distinct channels of feedback, economical growth (meaning more customers) and knowledge transfer in both ways. Furthermore, distribution channels are simplified and more accessible, and offering proper service gains respect and generates income at the same time. Hereafter, technological developments should be adjusted and simplified (disrupted) in order to attain a local availability and integration of capability versus innovation (appropriate).

3.1   BOP & Refrigeration General

In 2008, the World Bank stated that 24% of the urban, and 67% of the rural world population did not have access to electricity. At the same time, 79,5 out of the 80,6 million newborns are born within borders of less developed countries (Population Reference Bureau, 2006), which means the numbers are likely to be valid today. But ever so, the electrification of the world is ongoing, which means the market for solar powered solutions is slowly aging, or decreasing in size in the long term. Urban areas are growing, merging and consequently, electricity grids are being connected professionally or by mere illiterate force. The rural areas within the developing world are being connected in a lower pace, be it as it may because of a shear lack of economical or ethical interest. Indian government for instance, stated to connect most of its population to an electricity grid within a severe time span, but the vastness of the problem means millions of people will still live without for the coming century. In effect this means; decentralized, solar based refrigeration will still be economically interesting to many households, entrepreneurs and rural industries for a long period of time.

3.2   Domestic Segment

Lack of electricity means lack of refrigeration, which in its turn proves an indirect cause for health traumas in underdeveloped areas. Spoiled food or dairy beverages are an ideal platform for foodborne disease spread in developed as well as underdeveloped areas. Salmonella, Cholera, Listeria are considered emerging foodborne diseases according to the World Health Organization, and may lead to sincere infections of diarrhea, blood poisoning or for instance meningitis. Diarrhea alone, counts for a severe death toll of 2.2 million children per year (UNICEF / WHO, 2009). Most of these microorganisms or bacteria are already active at room temperature, but thrive in 50-60 degrees temperature ranges. Thus, in accordance with the latter, the WHO advises to cook food at temperatures higher than 70 degrees, and "refrigerate promptly all cooked and perishable food, preferably below 5 degrees Celcius".

Among a solarbear survey, conducted over 150 Surinamese remote villagers, domestic use showed a potential opportunity. Nearly all people questioned (85%) were interested in purchasing a solar ice maker like the solarbear, 50% of those were prepared to pay in between €37,50 and €50, while 45% expected to pay over €50. An assumption while this research was conducted was that solarbear could create 2Kg of ice. In remote area's, if present at all, refrigeration is commonly acquired by combining a diesel generator and a used refrigerator.

In Surinam's remote area's, this refrigerator is shared among higher ranked villagers but supervised by the village head. Most commodities inside are less used for fish, and other perishables, but mainly for beer. The generator is only switched on during certain hours in between sundown and midnight, providing the needed electricity for the refrigerator and other products like cell phones. Only four to five hours of electricity, in the evening, and the villagers hope that the refrigerator content stays cool for the rest of the following night and day. The supply of diesel is limited and more important: expensive to get inland (a 3-4 day journey to and from regular sale points near the city industrial districts, quadruling the diesel price locally). Furthermore, the generator makes so much noise that people, nor animals, would not be able to sleep, and then there is the stench, all making the current solution close to ludicrous. Wealthier members of larger villages have their own small generator, used for the same (small) appliances.

1   Size around 4 L bottles of beer.

| 2 | Very affordable, around €50-70 for 2-3 Kg of ice a day. |
| 3 | Culture plays highly important role, high involvement during design, production, sales and maintenance. |

3.3   Small & Medium Enterprises Segment

Figure II.7   (Very) Small Enterprise.

Small to medium enterprises which sell food and beverages have a clear need for refrigeration. These remain a constant but slowly growing market worldwide. Small static shops are mostly family owned and within this sector, more margin for a refrigerator type product can be made. In Surinam, 15% of the total workforce owns a retail type shop, of which many sell food and beverages, these are mainly situated in the special market places surrounding Paramaribo's suburbs. Vendors mainly sell fishes, meat and vegetables to clients, while having a similar sized shop as a dutch market stall. Furthermore, many street vendors can be found across the BoP countries, they are small entrepreneurs, who currently use a baskets / boxes in order to relocate their products for sale; "there are thousands of vendors on the street of Ghana, and they are found in every corner of the country" - Nelson Owusa Ansah (SIFE Ho, Ghana, 2010). The street vending business is a major source of income for low income families, and currently vendors are forced to constantly go back and forth to supply joints when they run out of (cold-)stock. In Surinam, beer is a common good, and by conversation retailers are expected to pay €2000 maximum for a refrigerator system with a 20 bottle capacity. Globally, especially cold water is a high commodity good within these hot global regions, and many vendors sell sealed bottles on the street as a core business. Consequently, the SME segment varies much in desired size, technological requirements and portability options.

1	Varying sizes ranging from a small basket to 200L
2	Higher margins, €50 up to €2000 depending on specific market.
3	Large and growing market segment, BoP global.

3.4　Touristic Trade Segment

Within many BoP countries, tourist number rise yearly because getting around gets more and more accessible and there are many things to see, from culture to nature. In Surinam, the touristic trade was profitable in 2009 and many (mainly Dutch) head inland towards the Amazon rainforest for a few days with a tour guide and pre-cleaned cottage. Talking to Surinamese people, it came to light that this is a highly profitable market for the local communities, supplying the tourists with cold beer is a properly payed job, and all the tourists really want after such a hot ride inland. In Surinam, it is common to buy 1 Liter beer bottles, and in a refrigerator system in such a remote area can cost up to €2000.

1　　Main use for several bottles of beer.
2　　Incorporating cultural ornaments could be interesting in the design.
3　　Higher margins, can cost up to €2000.

3.5　Industrial Food & Beverage Production Segment

In and around the larger cities in the world, there are many similar production facilities where outside temperatures need to be tempered, ranging from perishable food harvesting to juices to fish storage rooms. These are supposed to be giant refrigerator houses by the size of a common hut, and are found all over the developing world. A paprika producing company in Nickerie (sweet surinam peppers) for example, owns two greenhouses and a total of 850 square meters production site, and is looking to store their harvest of 4000 paprika's cold and a cheap and reliable way to cool the greenhouses themselves. These production or harvesting sites suffer similar problems, noise, expensive diesel or, when connected to an electricity grid, power failures. In some cases even, ice trucks are summoned in the early morning just before local fishermen return to coast, and ice is manually shoveled in insulated houses to be ready for preserving today's catch.

In September 2010, "Kort Fruit Juices" - a juice factory in Paramaribo, had to close down its freeze room due to complaints filed against it from its surrounding neighbors. The authorities had to shut it down because the generators exceeded legally allowed noise levels. A large, freshly produced, batch of juices suffered spoilage due to the sudden shut down (de Ware Tiid, 2010).

1　　Large sizes, similar to a hut
2　　For temporary storage.
3　　Single, customized projects, no single solution possible.

3.6　Medical Segment

Figure II.8   Medical Segment need for refrigeration

Furthermore, lack of refrigeration in the developing world has another draw back, immunisation. Measles, tuberculosis, tetanus, diphtheria, polio, and pertussis are all diseases which are preventable by immunisation. Combined they are responsible for 2.1 million child deaths each year, of which measles contributes nearly half of the total death count. The cause, lack of proper vaccine distribution to rural areas. Millions of doses of vaccine is wasted due to improper, unrefrigerated storage and distribution conditions, a loss of more than half of all distributed vaccines. According to the WHO, it is a logistical challenge to properly maintain the advised 2-8 degrees Celsius range, using refrigerators combined with generators, ice packs, and cold boxes for storage, transporting them by airplanes, helicopters, trucks, or they are even carried by hand to get to the remotely situated points of use. Because of the controlled environment in which the vaccines should be kept at all times, a low technological solution is most likely out of the question. The demands for a highly reliable refrigeration system range from a minimum 5 day (and night) continuous operation to storage without the risk of inactivating the vaccines due to freezing. In the case of a refrigerator this effectively means feedback controlled sensors and refrigerating activators, which adds many complications and eventually adds to costs. Lastly, there are new technological progressions in (measles-)vaccine production which enables storage at room temperatures and a longer shelf life. A typical cold chain is represented by figure II.9, reports from WHO suggest shortcomings concerning the cold chain such as power failures, next to improper or inadequate maintenance of the equipment. Furthermore, in these cold chains, reported shortages of temperature maintenance equipment keep on existing, only 58% of the sub-health centers researched in India, claimed to have proper vaccine carriers for transportation to rural villages, remote health posts. Furthermore, vehicles used for vaccine transportation become quite hot when sitting in the sun, it is therefore recommended to be able to use a plug and play carrier device (Sammat, 2007).

1   Plug and play carrier device.
2   Remote health clinics suffer power failures, or are not connected to any grid at all.
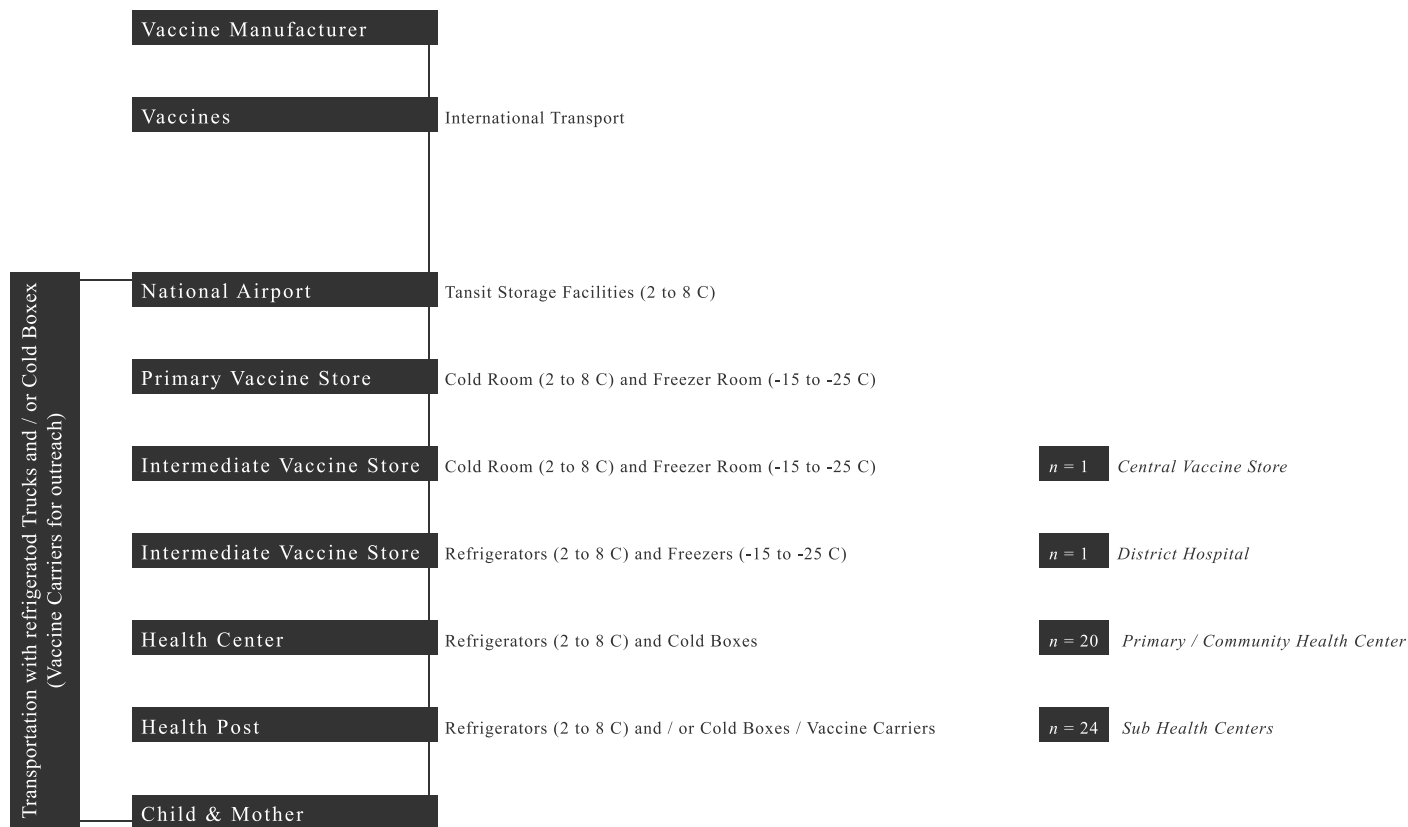3   In between 2 and 5 degrees Celsius for 5 days.

Vaccine Manufacturer

Vaccines — International Transport

National Airport — Tansit Storage Facilities (2 to 8 C)

Primary Vaccine Store — Cold Room (2 to 8 C) and Freezer Room (-15 to -25 C)

Intermediate Vaccine Store — Cold Room (2 to 8 C) and Freezer Room (-15 to -25 C) — $n = 1$ — *Central Vaccine Store*

Intermediate Vaccine Store — Refrigerators (2 to 8 C) and Freezers (-15 to -25 C) — $n = 1$ — *District Hospital*

Health Center — Refrigerators (2 to 8 C) and Cold Boxes — $n = 20$ — *Primary / Community Health Center*

Health Post — Refrigerators (2 to 8 C) and / or Cold Boxes / Vaccine Carriers — $n = 24$ — *Sub Health Centers*

Child & Mother

Transportation with refrigerated Trucks and / or Cold Boxex (Vaccine Carriers for outreach)

Figure II.9   Cold Chain (WHO)

B | BOP | 4   Market Segment Selection

Out of the earlier mentioned target groups, only the SME segment is chosen for further review. This has several reasons; concerning the product design, the expected amount of expenditure, the entrepreneurial spirit and the fact that salesmen need to stand out against competition are the most important reasons. Within this market segment, culture does still play a significant role in terms of product handling, look & feel, sales and strategy.

B | BOP | 5   Competition & Similar Solutions

Within the chosen market segment, there are already some refrigeration types available, ranging from diesel generated vapor compression refrigerators to evaporative refrigeration which use the evaporation energy of water to cool down the surface surrounding their produce. To be able to compare these, the wheel of Buijs is used (see appendix B.2.1 for a general description).

The criteria which were determined with the SME market in mind. Portability is a term concerning street vendors, which are supposed to travel back and forth to and from the market place. A high score on affordability means no to very little money will be spent on using the product, similar to the initial cost price. A high initial cost price would most probably scare eventual consumers in a low-income market. The term scalability is all about adjusting size or easily buying several more if eventually in a later stage entrepreneurs have generated more income. Furthermore it takes a closer look at the fact that no street vendor or small business has the same wishes for refrigeration. Useability looks at the practicality of3.2 use, i.e. constantly adding water in a evaporative device is found to be unpractical, especially when water is scarce, the same goes for adding ice in a coolbox. Last, cultural adoptability looks at how a refrigerator is, objectively, able to fit in a BOP type marketplace.
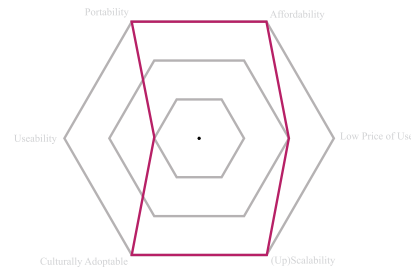
Although directly similar solutions to small scale solar refrigeration are not really available, a few were chosen as comparison. For more information on these solutions visit appendix C.BOP.2.
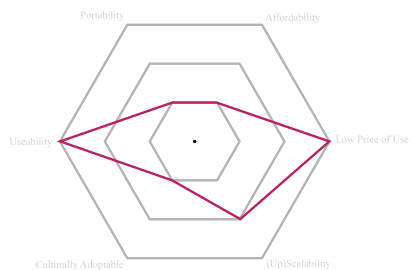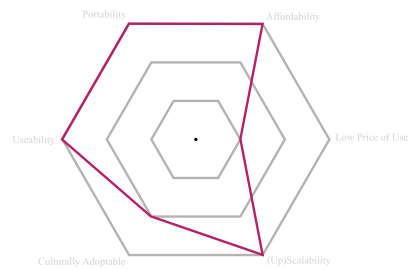
Generator & Standard Refrigerator
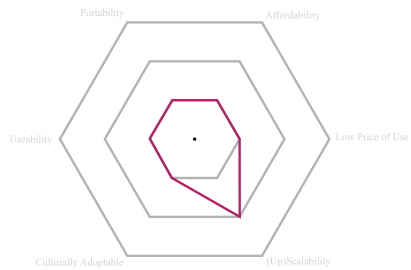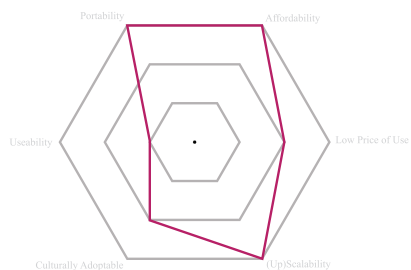

Coolbox & Ice

PV Cells & Standard Refrigerator

Small Refrigerator & Electricity (Chotukool)

Evaporative Cooler (Zeer Pot)

Solar Adsorption Refrigeration & Coolbox (Point Zero)
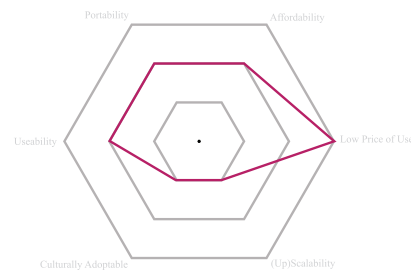
Figure II.10   Buijs Scores for Several Refrigeration Solutions within BOP situations.

From the chosen criteria, affordability, low price of use and scalability are of critical importance. These three criteria together form the right half of the hexagon in the proposed wheel of Buijs. None of the suggested solutions are able to meet all three of these criteria, although some of them score rather high, they immediately lack on the opposite ones; portability, usability, and culturally adaptably. The latter term refers to the earlier described use of appropriate technology and level of involvement in the many facets that surround any product (development).

sum   The new solarbear product should cover all criteria with high scores, but especially affordability, low usage costs and (up)scalability aspects should be reconsidered in order to differ from existing solutions. When the cultural adaptability is high within a new type of product, extra added value can be created concerning the involvement of local communities.

B | BOP | 6 SME Market Design Context

Context is defined as those aspects that may influence the experience of a person by using a product (Stappers & Sanders, 2003). In Western societies, the context of a product is becoming more specifically important due to the personification, or the increase in more specific products which are all used in more specific user group environments. In an environment of development, where primary needs form the base of product design, context is even more important in order to understand the level of acceptance by local inhabitants to a western made product (Sleeswijk Visser et al, 2005). Culture, art, affordability, rituals and values all play an important but different role compared to a western society. These contextual aspects need to be explored and understood by a designer (Papenek, 1985), before they can be righteously incorporated within the design of any product for the real world.

6.1   Research Set Up

Context mapping research is set up in the following matter; preliminary desk research has been conducted in order to define several methods, tools and pre-assumptions to research a focus group of ex-local villagers found within the Netherlands, hereafter these pre-assumptions are redefined and methods are adjusted for application research in the local villages.

6.2   Research Goals

- To understand local symbols, heroes, rituals and values.
- To understand the local importance of health care and refrigeration.
- To understand the cultural aspects that influence product design.
- To understand the service system that evolves around a product.

6.3   Research Questions

rq1 How does an average day look like?

rq2 How important is health within local societies of Surinam? What are the understood consequences of the lack of proper health care?

rq3 How is food consumed and prepared? Who and Where?

rq4 How does the hierarchical structure look like, who determines a purchase? Man / Women? How is possession shared? Is it a diffuse or specific culture?

rq5 How important are local cultural values in a technical driven product?

rq6 Is the principle 'refrigeration' understood, and how to explain if not? Are there comparable systems available locally?

rq7 How important is local entrepreneurship, what is it and how to stimulate it? How to change it, when broken, will it be fixed?

rq8 How to visualize a blueprint or manual? Use of pictograms, language e.d.

6.4   Hofstede

According to Hofstede, a Dutch cultural analyst, any culture can be divided into four different score types, which can be locally determined and globally compared. Although criticism around this theory remains, the scores do provide an initial platform for general cultural comparison. Different values are given to each researched or estimated culture; the power distance index (PDI), individualism (IDV), masculinity (MAS) and the uncertainty avoidance index (UAI).

The scores provide an potential overview in BoP countries, since they are nearly opposite to the western cultures in which the business was initiated. As seen in figure II.11, most listed BoP countries nearly score double on inequality and masculinity, while at the same time individualism seems commonly unappreciated compared to the Netherlands. Uncertainty avoidance scores nearly similar except in Arab countries and Surinam*
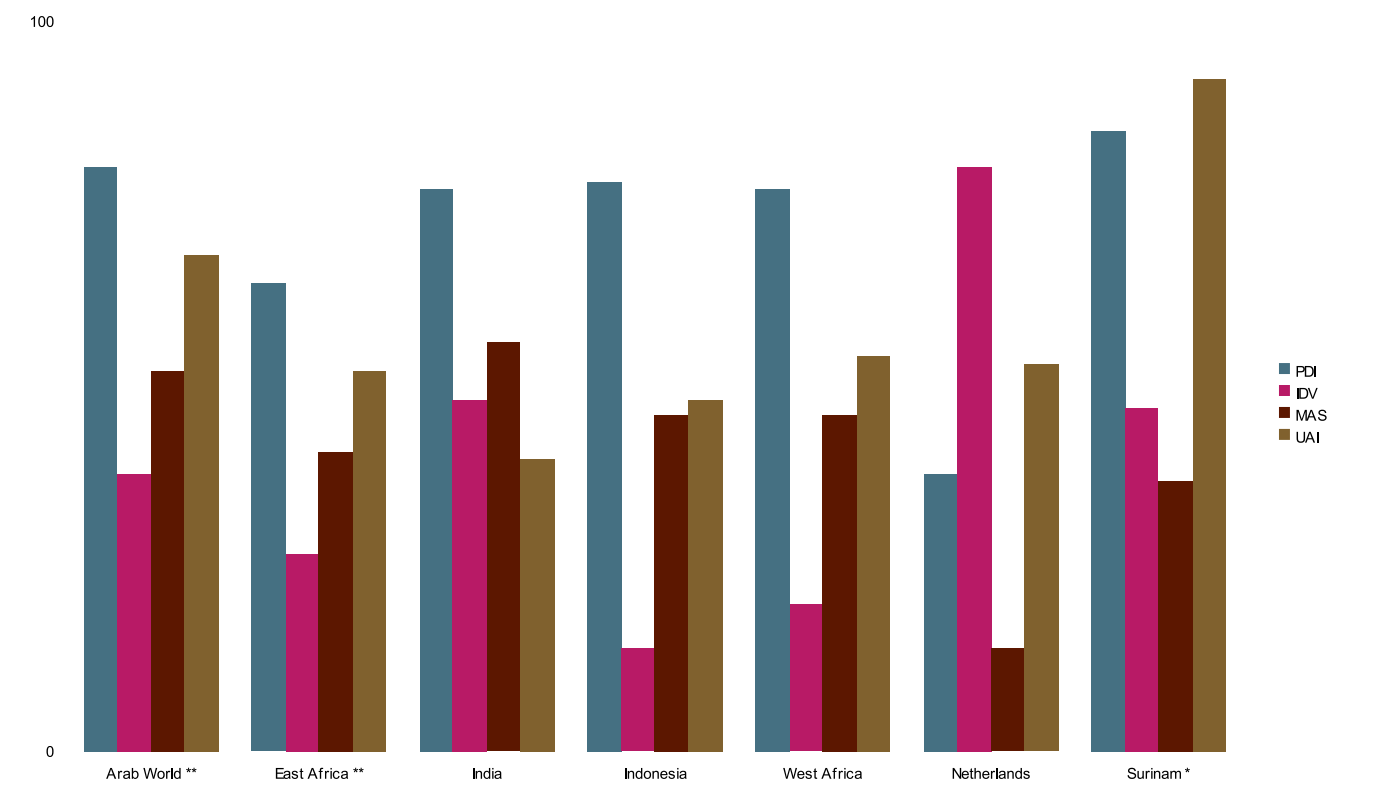
PDI   A high Power Distance Index score shows the extent into which less powerful members of organizations accept and expect that power is distributed unequally.

IDV   Low Individualism scores mean a collective culture, a culture where people are expected to look out for each other on personal and financial terms, while in an individualistic culture, everyone is expected to take care of themselves.

MAS   High Masculinity scores represent a competitive, assertive culture, while low scores refer to modest and caring societies.

UAI   The Uncertainty Avoidance Index is associated with cultures in which surprising, unexpected situations are avoided, by means of strict legal laws or religious ruling.

*   The scores of Suriname are estimates.
* *   'Arab World'   : Egypt, Iraq, Kuwait, Lebanon, Libya, Saudi Arabia, United Arab Emirates
         'East Africa'   : Ethiopia, Kenya, Tanzania, Zambia
         'West Africa'   : Ghana, Nigeria, Sierra Leone

Figure II.11   Hofstede Scores for generalized Countries in Development.

II.18

sum   The assumptions retrieved from the scores do not only influence the type of business model needed, but also influences the product design, its functionality and use. Inequality means conducting business with the right people of status to reach the desired collective group, while the product itself should provide a competitive advantage against others. In most of these cultures, personal history is highly valid, and doing business through the (unintentionally) wrong channels does affect resulting sales. The openness, or low uncertainty avoidance, reflects the opportunity of which any of the cultures are able to accept a new technology or the general idea of a solar driven refrigeration system.

6.5   Tools & Methods

Several research tools have been designed in order to come to a better understanding of daily life in present and future. Furthermore, the importance of health care and refrigeration is researched by means of a cultural probe booklet. These booklets were emailed before the focus group sessions in order to stimulate story telling, a still thriving cultural feature. The consequences of materials, local arts & crafts, sizes and sharing are researched with creating collages and by a preference tool, to determine local adoptability of the product. Lastly, a Go Fish (Dutch: kwartet) game was created in order to find out more on the general topics of the Maroon culture. The tools are presented in appendix C.BOP.4..

Two Maroons joined for the preliminary focus group session in the Netherlands. It was held at the 'Tropenmuseum' in Amsterdam during the exposition of "Art of Survival, Maroon culture from Surinam". Afterwards one of participants gave all of us a guided tour through the museum to offer the opportunity to share more intimate stories. The total session time took about 2 hours, including open discussion and was recorded on video. For the focus group session I joined forces with Ir. R. van de Velden, an expert in human centered research and design, she co-facilitated the session and has given clear distinct directions for its setup. The tools served as a means to engage discussion on cultural topics and the way a solar driven refrigeration system could properly fit within the chosen context.

B | BOP | 7   Results & Elaboration of Stakeholders and Social Vision

For the BOP, the product needs to be low cost and empowering.

The conclusions described in appendix V.C.BOP.4.2 are solely valid for Maroons from Surinam and Surinamese people in general, derived from the focus group. Although different BoP countries hold different values, some of the conclusions can be extrapolated and used as a more general design guide because of similarities in between cultures. Not only do the Maroons originally stem from multiple regions in Africa, within Surinam, they have learned to settle and keep their culture within a very cross cultural country. The Maroonial culture has roots in many different regions in Africa, and is therefore a strong general mix of these different regional African cultures and languages. Still, although superficially different, the essence of values and rituals are very similar (i.e. village structures, family structures, storytelling, (krutu) gatherings, expressions of belief/culture by obtrusive (& natural) ornaments, etc etc). For more information on the Surinamese culture and history please refer to appendix V.C.3.

Population Group	% (2010)
Amerindians	4
Old African Tribes	0
Boeres (Dutch)	1
Creoles (mixed descendants from Dutch & Africans)	18
Maroons	15
Javanese	15
Hindustani	27
Chinese	8
Brazillians	8
Other	4

Figure II.12   Cultural Groups in Surinam, History Present and Expected Future (based on literature, CBS Surinam, and research of T.Fey & M. de Thije.)

The chaotic history of Surinam, provides an excellent platform when taking into account the many different subcultures in the global BOP countries; it has highly mixed divisions of Western-African, Indonesian, Hindustani, Indian, and more recently Brazilian & Chinese origins. A global historical time line is shown in figure II.1, in which this mixed culture is clearly visualized through time. Most of these subcultures within Surinam, are still in contact with their land of origin in some way or another, still hold similar essential values but are able to make a living together at the other side of the world. Maroons, the less wealthy of the Surinamese, are representatives for the BOP target group within this project, they survive in similar living conditions as other global target groups in i.e. Africa, Indonesia and India. Commonly in remote, hard to reach area's where there is only unreliable electricity or no electricity at all. Or, at the city borders where hygiene, education, wealth is low, and where they make a living by selling produced or caught food, live on selling the roots of their culture, for instance by producing ornaments for tourists. But, at least one clear distinction should be made; the oppression of the Dutch during the formation of early Surinam, resulted in stronger cultural grip by the Maroons, of which they claim to have "The best kept true African culture".

Resulting from the Maroon focus group, internet & literature research, many personal confrontations and personally supervised research executed by solarbear student teams, it was possible to map the overall context through an adoption tool, which can be found in chapter II.C. And, by using the mentioned information, a collage was made, demands were defined and a global user scenario for the BOP SME segment could be created.

7.1   Research Answers

rq1 On an average day people just go to work, to make an honest living. But, time is relative and everything has its own pace. Getting up in the morning, going to work, in the meanwhile taking the needed breaks especially during those long hard and hot hours at noon. In Surinam, during normal weekdays, it is common to go home little past noon (in between 13-15u), although this is different everywhere, long noon breaks are common sights in Ghana, Morocco, Indonesia, and at varying spots in India. In most cases, people stay at the spot they later have to return to. What this means for a solar based refrigerator is that it should be able to easily take along to any spot desired. rq2 Healthcare is becoming an increasingly important issue, with globalization, examples are to be followed through movies theaters and other media, meaning the awareness for healthy food and refrigeration should be rising together with rising wealth. As stated before, physiologically, health should be the first thing money is to be spent on. rq3 In rural villages food is prepared whilst sitting on the floor, in almost all cases by women. Therefore, the refrigerator should be oriented low to the ground. The same applies for many street vendors, who sell their produce sitting on curbs or any other edge of a market place. rq4 In Surinam, it came to light that men do purchase items for the family, but as the females themselves said, they are the ones who decides what is needed in the house. Behind every Kabitan (leader), a woman stands firmly, apparently, their influence is greater than expected according to the two Kabitans in the Netherlands (both tribe leaders of the two main tribes). Meaning in the case of Surinam, the woman should want the product first of all. I reckon that this is a relatively rare occurrence, although of course all women influence actions of men, meaning this has to be reconsidered in other BOP countries. Culture plays a main role within every BOP country. In the specific case of Surinam many failed projects exist who did not recognize the great value and potential, even free aid has been refused, for the only reason wrong people represented it. Furthermore, old or ancient beliefs are still strongly valued, and expressed through many types of art. It is unlike the west, where art seems more a way of expensively expressing ourselves, art is who they are. Everybody seemingly expresses themselves more rigorously, through dance, chant and other arts like paint or wood carving.

The only realistic way to enter these local markets rq7 , is to involve or empower the people in it. No one will be interested when there is not anything of value in return, be it respect, knowledge, but most probably financially. The people do not want to just sold something, and their cleverness and handiness with locally known tools is not to be overlooked; there seems to be a great desire to grasp the future while enhancing cultural value. Still, the illiterate rate is high everywhere. Be it handyman or not, knowledge is passed on by storytelling and by the use of locally known symbolics.

7.2   Collage

The collage represents the SME market segment of the BOP. The BOP consists of many contrasts, of mass scale living against a highly specific and personal culture, or the seemingly sad conditions in which normal life is led against the sheer happiness most of its people seem to irradiate. Roots of most BOP cultures lay within the differences, as belief is highly valued while most money is earned through exploitation and sometimes even corruption. It is more about the people itself rather than the explicit ornaments we own; knowing people, friends of friends of friends are always more trustworthy as it implies a safe guard when things do tend to go wrong while at the same time the people provide each other ladders in order to climb up any social or financial scale. Therefore, cultural values are kept high, and specific rituals symbolize the bond in between family, groups, provinces, places and countries. These near-ancient values are unwritten and differ for each culture, and are therefore visualized as spiritual.

Figure II.13   Collage BOP

The numbers refer to the numbers in the scenario visualization.

A human being wakes up at home near the borders of the city center Whilst sitting outside to feel the early light recharging his heavy mind **1** , he is confinely contemplating on his basic morning needs; sex, drugs and rock & roll. While in search of wealth, one thing only, seemed liable and logical enough to make a proper living. An ancient and family owned act of business; he has always been good at negotiation. Still, his desire to obtain a television, a mobile phone, microwave oven and a proper ventilated house for his family, still seems far from reachable. His sales did not go well yesterday, meaning he only made 3 American dollars out of the usual 5. But, as if normal, he suddenly stands up and eagerly travels to the common production site **2** , in which many of his friends sell their freshly caught/produced produce, in this case it is fish. These were friends who he had met along the way, who's family had specified on waking up in the middle of the night and at 4 a.m. started deploying the nets, that was not for him, he owned his hard to earn motorcycle. Because he has had this occupation for a long time already, and his fathers before him, most fishermen knew him well, and because of this long established bond, he is able to negotiate a fair price for the fishes he is intending to sell on the market streets Some pieces, he has to buy himself from the little leftover of yesterday, but with others he has been able to establish the desperately needed bond of trust, and he is able to take a few winning fishes along to sell at commission He knows the value of the fish he takes, and he knows these people well enough to get at least a proper profit margin for himself. Furthermore, he loves the market, the people, and with his smiling, convincing eyes, he has always been one of the better salesmen on the street. With this in mind, he straps the basket full of fish on the back of his bike, and travels through what white people seem to judge as terribly chaotic traffic jams **3** . As he is able to naturally flow in between the restless sound of car horns, after an hour or so, he arrives at his destination. The city streets, where everybody is looking to get something to drink and eat for the family tonight. He has always treated his products as a commodity, clean and carefully he displays the best fish first, right on top of the plastic sheet he recently unfolded on top of the curb next to him **4** . The rest of the fish stay in the basket, protected from the sun.

As the day develops, he has been able to sell all three prize winning catch, and exactly 11 smaller ones, 3 of the fish he brought he had to give away due to the spreading rot, they are a present to the dogs who scatter the place at sundown. He has earned 9 dollars, it could have been at least 10. But the human being is content, he already knows, today was a good day because at the end of it, he is left with 6 dollars to save for himself and his family, the remaining three will go to his friend the fisherman. With an empty, heated basket he turns towards home, but first that little detour through the city center to absorb the laughter, tension and the eagerness for a better life of all the people there, he loves it, he earned it.

Figure II.14   Scenario SME for BOP

7.4   Possible Strategy for a Solar Refrigerator in the BOP

In the example of a (solar) refrigerator, there are a few possibilities to involve local communities, culture by service systems. Although, it has to be considered that the difference in size of a few bags of hygienic products or a portable telephone does not comply with that of a relatively large refrigerator system. Dependent on the eventual design, locals can become involved in production, distribution, service and/or sales, it seems important to create a self sufficient circle in which locals are involved where they are able to generate an income, use their skills and respect their culture. The construction of a standard refrigerator is a complicated process, but, if it is possible to reduce complexity, local entrepreneurs are able to aid within the process if given the necessary ingredients like manuals, freedom and components. Secondly, when an (up)scalable device is eventually proposed, locals can participate in an advising role, customized construction and maintenance. In both cases, they are offered essential components in which they are enabled to take a personal, culturally viable approach in distributing the refrigerator to third parties. IKEA has a similar approach in Western countries and up to this day stays an appreciated and flourishing foundation (one of the biggest foundations in the world), their products are cheap, compact and highly customizable. Thirdly, by purchasing a refrigerator, small entrepreneurs selling perishable foodstuff and dairies are able to generate money by saving money: no more spoiled items to throw away at the end of the day, and no more wasted time and money on gathering ice or cold drinks at the proposed city joints. Furthermore, another aspect that is very important is the common absence of education, although most entrepreneurs are true craftsmen; sales, reading or writing still remains difficult. What does comply and returns as a core business aspect within BOP success stories, is the coloring, the way of commercializing and envisioning value by symbols. Thus, a clear color scheme has to be chosen, which should be repeatedly used together with manufacturing, selling and distributing the product.

7.5   Positioning

To be able to strategically position any new refrigeration type concept within the BOP world, it has to be weighed against the other available solutions. As reluctantly came forward from earlier research, cost price and costs of use are of high importance. At the same time, the manner in which appropriate technology is applied does influence product efficiency, using accessible technology as described in chapter III, will lower effectiveness but increases local empowerment. These four different facets have formed the axes of two different types of positional strategies as seen in figure II.15 & II.16.

When looking at these two figures, it becomes clear where a new type of refrigerator should fit in order to differentiate from existing solutions, and it enables a hint of design parameters that are used in chapter IV. Figure II.15 shows a few possible positional gaps when compared to other solutions, but, considering BOP constrains only one is chosen; combining low costs of use with a low initial cost price. The second figure (II.16) shows a huge gap in between the highly efficient and appropriate technology axes. But, by choosing appropriate technology as a main focus, a combination with highly efficient solutions are a near impossibility. The technique used, as will become clear in chapter III, will be able to outperform solutions using ice and evaporative cooling, but is only able to approximate efficiencies of other (electricity driven) solutions. Therefore, the only possible position within this graph is making high use of appropriate technology while making a compromise on efficiency.
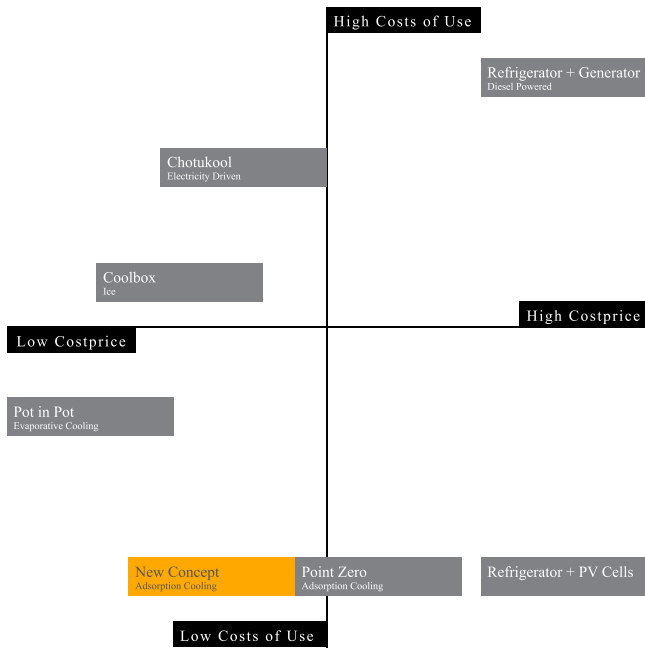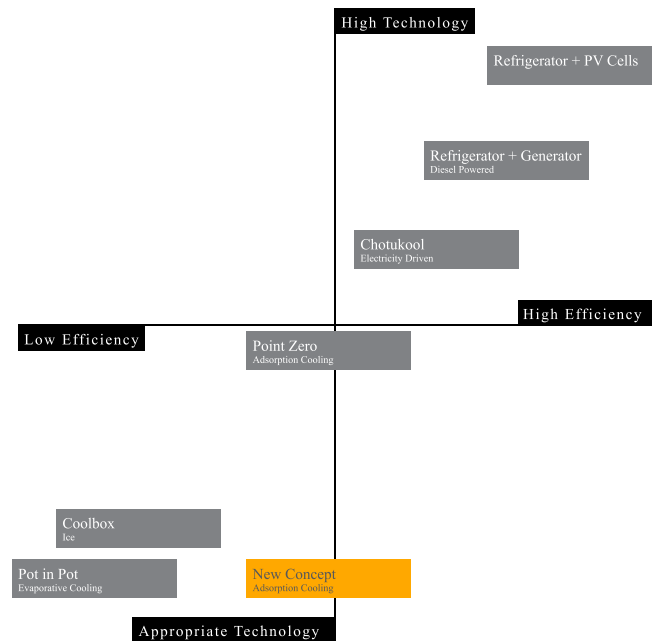
Figure II.15 & 16   Positioning of the new concept versus other solutions in terms of costprice and price of use & expected efficiency vs appropriate technology.

The demands enlisted below are concluded from BOP market research, and therefore form part of the basic guidelines which serve the eventual design of a solar refrigerator .

Cultural

- High involvement in development (empowerment).
- Common inequality means using respected people to set up a business with.
- High values for own cultural expression, make use of culture.
- Status increasing product, from masculinity.
- Include entrepreneurial activity in i.e. production, sales.

Functionality

- 3-4 Kg vegetables or;
- 3-4 bottles of water.
- Adaptable in size (upgrading/upscaling).
- Use of Appropriate Technology (M.A.Y.A).
- Can withstand harsh environment.
- Replaceable from one spot to another.
- Works in all, dry, and humid climates.
- Autonomous system.
- No electricity.

Look & Feel

- Related to normal fridge/coolbox.
- Supports cultural expression.

Pricing

- Lowest price possible.
- Between €50-70 for 2 Kg of ice in Surinam.
- Short payback time.
- Possible use of micro-finance.

Wishes

- Low use of water (scarce).
- Low number of actions.
- Enabling knowledge transfer.
- Watch out with using theft sensitive materials.

BOAT stands for the other extreme, the high end market in western societies. Instead of using a sole focus on cost price or costs of use, while empowering communities, different facets reach the surface. Within western cultures, there are many different user groups who all have different specific wishes, and whether these wishes are met determines the success of a product in terms of sales. Much more focus lays within expression of one self through products, although this seems similar to empowerment, it actually very much different. The actual need to own products is a creation itself. The difference can be best described by a simple example: while we struggle to get the newest mobile telephone from the store to be able to differentiate from each other, BOP struggles to get mobile coverage. Thus, the essence of need is different; the need for expression through lifestyle versus the fulfilment of essential needs for survival. Using Maslow's theories and a refrigerator the need is in the upper segment "esteem" (figure II.1). In the case of a solar refrigerator, the focus shifts to a lifestyle segment: sustainability. This kind of lifestyle is found in many different segments in western society, within the next chapters a combination is proposed where solar refrigeration is not only wished for, but needed as well.

B | BOAT | 2 Strategy

Many theories for product sales are thinkable, although one basic principle is generally most valid; cost price in combination with commercialized and targeted promotion. It is impossible to determine a proper strategy without a finished product or chosen market segment, but, it is interesting to contemplate on the combination of BOAT and BOP. As a way of generating funds to keep BOP price per refrigerator as low as possible, BOAT countries are able to partly provide. Openly targeting the refrigerator system (slightly) more expensive than needed in western societies, while repeatedly focussing on sustainability and the fact that buying such a system in the west offers a kind of micro credit for BOP entrepreneurs at the same time is a tactic that is often found within the Netherlands. For instance, the "Staatspostcode Loterij" (Dutch lottery) increase the price per ticket as part of their strategy, to exhibit an ethical image, and openly supports many causes in the developing world. Non-profit organizations like the World Wildlife Fund often sell all kinds of overpriced fluffy objects in order to support the decreasing world habitat. Furthermore, even the famous Dutch 'plakkies' (sandals manufactured by local African women) were a great success, not only were they made of old tires, the open support to African communities changed the way a lot of the Dutch stood their ground.

B | BOAT | 3 Possible Market Segments

Compared to the BOP markets, western markets can have much higher margins per product, creating higher revenues and profit for a starting company. Although the Dutch market is already much more fulfilled; it has many types of refrigerators or similar solutions, with the still raging trend of sustainability focused products and biologically produced food, people are becoming more and more aware of the possible change. For a solar refrigerator, that functions without electricity, only a few western market segments are possible. In all of them, higher margins per product easily make up for a smaller market size. There are many different niche markets possible for small, solar based (or off grid) cooling, and in most niches, sun is likely to be present at the time of activity.

The festival market, or the small scale drivable beverage shops, sell cold drinks to attending festival goers. These little to large festivals are mostly located at open spots, and every board of directors hopes for good weather. The stalls in which beer or other cold beverages are sold varies from small to larger, but all of them have room on top of the roof of the stall for the needed collector that drives the solar refrigeration system. These stalls are all, always, sponsored by large(r) companies. Herafter, the Netherlands has a relatively large camping or traveler nichemarket, many of the Dutch go out to France or other countries in relative close proximity, all of them are in search of the sun. A small scale refrigerator, for a few beers and maybe

a piece of meat, should be sufficient. This small scale device could also be used for short trips to the beach for instance. A downside to this market is the relative lower margin. People in the boating or sail market however, do have a relatively larger budget, and are more eagerly prepared to make a judgment in quality verses cost price. And even seen technically, it offers opportunities since water cooled condensation is much more effective (this is explained in chapter III.1.2) Assuming sailing on our lakes or doing trips with friends through the canals of Amsterdam is mostly done during those few sunny days in the Netherlands, this niche seems the wisest choice.

B BOAT 4   Market Segment Selection

The total market for recreational boats in the Netherlands is actually quite large, nearly 210.000 waterbased vehicles are presently in the water, at harbors, attached to houses and near the canal berths. The prospects for future growth are positive, the total number of available berths at the Ijselmeer for instance is expected to grow from 35.000 to nearly 50.000 by the beginning of 2020.

Within the boating market there are a few differences to be clarified, assuming different types of boats have similar needs for refrigeration, they do have different specifications. From a research commissioned by the Dutch Ministry of Agriculture, Nature and Foodquality (Dutch "Landbouw, Natuur en Voedselkwaliteit") in 2005, it appears that the number of cabinsail- and cabinmotorboats account for 80% of the total number of boats in the researched harbors, meaning a number of 140.000 (see appendix V.C.BOAT.1). The leftover is taken by flat-bottom types and open sail- and motorboats. Of course, within the larger category, varying size is another important consideration, and according to the same research it appears that most boats fall into the 7-11m category. Last, the type of material used for manufacturing is mainly polyester (62%), steel (32%), followed by wood. For a sustainable refrigeration system this could mean two things; a complete and portable refrigerator, or a modular type which is manually build in within the ship.
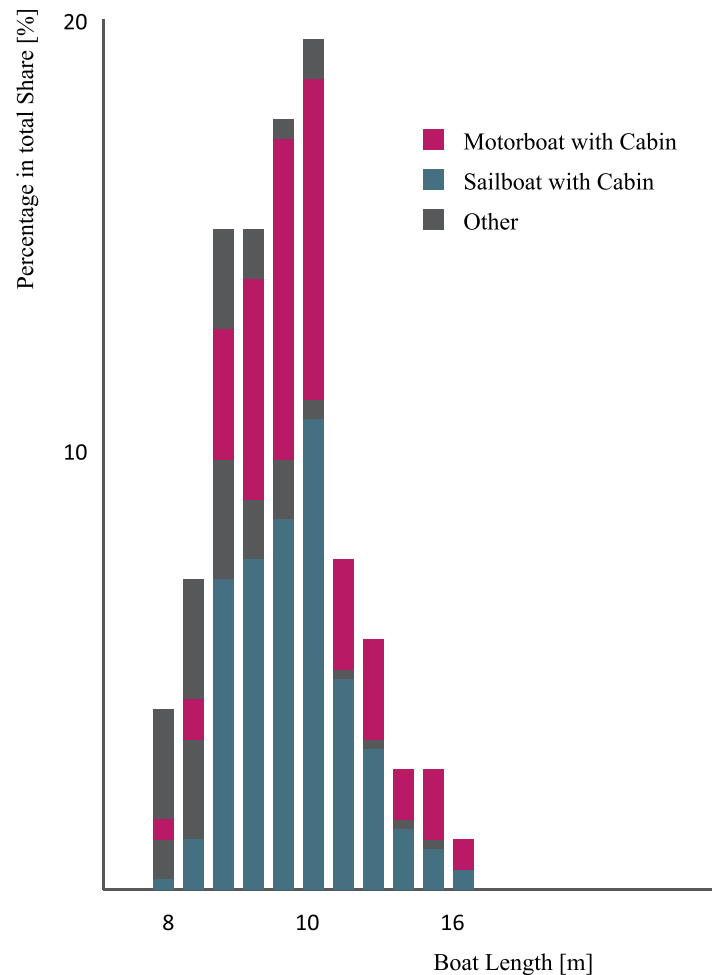
Figure II.17   Size and Share of Different Types of Boats

In cabinboats, be it propelled by wind or solely motorized, a fair share of the owners want refrigeration for those moments in time that it is possible to drink and sail. The whole day on the water is a moment for enjoyment, without any goal except to relax, and cold drinks are the usual part of it. Apart from the profoundness towards others, as the boat can be seen as an expensive extra car with a special drivers license, worth at least €20-200.000, a boat is always in need of certain maintenance and constant replenishing. People who own a boat are generally aware of risk of decay and reserve great care, time and money to keep her up for those rare but greatly desired occasions. Furthermore, especially with sailors, a close bond between certain waters are formed, nature provides. These are near ideal circumstances for a refrigeration system based on natural or sustainable principles.

There are some different types of refrigeration for boats available, with only one main difference, integrated (working

components) or a separate system (similar to a normal fridge). According to several boat appliance shops (i.e. korendijk watersport), the separate systems are hardly sold and most owners want their fridge to resemble their boat. The following systems are available for small scale boats.

Again the wheel of Buijs is used for overview, although this time different criteria are of importance. Costprice, as usual, together with useability are the same. A sustainability factor will replace the price of use, since research shows nobody actually knows, apart from the fact usage prices are low compared to income. A sustainable (or in this case "good for the environment") solution is of rising importance, also according to the rise of electrically powered boats. Hereafter, the extend to which the system can be integrated within a different type of boat, compatibility, is a factor that seems important to boat owners. One critical factor in the BOAT market is whether a system is always able to work, which of course could prove to be more difficult using a solar powered solution. The last factor, desirability, resembles the way to which objectively could be looked at the type of system. There are two types of systems evaluated; a refrigerator type which is sold as a complete package and a second which is sold as separate parts in order to integrate it within a boat design, sold at (starting from) 400 and 600 respectively.
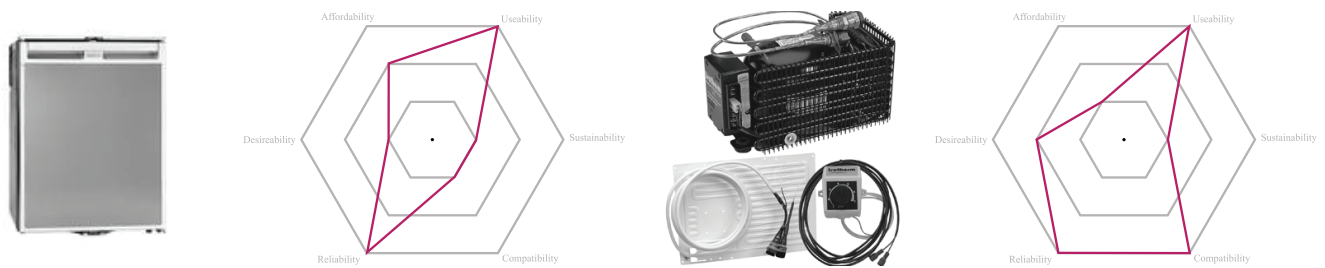
Figure II.18   Seperated &Integrated System against the wheel of Buijs respectivily.

When looking at the existing solutions from a Buijs wheel perspective, both score greatly on usability and reliability. Since for a solar driven system the latter is a hard to meet demand, focus should be applied on sustainability compatibility and affordibility of the system in order to differentiate.

B | BOAT | 6   BOAT Market Design Context

6.1   Questionnaire

In the overall short time span of this added market group to this thesis, a request for an internet questionnaire was sent out to readers of the boating magazine GodeVaert. Amongst the 13 participants it showed that just over 50% already own a refrigeration system, and from those nearly all were relatively satisfied (only one was actually unsatisfied), but still interested in new a new type of system. The average boat length was close to the results published by the Dutch Ministry at 6-8 meters, nearly all with cabin and some with sail (20%). Furthermore, only two participants were female, the rest was male, with an average age above 50, and purchased their boat around 3-5 years ago. For questionnaire results refer to appendix C.BOAT.1.2.

More interesting aspects concerning this short survey are the following, these owners all make short day trips at around 20-50 days a year, with a high probability on beautiful weather. Sometimes they take friends along, but want to drink cold wine or beer nearly every time. The refrigerator will not be used for food, but for drinks, and does not have to be on at all times but only when needed, it does not even need to freeze. This means it can get up to temperature if necessary. The desired

refrigerator itself can be relatively small (at the size of a crate of beer) because of the short day trips and the fact that people only want to cool their products for a short amount of time. Furthermore, sustainability issues for a solar driven refrigeration system are not seen as a problem; no issues were noted with an extra action if necessary. This is especially true for sailors who already have to do a lot of operations in order to dock or sail away from the harbour. Furthermore, there is around 0,4 square meters available for a properly designed collector and such a system is valued at around €300-400, or more (one mentioned €1000). Hereafter, price is more important than design but it is desirable that the system integrates, or resembles their boat characteristics; some participants already suggested to integrate the fridge in one of the storage cupboards.

These conclusions are very interesting for a modular refrigeration system, and even if only 2,5% of the potential market can be reached, minimal revenues could exceed €1 million with just over 3500 users.

7.1   Collage

The intended BOAT segment has a high connection to nature, to personal and tailored products. BOAT has an expensive hint of taste, and continuously explores means in order to grow first class. BOAT takes its time, like the flow of sand and water. It watches the dutch natural change with great appreciation. Moreover, BOAT is not all about the people, but about the boat itself, the care that has been taken to be able to use it throughout the year, the solitude and bond in between it and its owner.
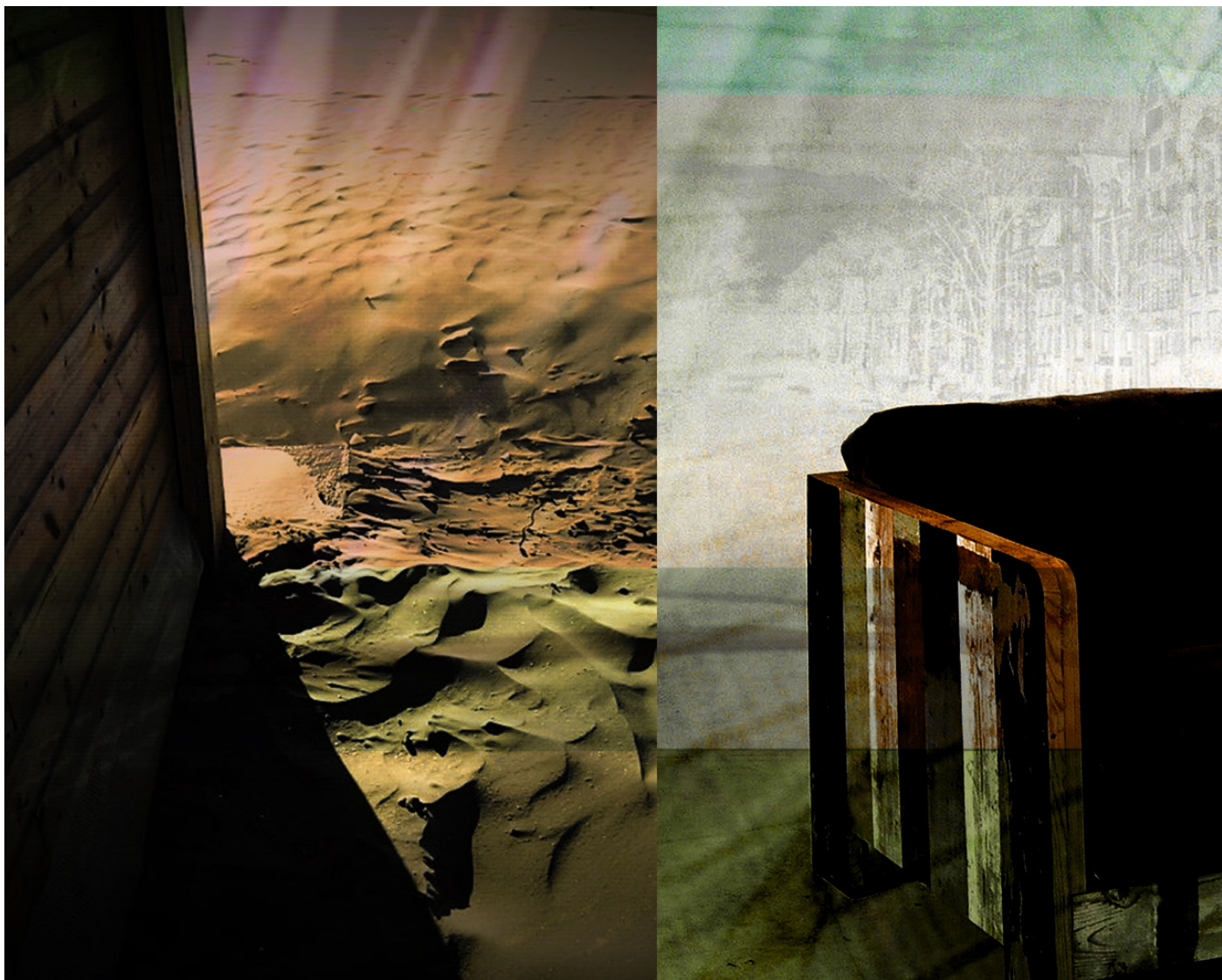
Figure II.19   BOAT collage.

The numbers refer to the numbers in the scenario visualization.

On a beautiful day in the weekend, probably a Sunday, a self made human being decides to use the boat he owned for a few years already. The boat, is one of shear excellent detail, and the curvature of the bent wooden boards follow the flow of the calmly surrounding water. While the dark wood stain reflects the rippled lake just like the boat builder intended to when the first sketches showed up upon the drawing table. This boat, as it means nothing to many, is a substantial part of the life of him. Great care has been taken to maintain its excellence, and every small bijou is kept as new. As much as possible, around 40 days a year, when the days are right and time is on their side, his old love is spun back into existence. Today is one of them. To celebrate this random beauty, a few bottles of dry white wine together with some snacks and soda were purchased **1** at some of the well known specialists within the surrounding area. Once the necessary money is spend, all the groceries for today's little trip are loaded in his classic old timer. Conveniently parked alongside the city harbor, only a short walk is needed in order to get to the boat. The groceries go into the fridge immediately **2**, and because this is the first time in a long while the boat is used, he flicks the switch to "on". A common trespasser would not be able to see the difference in between the normal cupboards, because the fridge has the exact same look & feel as the rest of the boat. And within only 20 minutes or so, partner and two friends arrive to share.

A little struggle when leaving the harbor, it has been a while, but the boat is on its way. And not much time later, the first bottle of wine is decapitated and enjoyed together **3**, although not that cold yet, the next one will be.

At sundown, the company returns to dock, left overs are taken back home. No hassle, no worries, a day of quality.

Figure II.20   BOAT scenario.

7.3   Possible Strategy for a Solar Refrigerator

Derived from the questionnaire and conversation with boat related shop owners, it would be best to offer the eventual product through existing channels: the boat shop and the internet is where people first look for new assets. According to Korendijk Watersport, regular or separate refrigeration systems are hardly sold, thus a focus should lay on the possibility to integrate such a solardriven system in the boat. This modular or scalable focus has another advantage when solar driven systems are taken into account, the fact that a solarpanel needs to be kept in the sun, and has to be kept separate from the other parts (see chapter III).

7.4   Positioning
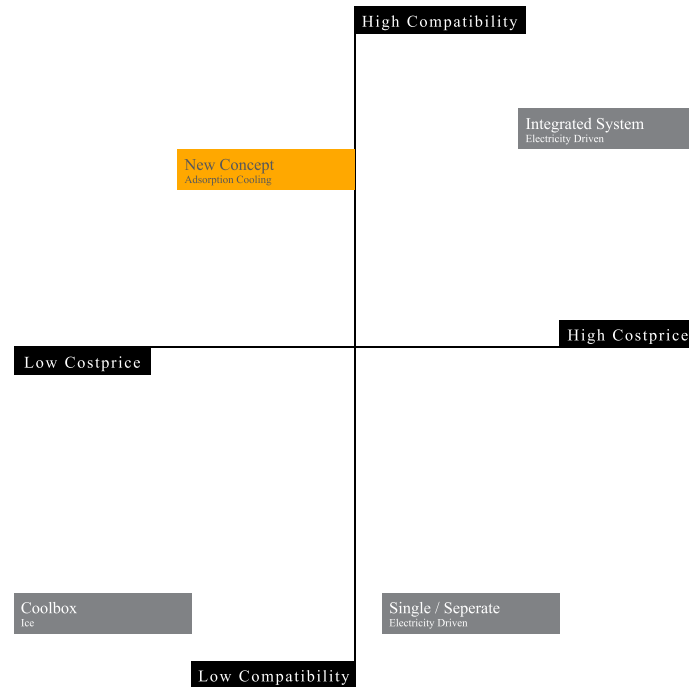
Figure II.20   Strategic Positioning in BOAT segment.

For positioning of the new concept, three existing systems were compared, the regular coolbox, seperate and integrated systems. Apart from the fact that any new solar driven system already has its differentiating focus on sustainablility, in needs to be able to be kept below the price of existing solutions, while compatibility or the possibility for boat integration should be kept as high as possible.

Cultural

- Plug & Play, no hassles, no DIY.
- Status enhancing product.
- Focus on sustainability, no problem with action.

Functionality

- Always functioning when needed. (20-30 days a year)
- Size around a crate of beer or;
- 3-4 bottles of wine
- Adaptable in size (upgrading/upscaling).
- Can withstand harsh environment.
- Collector size adaptable, but around 0,4 m2.
- Autonomous system.
- No electricity.

Look & Feel

- Integrated / resembling boat looks.

Pricing

- Lower than competition.
- Between €300-400.
- Short payback time.

Wishes

- Use of cupboards.
- Low number of actions.

When looking to integrate BOP markets to BOAT using the same essential technique, only one thing really differs; looks. Also according to C. Zeijlstra who redesigned the Philips woodstove from a rural Indian market to a European camping market, not much except looks and more multifunctional use is necessary. As she concluded her main research question "The final product proposal is suitable as cooking appliance for the Western camping market. In combination with the barbecue unit it is a multifunctional product which matches the camping experience". Thus, focussing on functionality while reconsidering the way an outer shell looks could transform the concept from a low income market to a high income market.

C 1   Adoptation Tool

A culture adopts and cares for a product if key aspects of it are reflected in the product.

Adoptation of the product is dependent on several context factors, derived from previously researched cultural factors, social and physical environmental factors. Determining these factors influences outlines of the product. Adoptation criteria are derived from literature studies on BoP projects mainly in India, but they are generalized factors.

The adoptability is of high importance for the success of implementation in Emerging Economies, consequently it can be stated that many similar projects have failed due to a lack of understanding of these factors. Furthermore, the cultural adoptation is just as important, or even more important, than the technical innovation brought to these area's.

The adoptation criteria can be divided into nine different subfactors; accessibility, affordability, compatibility, reliability, usability, empowerment, comfort, desirability and repairability. The goal of this study is to determine which subfactors are more significant within cultural boundaries and which factors influence the eventual shape, use, type of production and costs.
A more extensive description of these factors is given in appendix B.2.2, here the factors are placed in order of importance for the BOP and BOAT market to provide a clearer distinction in between the essentials of the two.

Figure II.21   The Adoptability of the two markets.

A returning factor in both markets concern product pricing , which is in many cases most important selling any type of product in any type of market. Furthermore, compatibility is another shared value, although it should be performed in a different manner; compatibility of the technique with its people for BOP markets, and compatibility of the technique with the boat itself in BOAT markets. But, when looking at the two markets in the adoptability graphic, it is more about the contradictions than anything else. First of all, the biggest contradiction is seen in empowerment and reliability, which have nearly switched place. For BOAT segments, the reliability of the system is of utter importance, while reliability serves a lower value in BOP markets. At the same time, being involved in anything surrounding the product (i.e. production or sales) is not a factor generally shared by BOAT markets, while it is most likely the only way to enable expansion in a BOP type marketplace.

There are many differences when the two different lists of demands are laid next to each other, some important ones are i.e. price range and of course functionality, in which the boat market is much tougher to meet. But, one important overlap, is the modularity, or adaptation to either culture or boat type. This means that the eventual product most likely needs to be scalable to fit any type of entrepreneur and boat, and be adaptable to the exact desire of each market segment.

- Price range BOP (< 70) much lower than that of BOAT (< 400)
- Functionality of BOP (as good as possible) is much less than of BOAT (always working)
- Scalability is found in both market segments
- Adaptability to BOP (cultural adaptation) is similar to BOAT (adaptation to boat itself)

A   Introduction

*T*his chapter concerns the technical side of this graduation, on the specific topic of adsorption refrigeration. Adsorption refrigerators have many different facets to be understood, ranging from general heat transfer to its essential parts, and accessories. Chapter III attempts to orderly attain an overview of each different aspect starting with generalized terms to eventually zoom in on the several available parts, (productional-) techniques and further details to eventually come to a list of demands that serves as a design guideline.

A 1   Heat Transfer

In pure essence, refrigeration is based on heat and mass transfer. By forcing the displacement of evaporating molecules from one place to another, heat and mass relocate because of the endothermic reaction of evaporation, storing energy in the form of heat. Because heat travels through a closed system, with different temperatures, speeds and pressures at several key points in the system, energy is constantly taken in or rejected, to or from a surrounding environment. Thermodynamical terms like convection, conduction and radiation play a very important role in the overall effectiveness of such heat transfer, and form the fundamentals of a refrigerator.

A 2   Convection

Convection is the work done due to the movement of molecules in between a solution, such as air or water and a surface. Convectional heat transfer is thermodynamically described as:

$$Q = hA (T_s - T_o) \qquad \text{eq. 1}$$

In this formula a fluid flows over a certain surface. And heat is transferred between the body's surface (T_s) and its direct environment (T_o). The total heat transferred is expressed in Watts, and heavily depends on the surface area (A) which is in direct contact with the transferring fluid's specific properties of heat transfer (h). Only two basic theoretical ways are possible to influence convectional heat losses. De- or increasing the surface area lowers or raises the total heat transfer respectively. Secondly, the specific heat transfer coefficient of a fluid (h) varies strongly on the type of that fluid; for instance, air has coefficients ranging in between 10-200 W/m2K, while liquids (water) are commonly 5-500 times more efficient in transferring heat and range in between 50-10.000 W/m2K.

A 3   Conduction

In conduction, heat is transferred between neighboring molecules in any substance where a temperature gradient is present. Heat always travels from a high temperature situation to a low temperature situation. Conduction is mathematically described as:

$$Q = - kA (\Delta T/L) \qquad \text{eq. 2}$$

Conduction losses are commonly the most influential losses which happens in for instance a insulated refrigeration box. To decrease total heat loss, the lower part of the formula is of importance, in which the thickness (L), the material constant (k) and the contact surface area (A) of a body in between two different environments at different temperatures (T_i, T_o or ΔT) influences the total Watts transferred. To lower heat transfer as much as possible, the variables k and A need to be small, while L needs to remain as large as possible.

A 4   Radiation

Thermal radiation is electromagnetic radiation, and depends on a body's temperature. The radiation of the sun reaches earth through the vacuum of space (where there is no convection nor conduction possible). In mathematical terms:

$$Q = \varepsilon\ \sigma\ A\ [(\Delta T)^4] \qquad \text{eq. 3}$$

The emissivity of a body (ε) and again the surface area are the influencing factors. Emissivity is the relative ability of a surface to emit energy by radiation. The value given for it is dimensionless, thus, a relative measure to which a body radiates its absorbed energy. A theoretical black body has a relative value of $\varepsilon = 1$, and does not radiate, in reality this is always less. Silver is an example of a highly reflective surface and has a very low ε value of 0.02-0.03, while an oil painting has an emissivity of ε 0.92-0.96. Silver reflects nearly all the energy that strikes its surface, while oil paintings only reflec 4-8%, the rest of the energy is absorbed by the oil. Emissivity is important in for instance the inside and outside of any refrigerator; inside, as much of the energy (or coldness) as possible needs to stay inside, thus radiating energy back inside is highly recommendable. Outside, as much heat needs to be kept out, therefore, low emissivity values are desirable.

B Adsorption Refrigeration

Considering refrigeration, there are many differing technical solutions which have been researched by L.Schürg in a previous solarbear oriented graduation, which describes the topic of low cost refrigeration and technical exploration. Next to vapor compression, Stirling, and even magnetic cycles, it showed that the adsorption is one of the most cost effective, relatively accessible, and possibly modular cycles considering the main overlapping demands of BOP and BOAT. So, adsorption refrigeration became the technical basis of this thesis.

There is a difference, and a commonly made mistake, in between absorption and adsorption cycles. Apart from the second letter itself, the difference lies in how the refrigerant fluid is absorbed, the type of chemical reaction. In adsorption, the refrigerant is contained within a surface of another *solid* material, the refrigerant in the absorption processes is absorbed in a volume or a *fluid*. The last mentioned generally have higher efficiencies but also add to the complication of the process, therefore being more expensive, less modular, and less accessible. The further exploration described within this chapter will only concern adsorption cycles.

Adsorption is a process which still works while moving because of the use of the combination with a solid material. This is unlike other techniques (i.e. absorption), because moving the internal (liquid - liquid) system will clog it and prevent it from working, this is the reason why waiting for a few hours is necessary before turning it on again, after moving a standard home refrigerator around the house.

B 1 General

The adsorption cycle can easiest be understood as being a battery type process having two different phases; the desorption phase and the adsorption phase. In essence it is an intermittent process, in which the first phase has to complete in order to initiate the second. But, there are many different options on a subsystem level, material variety and even shifts in working principles; the combined outcomes differentiate in being either intermittent, 'continuous', modular, appropriate, efficient and/or affordable. A very basic diagram of parts and phases is showed in figure III.1 - The Intermittent Adsorption Cycle, a more complete view of the different stages can be seen in figure III.2 - Adsorption Basic Principle in which the different phase levels in molecular description are displayed next to essential parts of a solar driven refrigerator. Note that the sun initiates the process and in figure III.2 it is displayed at the bottom instead of the expected top.
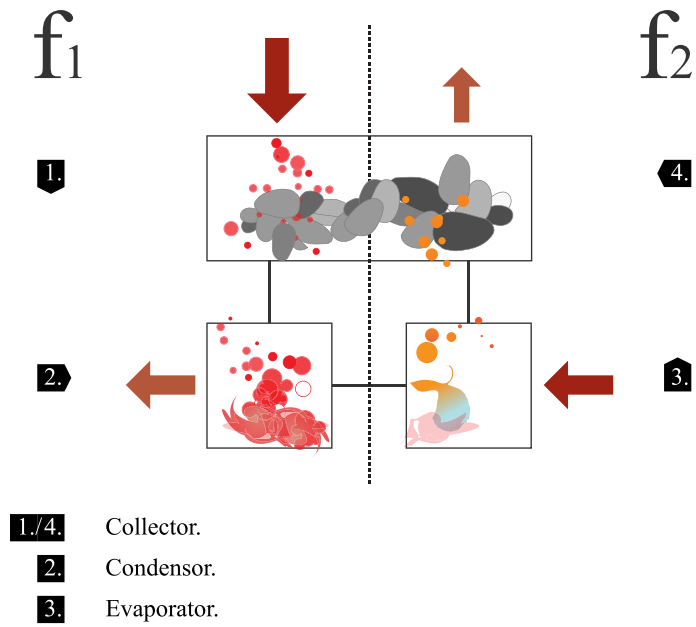
f_1 f_2

1./4.	Collector.
2.	Condensor.
3.	Evaporator.

Figure III.1   The Intermittent Adsorption Cycle Simplified.

adsorption

insulation

evaporation

condensation

desorption

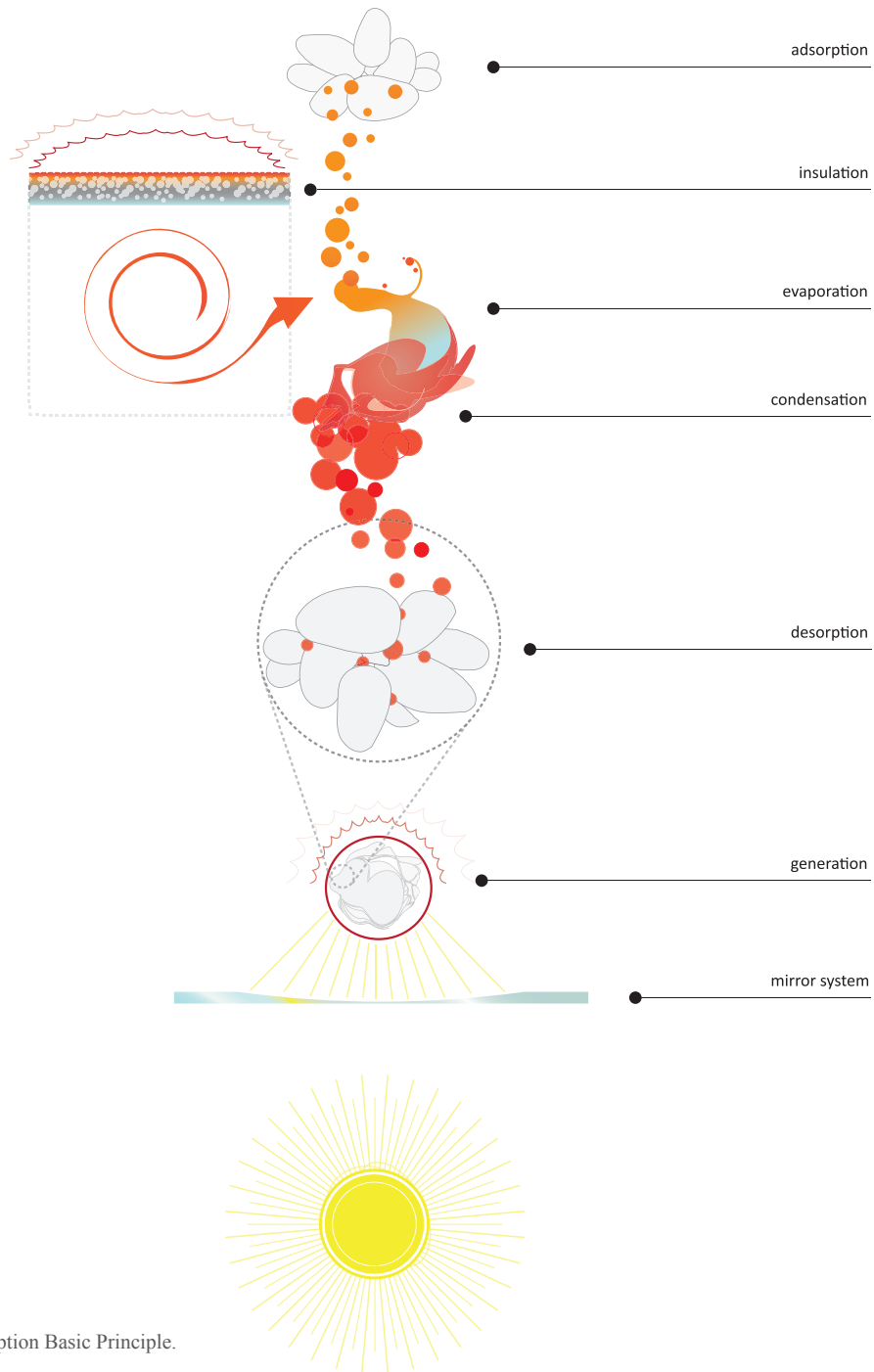generation

mirror system

Figure III.2   Adsorption Basic Principle.

B 2   Desorption Phase (f1)

The desorption phase can also be refereed to as the collection phase in an adsorption refrigerator system. It describes the phase where the needed energy input is generated, in the form of solar heat collection. The collector can be seen as a closed bucket constantly catching solar heat on its surface, and contained within is a solid material with a high specific surface. It is on the one side connected to the condensor and at the other side connected to the evaporator, but this last connection is shut off during this first phase (f1) so there is only one way out, towards the condensor. Captured within this solid material is the working refrigerant or adsorbate, which is the actual reason why this is a refrigeration cycle. The refrigerant needs to change state from fluid to gas in order for the endothermic reaction to initiate, but first, it needs to be turned from a gas into a liquid using the generally method described hereunder.

At the left side (f1) of figure III.X, heat is collected in the collector, which can also be called a generator. The heat causes the gaseous refrigerant contained within the solid material to vibrate which causes them to release from this surface because one of the lowest forces holding them within, van der Waals forces, break; this chemical process is called desorption. Because the pressure within the collector rises due to a rise of temperature and an increase of moving gasses within the available space that is left outside the solid surface material, the gaseous refrigerant is then forced towards the condensor, the only opening left open.

Here, heat is dissipated to the environment by conduction, convection and radiation, and the adsorbate (gaseous refrigerant) condensates into its liquid state. As a liquid, it travels down by gravity, and is further pushed by pressure. At the end of the condensor, it is contained like in a reservoir. The efficiency of this phase depends on temperature and pressure differences in between the reservoir and the generator; when the temperature difference is high, the speed goes up. The working pressure in this phase is determined by the condensor.

B 3   Adsorption Phase (f2)

In the adsorption or cooling phase which is seen on the right side (f2) of figure III.1, the adsorbate is still contained in the described reservoir as a liquid. In this phase, the actual reaction that causes refrigeration is initiated, due to the endothermic reaction of the adsorbate when it evaporates. But, only when the heat input at the collector drops enough (i.e. when the sun is down at night), the pressure within the whole system is able to drop sufficiently for this phase to start. The liquid adsorbate can only evaporate when a certain pressure in the system is reached, and the exact amount of pressure desired depends completely on the type of adsorbate used. Thus, the pressure in the system is sufficiently low, and the liquid is slowly dripped into the evaporator through a pressure regulating valve, similar to what happens in a percolator (the famous espresso maker designed by Bialetti). Because the whole system reached the desired pressure, all of the liquid wants to evaporate, a pressure regulating valve and the one way valves force the liquid to travel through the evaporator first, where it changes state to gas, and heat is subtracted from the direct environment surrounding the evaporator (i.e. the inside of a refrigerator), which is then stored in the evaporating adsorbate molecules. As a gas, it is only possible to travel one way, back to the collector where it all started in f1, but this time, because pressure and temperature are low, the gas is again captured within the solid material by van der Waals forces, and this last reaction release the heat captured by the gaseous molecules to its surrounding environment. This last reaction is called adsorption.

The working temperature and pressure in this phase are due to the desired pressure in the evaporator, and again, what these exact numbers are depend on the type of refrigerant or adsorbate used. Furthermore, the efficiency in this phase is strongly dependent on the temperature difference in between the adsorber and the evaporator.
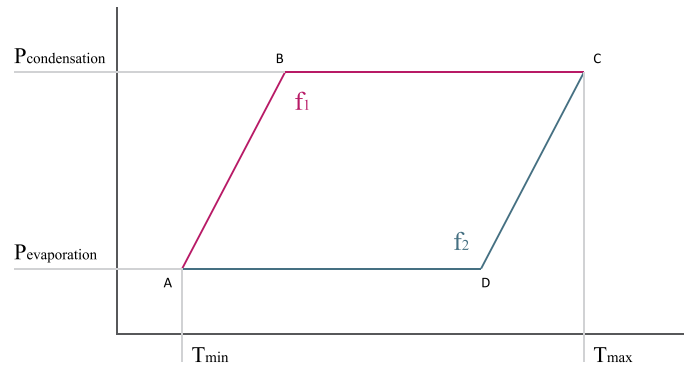
Figure III.3　　　Pressure Temperature Diagram of the adsorption cycle.

Another way to explain this schematically is by a visualizing a pressure and temperature diagram of both phases (see figure III.3 Pressure Temperature Diagram). The two different cycles work at different temperatures and pressure equilibrium. Desorption (see figure III.3, ABC) works at high pressures and temperatures, while the adsorption phase (figure III.3, CDA) works at both low pressure and temperature. Pressure and temperature within an adsorption system are highly related to each other which will be further examined within the chapter of adsorption pairs.

Solid sorption (= adsorption) systems need a different range power inputs, pressures and temperatures, depending on the working pair (the adsorbate), and there are many different possibilities described in chapter III.4.

Although the needed temperature input to initiate phase 1 varies in between pairs, an advantage of adsorption systems over that of absorption is that the input can be relatively low. For the desorption phase to initiate, temperatures as low as 50˚C (Wang, 2009) are sufficient and are manageable for low cost applications. The low power input also plays an advancing role for solar applications, when for instance there is more cloud coverage, the solar radiation can still provide enough energy to get to the initiating temperature. Furthermore, a low temperature input implies a more affordable collector, because getting to a higher collector temperature adds costs and complications. Furthermore, adsorption technology is suitable for moving refrigeration systems, unlike absorption systems which would have a liquid adsorbate moving around within the (liquid) system and clogging it eventually. In adsorption, the adsorbate is solid and does not move along when the system is shaken nor stirred, meaning it is a suitable technology for traveling applications (i.e. a ship [Wang, 2004]) or other means of transportation (Ron, 1984; Han et al., 1986).

C   Adsorption Refrigeration Facets

The general principle can be divided into several key aspects, but it has to be clear that all are interlinked because the complete process efficiency depends heavily on the interactions in between the different subsystems. But, for the sake of comparison of efficiencies, costs & relevance, all the different subsystems are extensively described. Although many options exist on a subsystem level, they have been separated into two main categories for synopses purposes; essential **ESS**, and accessory **ACC**.

ESSENTIAL

1 Adsorption Pair   The refrigerant pair which determines the thermodynamical principle.

2 Collector   In which the adsorbent is contained, captures and releases solar heat and uses it to drive the phases.

3 Condenser   Where the adsorbate condensates into a liquid, and is contained during phase 1.

4 Evaporator   Where the liquid adsorbate evaporates, and heat is subtracted from the surrounding environment.

ACCESSORY

1 Isolation   Which is the heat shield preventing heat to travel through its surface.

2 Valves & Flow   Which determine parts of the total efficiency of traveling fluids.

3 Cycle Time   The intermittent cycles can be shortened to simulate a continuous cooling process.

The goal of this research is to provide an overview in the limitations and possibilities of the technical aspects, to engage a discussion and weigh costs, efficiency, local availability, manufacturing processes and practicality issues in the form of a demand list.

The adsorption pair is of high importance for the working of this adsorption refrigeration cycle, it not only determines the internal working pressures and needed temperatures, but also forms a substantial part of the total eventual costs of a complete system (see chapter III.C.ACC.6.Prototyping). The adsorption pair consists of a solid material (adsorbent) and a refrigeration fluid (adsorbate). First they are researched seperately, and secondly combined conclusions are made.

1.1 Adsorbents

An adsorbent is defined as:

Adsorbent	*A material having capacity or tendency to adsorb another substance.*
Sorbent, sorbent material	*A material that sorbs another substance; i.e. that has the capacity or tendency to take it up by either absorption or adsorption.*

The adsorption process is basically a process in which molecules of a substance bind to a surface of some highly porous material. This binding process can be divided into physical adsorption and chemical adsorption. Physical adsorption is a process where van der Waals forces act in between the molecules of the adsorbent (surface material) and the adsorbate (refrigerant fluid). The physical process is similar to surface tension, and is also a consequence of surface energy. Physical adsorbents with mesopores can adsorb molecules in consecutive layers, those adsorbents with micropores have their pores fill up with the adsorbate. Physical adsorbents are produced in such a way that they are able to develop a kind of selectivity, and before implementation they undergo several specific treatments. Chemical adsorption is caused due to the reaction between adsorbate and adsorbate i.e. electron transfer, atom rearrangement and fraction or formation of chemical bonds. Furthermore, there is a difference in between naturally occurring adsorbents and composite adsorbents. Zeolite and charcoal are examples of natural (physical) adsorbents while i.e. metal chloride is a composite one; where a combination of chemical adsorbate and a porous medium is created in production processes. Adsorbents are commonly categorized with a pore size, ranging from 3A to 10A, where 4A is one of the most common ones, able to absorb water, ethanol, methanol and other adsorbates. Furthermore, the adsorption capacity is expressed as a Kg/Kg factor, the amount of Kg adsorbate which is able to be adsorbed in 1 Kg of adsorbent.
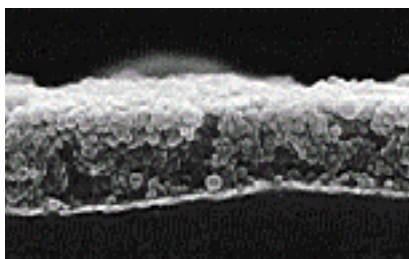
Figure III.4   Adsorption General, micrograph of a gas that is being trapped within a solid material.

Desorption, the release of refrigerant molecules out of the surface material is very important in the first phase of the adsorption cycle, the collection or generation phase. Hereafter, the binding of molecules happens in the second phase, in the cooling or adsorption phase. As stated earlier, in each phase different pressure and temperature ranges drive the process. Logically, the specific surface area plays a very important role in the amount of adsorbate which can be bonded to the surface.

For a more extensive study on the different adsorbents please visit appendix D.1, here .

1.6   Adsorbent Conclusions

For this specific application, the adsorbent must have a high adsorptive capacity at ambient temperatures ranging between 20-30°C for phase 2. Furthermore, a large specific surface area increases adsorption capacity per m3 of adsorbate, which depends on the number of nanosized pores.
For a choice of a suitable adsorbate, the following factors should apply:

1   High adsorption and desorption capacities for an optimal refrigeration effect.
2   Good thermal conductivity to increase speed of ad- and desorption processes.
3   Low specific heat capacity.
4   Chemically compatible with adsorbate.
5   Low costs and local availability.

Adsorbent	Surface Area [m2/g]	Price [€/ha]	Notes
Charcoal	600	8,3	Low adsorption capacity.
Activated Carbon	1000	10	Commonly used.
Bamboo Activated Carbon	1400	14	Sustainable.
Activated Carbon Fiber	1600	50	High adsorption capacity, shorter cycle times.
Silica Gel	800	12,5	Water.
Zeolite	-	-	Only with water, no freezing possible.
ZeoCarb	1000	-	Yet unknown in adsorption.

* are estimated values

Table III.1 Adsorbent Overview

In table III.1 it becomes clear that Activated Carbon should perform best versus price per hectare of surface area. Bamboo Activated Carbon comes at a very close second but the price has not been stable over the course of this thesis and varies in between €400-2000 per tonne. Charcoal is left out due to the fact a lot of it is needed in order for it to adsorb enough refrigerant (adsorbate, chapter III.C.ESS.2), due to its low adsorption capacity.

An adsorbate is defined as:

Adsorbate	*A material that has been or is capable of being adsorbed.*
Sorbate	*A material that has been or is capable of being taken up by another substance by either absorbtion or adsorption.*

The workings of refrigerant fluid is based on its evaporation point and strength. One of the most important factors is the latent heat of vaporization of a refrigerant, this is the amount of energy needed for vaporization within the evaporator. Here, energy is taken from the surrounding environment in the form of heat, and depending on the type of refrigerant, more Joules per Kg of evaporating fluid is needed from its surrounding. The point, or temperature (i.e. $0°C$), of vaporization depends on the pressure at which the refrigerant is put and this can be read with a vapor-pressure chart (see Figure III.12). Common refrigerants for adsorption refrigeration are Ammonia, Water, Methanol and Ethanol.
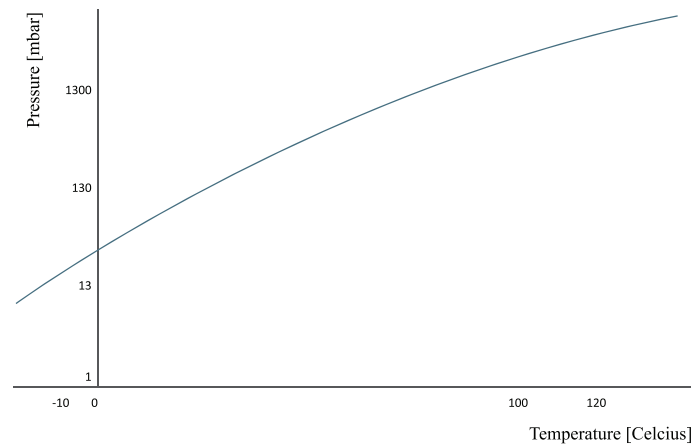
Figure III.12 Vapor Pressure Chart of Methanol.

Pressure is an important consideration within this project, since the system will be used in remote areas. When pressure within the system changes due to i.e. leakage, the system will not be able to work. Especially vacuum pressured systems, with vacuum pressure refrigerants like Water and Methanol (any refrigerant with a boiling point below $-10°C$ at 1 atm), could prove to be a problem because near vacuum is hard to achieve with common (local) tools. Although, a simple vacuum pump is does not have to cost more than a €400, moreover, hand operated vacuumpumps do exist in automotive industries for around €50 (see figure III.5). But, any pressurized system increases the risk of failure of the system, even a small amount of air infiltration could seriously compromise the system's performance. Ammonia is an example of a positive pressure refrigerant, and operates above atmospheric pressure, but here the same problem applies with included dangers, whenever a hole is made in the closed system, it will not work anymore. Although the hole would probably be easier to find since (hazardous) ammonia would be squirting out of the system because of the positive pressure; in a negatively pressurized system, air would be sucked inwards on failure. Perfect pressure would be around 1 atm, normal atmospheric, but as found in literature these are commonly toxic materials.

Figure III.5   Hand Operated Vacuumpump.

The optimal refrigerant should have:
1   High latent heat of vaporization per volume unit.
2   Thermal stability.
3   Environmentally harmless and non toxic.
4   Chemically compatible with adsorbent.
5   In a solar application it should be non-flamable.
6   Saturation pressures in between 1 to 5 atm.
7   Low viscosity, against obstructions in pathways through system.
8   Low viscosity, against obstructions in pathways through system.
9   Low price and local availability.

Property	Methanol	Ethanol	Ammonia	Water
Saturation Pressure [mbar]	30	13	16000	0-50
Latent Heat [KJ/Kg]	1102	842	1368	2258
Density [Kg/m3]	791	789	681	958
Normal Boiling Point [deg C]	65	79	34	100
Needed KJ	3600	3600	3600	3600
Expected Weight	3,27	4,28	2,63	1,59
Expected Volume	2,58	3,37	1,79	1,53
Price [€/Kg or L]	0,4	0,3	0,236	0,05
Price Total [€]	1,03	1,01	0,62	0,08

Table III.2 Common Refrigerants for Adsorption Cooling and their properties.

From table III.2, methanol and ethanol have similar saturation pressures, but the latent heat (the amount of energy it can absorb per Kg) of ethanol is only about 2/3. Methanol is generally non-toxic, but direct contact with skin and eyes can be

harmful, meaning precautions within the production process and on repair. A non-toxic working pair would be preferred. Such a fluid is water, which also has a very high latent heat, meaning it is able to absorb much more energy per molecule than other fluids, and is more easily obtained locally than for instance methanol. But, it has a big downside for an intermittent adsorption system, water is not able to vaporize below $0°C$. Not being able to vaporize below $0°C$ means water is not able to store its energy (coldness) in the form of ice because it would freeze the internal system, temperatures below zero must therefore be avoided. One possible solution for an water adsorption refrigeration system is reducing its cycle time to avoid freezing, and thus only maintaining certain temperatures just above $0°C$ inside the intended coolbox. Another possibility could be to store the energy in another phase changing material than ice, which has a freezing point above zero degrees Celsius.

If activated carbon or activated carbon fiber is the sorbent, other adsorbates like R134a, R22, R407c can be used. Compared with methanol however, their mass unit cooling power is smaller due to their small adsorption quantity or due to their low latent heat of vaporization. Besides that, HCFC's and HFC's are unwise due, especially within the scope of this project, their high global warming potential values.

General equilibrium adsorption curves for physical adsorption are shown in Figure III.6, where Pevaporation is the evaporating pressure and Pcondensation is condensing pressure. Figure III.6 shows that the adsorption quantity is influenced by two parameters, i.e. temperature and pressure.
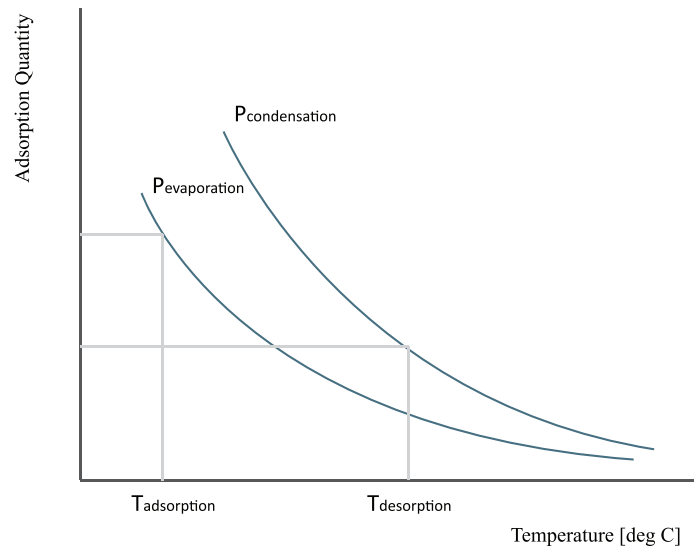
Figure III.6   General Equilibrium Adsorbates

4.3   Conclusions

Material		Ammonia	Methanol	Ethanol	Water
Charcoal			0,2	0.15	
Activated Carbon	*Super Char*		0.33	0.189	
	ACF		0.6		
	BAC		0.45		
	ICF	1			
	GFIC	0.95			
Silica Gel	*Mesoporous*	-	low	lower	
	Microporous	-	low	lower	
Zeolite	*13-X*	-	low	0.031	0.17

Table III.3 Adsorption Pairs Capacity [Kg/Kg]

Commonly, Activated Carbon & Methanol is chosen to be the working pair due to the large adsorption capacity, and low adsorption heat. This is due to its low relative input temperature for desorption (in between 80-100°C) seems promising for a low-income market, since the desired properties for the collector decrease in intensity and cost, and therefore seems a logical choice. Activated Carbon & Ammonia is another common working pair, but it operates at a much higher pressures than AC/Methanol (16 bar compared to 20 mbar) and desired input temperature. A higher operation pressure means a better performing mass transfer increasing efficiency, but, Ammonia is still a hazardous solution if not handled properly. Furthermore, Ammonia's incompatibility with copper (see the relevance in chapter III.9) and smaller adsorption capacity when compared to AC/Methanol at the same working conditions (meaning more AC is needed per L when using ammonia). Next, derived from experimental results, Activated Carbon & Ethanol has a COP four times lower than AC & Methanol[4]. The working pair AC & Ethanol, although non toxic and interesting when looking at BOP markets, did not lead to any creation of ice in experiments (Huang et al., 2004). ACF & Methanol does have an adsorption capacity of 2-3 times higher than AC & Methanol, and using ACF even significantly reduces cycle time. Although this is very promising, it is yet underdeveloped and will increase costs per Kg dramatically compared to AC/Methanol (Sumathy, 2003).

Due to the large adsorption heat and high adsorption temperature, Zeolite & Water perform worse than AC/Methanol at heat sources below 150°C, but do have a higher overall COP when the temperature of the heat source exceeds 200°C. The disadvantages of the pair is similar to those of Silica Gel & Water; its impossibility to evaporate below sub zero temperatures and bad mass transfer due to the low working pressure. Furthermore, high adsorption heat and desorption temperature, increases the cycle time, meaning it will take longer to extract the needed amount of energy for ice creation. Other composite adsorbents can work with ammonia at high input temperatures.

Pons and Grenier produced 5.3-5.6 Kg of ice per square meter (Miles, 1996), with their 6m2 collector containing 130Kg of Activated Carbon & Methanol. Cristoph and Vogel (1986) and Meunier too, studied varying working pairs to test performance issues for i.e. Activated Carbons & Methanol, Zeolite & Water and some others, and results of their studies show that Activated Carbon & Methanol is the ideal working pair for solar energy due to its high COP and low input temperature(Wang, 2003).

Working Pair	Coefficient of Performance	Costs	Notes
ACF & Ammonia	0,6	very high	Ammonia is unavailable in remote area's
AC & Ammonia	0,1-0,2	average	Ammonia is highly toxic
AC & Methanol	0,1-0,2	average	Methanol input T can not exceed 120 deg C
AC & Ethanol	< 0,1	average	Ethanol is easily obtained
Zeolite & Water	< 0,2	high	Zeolite needs high input T of 200 deg C
Silicagel & Water	< 0,14	high	Silicagel is unavailable in remote areas Water is unable to evaporate below 0 deg C

Table III.4   Adsorption Pairs Comparison

`sum` For the sake of relative simplicity, the working pair Activated Carbon & Methanol is chosen for its local availability and low costs, low input temperature and the fact that most adsorption systems work on this pair, while being relatively safe and non toxic. Furthermore, the low working pressure (20mbar) means any mistake (i.e. a punctured hole through the closed system during use) does not immediately affect its user, since the negative pressure range of near vacuum forces air to be sucked in, instead of the out of the system with positive internal pressures, which could be dangerous. For the sake of the project, other working pairs will be tested but outreach the scope of this thesis.

f_1 f_2

1.

4.

2.

3.

1./4.	Collector.
2.	Condensor.
3.	Evaporator.
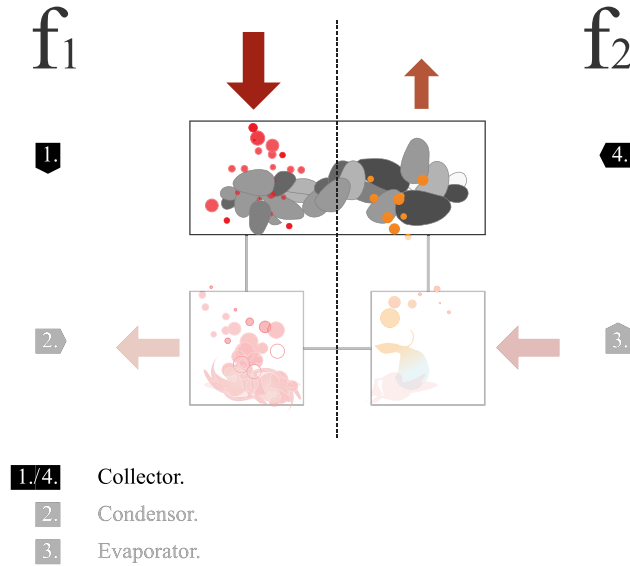
Figure III.7   Collector in the System.

For adsorption systems, the heat input by the collector drives the desorption process. With different adsorption pairs, different heat input temperatures should be reached. According to Hu (1998), input temperatures higher than 120°C should be avoided when using methanol. In a low cost adsorption system, the collector has two functions, one being the desorber in the collecting phase, and the second being the adsorber in the cooling phase. In the latter, pressures and temperatures need to drop sufficiently in order to speed up the cooling process, while in the first temperature and pressure needs to be high. Thus, the faster the temperature rise speed of the desorber, the less its desorption capacity becomes, and, the faster the temperature drop speed of the adsorber, the less its adsorption capacity (Wu, 2002). This of course forms many complicated design considerations.

In both phases, heat dissipation is an important consideration, because the sorption rate depends strongly on temperature. When adsorption takes place, heat is released, reducing the sorption rate. This is due to the equilibrium effect. Increasing the sorption rate is possible through a proper heatsink design but also by increasing heat dissipation, for instance by adding additives in the adsorbent material like copper or aluminum chips.

Solar energy provides us about 1000 W/m2, at maximum intensity (noon). In order to get to a certain temperature, as much of this work as possible needs to be collected, and just as important: stay within the system during the collecting phase. To get to such a consideration, emissivity needs to be taken into account, and here, convection, conduction and radiation play essential roles.

2.1   Insolation

The amount of energy that can be collected depends on the angle that the sun makes with the collector surface, since the sun's path changes over time throughout the year, solar insolation plays an important role. A greater angle reduces efficiency. The annual change in the relative position of the Earth's axis in relationship to the Sun causes the height of the Sun or solar altitude to vary in our skies. Solar altitude is normally measured from either the southern or northern point along the horizon and begins at zero degrees. In the figure shown, the angle is measured from the absolute North. Maximum solar altitude occurs when the Sun is directly overhead and has a value of 90°. The total variation in maximum solar altitude for any location on the Earth over a one-year period is 47°. This variation is due to the annual changes in the relative position of the Earth to the Sun. At 50 degrees North, maximum solar altitude varies from 63.5 degrees on the June solstice to 16.5 degrees on the December solstice. Maximum solar height at the equator goes from 66.5 degrees above the northern end of the horizon during the June solstice, to directly overhead on the September equinox, and then down to 66.5 degrees above the southern end of the horizon during the December solstice.
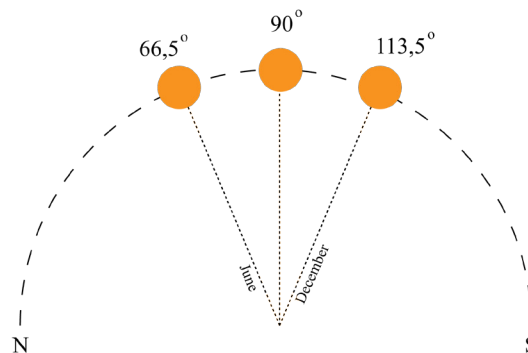
Soler angle at the equator.
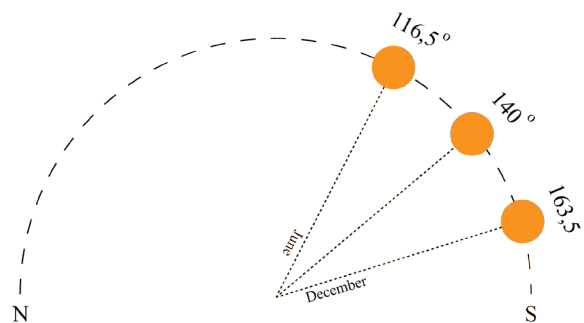
Soler angle at the 50 degrees North.

Figure III.8   Insolation of the sun throughout the year.

2.2   Collector Types

For the sake of the project, only low cost collector types have been examined. There are many different types available, but with modularity and mass production in mind, flat plate collectors provide one of the most promising options because of its simplicity. In the case of the first prototype, the collector had the highest share in total costs of the system which is why the type of collector is an increasingly important consideration (see chapter III.13).

There are two basic types of collectors available. A parabolic mirror system is able to reach up to much higher temperatures (over to 200 °C if designed at maximal efficiency), but requires tracking of the sun which adds to complexity, and (electrically) controlled moving parts. Furthermore, they are subject to high maintenance demands in order to keep efficiencies high. Another general type, flat plate collectors, can only reach a 150-200 °C maximum. But they have the advantages that they are able to collect sunlight directly and indirectly from diffuse (clouded or reflected) light, while being relatively fast and easy to manufacture.

Solar Radiation

Sheet Metal Absorber Plate
Air Flow
Insulation Material
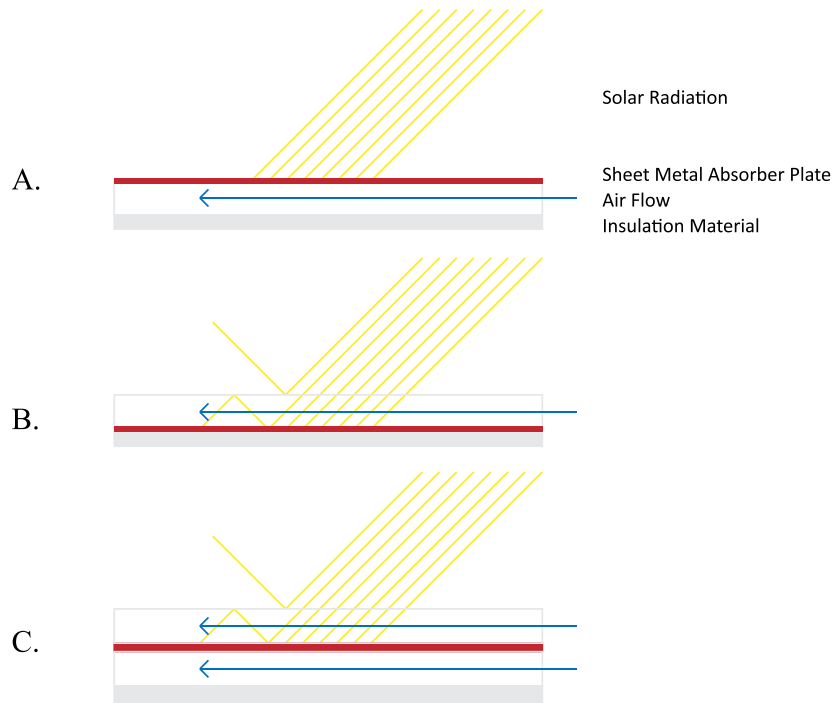
Figure III.9   Different types of flat plate collectors

Three different general types of flat plate collectors determine a choice in efficiency, complexity and costs; bare-plate, covered-plate and covered suspended-plate collectors. A suggested transparent cover material basically has two functions, reducing the direct convection losses occurring from collector surface to surrounding (moving) air when no cover would exist, and, because the cover material covers still air around the collector surface, more heat is trapped. The difference between each type is visualized in figure III.9. But they typically have one thing in common, a plate that collects the energy from the sun, and some kind of medium (i.e. air) that transports the heat from the collector to the point of use. In all general collector types, the collected heat is lost through the front, sides and back, by reflection from the cover (not all radiation passes

through) and by direct radiation from the heated flat plate. Type a, as seen in figure III.9, is a sole bare-plate collector, with an average efficiency of 30%, all convection and radiation losses occur directly into the surrounding environment. But between the available flat plate types, a significant increase in efficiency can be done by adding the transparent cover material (type b), reducing convection losses dramatically. Adding a cover material increases overall efficiency nearly 30%. If a temperature difference higher than 50°C needs to be met in between the outside and inside temperature, an additional cover can make a difference. But by adding more extra covers, reflection also increases meaning less heat will get to the system eventually. Last, is the suspended plate collector, in which the contact surface area of the heated flat plate with the circulating medium is doubled, these generally reach efficiencies of higher than 45% for converting solar energy.
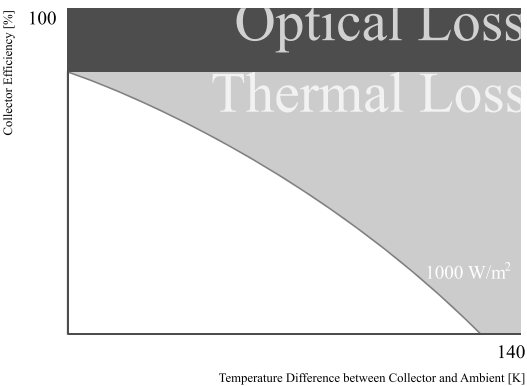
Figure III.10   Thermal losses against temperature difference between collector and ambient

A simplistic overview of the differences in between bare and covered plate efficiency.

	est. efficiency	usable solar heat	heat gathered in 6 hrs
Bare Plate	20 - 30%	200 - 300 W	4-6 MJ / day
Covered Plate	40 - 60%	400 - 600 W	10-13 MJ / day

2.3   Emissivity

Emissivity [ε] is the relative ability of a surface to emit energy by radiation. The value given for it is dimensionless, thus, a relative measure to which a body radiates its absorbed energy. A theoretical black body has a relative value of ε = 1, and does not radiate, in reality this is always less. Emissivity is the scientific measurement of the ability for heat to radiate (leave), an object. Chrome has an emissivity of ε 0.04 while black paint emits radiant heat at a rate of ε 0.95. While for instance true black paint will heat up faster and chrome reflects heat more easily, the black paint will heat up much faster but 95% of the heat that is absorbed is able to freely re-radiate back in the atmosphere, a chrome object will reflect 96% of the heat and will only absorb 4%, this heat, but, is trapped in the object. This means, a chrome object heats up slowly but can reach higher temperatures and keep it heated longer, while a black object heats up fast but reaches lower maximum temperatures.

Special coatings for solar heating systems are available for expensive prices. These selective surfaces absorb as much of the heat as possible while at the same time have a very low emissivity value, meaning as little heat as possible is re-radiated. Since most adsorption pairs do not need a high temperature input, special coatings should be unnecessary.

E.E. Anyanwu et al (2001) states that emissivity ranges in between ε 0,05-0,45 show nearly no effect on the predicted and

tested COP value of the total system when using a mirrored system. But for an absorbing plate or tube, there is a high dependence of the refrigerator performance on the absorptivity of the plate. In fact, an increase in absorptivity from ε 0.75 to 0.85 can increase COP by 53%. This means focusing on solar absorbivity of any coated material is of greater importance for the working of the system.

For low cost applications, solar absorbivity is of greater importance especially when working with a cover material as stated earlier. Heat of the absorbing coating will transfer to the inside material, eventually heating up to such a level that desorption is initiated inside the collector. Furthermore, a higher emissivity value means a greater radiation of heat in the cooling phase when heat from the vapor from the evaporator is dissipated.

Emissivity is also important consideration for the outer wall material of the refrigerator box, What that means is a low value, reflects as much solar radiation as possible, and therefore will not heat up the inside of the refrigerator box that easily.

2.4   Cover Material

Transparent insulating cover material (TIM) which should cover the collector to ensure a heat trap, or a greenhouse effect. Both transparency and heat transmitting properties are of importance for a choice of cover material. Glass is most often used for solar collecting because of its excellent properties, because it transmits incoming solar radiation but radiates almost no heat from the collector surface to the surrounding environment. Industrialized plastic cover materials have less workable properties but they ensure some advantages especially in sensitivity to handling in a harsh environment, as they are flexible and unbreakable. On the other hand, not many of these plastics are able to withstand the intense solar rays for more than a few years.

Material	Solar Transmittance	Heat Trap	Costs
Plastics	92 %	< 70 %	low
Glass	87 %	90 %	high

The properties are non interchangeable, according to Kaushika (N.D. Kaushika, 2003), the amount of transparency decreases with an increase in insulation of the material.
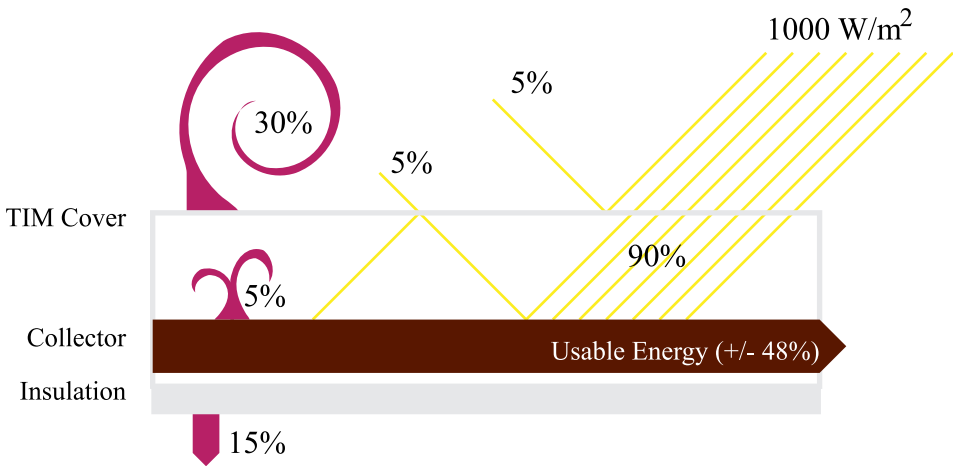
Figure III.11   Energy Losses while using TIM Cover.

2.5   Collector Coating Materials

To get to high absorption values, collector surfaces can be coated with selective surfaces, which are relatively expensive. Solar absorption properties for these materials can get up to 95%, and 15% emissivity (i.e. from solmax). But for lowest cost purposes, there are many other possibilities which can reach comparable properties. For instance carbon black (candle soot) or charcoal powder smeared over any metal surface which needs to be heated. These materials do have higher emissivity values which means heat is re-radiated into the surrounding environment, or a lower absorbivity of heat. Anyanwu et al (2001) states that emissivity ranges in between 0,05-0,45 show nearly no effect on the predicted and tested COP value of the total system. But, according to the latter, increasing absorptivity from 0.75 to 0.85 can increase COP by over 50%. This means the focus should be on absorbivity.

For a shortlist of interesting opportunities see table III.5, for further information visit appendix II.D.2.

Material	Absorbivity	Emissivity
Palm Oil + Mineral Oil (50/50)	0,92	0,2
Galina	0,95	0,3
Carbon Graphite	0,85	0,3
Charcoal Powder	0,80*	0,4*

* are estimates and can vary with different production processes.

Table III.5 Emissivity values of some interesting materials
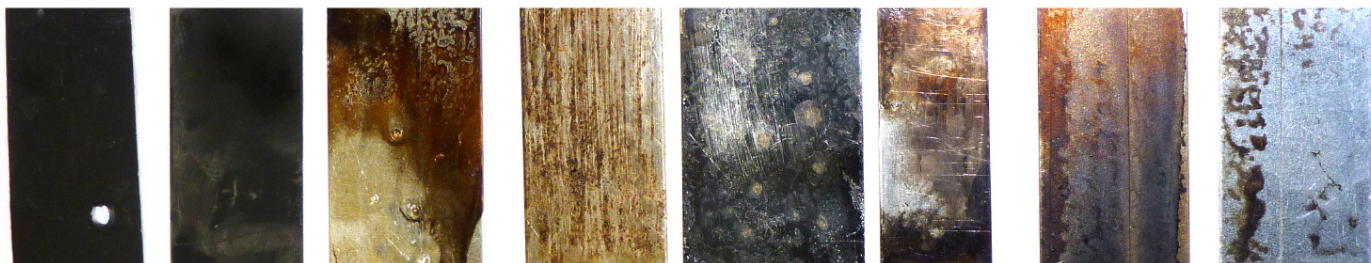
Figure III.12   Different Tryouts of Affordable Selective Coatings ranging from soot (extreme left) to butter and oil in ovens (done at PMP faculty shop).

sum There are some common materials found which do combine high absobivity values with low emissivity, these materials differ from expensive collector coatings due to the fact they can be produced locally and relatively easy. In india for instance, galina is mined indigenously (Chatterjee, 1993). Furthermore, coatings made from oil (soya, tung, corn, mineral and palm), wax, butter or lard do exhibit great values compared with costs (Schardein, 1982). Also, carbon graphite, charcoal powder or candle soot from fire can be used, when coated with i.e. a cheap hairspray for protection. For low cost purposes in a BOP market, the latter will be used.

2.6   Do It Yourself

Many examples of relatively cheap ways to create a solar collector panel are available on the internet. At one of the main web hosts like instructables.com or makezine.com, many examples of do-it-yourself versions of a solar collector can be found, this could be important since low cost and available materials are used within the instruction.

Varying concepts have led to many different temperature ranges through different use of materials. Many considerations on the designs have come from a desire to get things done in an affordable manner, when further examined the reasons are not that difficult because commercial or industrialized collectors still exceed €140-600 / m2.

Figure III.13   Solar Water Heater by " TheNaib" on Instructables.com.

This solar water heater heats cold/ambient temperature water up to 77°C by using very basic materials like aluminum foil, wood, glass from an old car window, duct tape and an old condenser from a broken refrigerator as a collector. The total costs, excluding the found refrigerator condenser were not more than over €5. The collector itself is about 1,5 m2. More examples can be found in appendix D.2.2.

2.7   Hybrid

Hybrid collectors could include thermoelectrical + solar driven, but more interestingly, solar + fire driven. In remote area's where there is no electricity this could be very interesting. Furthermore, fire can be made quite easily everywhere, when the sun has disappeared behind clouded coverage at spots enclosed by trees.

Difference is the input heat, since the heat of fire exceeds any possible solar input, different adsorption pairs could be considered. If using methanol as a refrigerant for instance, the maximum temperature cannot exceed 150°C because caution has to be taken when gas gets too much energy, molecules travel even further apart (the number of molecules per m3 decreases) and want to expand rapidly, risking leakage or explosion. Furthermore, Activated Carbon cannot receive too much heat because it could destroy its properties. But, instead of putting it directly in fire, it is possible to use an extra (water) cycle, heated by a fire and constantly traveling through the desorber. The latter of course does add costs to the total system and is out of the question on a boat. Next to that, a system can also be kept below 150°C when laid in a bucket of boiling water, which never exceeds 100°C (depending on altitude of course). Even more hybrid modes are possible, for instance by collecting waste heat from an engine, on a scooter, a motorcycle or boat propelled by a diesel engine (Han, 1996), at the notice that it has to run for several hours, and that (at least on some boats) the engines rotate, adding more complexity to the system.

2.8   Collector Summary

The solar collector driving the internal system should be kept as simplistic as possible when considering BOP markets. As the complete design depends on the surface area, the material, the (selective) coating, and whether the collector should be hybrid or not, it is wise to disintegrate each segment of the design. First of all, the collector itself can be separated from the coating material, which can be later applied during the production process, an affordable and accessible coating like charcoal powder could be used for BOP markets, while a more expensive selective coating can be later applied for BOAT markets. The fact that adsorption pair Activated Carbon & Methanol need a low temperature input of 100 degrees Celsius, means the collector type can be kept relatively simple; using a certain surface area covered by a Transparent Insulated Material like plastic. Furthermore, the design of a solar collector should be reconsidered to be highly scalable and adjustable in order to meet BOP and BOAT demands. Hybrid solutions need to be further researched during the course of the complete project, and are for now kept out of consideration due to the added complexity of the system.

$$f_1 \qquad f_2$$

1. | 4.

2. | 3.

1./4. Collector.
2. Condensor.
3. Evaporator.
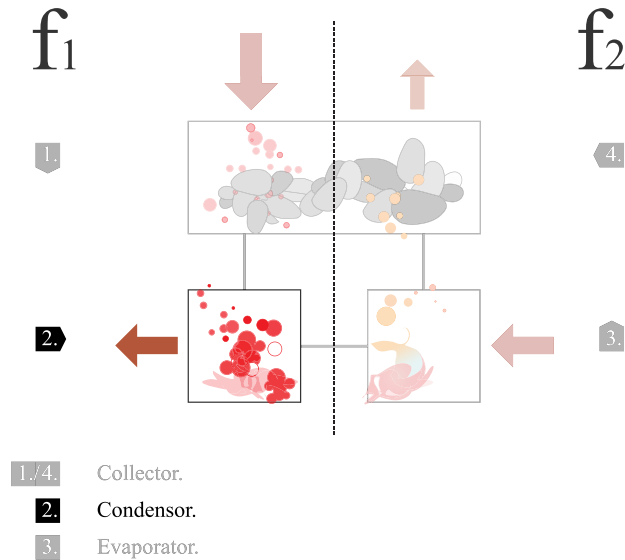
Figure III.14   Condensor in the System.

Condensation within the desorption phase, drives the working pressure and speed of desorption. For a refrigerant to condensate, it needs to release its energy gained due to solar heat from within the desorber/collector. Here, as much energy as possible should be released to the external environment. An important difference is the difference in the type of condensor, water or air cooled. Especially when looking at the BOAT market or to fishermen in BOP, water condensers are 5-200 times more effective than air cooled condensors (chapter III.1). To release as much energy as possible, surface area must be kept high in convection, and in conduction terms the material thickness surrounding the flowing refrigerant must be kept as low as possible to ensure as much heat exchange as possible, while radiating heat must be kept out meaning a high emissivity value (see chapter III.1).

Air condensors can come in many different types. Forced air convection, like using a fan in any laptop or computer, lowers thermal resistance, and the surface can cool down quicker meaning a higher release of energy. But, since the target market segments do not have access to electricity, forced convection is out of the question. Furthermore, to create a system that works everywhere, in any climate, water cooled condensers should only be an expansion option within the eventual design, because only air is available everywhere. A typical air condenser can be seen on the backside of nearly every refrigerator, in which the refrigerant flows through the bent tubing while the area releasing heat to the environment is increased by adding vertically placed rods. They are placed vertically since hot air travels upwards, flowing around the attached. The principle behind these vertical rods is found in all kinds of condensors, heat exchangers or heat sinks (Kordyban, 1998; Forghan, 2001), some have fins instead but they serve the same purpose of increasing surface area that is able to exchange heat with its surrounding.
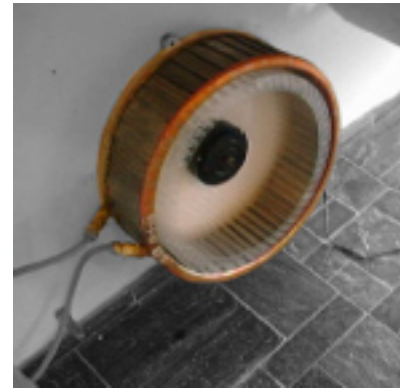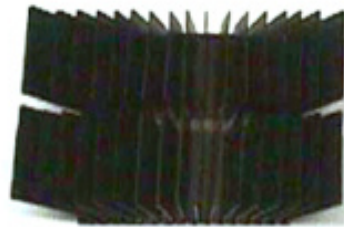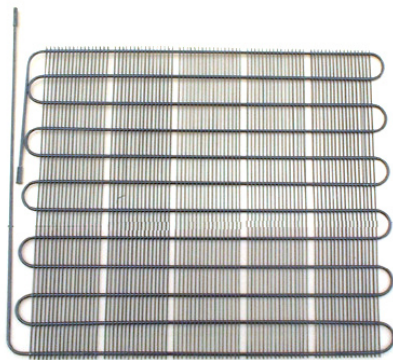
Figure III.15 (l)   A typical Refrigerator Air Condensor
Figure III.16 (m)   Optimal heat sink design, on the left MXFL-R can be seen, which scores the best values for low velocity air condensation (Forghan 2001)
Figure III.17 (r)   Fiwihex heat exchanger.

Forghan (2001) experimented with several types of heat sinks of which two distinct types clearly had the lowest possible thermal resistance at low air velocities (see figure III.16). This is due to the fact that its fins are spread out, therefore decreasing the entrapment of still air in between the fins as in standard heat sinks, air is able to flow past (up) much more easily due to the assist in natural air flow.

Other interesting developments in the field of heat exchangers are very promising, one of which is shown in figure III.25, a thin wire air heat exchanger called Fiwihex. Fiwihex is able to heat and cool a room by using an in- and outside temperature difference of merely 5 degrees Celsius, and therefore dramatically improves overall efficiency compared normal heat pumps. They are currently targeted for hotels and greenhouses, while a pilot is set up within the borders of the TUDelft (MSP). Although definitely worth mentioning, Fiwihex is still in development and needs further research, which currently outranges the scope of this thesis.

As example, generally a covered plate collector has an efficiency of around 40-60%, with an incoming solar radiation of 1000 W/m2 little over 400W needs to be dissipated by the condensor. Thus, with eq. 1 & 2 , to release energy coming from 1m2 collector, the surface area of the condensor should be in between 3-4,5 m2.

 sum   An air cooled condensor should have a 3-4,5 times larger surface area as the collector while a water cooled condensor should have a 1/10 times larger surface area as the collector.

C ESS 4 Evaporator

f_1 f_2

1./4.   Collector.
2.   Condensor.
3.   Evaporator.
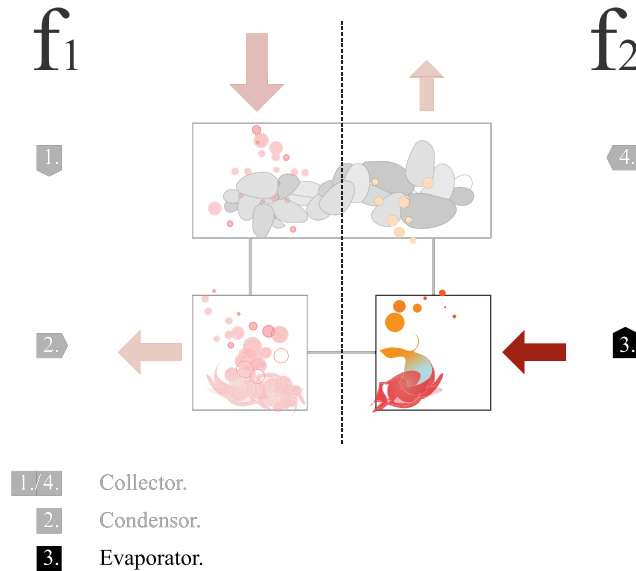
Figure III.18   Evaporator in the System.

Evaporation is the final stage in which the refrigeration process is actually happening. The refrigerant enters as a liquid and leaves as a gas. The strength of this endothermic reaction determines the cooling power within the refrigerator box. And just as in the condensor, it needs to subtract as much energy as possible from the water surrounding the evaporator. Although in the exact opposite direction, taking energy in. Here, convection works in the opposite direction, since the refrigerant flows past the still water, but conduction and radiation take account for the largest part of the energy transferred. Therefore, the material thickness should stay as low as possible to increase heat exchange. A downside to any ice making evaporator is to be cautious because ice formation around its surface decreases efficiency, since ice adds to the thickness and is a poor thermal conductor.

Evaporators are commonly not visible, but there are a few different types available ranging from tube, to plate tube and roll bonded evaporators (appendix D.3). Shown here is a simple tube evaporator, and a roll bonded surface evaporator. The roll bonded evaporator has a better heat exchange capacity, but is therefore more expensive (€15-30 instead of approximately €5-10).
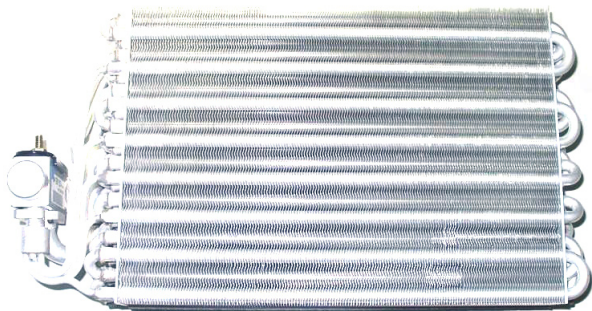
Figure III.19 (l)   Standard Tube Evaporator
Figure III.20 (r)   Roll Bond Surface Evaporator
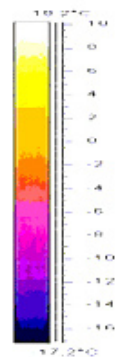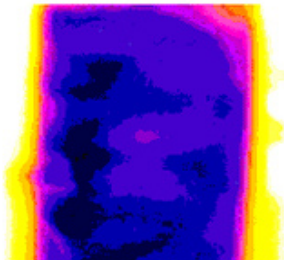
Figure III.21   Efficiency Difference of Tube (left) and Roll Bond (right) Evaporators.

4.1   Roll Bonding

Roll bonding does seem to be a very interesting technique, mainly because of its manufacturing process and practicality. In roll bonding it is possible to print (serigraphic) any type of structure to manufacture canalized panels, after which a special bonding technique is applied; a sandwich of two aluminum sheets by means of a special hot/cold rolling process. The welding is not applied at the places where the serigraphic ink is applied, to create an unwelded area of the desired pattern. After welding the two sheets together, air at very high pressure is inserting, blowing up the unwelded areas which become the flow channels. A great advantage next to its high capacity is the fact that it is relatively easy to bend afterwards as shown in figure III.20, due to the fact that both aluminum sheets welded together only have a usual 1,5mm thickness. Another great possibility of roll bonding is the fact that it is possible to print any type of channel (see figure III.22), in this case enabling the collector, condensor and evaporator to be rolled from the same part. But, there are limitations to channel size, which are eye shaped, and up to 4mm wide, 2,1 mm in height. And according to CGA, it is not possible to fill the channels with grains (the adsorbent) during the production process, thus post fillage would be necessary forcing those channels to be straight without meanders. The latter meaning that only the condensor and evaporator could be made from the same part in the case of an adsorption refrigerator. CGA however, showed that next to evaporators, also collectors can be created by roll bonding (figure III.23). And for a small production number of 500 pcs. CGA in Italy, can make them for around €30/m2 for a small type refrigerator like the solarbear, although this would be the price for an untreated or uncoated. Although there are of course other companies in China, according to the sales manager of CGA, they originally started a business in refrigeration production techniques which is of course an interesting combination with solarbear. For more information on roll bonding please refer to appendix D.3.
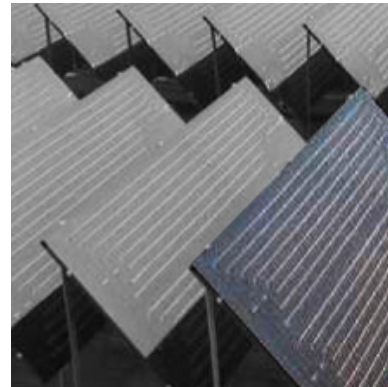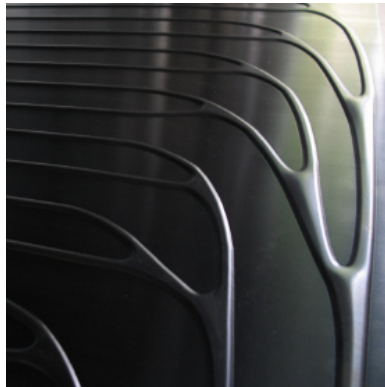

Figure III.22 (l)   Natural flow using Roll Bonding
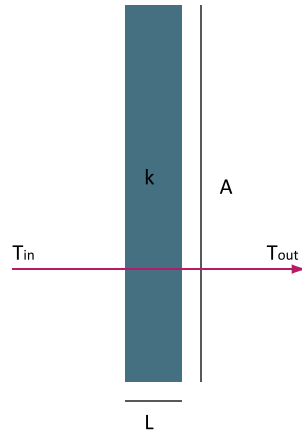Figure III.23 (r)   Roll Bonded Collectors

Figure III.24   Insulation through a Wall.

Insulation is the last specification which holds a large part of the COP value for an intermittent adsorption refrigerator, or any refrigerator for that part. With insulation it is very important to understand the conduction formula (eq 2) as described in chapter III.1, in which it becomes clear that any type of material has different specific heat capacity values, determining how quickly a temperature difference is leveled out in between the inner and outer surface of that material. If insulation is not manufactured correctly, it means the total previously described refrigeration cycle is of no value since all the surrounding heat outside the refrigerator can travel inside, melting the ice or simply bringing the inside of the refrigerator to room temperature in a short while. As a specific material has a specific surface area in which to exchange heat to out of the 'system' (-the refrigerator box), together with a specific heat capacity to hold the cold in the system, it also has a thickness (L). An interesting factor. One insulation material does not have to be as good as the other, especially when expenses play a role, because it is possible to increase the thickness of a material with lower conductivity values to get to the same eventual heat loss (Q, in Watts) as when a more expensive material was used. Again, as with actually all other parts, it is about finding a balance in between costs, efficiency, local availability, manufacturing processes and practicality of use. In the case of a low income market it is very interesting to look at other materials than those normally used in western markets, because nature provides a lot of different solutions for insulation like feathers, wood chips, wool, (hair)felt, rice hulls, and even burying something in the ground gives a near infinite thickness and therefore provides great insulation. We have not even begun to look at penguins. Of course, foam is also a great insulator, does not rot as easily nor does it attract any vermin, but it is more expensive and rarely available in low income markets. In table III.6 an overview of some strange but interesting materials are compared to industrial insulation.

Material	Specific Heat Conductivity [W/mK]	Relative Thickness [m]
Rice Hulls	0,0359	0,05
Paper	0,05	0,07
Sheep Wool	0,039	0,05
Cotton	0,03	0,04

Hairfelt	0,05	0,07
Soil	0,06 - 0,15	0,08 - 0,2
Styrofoam	0,033	0,04
Silica Aerogel	0,02	0,03
Vacuum	0,004	0,01

Table III.6   Natural and Industrial Insulating materials, relative thickness calculated with 20 W heat loss, over a 1 m2 surface, dT 27 degrees Celsius.

It becomes clear that insulation is a problem which can be locally managed. Especially wool, hair felt and rice hulls provide relatively interesting options. Within table III.6, relative thickness is shown as to provide a better view of what the thermal conductivity values conceal, the values here are the maximum values for a situation where only 20W of heat loss is allowed over a 1m2 wall of material, with a determined inside temperature of $2°$C and a outside temperature of $29°$C.
In insulation, you can have great theoretical values but still not the desired amount of insulation, this is probably due to thermal heat bridges. Any 'bridge' through an insulating material will form the weakest link, and all heat will try to escape through that bridge, for instance a nail through the foam almost reaching the inside of the refrigerator. Removal of heat bridges is common within Passiv Hauses, in which almost all heat is contained within the house, without nearly any possibility of breaking out to the outside.

Fluid flow is a considerably important aspect in adsorption refrigeration, since gasses and fluids circle through the system. A very simple rule, is that fluid goes down and gas goes up, although this may appear logical, it applies even in low vacuum. At some points in the system (collector/evaporator), molecular energy needs to be maintained as well as possible, while at others (condensor), increasing energy losses should aid the thermodynamical process. Fluid flow and its energy can thus be influenced easily when contradicting natural flow or oppositely, using it. Natural flow resembles blood veins, the water dissipation of trees, rivers or even droughts. Especially in heat exchangers, biomimicry could be considered relatively important, as energy in veins is constantly exchanged, hot blood streams are close to cold blood streams flowing in opposite direction. To increase energy exchange within large surface, a great simplistic example is an old radiator as seen in figure III.25. The old radiator resembles blood streams from our biology books, and can increase overall dissipation dramatically.
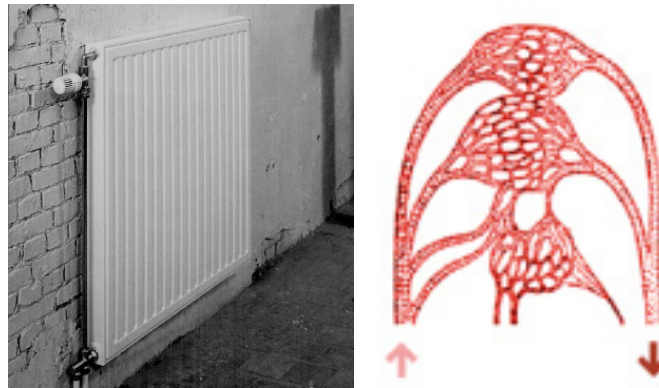
Figure III.25   Radiator 'Veins' simulate natural flow.

Victor Papenek in "Design for the Real World" (1984) gives one of the best real world examples for this phenomenon in 1984;

"Greater London, with a population close to that of NewYork City and with an unbelievably primitive and leaky water uses only one fourth as much water as is consumed in New York. The reason is a biomorphic one. D'arcy Wentworth Thompson quotes Roux in formulating the following emperical rules for the branching of arteries and leaf venation:

1   If an artery bifurcates into two equal branches, these branches come off at equal angles to the main stem.
2   If one of the branches be smaller than the other, then the main branch or continuation of the original artery makes with the latter a smaller angle than does the smaller lateral branch
3   All branches which are so small that they scarcely seem to weaken or diminish the main stem come off from it at a large angle, from seventy to ninety degrees."

Thus, by using a simple algorithm, instead of cornered 90° angles, only ¼th of the amount of water is needed to run the sewage system.

Furthermore, flow depends on several factors; viscosity of the fluid, the total travel length, directional change during flow,

specific drag of the surface (Reynolds number), and, the shape of the duct in which the fluid travels through. Best flow paths are achieved by utilizing circular shaped tubing instead of i.e. square shaped ducts. Herafter, an increasing number of connections, weldments, solder bonds or any other type of obstruction, increases fluid speed (v), while lowering pressure (P) and temperature (T) at the exit (figure III.33). Obstructions lower possible energy transfer.
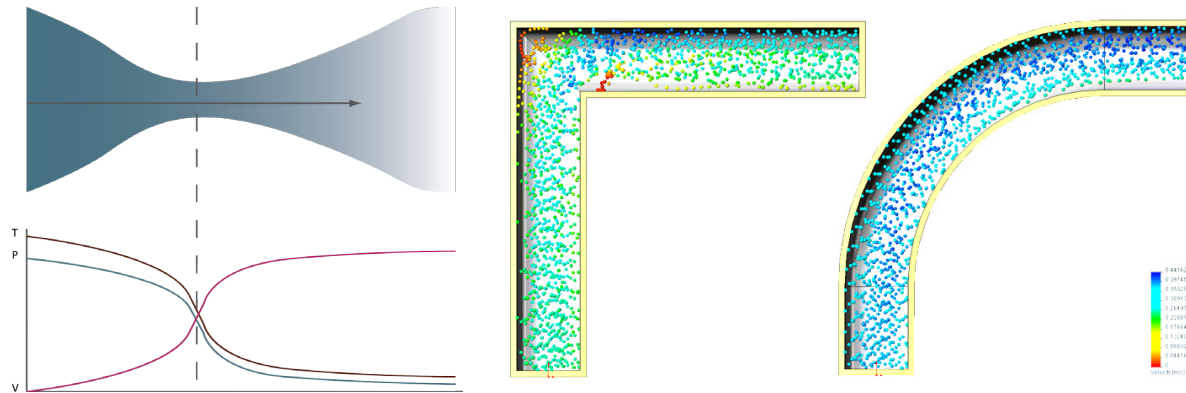

Figure III.26 (l)   Obstruction of Flow, Pressure, Temperature and Speed change.
Figure III.27 (r)   Obstruction of Flow differs in type of bend, blue and red are high and low speed/pressure respectively (Solidworks).

For bending circular tubes, an important rule of thumb applies when they are bent during production. To reduce the risk of 'folding' a tube when bending, instead of creating a nice bend; the minimal (mid-)radius of the bent equals three times the outer diameter of the tube. This limits the maximum surface area that can be created.

For any material that outlines the closed system, it needs to be able to withstand either positive or negative pressure (above or below atmospheric pressure respectively). Common plastics are able to hold a pressure for some time, but slowly disintegrate their functioning. There are special types of plastics designed for such applications but are much more expensive than other common, naturally occurring alloys of steel, copper and aluminum. In here, W/mK, or specific heat conductivity of a material, is the factor that makes the difference on how much energy is transferred in between the surface of the collector and the inside, where the adsorption should be initiated because of this energy. Furthermore, high specific heat values represent a better heat dissipation over the collector surface, heating the inside more homogeneously. Also, the homogeneous dissipation of heat inside the collector can be increased by mixing highly conductive material through the adsorbent, or by for instance creating a conduction raster / grid in which the adsorbent lies.

Heat sinks are types of highly capable heat exchangers because of their great surface area, transferring heat to air and therefore cooling the surface, they are found in almost all contemporary computers. The most common heat sink material is aluminum. Chemically pure aluminum, is never used in the manufacture of a heat sink, but rather aluminum alloys. Aluminum alloy 1050A has one of the higher thermal conductivity values at 229 W/mK. However, it is not recommended for machining since it is relatively soft material. Aluminum alloys 6061 and 6063 are the more commonly used aluminum alloys, with thermal conductivity values of 166 and 201 W/mK respectively. On the contrary of aluminum and copper, stainless steel is a very affordable material and widely available everywhere, even in remote areas, but with a density of 7.85 g/cm3, it is significantly heavier than the first mentioned. Furthermore, steel has a much lower specific heat conductivity, of up to 80 W/mK, meaning less heat transfer is possible. Of course aluminum has the added advantage of recycling.

Copper is also used for heat sinks, since it has around twice the conductivity of aluminum (pure copper: 369 W/mK), but is three times as heavy as aluminum and is around four to six times more expensive, although the latter is of course market dependent. Aluminum and steel have the added advantage that they are able to be extruded, while copper can not and in is milled in the case of a heat sink. Another method of manufacturing is to solder, or glue fins into the heat exchanger base, as is done at the first prototype "point zero" by L. Schürg (see chapter III.ACC.6), using solder.

Copper, steel, and aluminum prices through time can be compared in figure III.28, or on Internet websites, such as the London Metal Exchange or metalprices.com. The purpose of which is to calculate relative conductivity values compared to price as seen in Table III.7.

Material	Price [€/Kg]	Conductivity	Kg/m3	€ / m3	€ / WmK-1
Aluminum	1,6	200	2,70	4,3	0,008
Alu recycled*	1,2	140	3	3,6	0,009
Copper	5,8	300	8,94	52,8	0.019
Steel	1,4	80	7,85	11,0	0.017

*Conductivity and weight are estimations.

Table III.7 Price Conductivity Values

The first factor (€ / m3) shows the price per cubic meter of a material, the last factor (€ / WmK-1) shows how much one single W/mK costs for that material. The varying prices of some materials through the last ten years are shown hereunder, what is clearly seen is the high rising and fluctuated costs of the copper price over the years, while aluminum and steel vary much less and tend to average around a 2000 and 500 US$/tonne line respectively.
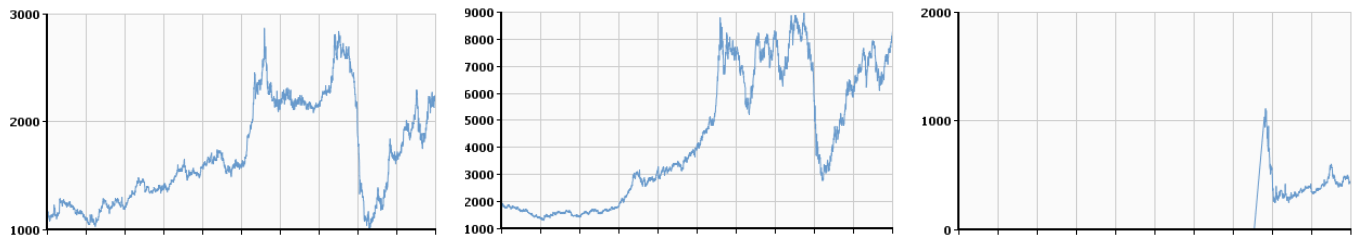
Figure III.28   Aluminium Alloy (left), Copper (middle) and Steel (right) prices in US$ per metric tonne from 2000 until 2010 (LME).

Another possibility, but which has not been done at any time before for heat exchangers (collector, condensor and evaporator), would be to use the same type of materials in for instance a medicine, food or drink packaging (see figure III.29). These layered materials generally consist out of PET, nylon, aluminum and PE sheets stacked upon each other and are vacumized before distribution. Since Activated Carbon & Methanol pair is used, vacuum (20 mbar) is exactly what the internal system needs. This packaging is a very easy and affordable production process, but vulnerable for sharp objects to penetrate through. PET has a good appearance in color printing which is highly appropriate for the collector emissivity for instance (increasing absorbivity values), nylon only transmits low rates of oxygen gasses (another material, air tight needs to replace this), aluminum is a good isolator and low illuminant while PE is a common inner packaging material. Thus, an interesting opportunity but hardly researched which means further in depth testing is needed before any conclusions can be made.

Figure III.29   Aluminum Food Packaging.

1. Desorber.
2. Condensor.
3. Evaporator.
4. Adsorber.
Ⓘ Switch.
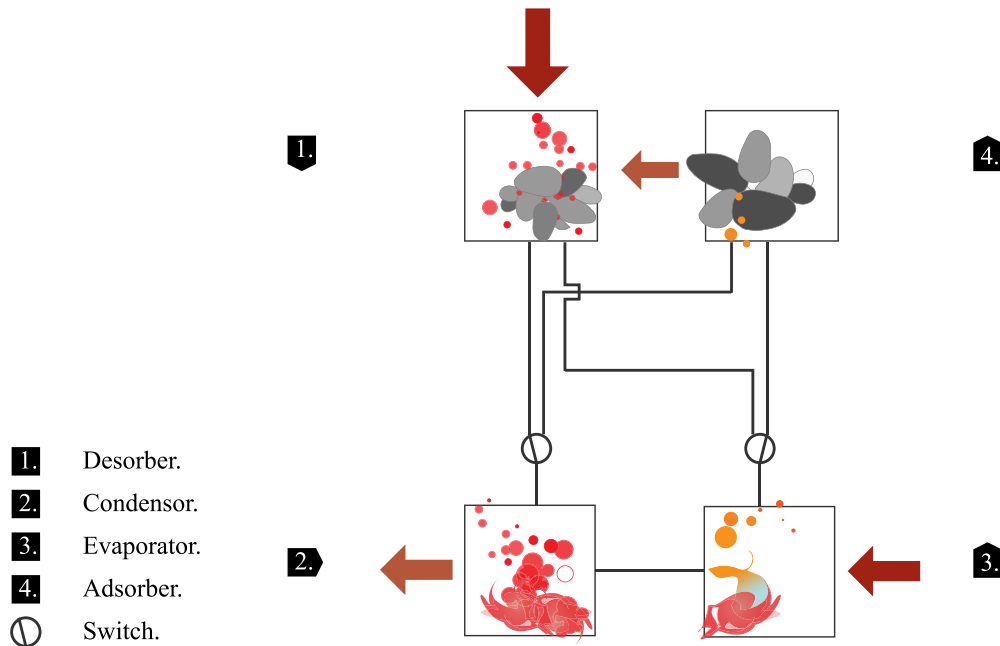
Figure III.30   A basic principle of a near Continous Adsorption Cycle.

Shortening cycle times reduces material costs since less of the adsorbent and adsorbate is needed compared to daily intermittent cycles. Shortening cycle times reduces the amount of Methanol that needs to be 'stored'. Furthermore, shorter cycle times increase COP value of the total system because heat recovery is made possible, COP could double from 0,5 to at least 0,75 and as high as 1. A cascading cycle reported by Douss and Meunier using two adsorber Zeolite & Water stages (high Temperature, and an intermittent Activated Carbon & Methanol stage (low temperature) was able to get experimental COP values of 1,06 (Alghoul, 2008). A near continuous cycle is made possible by switching two separate collectors in opposite phase, one is in the desorption phase and the other in an adsorption phase (figure III.30). When for instance the adsorption process within the adsorber/collector has started, heat is dissipated because of the exothermic reaction of the refrigerant obtaining its place within the solid adsorbent. In an intermittent cycle, this heat is simply lost to the environment, but in a short cycled system, heat can be redirected towards a second collector bed which is in its opposite desorption phase. In this way, a near 'constant' flow of refrigerant to and from the evaporator is secured. Unfortunately, having two adsorber/ desorber beds creates the need for timers, pressure valves and (mechanical) switches, because the flow of refrigerant fluid/ gas needs to be switched constantly, while optimum switch times lie around 16 minutes. This adds to the complexity of the system which does include extra costs. There are a few different options available to get to a near continuous system, but at low income markets it will prove difficult to manage.

To get to the lowest cost price as possible, a modular system design could make a huge difference. If as many parts as possible are produced in the same way (i.e. extruded pipes or by using other standardized components), costs per part go down dramatically. Sheet metal is also very affordable when used to its advantages in a modular designed system. Scalability proved to be an important issue concerning the BOP and BOAT market segments because of different wishes and demands of size within each of the chosen markets, apart from cultural looks and integratability in boats. Herafter, scalability could prove to be interesting since in a low income market, people can return in a later stage to upgrade their device.

All parts, condensers, evaporators, and collectors can be made from tubes or similar parts as is shown in figure III.31, whereas flow should differentiate, as well as inner volumes for the different parts. Furthermore, i.e. rounded surfaces will provide useful in the cooling phase, when the collector needs to be cooled, the total surface area needs to be as high as possible in order to conduct heat transfer to do a better job in cooling the collector/adsorber. If compared with point zero (the first prototype), with tubing, similar sizes and COP values of the collector can be achieved by using 0,03 tubes, when arranged in parallel. Because of the rounded tube, the surface in the sun is always 0,23 m2, while during adsorption phase that surface doubles to ensure a better heat dissipation to the environment.
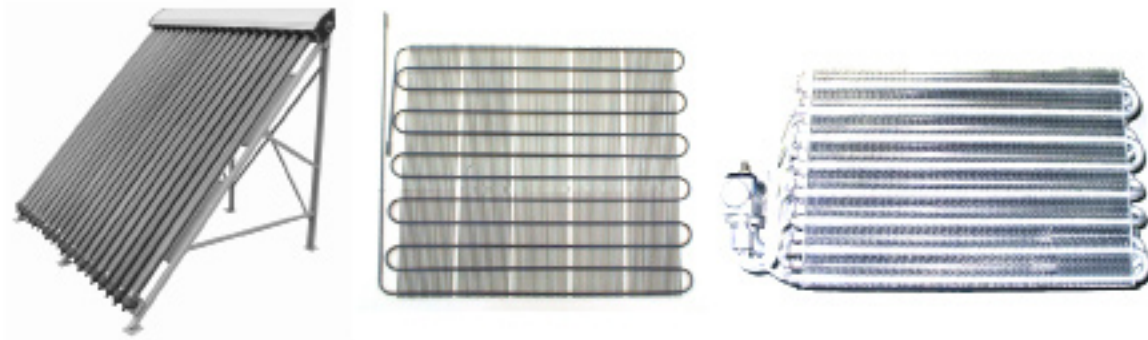
Figure III.31   Collector, Condensor and Evaporator Similarities.

During this thesis, and before, prototyping offered the best insights to test the limits of the adsorption principle. Because the many mistakes made could eventually lead to a better product, it is considered important to evaluate on the mentioned subject. First of all, the first prototype "point zero" build in December 2009 is evaluated, and secondly "zero point one", the second prototype which was build as a part of this thesis in August 2010. The insights from both form a stepping stone towards the third prototype which is to be build at the end of this thesis in Oktober 2010, after concept choice (chapter IV.D).

6.1   Point Zero

During the graduation of Ir. Leonard Schürg at the faculty of Industrial Design at the TUDelft, a prototype proposal was formed and manufactured in the last stages of his thesis in February 2010. Unfortunately, it did not work. Even after many tries of fixing the problems, up to the day of the writing of this thesis it is still not functioning unfortunately. Thus, the most important question, although one can only make assumptions, is why.

Since the first prototype did not show its complete potential in cooling nor collecting, it is up to now hard to determine what exactly went wrong. But by means of desk research and secondary advice from experts on thermodynamic principles (i.e. dr.Ir. C. Infante Fereirra, head of Process & Energy, 3ME at the TUDelft), many recommendations followed, which have to be taken into account for the next prototype(s). It is always easier to see and state what went wrong afterwards, it does not stand for the efforts made. For a better review on the original concept please refer to the graduation report of L. Schürg available at the TUDelft.

Point Zero was intended as a separate system, during the day the apparatus was meant to be hung next to a house, while in the second phase (nighttime) the system was ought to be carried inside and put partly (only the evaporator) in a coolbox the SME entrepreneur already owned. Its use is visualized in figure III.32, and photographs of the prototype are combined in figure III.33. Herafter, conclusions are punctually made and separated into facts and speculation.
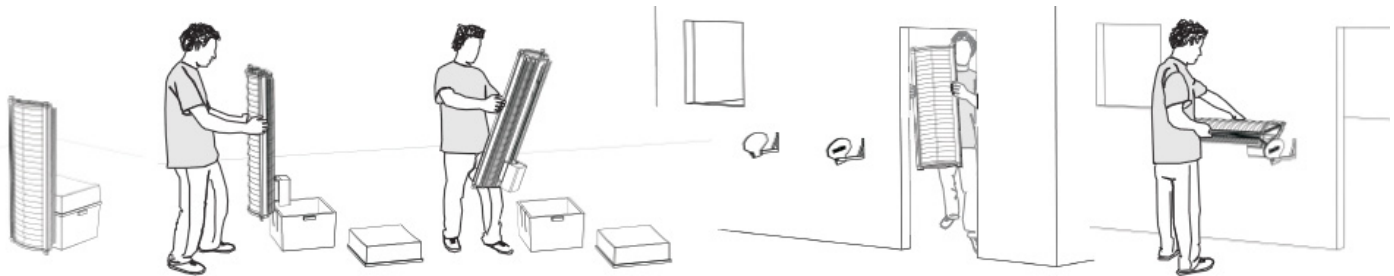

Figure III.32   Point Zero Usage Scenario, nighttime to daytime (left to right).

Figure III.33   Point Zero Prototype, desorption phase (left), adsorption phase (right), detail of the condensor (extreme right).
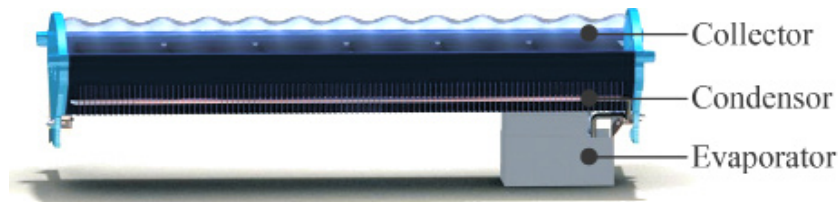

Figure III.34   Basic Parts in Point Zero.

1   The system leaks, and can therefore not reach the vacuum (20 mbar) needed for the cycle to work. This leaks are highly likely to be situated within the collector which was very hard to weld due to the large length that needed to be gas tight.

2   The condensor, which in this design serves as the condensor, and secondly as the way back for the gas from the evaporator to the collector. The system was supposed to be standing up in the cooling phase, but the condensor was designed for horizontal positioning, therefore, the gas from the evaporator was forced to go up for 1 meter (natural), back down again before going back up into the collector. To go back down as a gas is only possible with high pressures, something which is not possible at 20 mbar.

3   Many reused and resoldered parts.

4   During the cooling phase, the box like evaporator is attached to the system by a plastic piece of material, and has to go through precutted holes in a coolbox. These holes will form thermal bridges and therefore the coolbox would be unuseful.

5   Different choice of materials (messing) in prototype for the evaporator, while the shape was square, had a high surface area and was therefore increadibly hard to solder gastight.

6   Collector was made unnecessary weak, from expensive selective coating material of not much more than 0,5 mm thick. The total surface was soldered together, which is almost impossible to make vacuumtight.

7   The system was not modular nor scalable as proposed, upscaling the system longer than 1,5-2 meters (for more than the proposed 2 Kg of ice) prevented it from going through any door or from standing upwards in a house inside a box.

8   If ice forms on the evaporator during the cooling phase, you cannot remove the system from the coolbox easily.

9   The collector was totally made from selective surface, while only the top should have been enough.

SPECULATION

1   Although Schürg found literature on valveless systems, Fereirra insisted on using them because of the risk of failure, the risk of vaporization anywhere within the system (without one way valves) and a decrease in effectiveness or efficiency due to the fact the Methanol is stored within the evaporator instead of the condensor.

2   The condensor fins could have been too close to each other so that air is trapped in, reducing heat transfer.

3   The distance the gas needs to travel back to the collector is too long relatively seen.

4   The many soldered parts could clog the system.

5   The system was unappreciatedly heavy at above 16 Kg.

6   The collector was able to wobble, because there was no inside framework present, an inside framework could have also increase heat dissipation.

7   The system is too expensive for its (social)value and practicality (€140).

8   If ice forms on the evaporator during the cooling phase, you cannot remove the system from the coolbox easily.

9   The collector was totally made from selective surface, while only the top should have been enough.

An overview of raw material costs and weight of the original concept can be seen in figure III.38, it shows clearly that the collector, condensor and adsorption pair own the highest percentages. Reducing total price means a reconsideration of these parts.
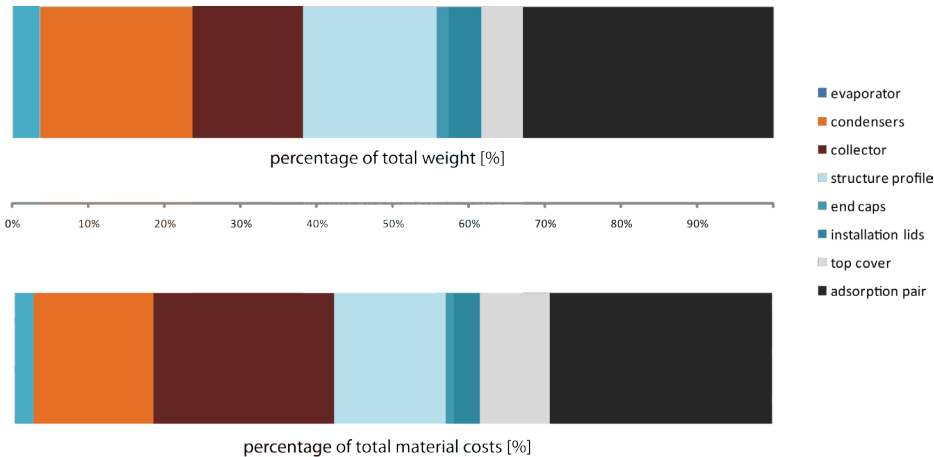

Figure III.35 (Mended) Cost and weight ratio's of the first prototype.

6.2   Zero Point One

With the main reason that point zero did not work as expected, I used one of my early ideas (Chapter IV.C.1) to build a simplistic and small prototype, in order to try and prove the working principle. Although this prototype served no function as a product, but only as a mere test in order to evaluate the working principle of adsorption refrigeration and its modularity, which is the key feature of the concept next to the fact that it can be made for under 20 Euro's. Fortunately, most likely due to its simplicity, it at least proved the adsorption phase and was able to bring temperature down way more than initially expected. First I will briefly discuss the manufacturing process and secondly evaluate on its workings. The prototype is simply build by bending 3m long tubes in a squared shape, and welding them together. Two valves control the gas and fluid inlets manually, in order to direct the refrigerant to the right parts. All three parts are made the same, while only the collector (the top part) is filled with Activated Carbon granulate and later covered with an absobtive coating (black).
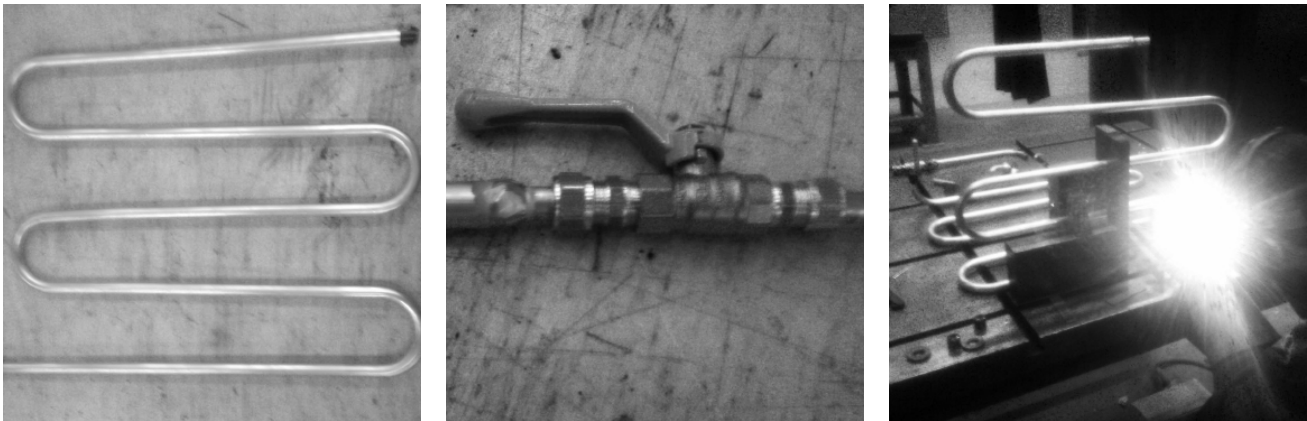
Figure III.36   Manufacturing Zero Point One Prototype, tube bending (left), compression couple (middle), TIG welding (right)
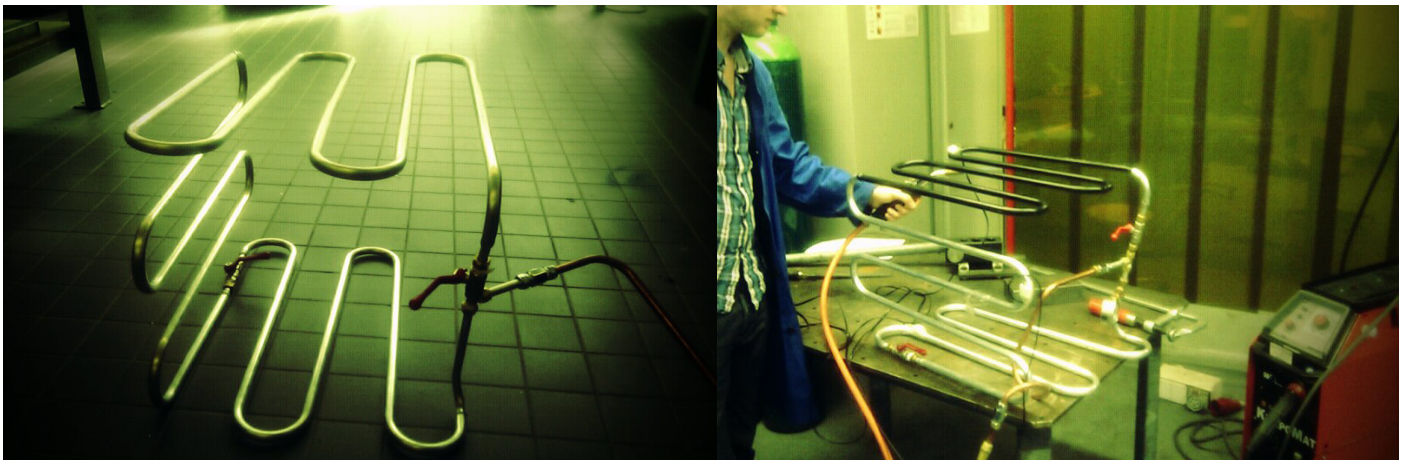

Figure III.37   The Finished Prototype (left), with on top the collector, on the side the condensor and on the bottom the evaporator, and Test Set Up (right).

What I learned during the manufacturing process of this prototype, ranged from the practicality of compression couplings to welding restrictions.

1   The collector surface is not large enough but could be made larger by laying a sheet of aluminum on top, or by bending the tubing in a more efficient way.

2   The inner volume of the collector containing only 0,4 L of Activated Carbon (≈ 0,2 Kg) is only enough to adsorb 0,07 Kg of Methanol, never enough to create enough ice (or a calculated cube of ≈ 0,2 m3).

3   Tube bending is a very easy to learn manufacturing process.

4   Using small thicknesses (< 1,5mm) for welding aluminum tubes together creates complexities for the welding process when it is not industrial.

5   Using only two pliers and some gas tight tape enables anyone to make a tubed system gastight, but only up to 200mbar. Gastight or PTFE tape is not made to go as low as needed (20 mbar). This restriction was found out much later, because the pressure sensor (manometer) attached to zero point one remained at exactly 200 mbar for more than a month. See figure III.46.

6   To first bring the system down to the desired pressure, and afterwards let the Methanol be 'sucked' in due to this negative pressure causes unwanted air to get mixed within, possibly creating bonds with the Activated Carbon. A better system is needed for methanol insertion.

7   'Sucking' in the Methanol is a very quick process of which it is difficult to stop at the right amount needed inside.

8   You cannot see if the system works, it would be nice to have optical feedback of a working fluid.

9   All valves or compression couples are designed for 12 or 15 mm diameter.

10   At first the inner pressure was accidentally positive, because too much methanol was sucked inside. Although it probably would have been vacuum, after heating the collector, the methanol combined with air expanded in such a way a positive pressure was created.

11   The test set up used was unprofessional, although good sensors were used there was neither a controlled environment or properly designed isolation.

12   The evaporator got coldest at the part which was lowest (not all bends were straight), meaning gravity has a great influence and should be highly accounted for within the design phase.

6.3   Test results Zero Point One

The test results (figure III.38) show that the evaporator does significantly drop temperature. The unprofessionality of the test set up causes the evaporator to lose a most of its energy directly to the surrounding environment (it had to basically cool a large room temperature volume of about 5 x 5 x 2 meters), and the steel table beneath it probably conducted a lot of energy away from the sensor. The evaporator was not placed in a bucket of water and therefore it is likely that when the evaporator would have been placed in a small isolated box, the temperature would have gone much lower, probably reaching zero degrees Celsius. Another factor, which had to do with the availability of tools in the faculty workshop at the time of building, was the fact that the tube thickness was more than calculated (1,5 mm thick instead of the intended 1 mm), meaning more energy went in the material than to the sensor which was placed on the outside of the tube. However, once the methanol was filled in, the system immediately started working, which was recorded with temperature sensors on the outside of all three parts, and the results are shown beneath.
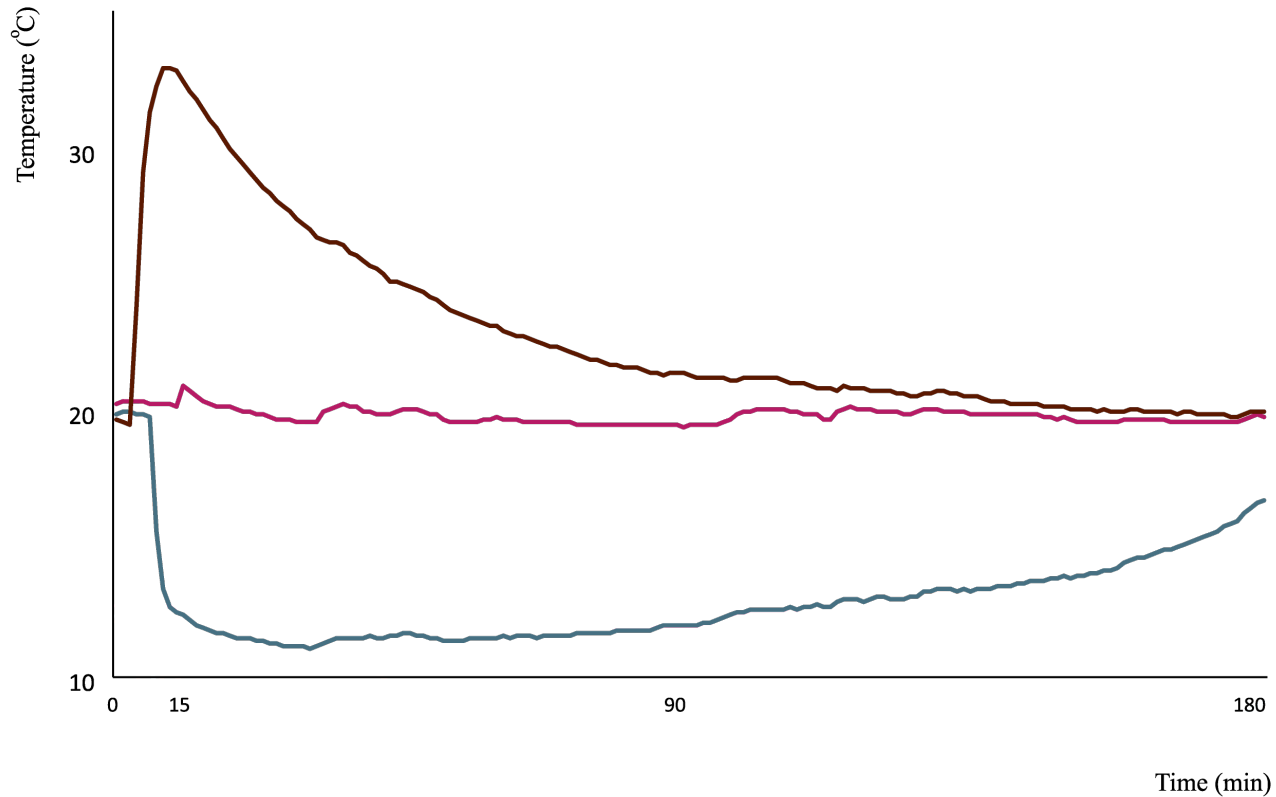
Figure III.38   Zero Point One Test Results of the Adorption Phase.

Another significant insight was the fact that the PTFE tape is basically unsuitable for this application where a pressurized system of 20 mbar should be reached and maintained. The tape used, and the only one available, has a class of .2, which means it can hold a 0,2 bar negative pressure maximum; 200 mbar. After a few days time, the pressure in the system of Zero Point One gradually went back up towards atmospheric pressure (1 bar) from the intended 20 mbar, but the rising seemingly stopped at 200 mbar. It was only by then noticed that this was due to the tape which is meant to be a gas tight barrier in between two (screw lock) connections. This means PTFE tape can not be used for a Activated Carbon & Methanol pair until one is found that can hold a really low vacuum. The system though, many weeks later, still remains at the 200 mbar pressure which shows that all the other (welded) connections are gastight.
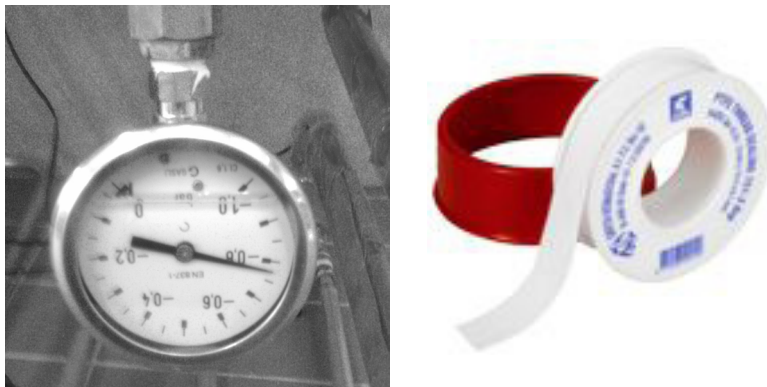
Figure III.39   Zero Point One system Pressure (- 0,8 bar or 200 mbar, left) and PTFE gastight tape (right)

C ACC 7 Calculation Overview

Relations in adsorption refrigeration are shown in the figure III.40. Beware these are still not anywhere near the desired level of a Mechanical Engineer, even despite the aid in setting this up by Bsc. F. Esrail and Bsc. M. Ruppert, students at 3ME who provides input for the solarbear initiative. However, these calculations are still rough estimations but do provide a general view on the possible application of adsorption refrigeration. As stated earlier, every subsystem is connected, and influences the other subsystems, there is no one way calculation possible without making assumptions or estimations. The latter is why creating overview in these relations is important for a designer who was originally trained to examine stools and coffee makers.

The calculations have been put into Microsoft Excel and are therefore interactive, and not placed here but can be found digitally. Below are a few design statements and a calculational visualization for overview purposes.

sum For every Kg of ice, 480 KJ needs to be extracted at a 35 degrees Celsius temperature difference (i.e. 30 Degrees outside and -5 inside the refrigerator). With an assumed heat flow to the inside of an insulated Kg of ice, estimated around 5-10 W, around 1-1,5 L of methanol needs to evaporate in order to create the 1 Kg of ice. To adsorb 1 Kg of methanol, around 3 Kg of Activated Carbon is needed, which is little less than 6 Kg.

Methanol Properties	Constants	Formulated
Density at 1 bar 293 K	0,798 Kg/m3	$Q_{ice} = m_{ice} \times (h_{latentH2O} + C_{pwater} \times dT)$
Heat of Vaporization	1142 KJ/Kg	$Q_{ice} = 1(333 + (4,2 \times 35) = 480$ KJ
Water Properties		$Q_{loss} = t_{adsorption} \times P_{in}$
Density	0,998 Kg/m3	$Q_{loss} = 24 \times 3600 \times 5$ or $10 = 432$ or 864 KJ
Latent Heat (energy for melting)	333 KJ/Kg	$m_{methanol} = (Q_{ice} + Q_{loss}) / h_{vaporizationmethanol}$
Cpwater	4,2 KJ/KgK	$m_{methanol} = (480 + 432) / 1142 = 0,8$ Kg $= 1$ L
		$m_{methanol\ max} = 1,17$ Kg $= 1,4$ L
Other		
Heat flow into the coolbox (Pin)	5 W	$m_{ac} = m_{methanol} / a_{cacmethanol}$
Adsorption Capacity AC & Methanol	1/3	$m_{ac} = +/- 1$ Kg $/ 0,33 = 3$ Kg $= 6$ L

D   Conclusions

Derived from the described literature research, collaborated experiences and prototyping, hard technical demands were established and enlisted hereunder.

D | 1   General Rules

- High surface area means more exchange in energy.
- High emissivity values absorb more energy, low reflect more energy.
- Still air holds energy, moving air transports energy.
- Low specific heat of certain materials block energy transfer, high values promote it.
- From 30 L cooling volume onwards, price is only of relative importance.
- 12mm is a common used diameter for valve systems.
- For bending tubes; the mid-radius of the bend equals 3 times the outer diameter of the tube.
- The system has to withstand peak intensity at noon (1000 W/m2).
- Has to encompass natural flow as much as possible.
- The regenerating time is most during daily solar peak (noon).
- The adsorption time and regeneration time are estimated to be around 4-8 hrs.
- The adsorption cycle is moveable during the process.

D | 2   Desorption Phase

2.1   Collector

- Has to utilize a high temperature, high pressure and low speeds.
- Little to no heat that is collected should be exerted back into the environment.
    - By using a TIM cover.
    - By using a collector surface with a low emissivity value and high absorbivity.
- Has to dissipate heat as good as possible.
- High temperature difference compared to environment enhances efficiency.
- Methanol gas should only travel towards the condensor.
    - By using a one way valve at the evaporator exit.
- Has to encompass around 3,33 the amount of needed Kg of Methanol, in Activated Carbon.
- Has to encompass enough space for Methanol has to escape and move around.
- Has to be optimized to the angle of the sun, depending on earth's location.
- When selective coating is used, flat surfaces enhance the performance.
- Optimalize for a low temperature difference in between the collector and Ambient.

2.2   Condensor

- Has to utilize a near environmental temperature, high pressure and high speed.
- Has to dissipate enough heat to external environment to be able to condensate Methanol gasses coming from the collector.
- In air cooled solution has to have 3 - 4,5 times the surface area of the collector; in water cooled solution 1/50 – 1/100 times the surface area.
- Methanol gas has to have the opportunity to naturally flow downwards by gravity.

- In air cooled solution, as much air as possible should be able to flow past the condensors surface.
- Should only dissipate heat into the direction that is wanted (i.e. not towards the refrigerator box)
- Can release its heat towards the collector; reusing the heat.
- Condense has to be stored until the adsorption phase.

2.3   Evaporator

- Has no function in this phase.

D 3   Adsorption Phase

3.1   Collector

- Has to reject as much heat as possible.
- Should dissipate heat, and Methanol gas, as much as possible.
- Has to adsorb 1/3 Kg of Methanol for every Kg of Activated Carbon.

3.2   Condensor

- Should serve as a supplying reservoir to the evaporator within adsorption phase.
- Methanol liquid should not return to the collector through the condensor.
    - By using a one way valve at the collector exit.

3.3   Evaporator

- Has to utilize low temperature, pressure and speed.
- Has to have a surface area of 1/3 the times of the collector.
- Has to stay as close to the water as possible to be able to turn it into ice.
- Has to be able to absorb energy as good as possible, i.e. by a using small thicknesses.
- The distance Methanol gas has to travel to the collector has to be as short as possible.
- Methanol gas has to travel to the collector as naturally as possible.
- As much of the energy input should go into the water.

Solar Insolation

maximum irradiation at noon Q,s
avareage sun hours hrs
average daily sun kWh $Q,sday$
average daily sun Joules Q,sj

Q,s [1000 W/m²]   x   hrs   [6 h] = $Q,sday$ [kWh /day]

$Q,sday$ [kWh]   x   3600   = Q,sj [kJ / day]

Cover Material

energy loss through TIM   TIM
energy left through TIM   Q,TIM

Q,sj [kJ . day] —   TIM   [⅓ Q·sj]   = Q,TIM   [kJ / day]

Insulation below Collector

energy loss through insulation   INS

Q,TIM   [kJ . day] —   INS   [⅓ Q·TIM] = Q,col   [kJ / day]

Collector

material specific weight ρ,col
surface area of collector A,col
needed height of collector h,col
energy left contained in collector Q,col
maximum power P,col
overall thermal conductivity collector U,col

$$\frac{V,AC / 1000 \quad [m^3]}{l \times w \quad [m^2]} = h,col \; [m]$$

$$\frac{Q,col \quad [kJ/day]}{hrs \times 3600 \quad [s]} = P,col \; [W]$$

T,o [30 ºC] A [m²] k [W/mK] $Q,d = -kA[(T,i\text{-}T,o$
T,i [2 ºC] A,out [m²] L [m] $Q,v = h,air*A,out$
h,air [50 W/m²K] l [m] ε [-] $Q,r = \varepsilon \, \sigma \, (T,s^4 - T,$
    w [m] σ [5,67ε10⁻⁸ Wm⁻²K⁻⁴]
    h [m] T,s [ºC]   Q,total x 8 hours

Environment

outside temperature T,o
desired inside temperature T,i
heat transfer coefficient air h,air

Coolbox Size

internal volume V,i
total internal surface area dissipating heat A
total outter surface for convectional transfer A,out
length l
width w
height h

Coolbox Insulation

material type (specific heat conductivity) k
material thickness L
emissivity value ε
Stefan-Boltzmann constant σ
outer surface temperature T,s

$$U,con \; [W/m^2K] = \cfrac{1}{\cfrac{1}{h,air \;\; [50\,W/m^2K]} + \cfrac{t,con \;\; [m]}{k,con \;\; [221\,W/mK]} + \cfrac{1}{h,r \;\; [2500\,W/m^2K]}}$$

Condensor

specific heat conductivity of material condensor k,con
material thickness condensor t,con
material specific density ρ,con
needed surface area condensor A,con
overall heat transfer coefficient condensor U,con
maximum temperature difference condensor and T,o $\Delta T,con$

$$A,con \; [W] = \frac{\Delta T,con \; [4\,ºC] \times P\,col \; [W]}{U,con \; [W/m^2K]}$$

conduction $\quad\quad\quad\quad$ Q,d = -kA[(Ti-To)/L]

convection $\quad\quad\quad\quad$ Q,v = h,air*A,out(T,o-T,s)

radiation $\quad\quad\quad\quad$ Q,r = ε σ (T,s4 - T,o4) A,out

ρ, aluminum $\quad\quad\quad$ 2,7 Kg/m³

total approximate weight $\quad\quad$ m,t = (A,col x t,col x ρ,col x 2) + (A,con x t,con x ρ,con) + (A,ev x t,ev x ρ,ev) + m,AC + m,r + m,ice

Adsorbent (Activated Carbon)

adsorption capacity $\quad\quad\quad\quad\quad$ a,AC
needed mass of adsorbent $\quad\quad\quad\quad$ m,AC
specific density of adsorbent $\quad\quad\quad$ ρ,AC
needed volume of adsorbent $\quad\quad\quad$ V,AC

$$\frac{m,r \quad [Kg]}{a,AC \quad [\tfrac{1}{3}]} = m,AC\ [Kg] = V,AC\ [L] \quad \times \quad \rho,AC\ [0,48\ Kg/L]$$

)/L]
(T,o-T,s)
o⁴) A,out $\quad$ +

$\quad$ = Q,t = heat losses total [KJ / day]

$$\frac{Q,t \quad\quad [KJ / day]}{hv,r \quad\quad [1104\ kJ/Kg]} = m,r\ [Kg] = V,r\ [L] \quad \times \quad \rho,r\ [0,7918\ Kg/L]$$

Refrigerant (Methanol)

heat of vaporization refrigerant $\quad\quad\quad\quad$ hv,r
needed mass of refrigerant per day $\quad\quad\quad$ m,r
specific density refrigerant $\quad\quad\quad\quad\quad$ ρ,r
volume needed of refrigerant per day $\quad\quad$ V,r
thermal conductivity of refrigerant $\quad\quad\quad$ k,r
heat transfer coefficient refrigerant $\quad\quad\quad$ h,r
evaporation temperature $\quad\quad\quad\quad\quad\quad$ T,ev

Ice

latent heat of fusion $\quad\quad\quad\quad\quad\quad$ lh,ice
needed mass of ice per day $\quad\quad\quad\quad$ m,ice
specific density of ice $\quad\quad\quad\quad\quad\quad$ ρ,ice
needed volume of ice per day $\quad\quad\quad$ V,ice
thermal conductivity of water $\quad\quad\quad$ k,w
heat transfer coefficient water $\quad\quad\quad$ h,w

$$\frac{Q,t \quad\quad [KJ / day]}{lh,ice \quad\quad [334\ kJ/Kg]} = m,ice\ [Kg] = V,ice\ [L] \quad \times \quad \rho,ice\ [0,99\ Kg/L]$$

$$U,ev \quad [W/m^2K] \ = \ \frac{1}{\dfrac{1}{h,ev\ [100\ W/m^2K]} + \dfrac{t,ev\ [m]}{k,ev\ [221\ W/mK]} + \dfrac{1}{h,r\ [2500\ W/m^2K]}}$$

$$A,ev \quad [W] \ = \ \frac{\Delta T,ev[^oC] \times Q,t\ [W]}{U,ev \quad [W/m^2K]}$$

$$\Delta T,ev\ [^oC] \ = \ T,i\ [^oC] \ - \ T,ev\ [-10\ ^oC]$$

Evaporator

specific heat conductivity of material evaporator $\quad\quad\quad\quad\quad\quad$ k,ev
material thickness evaporator $\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad$ t,ev
material specific density $\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad$ ρ,ev
needed surface area evaporator $\quad\quad\quad\quad\quad\quad\quad\quad\quad$ A,ev
overall heat transfer coefficient evaporator $\quad\quad\quad\quad\quad\quad$ U,ev
maximum temperature difference evaporation temperature and T,i $\quad$ ΔT,ev
heat transfer coefficient of iced water around the evaporator $\quad\quad$ h,ev

A Introduction

*B*uilding on the earlier described market and technical exploration, several conclusions were formed which in its turn established the design parameters needed during the idea generation and conceptual phases.

A 1 Demands

The long lists of demands (see figure IV.1) as described in previous chapters (II.B.BOP.7, II.B.BOAT.7, II.C & III.D) has been cut down to its essentials below.

A 2 Demand Shortlist

BOP

1. Price below €70, as low as possible.
2. The product needs to empower local communities; meaning, locally collaborating in entrepreneurial terms on sales, distribution, use and as many other aspects as possible that evolve a BOP product.
3. SME entrepreneurs all have specific needs for refrigeration; scalability & adaptability in terms of function, size and culture need to be incorporated within the design where possible.

BOAT

1. Needs to work whenever needed. But, there is no problem experienced by having to do (an) extra operational aspect(s) in order to make it work.
2. Price below €400, to offer a sustainable solution while being more affordable than competition.
3. The product needs to be adaptable to varying boat types.

BOP vs BOAT

a. Possible price range of the product differs heavily (< €70 vs < €400).
b. Functionality of the product differs heavily (as good as possible vs always working)
c. The need for adaptability of the product is similar (culturally & size vs boattype)

TECHNIQUE

a. Adsorption refrigeration is able to be low cost.
b. High functionality adds to the total costs of the system, meaning both markets can be served properly when adjustments are made accordingly.
c. Adsorption refrigeration is highly adaptable in size and shape.

A 3 Technical Design Rules

The design rules are meant to serve as generalized design parameters. Since every subpart of the system influences the others, design rules and ratios of different system aspects were created to ensure an open idea generation phase. For a visualization on these rules see figure IV.2.
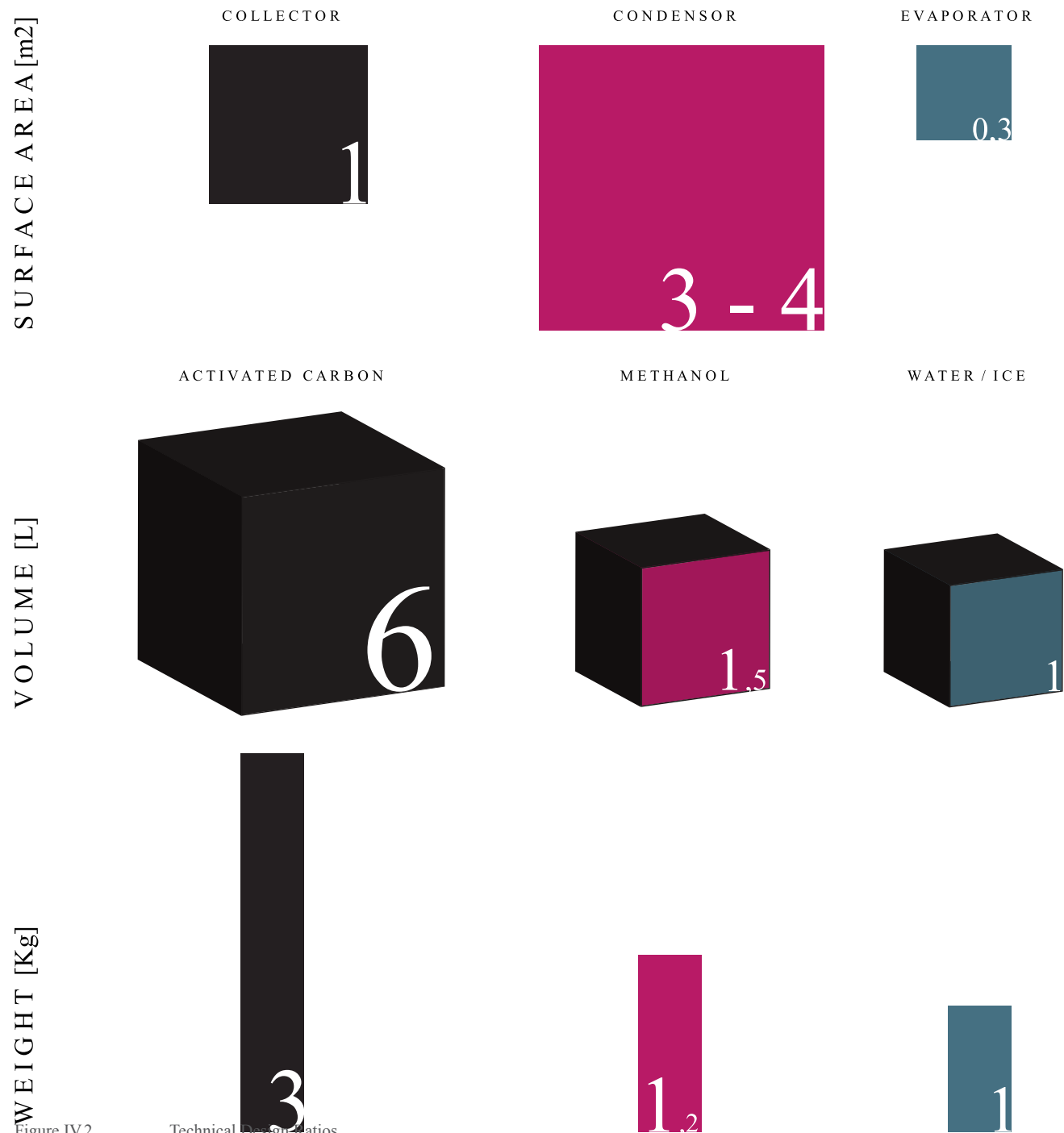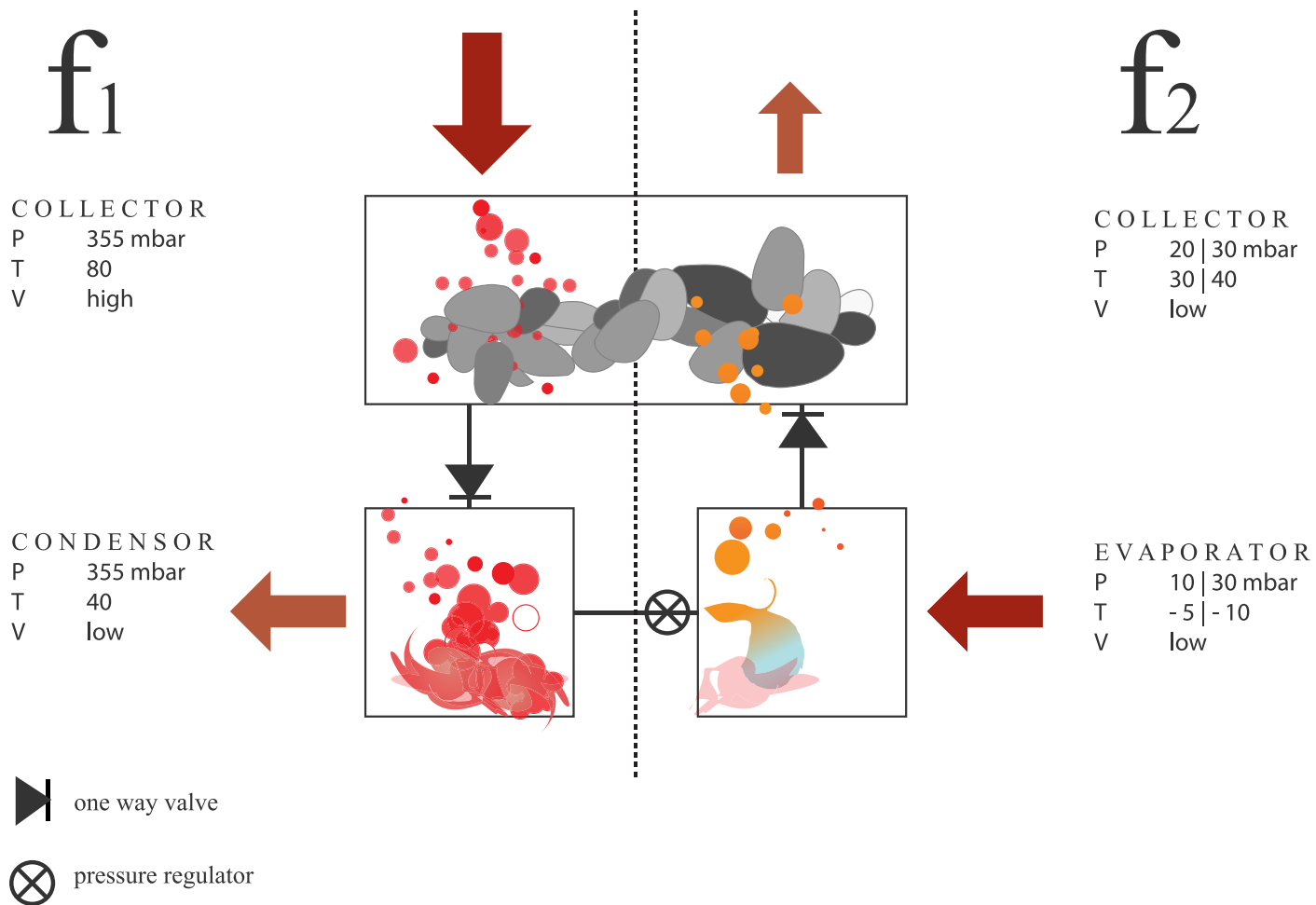
LOW COST REFRIGERATOR FOR BOP [<€70] | EASY TO MANUFACTURE | SMALL & PORTABLE VOLUME | SHOULD COOL 3−4 KG OF VEGETABLES OR; 3−4 BOTTLES | NO ELECTRICITY | HIGH INVOLVEMENT IN DEVELOPMENT (EMPOWERMENT) | STATUS ENHANCING PRODUCT | UPSCALING POSSIBLE | M.A.Y.A.-PRINCIPLE (APPROPRIATE TECHNOLOGY) | WITHSTANDS HARSH ENVIRONMENT | WORKS IN ALL CLIMATES | AUTONOMOUS OPERATION | SHORT PAYBACKTIME | INCLUDE ENTREPRENEURIAL ACTIVITY | SUSTAINABLE PRODUCT | ALWAYS FUNCTIONING WHEN NEEDED | SALTY ENVIRONMENT | NO PROBLEM WITH EXTRA ACTION | ONLY TO COOL DRINKS | NO FREEZING NECESSARY | EXPECTED COSTS AROUND €300 - 400 FOR BOAT | INTEGRATED SYSTEM IN BOAT DESIGN | SUGGESTIONS OF CUPBOARD | SIZE 1 KRATE OF BEER | BOAT TRIPS 20−30 DAYS A YEAR | AROUND 0.4 SQRMTR AVAIABLE ONDECK | SOLAR COLLECTOR NEEDS TIM COVER | NEEDS TO HOLD AS MUCH HEAT AS POSSIBLE IN f1, AND EXERT IT IN f2 | CONDENSOR NEEDS A 3-4,5 TIMES LARGER SURFACE AREA THAN THE COLLECTOR | NEEDS TO DISSIPATE AS MUCH HEAT AS POSSIBLE, PREFERABLY TOWARDS DESORBER; BY USING THIN MATERIALS WITH HIGH HEAT CAPACITY | FUNCTIONS AS THE RESERVOIR IN f2 | EVAPORATOR NEEDS TO BEABLE TO ABSORB AS MUCH HEAT FROM THE ICE AS POSSIBLE, USING THIN MATERIALS WITH HIGH HEAT CAPACITIES | SHORT DISTANCE BETWEEN THE EVAPORATOR AND COLLECTOR 12 MM IS A COMMON USED TUBE DIAMETER FOR VALVES | NATURAL FLOW INCREASES EFFICIENCY | SCALABILITY / UPSCALING / MODULARITY

Figure IV.1   List of Design Demands.

SURFACE AREA [m2]

COLLECTOR

1

CONDENSOR

3 - 4

EVAPORATOR

0,3

VOLUME [L]

ACTIVATED CARBON

6

METHANOL

1,5

WATER / ICE

1

WEIGHT [Kg]

3

1,2

1

Figure IV.2   Technical Design Ratios.

f₁

C O L L E C T O R
P   355 mbar
T   80
V   high

f₂

C O L L E C T O R
P   20 | 30 mbar
T   30 | 40
V   low

C O N D E N S O R
P   355 mbar
T   40
V   low

E V A P O R A T O R
P   10 | 30 mbar
T   - 5 | - 10
V   low

▶▏ one way valve

⊗ pressure regulator

Figure IV.3   Final Technical System including pressures (P), temperatures (T) and speeds (V), including heat transfer in and out of the system (arrows).

B   Idea Generation

As the design of the system sub parts are all interlinked, many ideas are already near complete concepts. A selected few sub ideas are shown below to visualize key aspects of later generated concepts, while describing the (dis)advantages of each. Only a few key items were selected to show here, on the topics modularity, insulation, and shorter cycle times.

B 1   Morphological Map

Functioned as a form of design grip, not used as literally as meant by the design curriculum. The morphological map served more as a chart of possibilities. The chart is found in appendix E.2.

product scalability
involve local communities
simplicity
appropriate technology
low cost
product should be adoptable to culture and size
modular
adaptation to boats
empowerment
low efficiency
low cost technique
building bridges building bridges building bridges building bridges building bridges building bridges building bridges building bridges building

Figure IV.4   From Ideas to Concept impression.

As found in the market demands, modularity, or the desire to be able to easily adjust size of the complete system to a specific need, had to become a key aspect of the design. Since every component can be made out of tubes, bending them in the desired shape would be an ideal solution to that problem. But, there is one other problem, the ratio of outer tube diameter to bend radius (3 times the tube diameter) prevents the collector from obtaining enough surface area, or inner volume for the Activated Carbon per m2. I tried to look for ways to use the bending ratio while at the same time increasing the collector surface (A). At the same time tubing would need to be connected easily without creating flow obstructions. An idea which encorporates differing melting points of different materials (B), squeezing the tubes together while heating enabling melting of the outer surface of the connection part(s). Thridly, a simplistic cheap valve idea to create the desired shortcut from the evaporator to the collector in phase 2, which at the same time prevents gas that flows from the collector to the condensor would not be able to enter that shortcut in phase 1 by using pressures similar to the workings of a so called reed valve (see appendix F.3). Most credits go to F. Esrail (C).

max bend radius = d$_{outside}$ x 3

■ low melting point
■ high melting point

■ pressurized flow from collector to condensor (f1)
■ pressurized flow from evaporator to collector (f2)
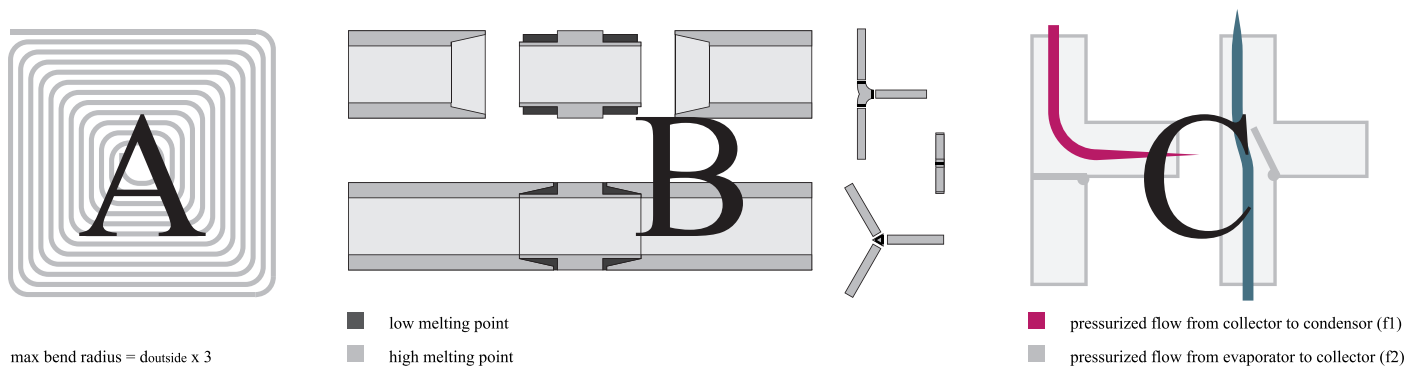
Figure IV.5   Modularity Issues, tube bending (A), tube connection (B) and cheap valves (C).

Since coolbox insulation forms an annoyingly high share within total costs of the system, I had a desire to integrate this within the modular parts. Taking a look at the specific heat conductivity values of all types of materials (i.e. table III.6 in chapter III.C.ACC.1), a vacuum insulation performs the best. This principle is also used double glazed insulated windows. Since the system in adsorption refrigeration using the Activated Carbon & Methanol pair already needs to have a negative pressure at near vacuum (20 mbar), I contemplated it should not be a complicated step to use vacuum for insulation as well. In a box type modular system (in which aluminum welded panels are used), an extra panel could be welded on top or bottom, wherever the insulation is needed, and during the production process both separate volumes can be depressurized to vacuum by using a vacuum pump with a split connection, or they can be brought up to pressure seperately. The problem is, that non-ferrous aluminum panels can not be welded to ferrous materials i.e. stainless steel. Stainless steel is needed because of its (affordable) property to hold a vacuum, but at the same time has a much lower heat conductivity value. Using aluminum would create heat bridges which would only defy its own goal in insulation (i.e. it would be heated nearly as much as the collector on the other side). Only if a way of welding aluminum sheets to a material with low conducting properties can be found, this option can be very interesting. This idea has the advantage that the relative thickness of a vacuumized insulation panel compared to for instance costly material like Styrofoam, can be 3 to 5 times thinner, furthermore, using high

emissivity values of the extra panel, the insulation automatically re-radiates coldness back inside the refrigerator box, next to the fact insulation and working principles can be combined during production.
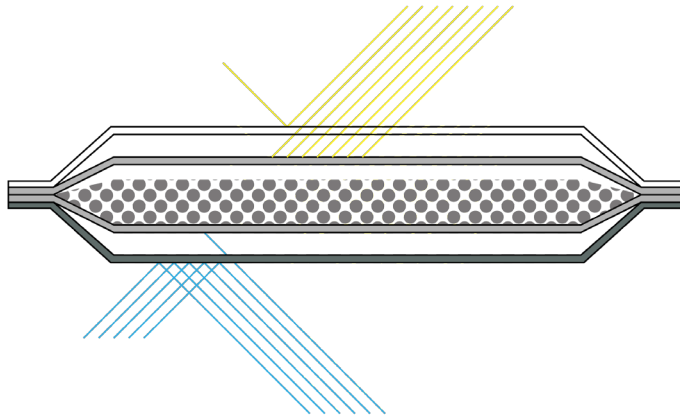
Figure IV.6   Combining vacuum of the system with vacuum insulation.

B 4   Shorter Cycle Times

Because shorter cycle times increase overall COP value of the system, decrease total needed adsorbent & adsorbate, but increase complexity and costs, it was important to take a serious look at. When shorter cycle times are desired, we need two collectors which function in opposite phase; at a moment in time one collector (A) should be in the desorbing phase, while the other (B) should be kept out of the sun since it needs to adsorb gas at low temperatures. The collector in adsorption phase dissipates heat while the other should absorb as much heat as possible. COP values in multiple stage adsorbers described in literature dramatically increase due to the regeneration of heat dissipated from the collector in opposite phase. This means, literally, the collector that is in the sun should be kept close to the one out of the sun. To enable a low cost technical solution, putting two adsorber/desorber beds on top of each other and rotating them is a logical first step, but when using i.e. tubes, sun will still heat the lower (supposed to be) adsorber. At the same time, a lot of the heat that radiates out of the last mentioned adsorber bed (B) is lost to the surrounding air instead of to the other collector, furthermore, a lot of the solar rays do not heat the desorber (A) direct or indirectly. An idea, was to use the density properties of water and oil, floating on top of each other, and enclosed in a transparent box. Instead of losing the solar rays to the adsorber (B), the rays hit and heat the oil, which dissipates its warmth directly to the tubing of desorber (A). Ideally, the surface height of the oil should be exactly in the middle of the desorber tube diameter. Meanwhile, the solar rays do not puncture through the black oil that lays on top of the water, protecting the adsorber (B) from heating. Furthermore, the heat that is exerted by the adsorber mix with the water (which also has a much higher heat capacity than air), and this heat is forced upwards because that is what heat does. When, after a predetermined time, the complete collector subsystem is flipped to switch phase of adsorber and desorber, the black oil wants to float on top of the water again, while the movement of the water ensures a forced convection, cooling down (A) which is now in its adsorbing phase. I filled a bottle with water and oil, and for at least a few months (until the oil was used for cooking again), flipping the bottle around always caused the oil to float on top and did not eventually mix with the water beneath. Although the idea would most probably increase COP dramatically, cooling is obtained at the moment the sun shines instead of an daily cycle where ice is created, there are many downsides to such a 'flip' system in general. The ideal phase time that such a switch should be made was considered to be around 15 minutes, meaning a person would have to flip the collector many times a day. This time could probably be somewhat increased by increasing the collector size but

it would stay within 30 minutes range. Furthermore, because the water and oil would always stay in the horizontal surface, angling the system to the sun would not be possible. Apart from that, the biggest issue, there is no such valve that exists which rotates, switches the adsorber to the evaporator while switching the desorber to the condensor, and at the same time keeps the complete system on the desired vacuum level of 20 mbar. Meaning a highly complicated valve would need to be designed, increasing costs dramatically. I did put a Mechanical Engineering student on the assignment to design or find such a mechanical valve, but unfortunately I never got to see any results from that.
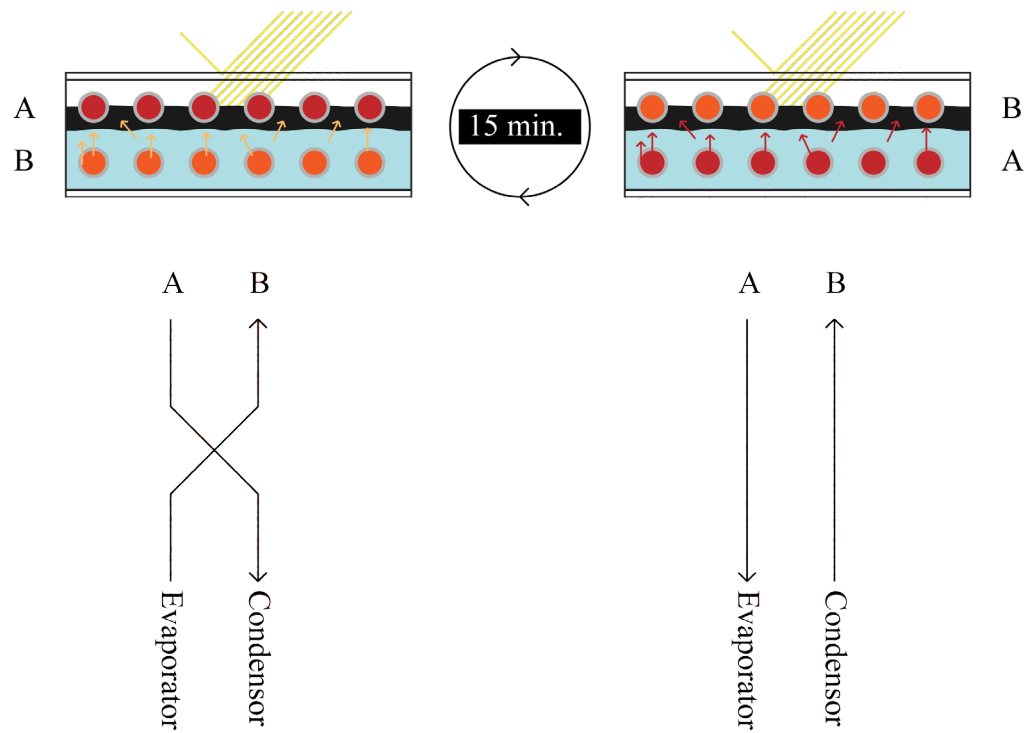
Figure IV.7   Heat Regeneration and increasing COP through shorter cycle times using oil and water.

During this thesis, six complete concepts were modeled out of many books of written and drawn ideas. The reason to model six instead of the recommended three to four, is because the idea generation phase is hard to visualize compared to other projects at the faculty of Industrial Design. Furthermore, I thought it necessary to conceptualize as divergingly wide as possible to show the many varying ideas behind the concepts.

In all concepts, the collector contains the Activated Carbon granules, and collects (solar) heat. The condensor dissipates the heat and stores the liquid methanol, while the refrigeration process is driven by the evaporator.

C 1   E I N S T U B E

Einstein once said that when a physical rule, or formula, is not simple it can not exist in nature, which I reckon is one of the best defenses of his relativity theory of $E = mc2$. Not at all that I claim to be capable of thinking anywhere near his ingenuity, all is relative, but I like to think of designing as getting rid of all unnecessary extra complications to eventually get to the essence by functional design. The reason whereof this one-tubed-concept derived its name was actually a teachers fault. The core value of this concept lays in its simplicity, easy manufacturing and adjustability.

Dimensions
Scalable, in this case;   400 x 500 x 400 mm
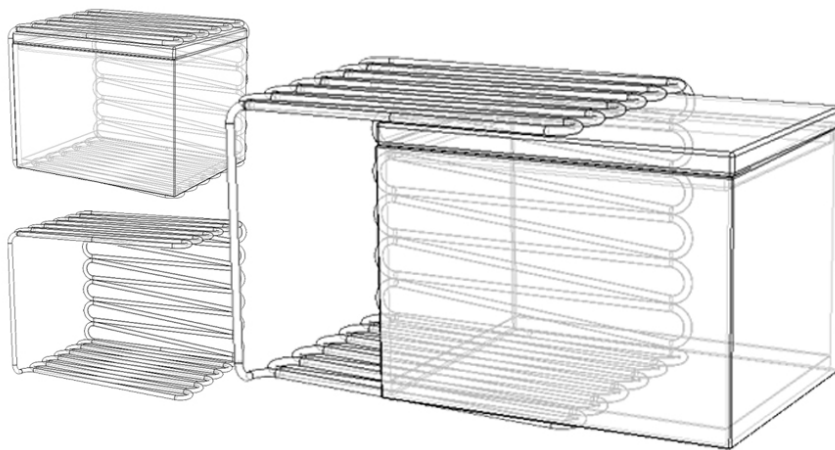
Figure IV.8   Einstube's intended use.

Use
In the figure above, it can be schematically seen how its use was intended. For the desorption phase, the system itself is placed outside, the sun heating the collector tubes covered by TIM material and insulated below (cheaply). Next, at the end of the day, the system is placed inside, the insulation material is removed and a (self-made) coolbox is placed over the evaporator. The removed insulation can be put beneath the evaporator to ensure a better heat exchange with the bottom of the coolbox, where the ice will be created. The next morning, the coolbox can be removed which now has ice at the fake bottom. For insulation purposes, an insulated piece of foam or something comparable should be replacing the space where the evaporator went at the bottom. Now the coolbox can be easily carried to any spot.
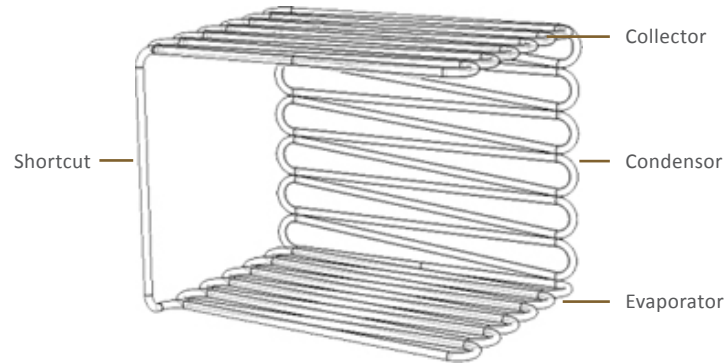
Figure IV.9   Einstube Basic Parts.

The concept is completely based on (up)scaling, or modularity, combined with natural flow. It uses 12mm diameter tubes which are easily bent and connected to standardized industrial oneway valves and pressure regulators. At the same time, one of the other roots of this concept is to be very affordable because ø12mm aluminum tubes are around €0,72 per meter (retail, at the PMP, faculty shop) and the concept is very easy to manufacture because bending tubes can be done without any extensive knowledge but by the simplest of rules. The total tube length in this concept is around 18 meters, meaning €12 of tubes at retail price, together with the needed valves in mass production the material costs would assumingly not exceed €25 for its pure working principle (valves are little more than €8 at the GAMMA, Delft), including Activated Carbon & Methanol. But there is a problem with the expected cooling capacity of this principle, due to the limited surface area and inner volume of the collector. Surface area can be increased by welding or soldering a flat aluminum sheet on top, worth €0,80 for 400 x 500 mm. But the inner volume remains way too small, at a partial length of 7m tube, inner ø10mm, the inner volume can be only 0,55 L, meaning room for just 1 Kg of Activated Carbon, which can contain around 0,33 Kg (0,40 L) of Methanol, evaporating 0,33 Kg in a day equals around 360 KJ while we need at least 1000 KJ a day at maximum creating around one gram of ice, which is way to many. To increase capacity, the inner volume has to be enhanced at least more than twice of what it currently is for a proper insulated refrigerator box to be able to hold enough ice during the day.

Unique Selling Points

1 Modularity/scalability.

2 Simple and quick manufacturing process.

3 Expected low costs.

4 Incorporate locally available materials for insulated box.

5 Option to incorporate own culture/design for insulated box.

Problems

1 In this design, condensor tubes are not promoting gravity, they need to be horizontally placed.

2 Angle to the sun is improper.

3 Heat dissipation of the collector, volume of the collector.

4 Volume contained within the collector is not enough for the needed amount of Activated Carbon.

Possible Solutions to Problems
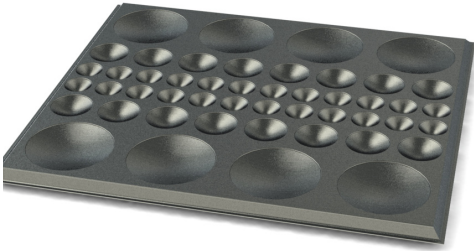
The heat dissipation, surface area and volume of the collector are too small. To increase this another design for this specific part is proposed based on natural flow and common radiators. Two sheets of aluminum are welded together and deep pulled until the shape below is approached. As can be seen in figure IV.11, the natural flow of gas molecules is spread by the principle similar in human blood veins (see inspirations below). All naturally occurring growth and flow is somehow related to the Fibonacci numbers (0,1,1,2,3,5,8,13... etc), the branching of veins for instance. Therefore the circle diameters and distances are based on this series of numbers, and the occurring 'veins' (negative to the indent circles) ensure rapid heat exchange.

Figure IV.10   Natural Flow from Fibonacci

Dimensions

300 x 80 mm

Use
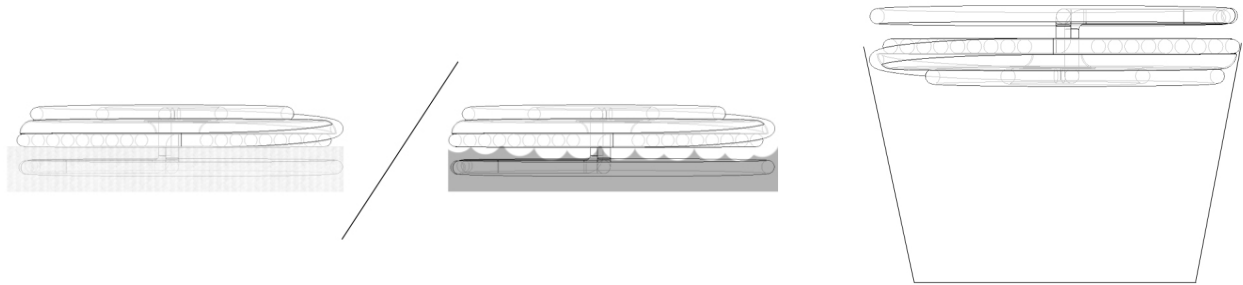
Figure IV.11   Intended Use for Spyraliced; desorption phase, air or water cooled (left), and adsorption phase (right).

Using this object is a little bit different, as antrepreneur, you would probably have to own multiple to use it properly, but they should not be very inexpensive. Its use is based on the fact that most low-income entrepreneurs sell their produce like fishes or other perishables, in a containing circular type basket. The use schematic is as follows; for the desorption phase, place the object upwards in the sun, either in a river or basin of water, or in the optional air condensor base. It will charge (or condensate the methanol) itself quite fast due to its low volume. The next step is to remove the system out of the base or basin, and place it upside down on top of the basket's content. Just before the user is ready to sell, a valve has to be opened and the adsorption phase will start.

Function

Evaporator

Collector (upwards)
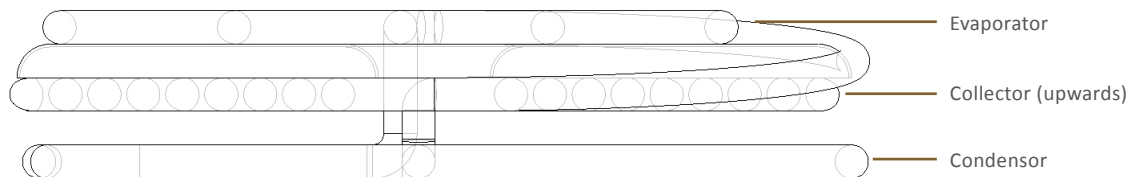
Condensor

Figure IV.12   Basic Parts Spyraliced.

The set up of the system is a little different than usual, because when placed upwards, the evaporator is on top, followed by the collector and the condensor. Furthermore, there is a plastic TIM cover stuck over the top half of the collector, and on the bottom to ensure a heat trap. The top half of the collector is painted with highly absorptive coatings while the bottom half is reflective. When the system is placed in water, it will float due to the TIM cover at the bottom and the vacuum in the system, but the advantage of this is that the condensor can be water cooled. If no water is present, a special base (basically many fins in a circular pattern) can be used for air cooling. The collector itself is a spiraled tube, while the tube is stacked as close together as possible to ensure a better heat exchange, and increase surface area per m2. The collector itself has a tube

length of around 6m, meaning little less than 0,85 Kg of Activated Carbon can be inserted. The coolness is not transferred into ice, but directly into the air beneath when the system lays upside down over/in the basket. It makes use of the fact that cold air travels downwards. The system layout is based on the fact that you have to use gravity for the condensor to condense the refrigerant in the desorption phase, while the refrigerant is kept there (through one way valves) to wait for phase 2. Turning the system around ensures the shortest distance from the evaporator to the collector. And while the collector is upside down, the reflective surface keeps solar rays from entering the basket. Furthermore, the condenser is dimensioned in such a way that, when it is on top in phase 2 and does not have any function except supplying the refrigerant to the evaporator, it can be used as a handle to open and close the newly bought lid for the basket.

Unique Selling Points

1   Low cost and low capacity.

2   Compact design, all of the system in one..

3   Use specifically for baskets.

4   Water condensation possible.

Problems

1   Low cooling capacity to air.

2   Basket probably not insulated, much losses.

3   Single purpose only.

Possible Solutions to Problems

1   Placing (only the evaporator) at the bottom of the basket instead of the top could create ice when water is layed over and only when the basket is water tight.

2   Supplying aluminum foil and flexible cloth/foam together with the system, the basket has to be internally dressed with this sheet for proper insulation.

Dimensions

Varying, per piece   60 x 60 x 15 mm

Use

This concept evolves mainly about modular set up, in relatively large scaled solutions. The collector, condensor, and evaporator are all made from the same part whereas only the collector has a different top coating. It is meant to fit ø12mm tubing to connect each modular sub part (i.e. the collector connected to the condensor). Because all of them have four different exits, almost all forms in a horizontal surface can be created, laid down on a rooftop to connected to the condensor on the side wall which in its turn is connected to the evaporator inside a storage hut for paprika's for instance.

Function

Figure IV.13   Compression Couple, wrenching the parts together deforms the compression ring, which locks itself around the tube.

The concept is based on the workings of a compression coupling system, which is a really easy way to connect tubes and create a vacuum. By just using two wrenches, one bolt and some strength, it is easy to connect two parts together. The threads on each opposite side are mirrored, meaning a turn of the bolt will pull the two parts closer together. In between the bolt and a specific part a ring of relative soft metal is inserted, thus, when they are tightened, the soft metal is squashed, leaving no room for air to escape or enter the system. Because each part has four exits, heat can be easily dissipated throughout the whole surface. Above that, Activated Carbon can be easily inserted in the parts that form the collector. At the sides of each surface, at the openings which are not connected to another piece, can be screwed tight with a lid instead of an open bolt. Lastly, the system still needs to be insulated and covered with a TIM material.

CROSSFIRE

IV
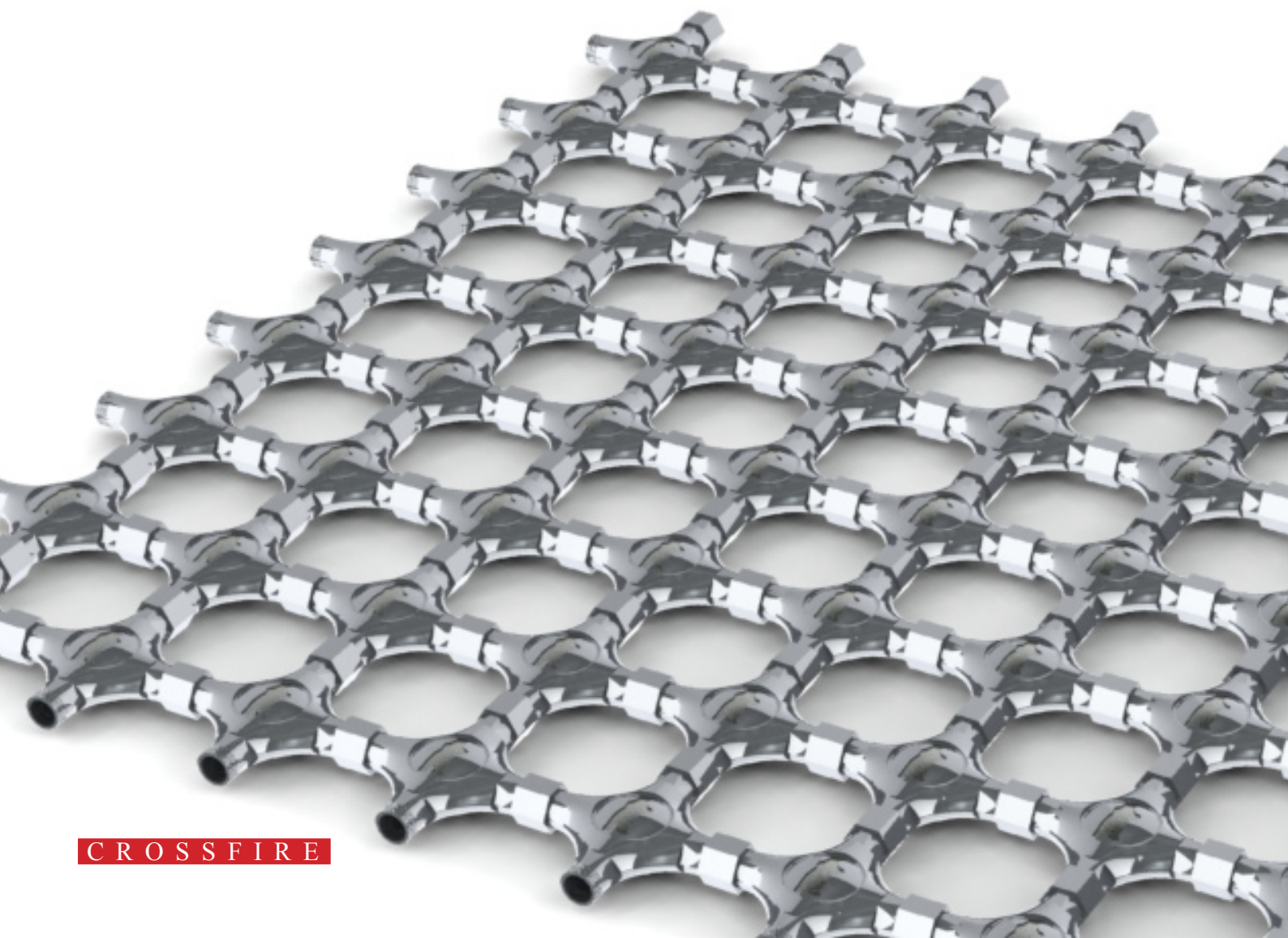
Unique Selling Points

1   One simple click and play manufacturing process.

2   Completely modular to any shape.

3   High heat dissipation.

Problems

1   Probably expensive per part, similar parts are about €10 a piece in retail.

2   If there is leakage, it will be very hard to locate.

3   Once tightened, they can not ever be loosened without replacing the compression ring.

Dimensions

100 x 300 x 450 mm

Use
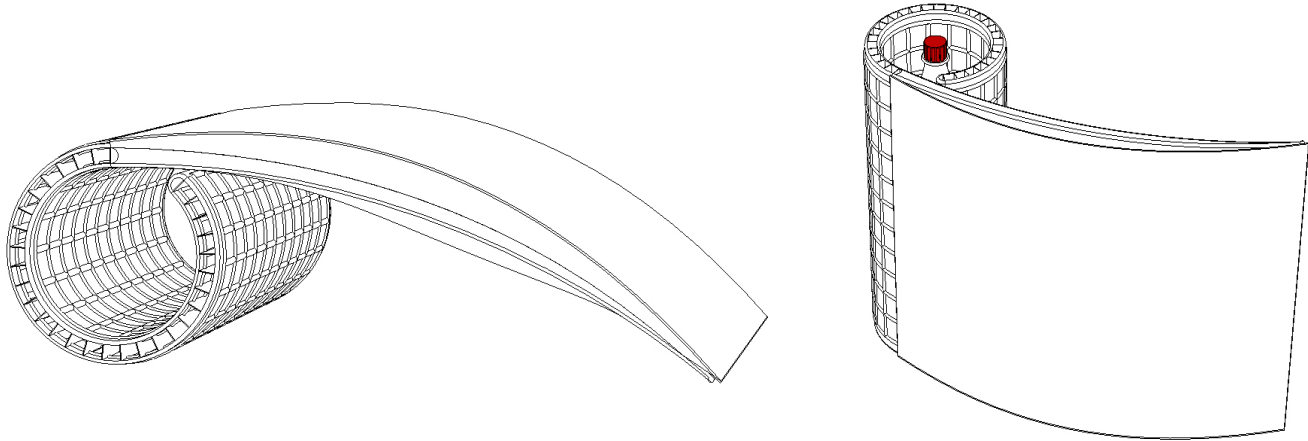
Figure IV.14   Intended use of BNR, desorption phase (left), and adsorption phase (right)

Only intended to refrigerate one bottle of 1,5 Liters of water to ice. This bottle can later on be placed inside any coolbox to keep down overall temperature for a period of time. First, the object has to be placed in the sun, resting on the circular 'wheel'. At nightfall, the unit has to be taken inside to be placed on one of its sides, designed for a single bottle which has to be inserted from the top. All that is needed is to open a valve and the second phase will start. It would be wise to use an insulated foam like material as lids on bottom and top of the bottle to ensure as much heat is extracted only from the bottle.

Function

TIM Cover

Collector

Evaporator — Condensor
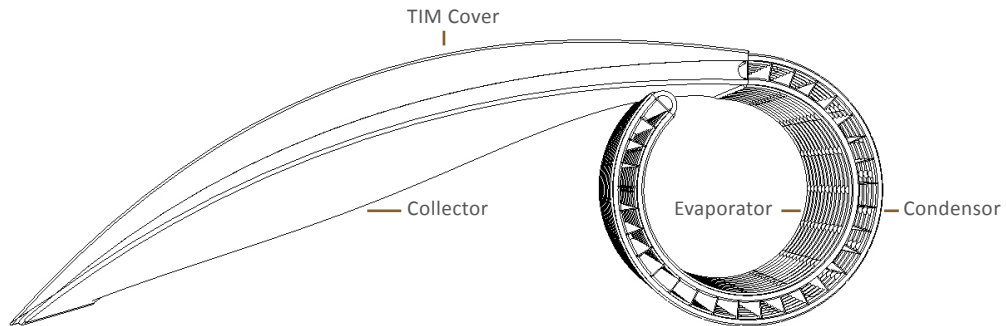
Figure IV.15   Basic Parts BNR

The concept combines several principles in a great way. First of all, in the desorption phase, the unit is placed outside on top of the so called wheel, this wheel ensures that the collector stands stable but at the same time the collector stands angled towards the sun. Within this collector, hot gasses travel upwards to enter one of the many outlets towards the condenser, which is directly attached at the top of the collector. The circular shape of the condensator is directly attached to the evaporator, using that surface as well to ensure the high surface area demand for the condensor is met. Above that, air can flow through and past the wheel. When air flow is coming from the perpendicular direction from the side of the collector, the wing-like design of the collector bottom forces airflow towards the condenser. After which, the condensated refrigerant flows downwards where it is kept until the next phase. In the adsorption phase, a valve in between the condensor and evaporator must be opened, and the evaporating gas will travel through the inner ring of the wheel, in near direct contact with the water bottle. The end outlets of the evaporator go into the bottom of the collector, besides the shortcut, it ensures great dissipation of gas molecules within the Activated Carbon. Furthermore, the liquid in phase 2 (adsorption) is laid at the bottom when the system is put on its side, and will travel upwards when evaporating. Therefore, the water bottle is cooled from the ground up. Next, the condensor without function in phase 2, entraps still air in between the inner (evaporator) and outer (condensor) concentric circles, using that for insulation. On top of that, the condensor and evaporator can be made out of one roll bonded sheet of aluminum which does not have to cost more than €20 for these measurements. What is not seen in the design is that two lids have to be placed, one at the top and one at the bottom of the bottle to ensure insulation.

Unique Selling Points

1. Specifically meant to cool a single bottle.
2. Uses design to get a good angle at the sun.
3. Combines condensor surface and evaporator surface for optimal surface area.
4. Uses the roll bonding technique for natural flow, optimal efficiency as a low weight application.

Problems

1. For one single purpose only (the water bottle).
2. Will probably be relatively expensive.

Inspirators

This concept mainly derived from the possibilities achieved with roll bonding. The possible deformation after production offers great opportunities, while the roll bonding printing process stimulates natural flow, with only a restriction in channel diameter.

Figure IV.16   Roll Bonding printing.

C 5 LITTLE COOL BAG

The little cool bag is exactly what it is supposed to be, a little bag that cools little. Only when multiple of them are placed on top of food or anything else, it is able to refrigerate significantly.

Dimensions

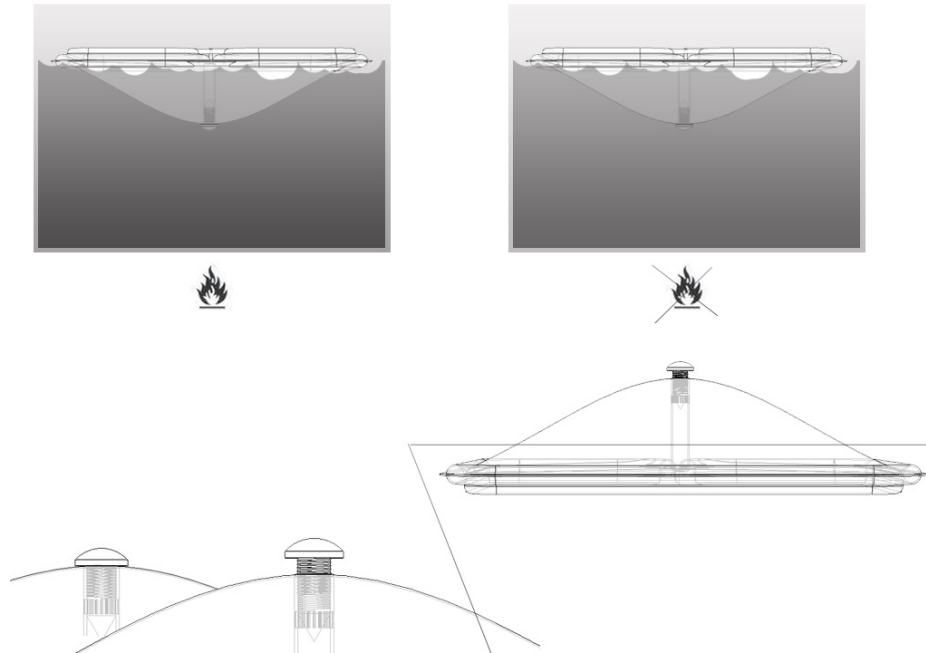100 x 100 x 20 mm

Use

Figure IV.17   Intended use of Little Cool Bag, desorption phase (up), adsorption phase (down).

This concept is a complete different one, in order to evaluate hybrid adsorption possibilities. The bag is placed upside down in a pan of boiling water. After only a short while (approx. 20-30 min), the bag can be let to cool down in the water that stopped boiling. During the day, or whenever it is needed, turning it upside down while the knob on top can be turned which initiates the cooling process and heat is transferred from below to the top surface, cooling the air beneath. The concept is based on the fact that more of these should be brought along and placed upwards on top of any content in a box or circular basket.

Knob   Collector

Water Condensor
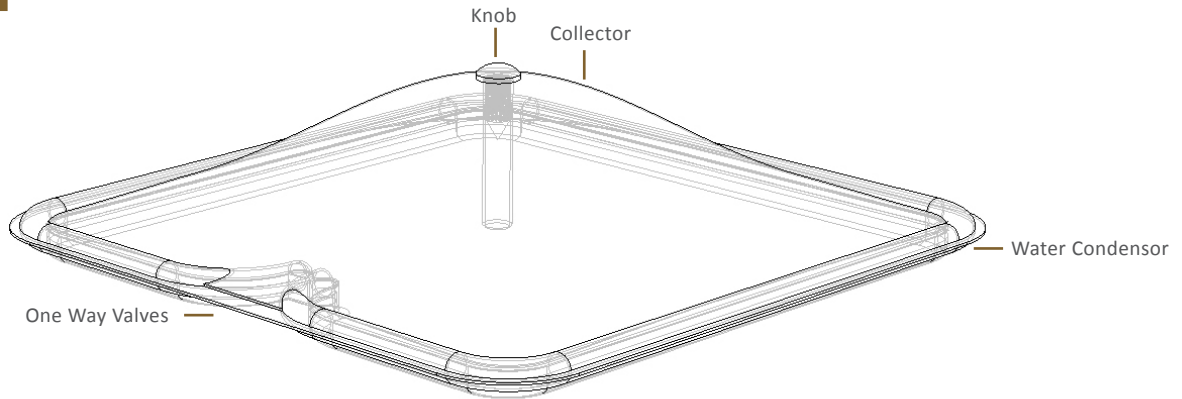
One Way Valves

Figure IV.18   Basic Parts LCB.

The reason for putting the object in boiling water is for the 'collector' to reach a hundred degrees Celsius. Hereafter the gas is forced through a one way valve of of the condenser tube (circling the side), where it stays gaseous until the boiling stops. The surrounding water should be left to cool with the unit floating inside, at that point the condensor tube cools down and the gas is condensed because the remainder of water now serves the water cooled condensor. At this point the knob is still down, but at any point in time in a later stage, the knob can be twisted open, opening a gate for the liquid that wants to turn to gas to escape, back into the 'collector'. Although the rendering suggests otherwise, the used material here is that of aluminum packaging.

Unique Selling Points

1   Small, affordable and portable.
2   Use at will.

Problems

1   Uncertainty of working.
2   Needs to be placed in boiling water, and will probably touch the potato's.

Inspirators

This concept came from the seemingly ideal combination of vacumized aluminum food packaging as described in Chapter III.C.ACC.3. The concept can be very affordable.

Figure IV.19 Aluminum Packaging.

Dimensions
Scalable   ø12mm

Use

Figure IV.20   Some of the many Varying Applications of Flexercice.

This concept focuses more on easy installment and extreme scalability, since it is to be used anywhere. Because the whole of the working principle is basically a closed circle, flexible tubing is an option. It is, again, based on ø12 mm tubing (because of the valves involved). But, because of the flexibility, it can be pre vacumized after which it can be used in any type of solution, be it a parasol salesmen, a house, a box, boat or anywhere else, as long as the collector stays in the sun, the surface ratio of the condensor is rightly executed over the length of the flexible tube and the evaporator lays somewhere in a supply of water to turn into ice.

Function

Collector / Condensor / Evaporator

One Way Valves
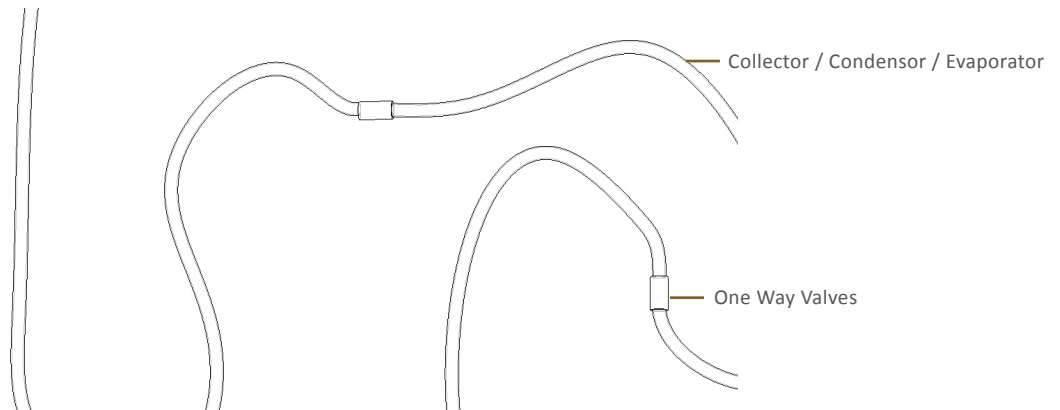
Figure IV.21   Basic Parts Flexercice

Flexible tubing works because a long twisted aluminum spiral is wound up in a rubber one. It has an inner diameter of 9,7mm, while the outer diameter after slipping it in a rubber sleeve is around 15.8 mm, above that, near infinite length is

FLEXERCICE

possible. According to Kaiphone Technologies in Taiwan, it is possible to maintain a 20 mbar internal pressure, because they are selling it to a customer who needs it to function at 50 mbar. Kaiphone Technologies offers it for €0,76 /m without the rubber sleeve. But unfortunately, rubbers are not the best known vacuumtight materials, so it has to be proven whether this does work or not, a custom made sample piece (they normally do not produce aluminum) is on its way to the Netherlands for testing purposes concerning this project, but will most likely arrive after graduation date. This concept will be further explored within the solarbear project scope but left out of further discussion.
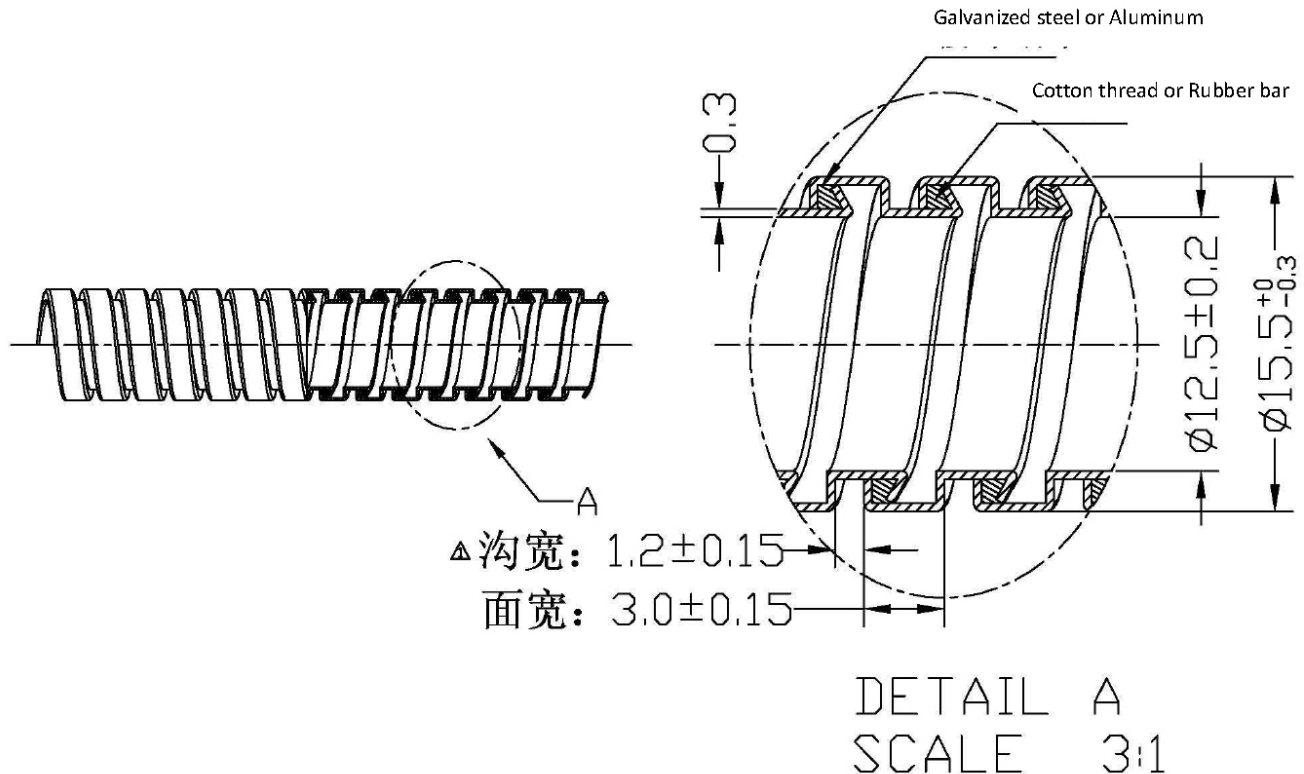
Figure IV.22   Flexible, Vacuumproof Tubing, from Kaiphone Technologies.

Unique Selling Points

1   Employable anywhere.
2   Extremely modular or upscalable.
3   Relatively affordable.

Problems

1   Uncertainty whether it is capable of holding a 20 mbar pressure for a long period of time.

Concept choice has been done in the same manner as comparing existing solutions within chapter II.B. Using the same criteria, it is easily seen whether or not a concept has a chance of success compared to the other, and previously explored solutions.
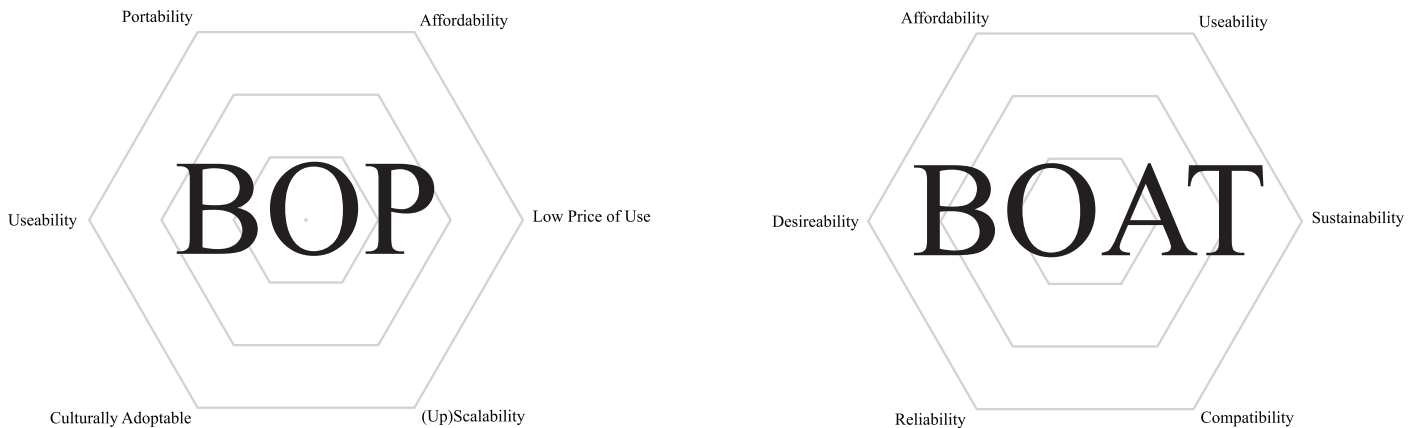
Figure IV.23   Wheels of Buijs for BOP and BOAT markets (left and right respectively).

From figure IV.24, it is clearly visible that the 6th concept "Flexerciced" scores best in both BOP as BOAT markets, as well as against competition described in chapter II.B. But, as stated earlier, the uncertainty whether or not this concept is able to hold a vacuum of 20 mbar over the years remains very uncertain until it has been properly tested which is at the moment impossible. Furthermore, the flexibility of the tube using rubber sleeves adds to the risk of failure especially in dry climates. Hereafter, the first concept "Einstube" is second best, also has high adaptability scores, although harder to accomplish (bending the tubes against simply laying them in the right place. Einstube is also much more reliable in terms of failure, aluminum tubes are not easily punctured. Although, it has to be taken into account that Einstube at its current state is unable to relatively adsorb/desorb enough methanol gas since the internal volume of the collector is yet insufficient. Other concepts score low on the more important side of the BOP wheel. At the top right corner affordability is a great concern for other highly scalable or adaptable concepts, and the ones that are affordable are not affordable enough.

For the BOAT wheels, all concepts score the same on sustainability, but there are clear distinctions in compatibility and desireability, also here the Einstube concept is second best.

`sum` Einstube is chosen for further development, although adjustments to the solar collector have to be made without losing the core values of this concept; the high adaptational aspects and affordability.
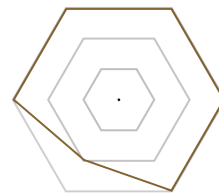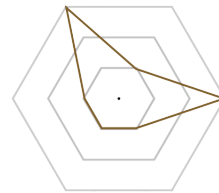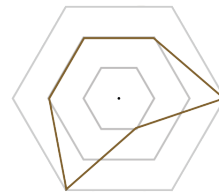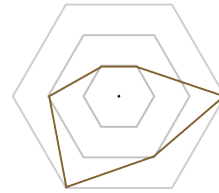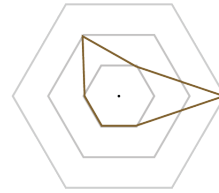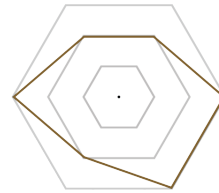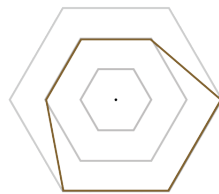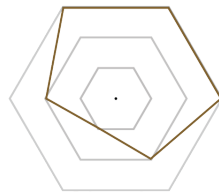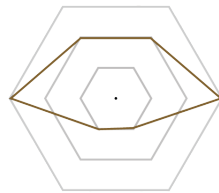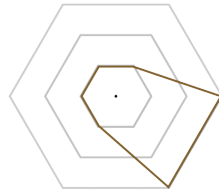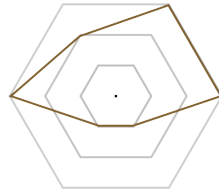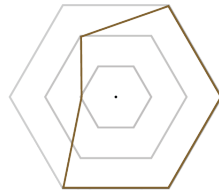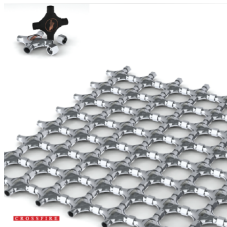
Figure IV.24
Concept Overview

BEARNAKED

The Bearnaked proposal empowers in terms of production, sales, and even in design, it enables high levels of co-creation especially in the BOP segments. At the same time, it uses one of the key elements of the adsorption technique to its fullest by incorporating scalability as a core value of this product. The latter having two main goals, to serve the adaptation needed to enter culturally driven SME markets in BOP countries, and in size to offer a custom solution to all the varying boats available in the BOAT market.

I chose to visualize a single possibility of the modular system here, and use this as a guideline in the proposal that follows later on. This design forms the fundaments on which adaptations can be made according to specific wishes. In the end, the pure concept evolves around the naked working principle that is easily adaptable. The power of the Bearnaked concept is found in the combination of appropriate technology, (up)scalability and the high level of BOP involvement. Key aspects of adsorption refrigeration are encorperated, scalability and portability.

As stated earlier, the Einstube concept was a great concept in its simplicity, but, in terms of collector capacity it needed change. To keep it low cost, I have chosen the collector to be as simplistic as possible. I will go through the concept step by step, treating its use, function, efficiency, price and added (social) value. Hereafter the collector will be weighed against the demands, in terms of importance and viability.

In the specific case of the example concept shown on the right, there are a few main differences compared to the earlier concept Einstube. First of all, the system is now treated as a whole, single refrigerator, for the simple reason of creating semantic value in terms of product innovation. The technique itself is already innovative in terms of market choice, and I believe deflecting from the long established semantics of a standard home refrigerator too much would jeopardize the way it is adopted by any BOP culture. Apart from that, further complicating usability by incorporating different usage techniques will distant the refrigerator in terms of practicality, next to the fact it was forcing thermodynamical imperfections. The latter meaning for instance, in Einstube, the refrigerator box should have been separately removed from and placed upon the pure system, which means moving all kinds of different parts around, exchanging insulation panels. In thermodynamic terms there would have been to much energy loss at the evaporator because it would not be in close contact with the water it is trying to freeze; air, and a sheet of metal would have been standing in the way of heat exchange. Apart from the risk of theft since the system needs to placed outside unguarded. Keeping the system Integrated, everything will work properly and optimally, while an entrepreneur is able to carry this to the working spot.
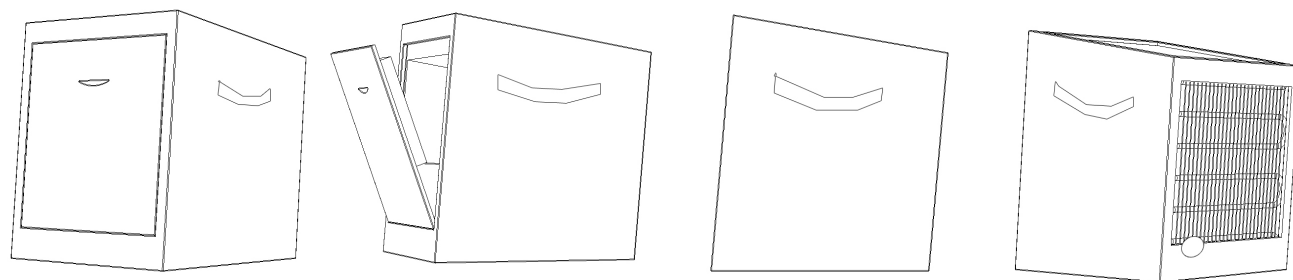
Dimensions

550 x 500 x 500 mm

Figure IV.25   Schematic Use, in which the handles are seen, and the switch on the back.

I have chosen an example low-income market, in Ghana, as starting point. Ghana specifically because while writing this thesis, I simultaneously guide two TUDelft students who are at this very moment researching solarbear applications in Ghana locally. Although their findings will not be concluded before the end of this graduation, chosing this target market specifically would already be a step in the right direction of actual implementation.

Reintegrating the earlier made demands, scenario and collage are contained within the design proposed here. The use is left fairly simple, using long established usecues from any other type of refrigerator, but with only one main difference, it should be placed in the sun. The example fridge has the intended use as follow: **1** it is taken outside the house in the morning, and contains ice generated the evening before, the switch on the back (far right in figure IV.25) has to be turned to the day setting. Then during the day, the door can be opened and closed taking refrigerated items in and out **2** while the entrepreneur is selling its produce in the sun, enabling the collector to initiate the desorption phase. Back home, after selling produce and after the ice contained in the container has melted the switch on the back should be set back **3** to night mode. Before the switch was turned, the collector was able to desorb and condensated enough Methanol, which after the switch is set on night mode will slowly evaporate through the evaporator, creating ice again. The switch itself can be very simple, using commonly known symbols, the sun and the moon, as valve settings (see figure IV.26). Hereafter, because the heat that is dissipated by the adsorbing Methanol, the TIM sheet should be removed **4** from the top.

As illustration of usage, a follow up written BOP scenario with the use of this product can be found in chapter IV.D.4.
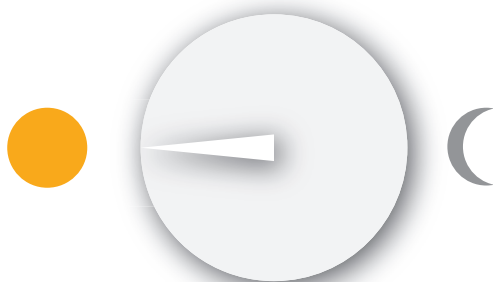

Figure IV.26   Switch

Frame —   TIM cover   Collector

Oneway Valve —

Door —

Insulation   — Condensor Mesh   Condensor —
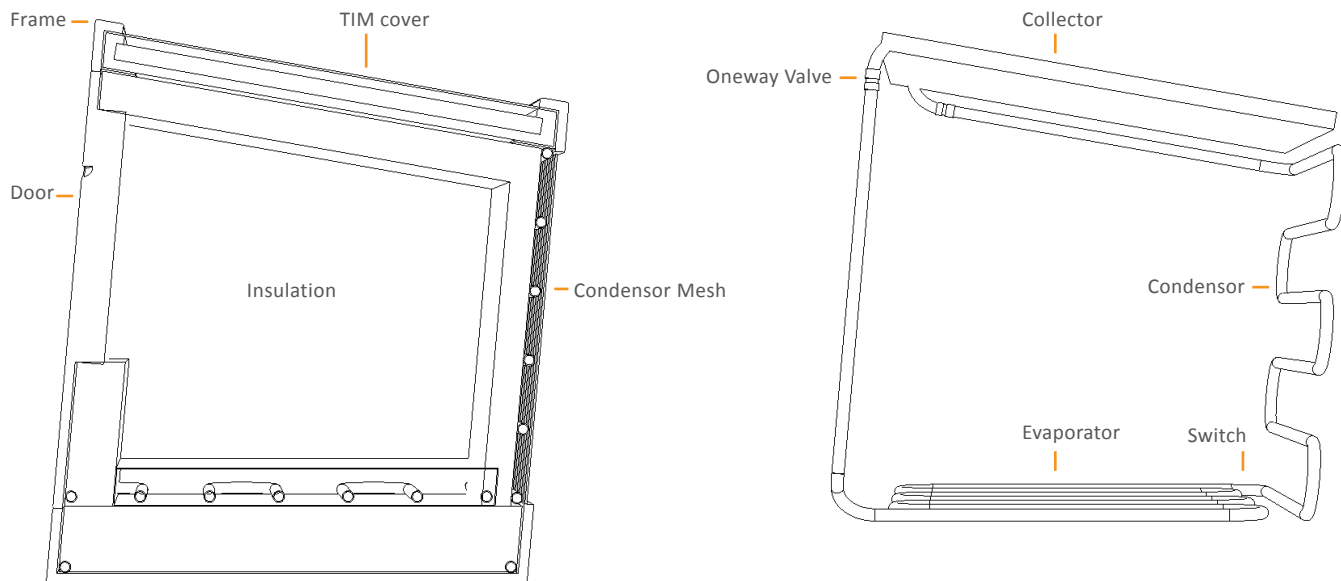
Evaporator   Switch

Figure IV.26   Basic Parts Bearnaked concept (left with insulation, on the right the bare system.

I designed the system in such a way that people are able to adjust it to their own needs and likings, in terms of culture, size and local available materials (influencing efficiency). The concept evolves around the easily manufactured and pure essential system. During this project it became very clear that stimulating entrepreneurial activity in BOP countries should be highly valued for a refrigerator like this, to ensure local involvement. It is the BOP market who should benifit from this concept, and this is only adopted when empowered. Thus, apart from the essential parts (the collector, the condensor and evaporator), all of the insulation, looks, feel and other aspects which increase efficiency, are to be determined locally at each of the different markets. For instance, the essential system would fit perfectly in the old and beautifully crafted boat you already own for years, but at the same time the same essential working system would be perfect for a low-income market, where the basic functionality and costs are of a higher importance and the exterior is able to adapt to its culture automatically. Examples of the latter are given in the chapter of added value (IV.D.5).

3.1 Collector

The design is crooked, adjusted to the optimal angle of the sun around the equator. The optimal seasons for solar energy in Ghana, taking into account the chance of yearly cloud coverages, is in between September and March. At that point in time the solar angle varies from equinox from 0-20 degrees, both ways. Therefore I have chosen it to be in the middle, at a 10 degree angle.

Instead of using the tubing as in the Einstube collector, a flat plate, aluminium container is easily manufactured and strong, and moreover can contain much more Activated Carbon granulate. It is strong not only because of its thickness of 1 mm, but also because the ribs inside hold it together (see the figure to the left). These inner ribs have a second function, dissipating the heat from the top surface of the collector to the sides, and inwards. More heat dissipation means a better overall heat

conduction and therefore a better eventual performance. Furthermore, each rib contains a handful of Activated Carbon granulate, many times the amount of grams that could have been achieved by the Einstube.
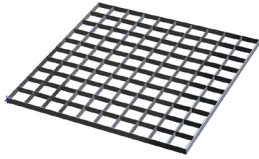
The reconsideration to use flat plated aluminum instead of tubing for the collector was a necessity. And of all other options that provide a larger internal volume, a 1mm thick sheet costs only €11,99 / m2 at retail (PMP). Meaning that the costs will be €6 for two aluminum sheets of around half a square meter, and far less in mass production. There are even standardized boxes available on the market (see appendix E.4) similar to this proposed design. Even if it was possible to weld tubes stacked right next to each other, at a ø12mm outside diameter, the total costs would rise up to €60 / m2 while the inner volume would only be 6 L/m2 against 10 L/m2 (inside ø10mm against inside 10mm box height respectively). The only advantage would be the surface area which is in the sun, at 1,3 m2 versus 1m2. Therefore, a flat surface was chosen. Which does however, decrease the modularity or scalability of the design by little, but since aluminum sheets of 2000 x 1000 mm are readily available and easily welded together, inner volume, price and practicality weigh more highly against the larger modes of upscalability.

The rest of the scalable design is kept similar to that of the Einstube, to ensure many different possible customized solutions.

3.2   Evaporator

Another difference, is the fact that in this design, the evaporator is enclosed by a water bucket of any watertight, affordable and locally available material. Meaning the evaporator is in direct contact with the water, and the evaporator is able to transfer as much heat as possible. A downside to this solution is, the more ice it creates around the evaporator tubes, the more insulated it becomes, which gradually decreases efficiency.

3.3   Condensor

The condensor needs a higher surface area to which it dissipates its heat. There is one simple solution to both; (thermoconductive) glue, soldering or welding and I.e. a mesh like material which can be found in nearly every animal shop (see figure displayed on the left, a rabbit cage).

3.3   Valves

There are two types of valves in the system, as they are needed to direct the flow in the intended directions (see figure IV.2). The first type is a one way valve, of which a cheaply manufactured is called a reed valve. Retail sells these one way valves at a €8 price, meaning in mass production this can be way lower. But, a reed valve should be fairly easy to manufacture by hand (using lathing machines), which brings the price down to only €0,50 - 1, taking no longer than half an hour. A commercial and and a proposed hand made reed valve are shown in figure IV.27. One oneway valve should be placed in between the collector and condensor, the other one in between the evaporator and collector.

Figure IV.27   Commercial (left) and Hand Made (right) Reed Valves.

The second valve, a switch, turns the adsorption phase on (opened) or keeps the adsorption phase from initiation (closed). It should be placed in between the condensor and evaporator. Commercial gas tight switches (with compression couplings) are around €9 at the GAMMA. But, for the sake of this project, this switch needs to incorporate two other functions: at the same time it is the opening at which in production the internal system gets pressurized to 20 mbar by a vacuum pump, and it is the place where the Methanol fluid is filled in afterwards. Furthermore, the switch should not be fully opened, but only a small gateway opening prevents the Methanol fluid to go through all at once unintended, and, for optimal performance the switch should regulate pressure. A redesign is therefore proposed, similar but with an extra (afterwards closable) opening, and estimated at the same price range due to the use of simplistic production principles. The redesign of two different valves form part of the solarbear's core business, combining patentable technique together with extensive knowledge on adsorption refrigeration. In figure IV.29 the working principle of the proposed valve is shown during usage of the refrigerator, while in IV.30 it is visable how the same valve can used during production; vacumizing the system, filling the methanol and closing the system.
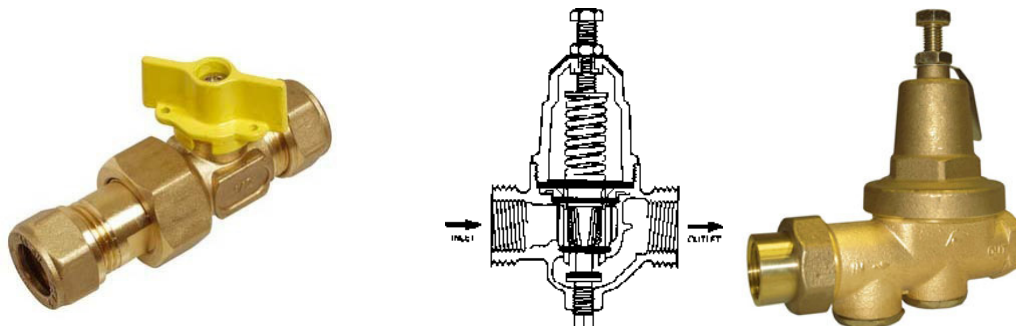

Figure IV.28   Commercial switch (right), and commercial pressure regulating valve (middle & right)
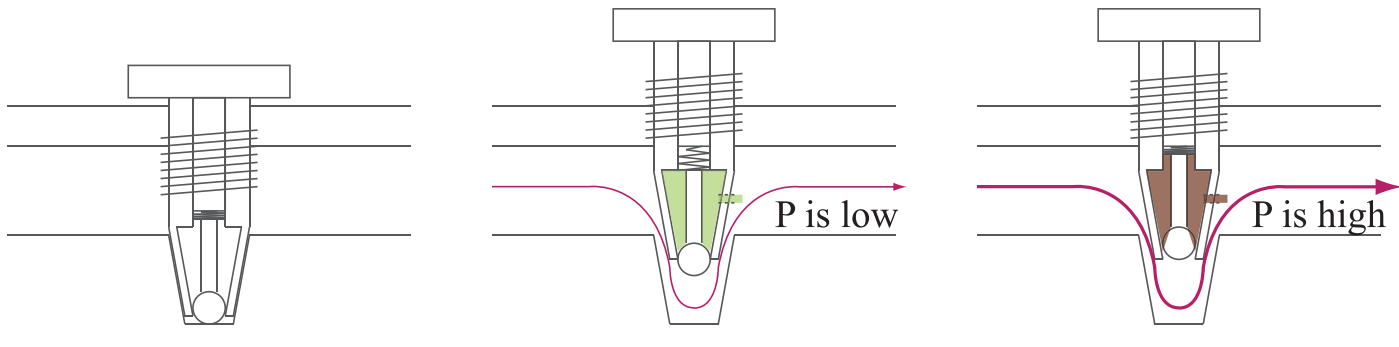
Figure IV.29   Schematic Proposal Working Principle, closed (left), open and pressure regulated through the pressure (P) chamber (middle and right). The valve needs to increase fluid flow when the pressure is higher at the exit than at the entrance of the switch, while it needs to reduce flow when pressure is lower at the exit than at the entrance. Instinctively a pressure regulating valve works opposite.
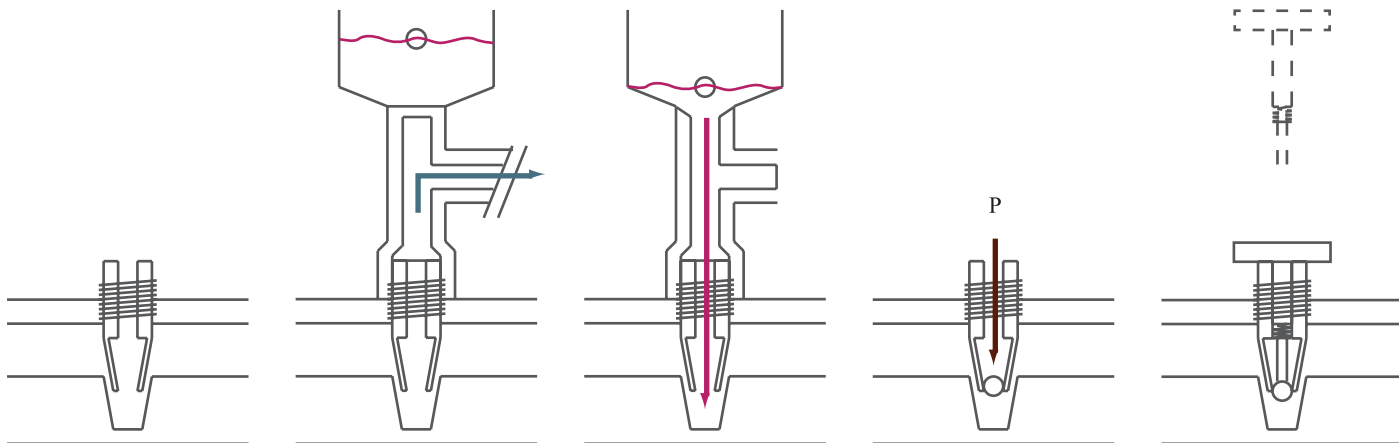

Figure IV.30   Schematic Proposal for Filling and Vacumizing, 1. Normal, 2. Vacuumize (gate to methanol container closed, gate to vacuum pump open), 3. Fill with methanol (close gate to vacuum pump, open to methanol), 4. Floating ball closes gate (pressure from outside will keep the gate closed while the filling apparatus is removed), 5. slide in button and solder gas tight.. The system is put on pressure, filled with methanol, and closed by using the same valve, meaning no extra parts are needed. The switch itself is diagonally threaded, and therefore vacuumtight. In this proposal only basic production techniques are used (drilling), and the spring that is attached to the ball to make it go up and down can be adjusted in strength to ensure the scalability of the Bearnaked concept as described in chapter IV.D.4.1.

   Door

The door opens up vertically from the top down, this is because coldness flows downwards and this way as much of the coldness is kept inside the refrigerator box. Furthermore, some protection on the sides is added (i.e. a plastic sheet) in order to keep the heat from blowing past the opening and taking away the coldness.

Added value of the Bearnaked proposal is to be found in three different applications, by combining technical possibilities and incorporating market values. First and secondly the adoptability of the concept in terms of culture and dimensioning, and thirdly, the high possible level of involvement by its proposed strategy meant for implementation at the BOP market segments. These three aspects will be explained here.

4.1   Adoptability

Bearnaked is adaptable in many ways, but, what is first noticed and easiest to show is the exterior. As explained in chapter III.B.ESS and III.B.ACC, many accessories of the technique are locally available and produced with BOP knowledge. As this concept evolves around the stimulation of local entrepreneurial activity, I chose to involve local craftsmanship where possible through design. Except for the exterior, the insulation, frame, collector coating, TIM materials, and the increase of surface area by meshes are all possible to create locally. Of course this does not mean solarbear will *only* sell the essential parts, but it will partner up with local entrepreneurs like sheep farmers (wool insulations), taylors (wood exterior and/or frames), steel workers (i.e. frame). Solarbear itself will produce the essential system and will perform the end assembly, see strategy.

4.2   Cultural Adoptability

Cultural adoptation is made possible by a core integration of local design, arts & crafts, in combination with a pure use of the essential technique. As the pure system type is chosen through a set of requirements stated by its end user (see IV.4.1 Technical Adoptability), other requirements can vary through different BOP areas or BOAT types. As example, different possible types are shown in figure IV.32-33 on the next pages. This part of the proposed concept was inspired by Victor Papenek & George Seeger (around 1970-1980), who believed in integrating accessible technique with local values. Figure IV.31 shows an example of their vision in BOP product design: an easily (and locally) manufacturable radio made from a tin can and an old wick (Dutch: lont), using burning parfin wax as a power source. The rising heat sufficiently powered the receiver, and when the wax was gone it could be replaced by basically anything that is able to burn. While the internal system was kept at a mere US$ 0,08 at the time, local Indonesians decorated them by their own creation and initiative.
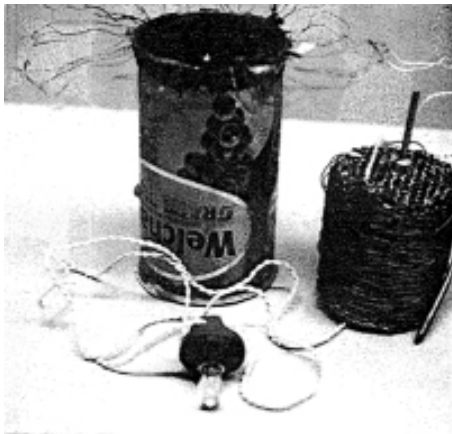

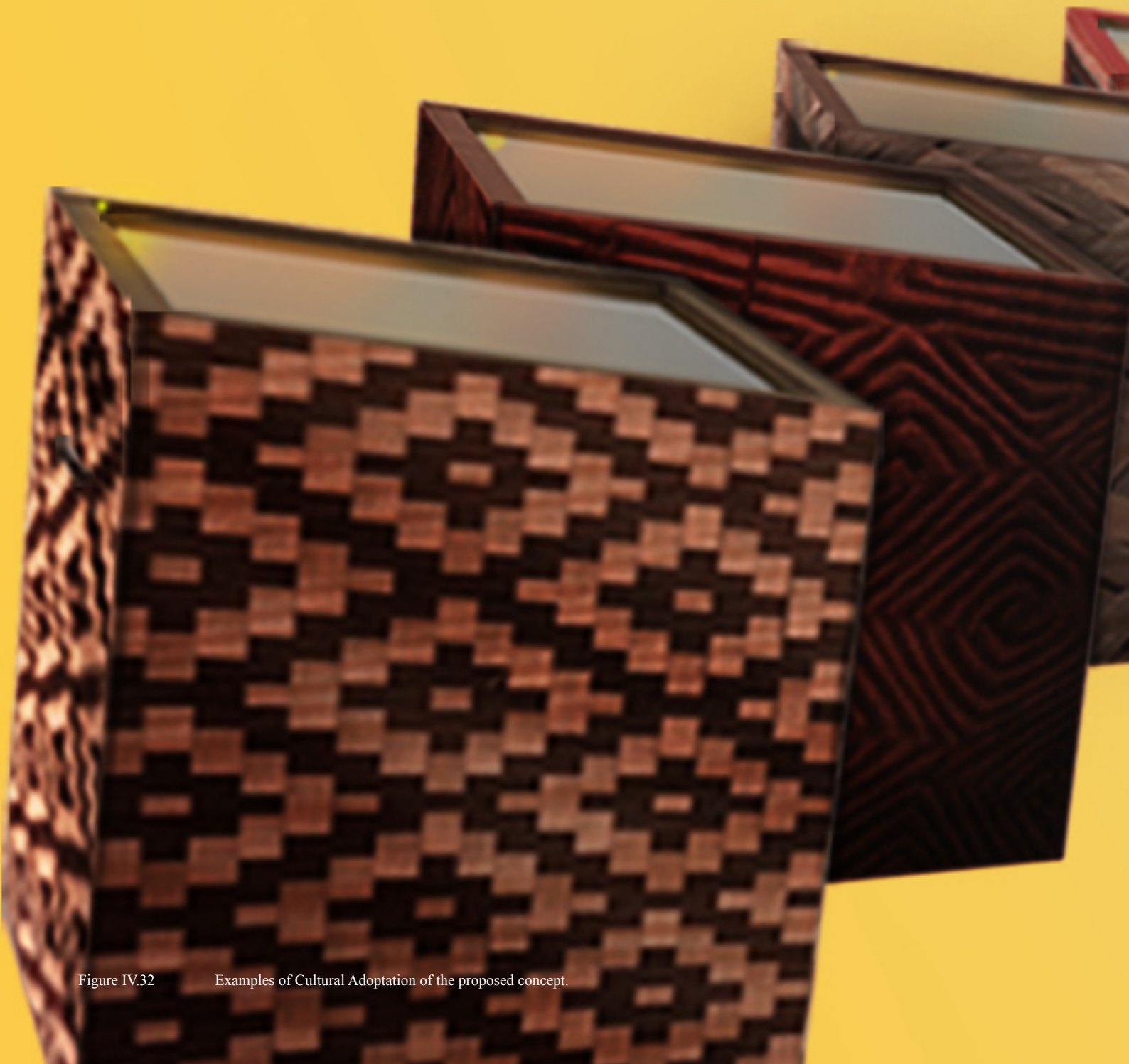Figure IV.31   0,08 radio US$, "Design for the Real World", Papenek (1984)

Figure IV.32   Examples of Cultural Adoptation of the proposed concept.

4.3 Scenario

A man wakes up with his face turned towards the early sun, not having much to spend doesn't mean no work has to be done. While he sits to drink some water he revalues his fee from yesterday, with a mere 6 dollars, it is annoying to keep giving stuff away. But times have changed. Today he will go and spend 5 out of his 6 dollars he decides. He picks up his beautifully handcrafted cool box, eagerly puts it on his motorcycle and travels towards the common meeting grounds, where his old friends are already awaiting. The cool box, still on the back of his bike, he was able to rent from a new type of company in the middle of Accra, one of his friends recommended it because he was the one that actually fabricated the box itself. Looking at the detail, the meaning of the symbols, and the coloring it came to mind how beautiful and strong his own culture was still pumping through his veins. And apparently, he wasn't the only one. Soon after his arrival, his old friends came curiously towards the back of his motorcycle, while he was trying to bargain some large fish from their neighboring salesman. And of course, the detail was noticed. He was ordered to their stand and asked where he got such a thing, and why. Explaining that he was able to define the size and shape, and able to rent it for a some time, this crazy little machine could actually make ice from nothing at all. His friends said to buy their fish while telling them more about it. He bought, and borrowed, the same amount of fish as the other day, but went for the bigger and better ones, because this time he knew they would not rot to nothingness despite the higher bargain. For his story, he got a few small fishes extra when he was able to promise a recommendation for his friend who crafted the outside of his box. He opened the door and went off.

At the market place, he would show some of the best looking fish on that old plastic sheet, while maintaining the others inside the box. And kept telling people he offered the best fishes, not rotten, not eaten by vermin. Before the day was really over, he already sold his stock. Maybe because he was feeling happy, maybe because suddenly all buyers seemed more interested, but he bargained at least 11 dollars, meaning 7 would be his this time, 2 would go to the strange little company in Accra, and 2 to for the borrowed fishes. He placed the empty box back on his motorcycle and drove back home where he took his box inside and sat down a satisfied man.

4.4 Technical Adoptation

One of the key features of the adsorption refrigeration technique is that it is highly modular or (up)scalable. This means it is adaptable in size to the need of a specific SME BOP entrepreneur, but also to any boat type if the technique is implemented correctly. Using the set of technical design rules as mentioned in IV.A.3, different needs can be rather easily met. Technical adaptation is another focus of the Bearnaked concept due to the varying demand in refrigeration; no SME BOP type entrepreneur (i.e. a fish salesman) is the same, and wants to stand out from its competitors, while at the same time could have a little more to spend over his colleagues. Making several options available, and using accessible production techniques (see chapter IV.D.5) the essential working principle can be modified by using locally available knowledge or skills that are easily learned. Of course, modifying it has its price (chapter IV.D.6) but scaling it up will increase overall effectiveness of the system. At the same time, the pure system can be offered relatively cheap, and especially in very low income markets, a Kg of ice per day can be created at around €25; by incorporating a bit of personal labour for a hatch door and a hole in the ground for infinite insulation. This is especially due to the tubing system, which is very easily deformed in the right angles using little knowledge. Some examples are shown in figure IV.34 on the next pages. Technically, it is possible to use the fabrication limits of aluminum sheets (2000 x 1000 mm) as a maximum size of the collector, but it is more likely that a single module of the collector (450 x 450 mm currently) is mass produced and welded together locally.

In all scalable solutions, the switch still functions as described earlier, but when it is not turned from 'day' to 'night', the methanol liquid will remain within the reservoir. For the BOAT market this means that the switch should be flicked for the refrigeration process to start at the moment of arrival at the boat itself, while at the same time a protecting layer (i.e. a white blanket) should be laid over the collector surface to keep it from heating up if the sun is which will pressurize the system, preventing the adsorption phase (refrigeration) to start.
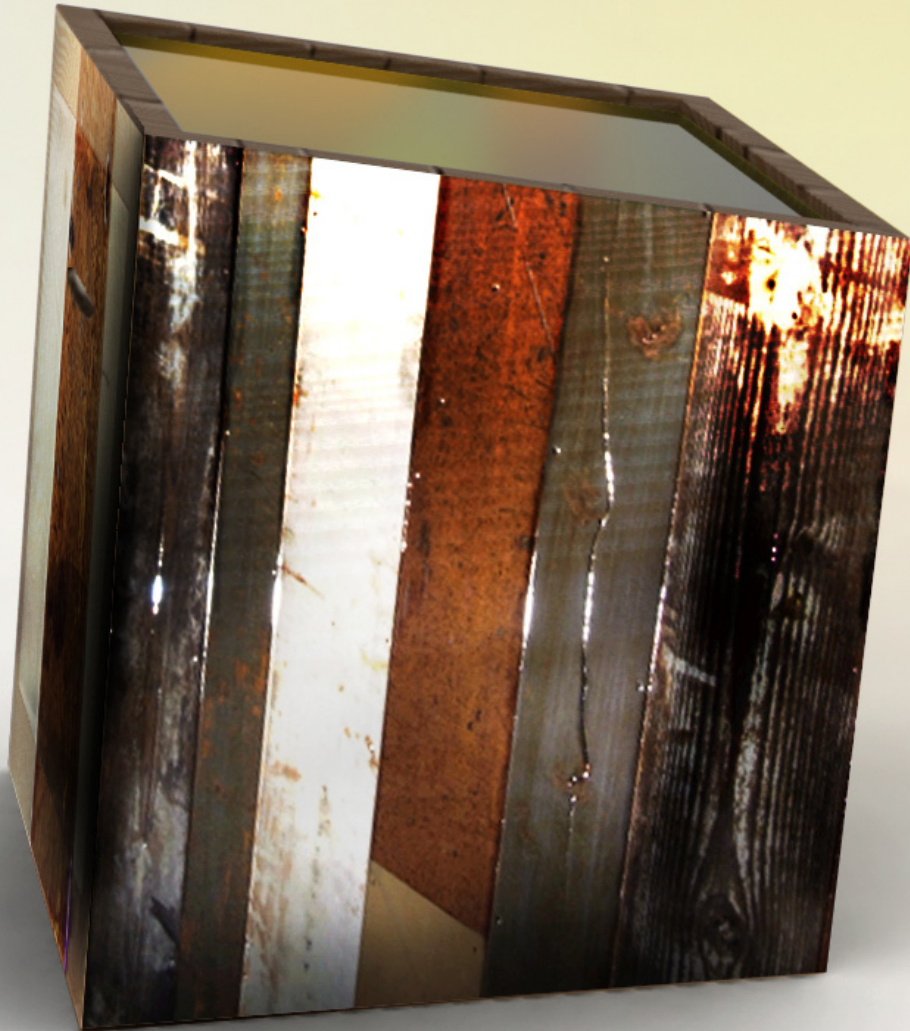
Figure IV.33   (Western) Cultural Adoptation.

Figure IV.34   Examples of Technical Adoptation of the proposed concept.
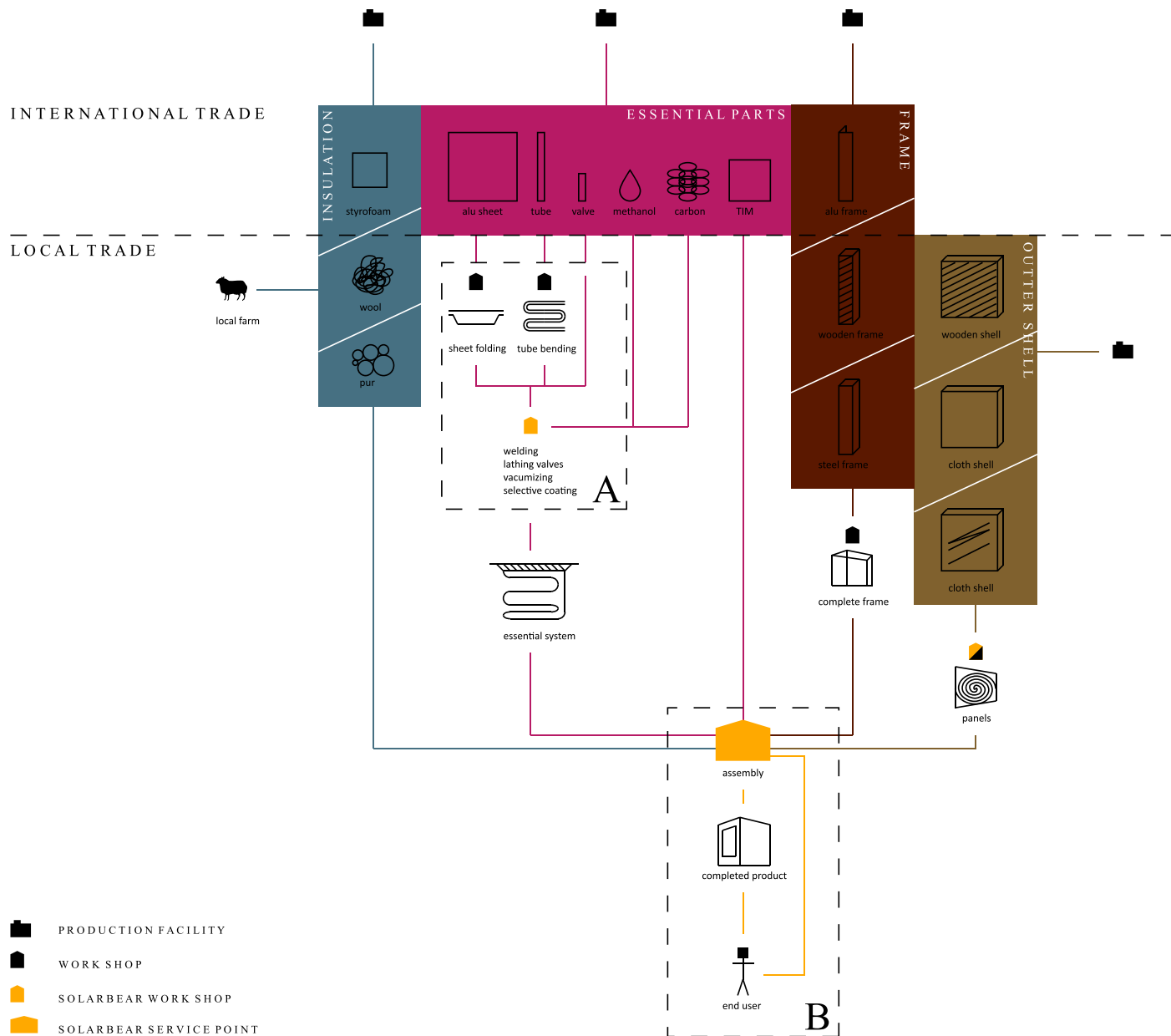
The product comes complete with a proposed strategy for the BOP, because especially in these markets, strategy is of essential value as explained in chapter II.B.BOP. A schematic overview is provided on the right in which as many product facets have been visualized (figure IV.35 on the next page). The main focal point of the strategy evolves around productional aspects, first to reduce total costs, secondly to offer culturally adaptable solutions and thirdly to incorporate as much local knowledge or empowerment as possible. Out of figure IV.35, two specific facets have been further visualized in figure IV.36, to show arguments for Appropriate Technology and an attempt to bridge cultural gaps when choosing a technical adaptation type as described before. A. the accessible production techniques and estimated costs, and B. in which the form is shown on how refrigeration needs are translated into technical aspects.

		Price [Euro] (Secondhand/New)	Level of Difficulty (1-5, relative to each other)
Sheet Bending		300 / 2.000	■
Tube Bending		20 / 60	■
Sheet Cutting		20 / 2.000	■
Lathing		1.000 / 10.000	■■■
TIG Welding		500 / 5.000	■■■■■
Vacumizing 20 mbar		100 / 500	■■
Total		1.940 / 17.560	■■

A

B

Figure IV.36   A. (left) All needed (Appropriate) Production Techniques, B. (right) Form in which the End User is able to fill in their specific needs which are easily translated in terms of costs and efficiency.

INTERNATIONAL TRADE

INSULATION

ESSENTIAL PARTS

FRAME

OUTER SHELL

styrofoam

LOCAL TRADE

alu sheet   tube   valve   methanol   carbon   TIM

alu frame

local farm

wool

pur

sheet folding   tube bending

wooden frame

wooden shell

steel frame

cloth shell

welding
lathing valves
vacumizing
selective coating

A

cloth shell

complete frame

essential system

panels

assembly

completed product

B

end user

PRODUCTION FACILITY

WORK SHOP

SOLARBEAR WORK SHOP

SOLARBEAR SERVICE POINT

Figure IV.35   Schematic Strategic Overview

Furthermore, additional strategic aspects are also of importance, the most important one being repairability and accessibility. Since the local solarbear shops (or service points in figure IV.35) only need a small amount of tools for final assembly (i.e. vacuum pump), they can be kept relatively small, which means multiple stores can be opened up throughout a BOP area relatively inexpensive and easy. Furthermore, most of the necessary tools for repair are available here as well, enabling service at hand. When serious problems arise, systems are sent to a main point in the city where more extensive knowledge on the inside workings and more specific tools on adsorption refrigeration are found. All of these stores, and the selected ones who (specifically) cooperate with solarbear in a certain facet of the production process (i.e. woodcraftmen), are (partly) painted in a distinct color on the outside walls for clear commercial and distinguishing local advertisement purposes; orange r247g147b30. Furthermore, in cooperation with local entrepreneurs, the current working name should definitely be changed to fit each local BOP type market.

D 6 Calculated

The first small example concept will be good enough for creating around 1 Kg of ice at night. The used prices are retail prices in order to incorporate labor and distribution. In calculations_and_results.xls, a more detailed pricing can be found. It is calculated with a 35 degrees Celsius temperature difference and a heat loss of 10W.

Bare System

Inner volume of the collector	8 L
Activated Carbon	4 Kg
Methanol	1,5 L
Ice	1 Kg
Weight of bare system	5 Kg
Est. costs of bare system (*retail*)	€23
Est costs of machining (+ 50%)	€10
Total	€33

Primary Optional / **Price** / **Efficiency**

	Price	Efficiency
TIM	€5	+ 30% collector
Selective surface (retail)	€2	+ 350% collector
Mesh condensor	€4	+ 20% condensor
(Complete) Styrofoam insulation	€30	+ 40% evaporator
Frame ALU	€8	

Secondary Exterior

Wood Cover	€30

Essential System Cost Structure

Primary Optional System Cost Structure

- Essential System
- Primary Optional
- Secondary Exterior

- Aluminum Incl. Valves
- Activated Carbon
- Methanol
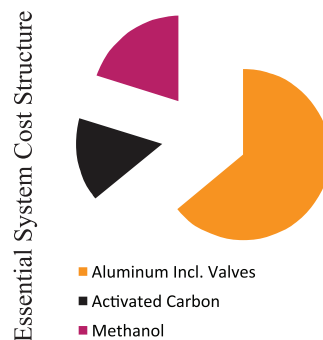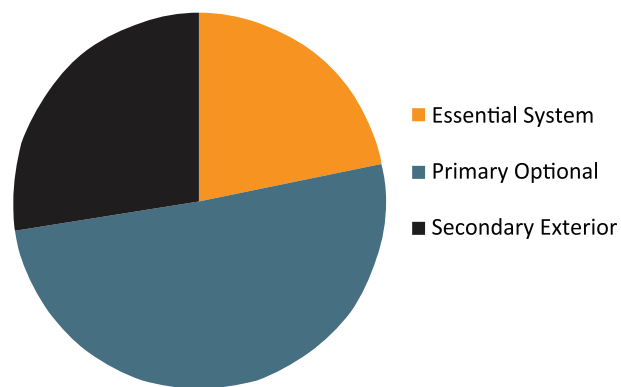
- Insulation
- TIM
- Mesh
- Frame
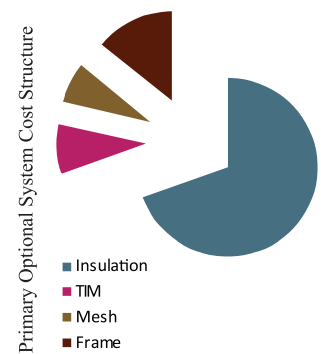
Figure IV.37   Cost structure of the several options.

6.1　Scalability

As can be seen from the following graph, as the internal to cool volume increases, the price per Liter goes down, this is especially true for a complete solution (blue line) including primary and secondary options, the Bearnaked system only slightly decreases.

Desired Size [L]	Ice per Day [Kg]	Internal System [€]	Primary Optional [€]	Secondary Exterior [€]	Total Costs [€]
20	1	23	50	30	110
50	2	30	75	45	165
200	5	50	140	85	330
5000	44	300	830	530	2000
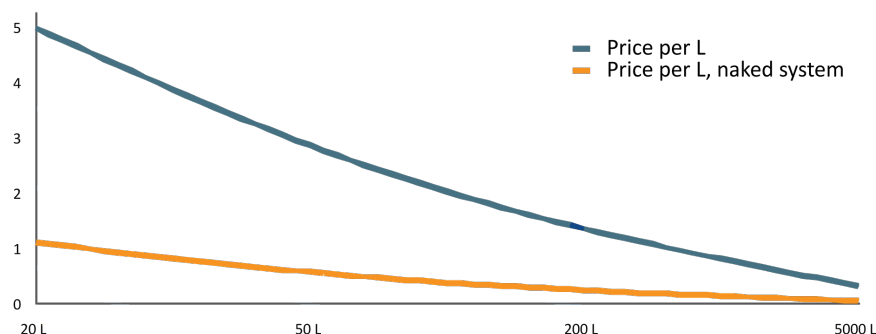
Figure IV.38　　　　　Price per Liter according to increasing internal volume.

6.2　Payback Time

There are different ways to calculate the payback time, in terms of the current costs of ice, or in terms of losses.

For an entrepreneur in Surinam, a bag of 10 Kg ice costs €2, in Ghana it is assumed to be around €1,5. In case of the small refrigerator type, producing 1 or 2 Kg of ice per day, which values at 0,15-0,30 cents a day. At a system (including primary options) price of €70-100, it will take around 200 - 600 days to payback the system. Also, when no refrigeration is used, it can be determined in losses, for instance, a proper fish is assumed to be valued at €0,30, if someone loses around 10% of his fish a week due to spoilage, it means the entrepreneur loses over €100 a year at a capacity of 10 fishes a day, making the payback time in between three quarters to a year.

The investment of €70-100 is a mere 3-4 percent of the yearly income of an entrepreneur at who lives on 10 US$ (€7,2) a day. But, €70-100 is a more serious 20% of a yearly income for someone living at the arbitrary line of 2 US$ (€1,4) a day, making structural partnering with banks that provide micro-finance almost mandatory when the true low income sector is included within the eventual solarbear business plan.
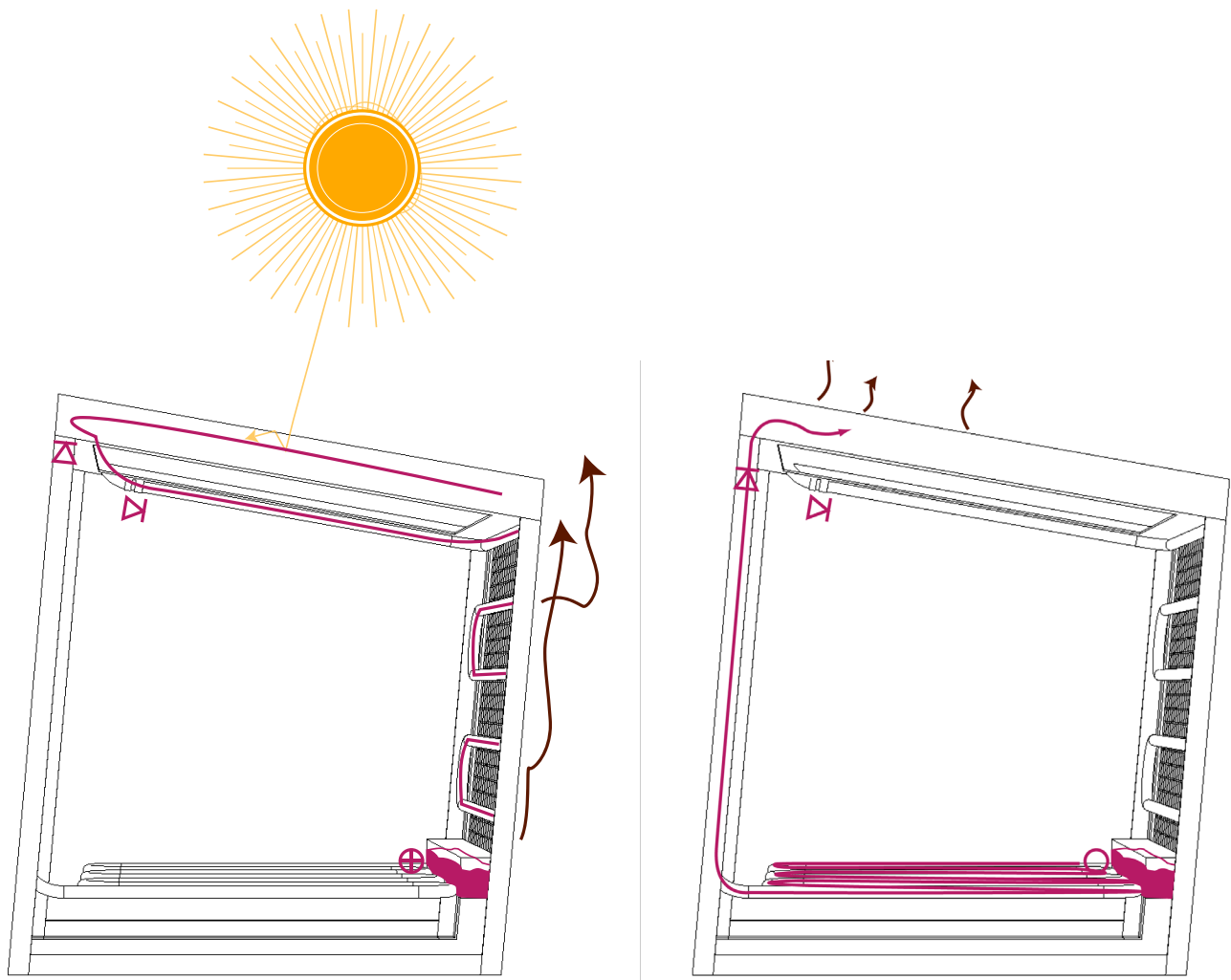
f_1

f_2

Figure IV.39   The desorption cycle (left) and adsorption cycle (right).

Prototyping was again an eye opener, and caused many difficulties as in the first prototypes. I enjoyed a lot of assistance from L.Schürg, and practical knowledge of the PMP staff. Some important considerations for future builds followed from building the prototype, enlisted hereunder in staccato.

1. Welding of aluminum plates of less than 2mm thick causes risks. The heat coming from TIG welding machine is too much for such a thin plate when prototyping in the PMP faculty machine hall. The machines are too powerful for such applications and is therefore very hard to create a gas tight bucket (the evaporator).
Welding would have been easier when the corners would have been flanged or a different solution should be proposed (see IV.D.8).

2. The proposed oneway valve (reed valve) did not work properly, and is too hard to adjust.
A simple bearing ball of 6mm will close a hole of 5,5mm diameter. When the one way valves are always placed upwards (vertically) they work and cost less than €0,20 total excluding lathing operation costs. For the new proposal see IV.D.8.

3. The foam used as insulation is not difficult to manufacture but very time consuming.

4. The evaporation capacity is largest at the lowest spot, therefore the lowest point of the total system should lay in the evaporator.

5. Vacumizing and filling the system with methanol has to be done very precise, the valves used from the GAMMA and ROMIJN are not sufficiently easy, a redesign is needed and already proposed.

6. The compression couplings (valves and switches) from the GAMMA and ROMIJN are difficult to close fully, and therefore form a weak link in the system, causing air to fill within through tiny leaks.

7. PTFE tape is only capable of holding a maximum negative pressure of 200 mbar, instead of the intended 20 mbar, it should therefore not be used

8. A mistake in the prototype design calculation caused a dramatically little volume capacity for the condensated methanol, the prototype was therefore adjusted, and several tubes were cut and replaced by squared profiles with a larger inner volume. This mistake is readjusted for the new design as in D.9, the earlier made calculations have already incorporated this and are properly displayed IV.D.8.

7.1 Prototype Phases

For the prototype I chose to use driftwood as exterior, i.e. gathered from houses that are being destructed in Delft. Clearly, it is an inspiration on Piet Hein Eek, a Dutch furniture designer, who I contacted beforehand to show the general idea. Driftwood was chosen to show the many possibilities of exterior design, but mainly to press upon one of the key features of the proposed concept: local availability. Basically, I, myself was the one who bought a small version of the Bearnaked concept, and used my skills and knowledge to style the solar refrigerator to my likings.
The prototyping went separately in a few phases, some pictures are shown in the following pages..
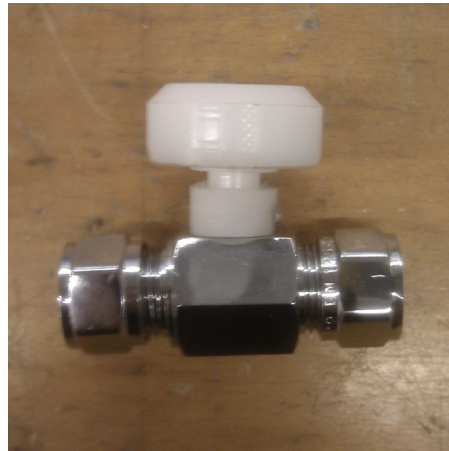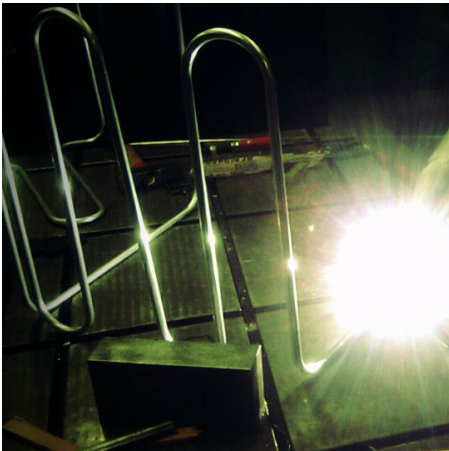
7.2   Functional Test Results

Unfortunately, the test of the Bearnaked prototype failed due to microscopic leaks caused by insufficiently industrialized welding of the collector. To keep the system at the desired 20 mbar pressure in the adsorption phase no leaks should be present at all. It is nearly certain the collector is the problem causing the leaks because first of all it is the longest weld in the whole of the closed system, giving much chance for leaks to occur. Secondly, the one way valve from the collector to the condensor is working (you can hear the all bouncing rapidly), meaning that the pressure in the collector is higher than in the rest of the system, which should be impossible in the adsorption phase, where the pressure of the system actually should have been driven by the evaporator at 20 mbar. Furthermore, because the way to the evaporator is blocked by the other one-way valve. Together this probably means that pressure rises in the collector due to a leakage, pushing the methanol gas to the only way available: to the condensor through the working one way valve. Still, the evaporator did get colder meaning that when the leak was not present, it would have worked. We must take into consideration that the temperature sensor was wrapped in plastic (for protection) at the evaporator bucket, filled with 3 Liters of water that in total got 2 degrees colder during the adsorption process, this is actually quite a lot for a leaking system considering the energy needed for water to turn into ice.

At this moment in time it is uncertain whether it is possible to fix the system to be able to show a block of ice before graduation date because of other pressures; time. But, when the collector would have been fabricated industrially and gastight, it would have guaranteed have worked, especially when the other prototype ("Zero Point One") is taken into consideration, that is up to this day still depressurized at the 200 mbar range.
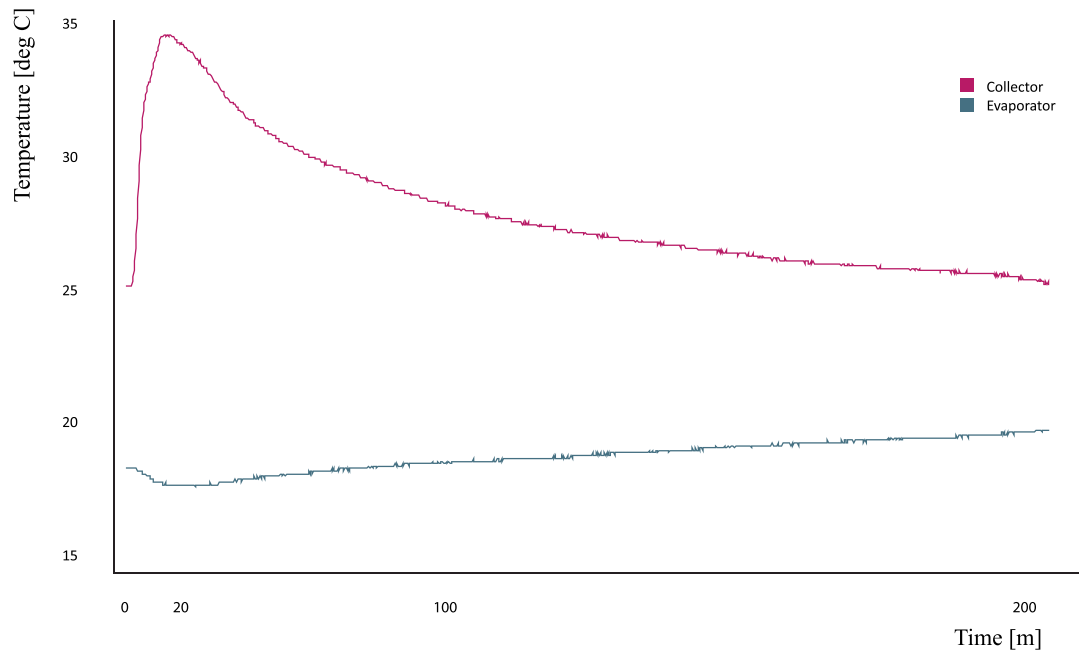

Figure IV.40   Test Results

For the expert walkthrough I collaborated in its set up with Ir. J. van Hoevelaak, who aided me with notes and storytelling. Overall, it was a good learning experience, providing several momentary insights for further development. The test was to see and let others experience the refrigerator as it is now, and it was set up by playing out several situations in order to get a better grip on the product design and its experience. Situation **1** started on a Sunday, in which no work was to be done; the assignment was to put the refrigerator in the sun correctly and to try and set the refrigerator by using the knob. Within situation **2** it was the same Sunday evening, to put the refrigerator back where it belonged (inside the house) and again, setting the turning knob. Situation **3** and **4** were the following day, a Monday in which firstly the entrepreneur would set his fridge to the right setting, then he should go to his wholesaler, buying his stock for that day, and selling it afterwards somewhere else, eventually reaching home at the evening. Two subjects tested simultaneously, which allowed room for open discussion. Quotes during these situations are enlisted below.

1   "To carry the box is a bit bulky, not necessarily heavy but clumsy."

"It would have been nice if the knob would travel with the refrigerator box." - the knob was loose

"The box is not as light as you expect it to be, when more stuff would go inside the box it will become even heavier which makes personally carrying it annoying, wheels could provide an answer."

2   "The knob is very clear, even though I am uncertain what it is for technically."

3   "You have to aim the top to the sun but also want to get a good angle (the door) to your clients."

4   "When it would be for families, more handlebars could be attached in order for the whole family to carry it outside.

sum The main conclusion would be that the box is too bulky to carry alone (although it weighs not more than a few Kg), in this configuration. But, this is of course completely dependent on what the entrepreneur desires, what his configuration would be, whether he has a bike or uses it near home. It is though very possible to integrate wheels in a configuration in which it is easily attachable to your bike or bicycle.

Figure IV.41   Expert Walkthrough, setting the box in right position and setting, carrying it, buying stock, selling to customers.
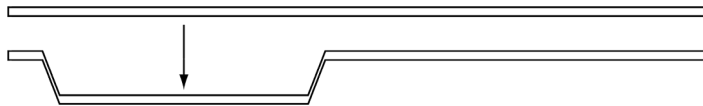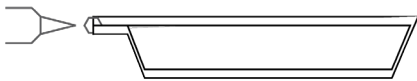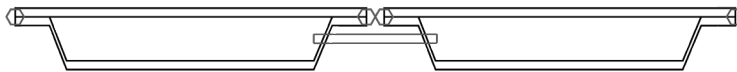
Collector Production
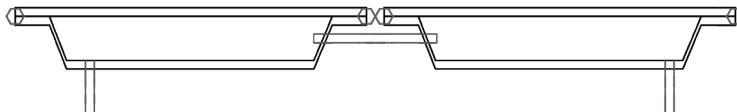
450 mm

450 mm

t = 1,5 mm

Deep Drawing one part of the sheet.

Weld the three flanged edges of the sheet after folding.

Connect multiple collectors with tubes for larger modules.

Connect tubing to evaporator / condensor.

Figure IV.42   Easier Collector Production.

The risk of leaks in a closed vacuum system is very present and has up to now made it near impossible to prove the working principle. Leakage of the system occurred in prototype "point zero" (at the collector), "zero point one" (the PTFE tape), and in the prototype of Bearnaked (at the collector and the pressure sensors, and GAMMA valves). Although they do occur for different reasons, it is clear that as little opportunity for a leak to happen has to be incorporated in the (production) design of a commercial adsorption refrigeration system. During the build of the last prototype, it became utterly valid that welding

edges perpendicular to each other has negative effects on the material surface, with (very very tiny) holes as a consequence. And flanged edges are way easier to weld. This is a collector production proposal especially meant for the BOP market segment, with easier production and less welding spots needed, increasing modularity and scalability while decreasing chance of failure. For the BOAT market this is not an option since specific (i.e. pointed) shapes are to be customized, meaning the deep drawing moulds would have to be customized each time or standardized measurements have to be found to enable collector placement at the front, or rear side of the boat.
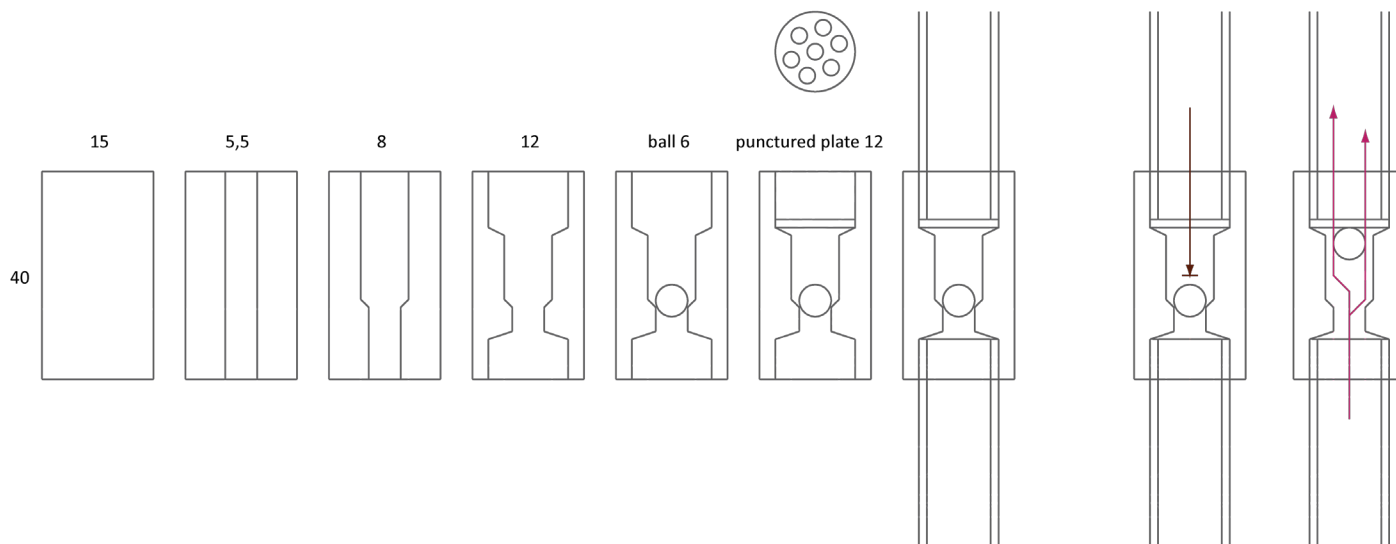
One Way Valve

Figure IV.43   One Way Valve, using only lathing as a production process and works on gravity only. The numbers above are the diameters of the lathed holes.

The simplistic one way valve created and tested during prototyping (see IV.D.7) only costs €0,13 of material (PMP retail), including ball and punctured circular plate. Next to only 10 minutes of lathing work. The pipes of 12 mm diameter hold the punctured plate in place which in its turn prevents the ball from going astray. The valves work with gravity only, and cause a pressure drop of around 4% in this configuration, this can of course be easily adjusted by making the ball smaller, less weight reduces pressure drop, which also means that the first lathed hole must be smaller. Because it works on gravity, it must be clear that the tubing of the system needs to be adjusted accordingly.

Reservoir

Here, the reservoir is added to the functional design, in order to create sufficient volume for the condensed methanol. The reservoir is placed to bridge the tubing of the condensor and evaporator, where a weldment was already needed, the costs of such a reservoir are around €1,20 (PMP retail), €0,80 more if 12mm diameter tubes were used like in the earlier proposed system. Furthermore, it is possible to integrate the switch at the end of the reservoir.

Figure IV.44   Reservoir, lower right, in between the condensor and evaporator.

During the writing of this thesis, it gradually came to mind that currently available adsorption systems are not viable in financial terms, neither are these proposed designs targeted at the right market in which the technical limitations are turned around in possibilities. Through a simple calculation it becomes clear that current adsorption systems will not be able to outperform its competition: an adsorption system has a COP of around 0,1-0,20; thus the solar energy (1000 W/m2) left to use in the end in this type of refrigeration is 100-200 W/m2. A Photovoltaic Cell system, with an efficiency of around 20% leaves at around the same value, although initially more expensive, they are able to serve multiple purposes instead of solely refrigeration. The costs of both different systems (targeted for refrigeration) are €400, and €800 respectively, while in Ghana, electricity costs €0,03 for a kWh. It becomes clear that adsorption refrigeration will not be economically viable in pure financial terms.

	Initial Costs	Output [W]	Output per Day [kWh]	Yearly output [kWh/y]	Costs per kWh over the initial purchase year [€/kWh.y-1]
Adsorption Refrigertation	400	100-200 (150 avg)	0,8-1,6 (1,2 avg)	440	0,9
Photovoltaic & Refrigeration	800	200	1,6	590	1,35
Electricity & Refrigeration Costs Ghana	300			200	0,6

Table IV.1   Pure Financial Viability of generalized adsorption refrigeration solutions as proposed by competitors.

BOP

But. The Bearnaked concept removed all the unnecessary extra's to a pure and simplistic system. And incorporates standardized and otherwise expensive subsolutions through the use of one singular and scalable design. Undressing an otherwise expensive concept to an essential, customizable system creates big chances in terms of a low initial cost price, involvement of local expertise and knowledge, while the technique remains (BOP locally) accessible and appropriate through its design and technical choices.

Furthermore, what has not been done before with the adsorption refrigeration cycle, is to enable adaptation of the adsorption principle, for BOP market especially, in such a way that another type of value is created: social value. The adaptable system serves as icemaker in remote areas where no electricity is available or where power outs are common, while the product proposal itself connects multiple facets of product development through involvement of local entrepreneurs. This high level of involvement by creating opportunities for cooperating stakeholders is envisioned as the only true type of solution to a product-market combination in the BOP segment. Furthermore, through the proposed service system that evolves around the technical system of Bearnaked, adaptation is enabled to the many different types of specific needs and budget in the SME BOP segments.

Solid use of the chosen material enables the internal workings to be autonomous for many years. And except for the purchase of a proper vacuum pump and low powered TIG welding machine, a product & service shop is easily to set up because low entry production technologies were chosen. Further use of local available materials, art and knowledge allows the design to develop over time and be made available for everyone in need of refrigeration, either as a very cheap home appliance, a portable / transportable refrigeration system according to ones specific wishes in size or capabilities. Furthermore, using upscaling principles, adding or upgrading components leaves each entrepreneur to decide on his own return of investments,

either by personal budget or in combination with micro finance.

BOAT

It should have become clear that the high adaptability of the product proposal is technically designed in such a way that it can be customized to the specific shape of any boat type. Furthermore, the bare system should be much more affordable than competition, while it is easily integrated within the boat, using the existing cupboards for instance. It is the only sustainable option available. Furthermore, the collector can be kept relatively small because only a few hours of cooling are desired each time the owner uses the boat.

Technique

Technically, there is not any problem that could lead to failures when (partly) produced by proper techniques. But one thing keeps coming back throughout the three prototypes: the needed vacuum of the system. In the tubing or other small parts that need welding, no problem arises when trying to obtain a vacuum pressure, but, for larger weldments like needed at the long edges of the collector it seems a near impossibility to create weldments without any holes. Therefore, the vacuum of the system is a problem, may it be one of the few. There are three ways to solve this, first of all redesigning the collector in terms of welding length, secondly, another air tight and heat resistant coating could be applied over the welded areas (i.e. epoxy), or, a reconsideration of the working adsorption pair. The latter especially seems more viable as a solution, because another working pair (i.e. Activated Carbon & Ammonia), is able to work at higher pressure ranges instead of the vacuum that is needed for Activated Carbon & Methanol. Furthermore, high (positive) pressures increase heat exchange within the system but more importantly there are many commercial parts available (i.e. PTFE Tape) that do work at these ranges. This could compromise an earlier made demand: the non toxicity of the working pair, and the safety of the system. When Ammonia is in positive pressurized system, and a hole would occur during use, the ammonia liquid is pushed out of the system, which could lead to severe injuries for a user because of the toxicity levels of Ammonia. The reconsideration has to be discussed and executed In accordance with the solarbear initiative members.

9.1   Unique Selling Points

Laid next to the essential Lists of Demands

BOP

1   Affordable Refrigeration.
2   Off-Grid & Decentralized Refrigeration (no need for electricity).
3   High Levels of Empowerment (involvement of stakeholders).
4   Culturally Adaptable (long term social vision).
5   Technically Adaptable (through customization & appropriate technology).
6   Movable while working.

BOAT

1   Sustainable Refrigeration.
2   Integration to boat type.
3   Use when Needed.

4   More Affordable than competition and no costs during lifetime.

5   Movable.

9.2   Next

What will happen next, is to create a new working system based on the Bearnaked concept, and the learnings of point zero, from solarbear's technical student team, and the students who are currently researching Ghana, to create a prototype for a specific user group. Many options have thus far come in close proximity of the solarbear initiative and according to the overall timeline (figure I.2), the solarbear should be conducting pilots by the beginning of 2011. Currently, four options are being validated before conducting a local pilot study, each in a different region of the world. Solarbear will start most of the prototyping within the machining room of our trusted faculty. Assembly, depressurizing, filling and closing up the system locally. The pilot study will determine whether the concept is culturally and technically valid. I will enlist the options for clarity in alphabetical order, a choice will be made after report hand in.

A   Amazon Conservation Team (ACT) | Paramaribo | Surinam, Colombia, Brazil

ACT is a foundation which conserves the Amazonial area and its indigenous animals and people (i.e. Indians & Maroons). It does this by education, sustainable solutions and other initiatives. It has complied to be able to work together with solarbear (see Appendix for MoU).

B   Ghana Moves | Accra | Ghana | Africa

A project set up by Esther Blom and Boukje Vastbinder from the TUDelft, DCE, one of solarbears stakeholders. Ghana Moves produces locally manufactured bicycles for entrepreneurs. Above that, DCE is also behind the primary team that guides the solarbear students in Ghana, and has been highly involved since the beginning of this solarbear initiative.

C   Onergy | Calcutta | India

Onergy is an initiative of Vinay Jaju, who has done several pilot projects concerning sustainable solutions for the Indian rural markets surrounding Calcutta. Onergy has several workshops in these rural areas and has complied to cooperate with solarbear (see MoU in Appendix). Vinay was in the Netherlands and was enthusiastic about the prototype, and suggested a solar ice maker in its purest form, at about the same size. He offered to develop this together using our expertise and their resources.

D   Sakaramenta | Malawi | Africa

"Sakaramenta produces strong and durable push and bicycle carts in Malawi". Their workshop, started by a Dutch entrepreneur, is based in Blantyre, at which they produce three different types of carts; ambulance, transportation and water bicycles or carts. They target entrepreneurs and have complied to cooperate with solarbear.

9.3   Personal Evaluation

The personal evaluation can be found in Appendix IV.F.6

9.3   Summary

The product summary is delivered separately.