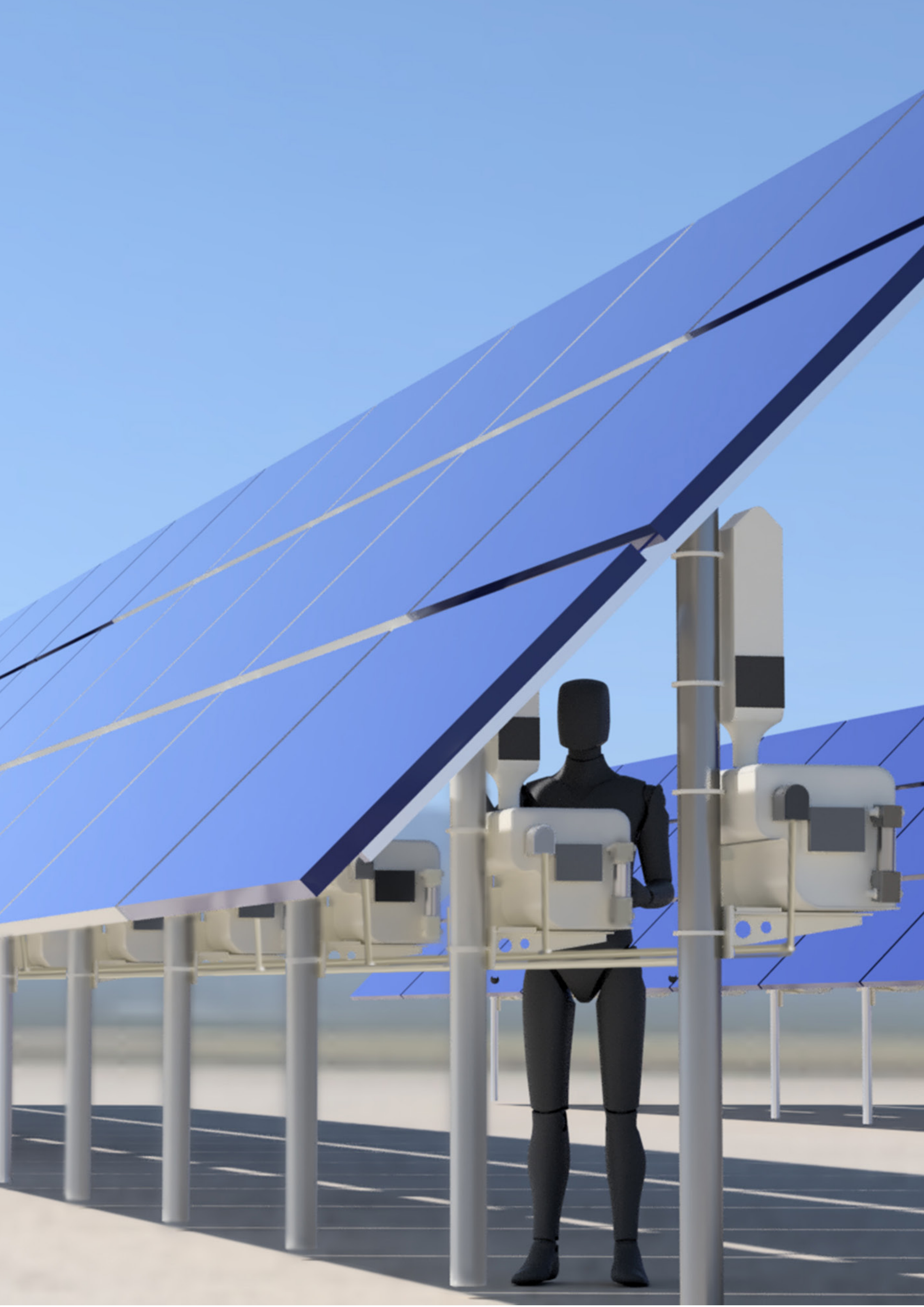
A SYSTEM INTEGRATION FOR SOLAR POWERED METHANOL SYNTHESIS

D. B. van Nunen

A System Integration for Solar Powered Methanol Synthesis
May 27, 2019

David Benjamin van Nunen
MSc Integrated Product Design
Faculty of Industrial Design Engineering
Delft University of Technology

Supervisory team
Chair: Prof. ir. J.E. Oberdorf
Mentor: Dr. ir. F.E.H.M. Smulders
Company mentor: J. van Kranendonk
Company: Zero Emission Fuels (ZEF)



ABSTRACT

With the rising renewable energy demand, sustainable energy storage systems become more important. Zero Emission Fuels (ZEF) is developing a solar powered methanol micro-plant that produces methanol, using water and carbon dioxide, out of the air. ZEF's focus this far was on developing the subsystems for the micro-plant. This report is about the integration design of the different subsystems. The main integration challenge was to design a functional micro-plant concept that produces methanol at a low cost. The state-of-the-art subsystem designs were researched, and a base-case cost estimation was conducted. Next, in a scaling research it appeared optimal to implement one micro-plant per three solar panels, instead of one plant per panel. A functional configuration architecture was designed and conceptual mass producible subsystem designs were developed. These designs were used for building a scale 1:1 integration prototype and for conducting a cost analysis of the concept. The micro-plant concept would produce methanol at a significantly lower cost compared to the base-case. Consequently, the micro-plant reached the target cost. Design guidelines and recommendations are given for further optimising the micro-plant's integration design and costs.

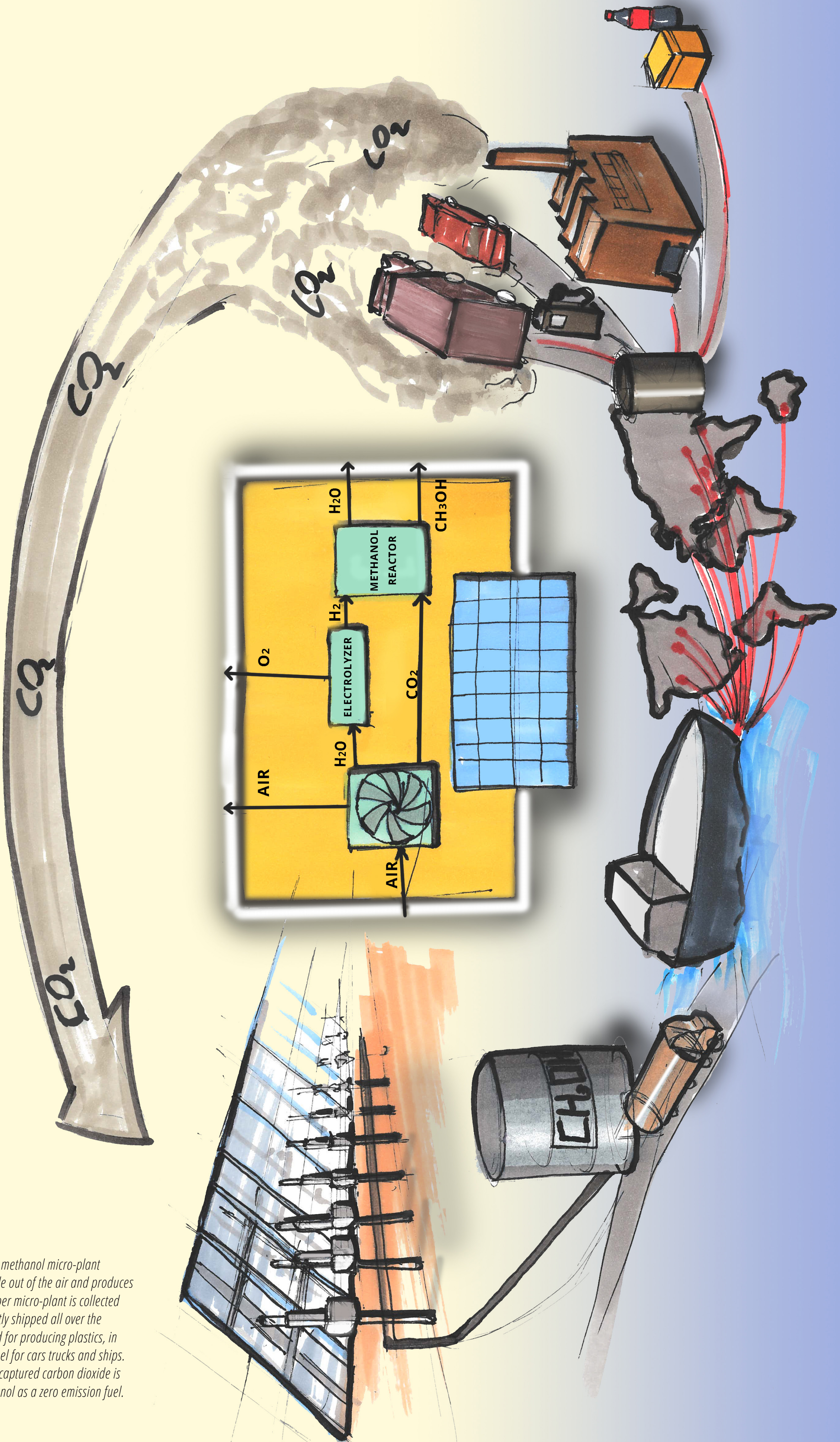


Figure 1. Methanol cycle. The ZEF methanol micro-plant absorbs water and carbon dioxide out of the air and produces methanol. The methanol output per micro-plant is collected in a storage tank and consequently shipped all over the world. Next, the methanol is used for producing plastics, in the chemical industry and as a fuel for cars trucks and ships. At the combustion the previously captured carbon dioxide is emitted again into the air. Methanol as a zero emission fuel.

PREFACE

A designer is no longer someone who merely designs a new product with improved functionality. Designers form the bridge between ideas and reality, business and environment, user experiences and technology. Where engineers and business experts narrow down on their specific tasks, designers should evaluate the wider scope and from there iteratively converge to details and diverge the focus back to the overall product. Designers can deliver creative solutions in highly complex situations and break down highly complex problems to become understandable.

Note *When talking about designers I mean industrial designers educated at Delft University of Technology, as I am less aware of the focus of designers from other branches of education.*

PERSONAL BACKGROUND

A brief introduction from my side. I started my Bachelor program in Industrial Design Engineering in Delft in September 2013. Three years later I continued with the master Integrated Product Design and dedicated my studies to specialising myself in sustainable development. The main projects I have worked on during my master were designing a biomass fuelled heater in the form of a pellet stove and the sustainable energy generation from solar panel embedded windows. Next to this, I followed the courses and tracks for the annotation 'Technology in Sustainable Development'. In the second year of my master I explored (circular) design on the other side of the world, in Taiwan, by doing an internship at the Taiwan Design Centre. This was my educational background when starting with this master thesis.

During my entire study period I have also been active as a fencing athlete in the National team. I trained one to two times per day and spent many days abroad on competitions. This divergence in focus between top-sports and study enabled me to activate my mind and body in different ways, but of course it required tight schedules. To get most out of this graduation project in combination with sports I decided to work on the graduation 28 hours per week. Many students continue studying overnight when they are behind in their planning, but as most non-studying time was filled with training and competitions, this was no option for me. Planning was key.

GRADUATION TOPIC FORMULATION

Although I had been working with sustainable energy production and solar panels before, designing a solar powered chemical plant had never come to my mind. Until Zero Emission Fuels (ZEF) approached me and offered a graduation opportunity at their start-up company. ZEF worked with teams, developing a so called solar powered methanol micro-plant. This could be visualised as a device hanging underneath a single solar panel that used the solar power to produce sustainable methanol. What mainly interested me in this concept was the numbering-up potential of these devices, as they would eventually be mass produced. This way the 'methanol factory' could be considered as a product. Still this product differed significantly from my previous design topics, as the micro-plants would be placed in desert areas and the end user of the methanol would never get in touch with this production device. This was in contrast with the consumer product and user centred design approach of the faculty of Industrial Design Engineering.

This far, most of ZEF's attention had been on technically developing the needed subsystems for the methanol production. In parallel with this graduation project ZEF continued with the subsystem's technological development. For my graduation project I decided to target a wider scope, i.e. the integration design of the entire micro-plant. My initial aim was to integrate the individually designed subsystem prototypes into a single micro-plant.

THE GRADUATION PROCESS

The first months of my graduation project I worked on analysing the context of the project. At first, I conducted researched on methanol, whether it had future potential and how ZEF would fit in the market. To do so I also used the marketing mix method, as commonly used in IDE. Alongside this context research, I invested quite some time in understanding the working principles of each subsystem of the micro-plant. I continued elaborating on this during the entire project. This caused a dynamic research environment, in which I regularly adopted ZEF's new findings and conceptual changes. To evaluate the current status of each subsystem I defined their technology readiness levels. During this context and system analysis I was mainly researching the things already known by ZEF, but it was very valuable for my research to get a complete system understanding.

The micro-plant needed to be low priced to produce competitively priced methanol. However, there was no elaborate data on the complete micro-plant's costs. For this reason, I started creating the complete bill of materials of the available prototypes of ZEF. Next, I estimated what the parts would cost if they would be under mass production. To define and understand the BOM, my obtained system understanding already came to use. For the costs analysis the micro-plant's components could be divided into two main categories: purchase and self-developed parts. For the purchase parts I looked at ZEF's purchase channel and defined the components costs when ordered in bulk quantities. For the self-developed parts I was in touch with ZEF team members to receive part and quantity data and I researched the components masses in the Fusion (CAD software) model. When finishing the BOM and base-case costs analysis, I found that the production costs of the micro-plant were extremely high. This was the result of defining the costs of the current prototypes in mass production: e.g. many metal parts were machined and even in high quantities machining remains very expensive. In a realistic scenario, more favourable methods like casting and injection moulding would mainly be used. Therefore, I assumed that all parts would be suitable for common mass manufacturing techniques and defined a second costs scenario. This second scenario resulted in more realistic production costs, but it became very clear that two component categories were way too expensive. The electrodes and valves could likely be sourced at lower costs. This finding resulted in ZEF to designate a graduation project on the electrodes. Together with ZEF I made some assumptions on more likely valve and electrode costs and implemented these in a third costs scenario. This delivered the most realistic costs scenario of the current prototype design if it was optimised for mass production.

The comprehensive subsystem and state of the art understanding I acquired at this point, led to reformulating my design brief. I found it would not make much sense to integrate the subsystems' prototype stages with each other. This would make me highly dependent on the work of others and the subsystems would probably not be ready for integration during this thesis. Therefore, together with my graduation team, I decided to enlarge the scope of the project from a physical to a conceptual integration design of the methanol micro-plant. The goal of this project became to design a micro-plant integration model with guidelines, that would be interesting at this stage, but also when subsystems further developed.

The shift towards a more conceptual design direction enabled me to research the integration design without the limitations of the current prototypes. I defined three main directions to work on for the conceptual integration: system sizing, system configuration architecture and basic embodiment. These three directions were chosen for the following reasons:
At first, system sizing. At the base-case costs analysis it appeared to me that the costs of certain components were fixated, while other costs were directly related to the system's yield. The non-proportional sizing related component costs could possibly majorly impact the costs of the methanol production. ZEF pointed out that they had decided to make one micro-plant per solar panel to start with, but that there was no thorough research supporting this decision. We all became very curious as to whether it would be favourable to have a different ratio of the number of micro-plants per solar panel.
Secondly, there is the configuration architecture. When researching the subsystem's working principles, I found all subsystems to have their own orientation demands. Simply attaching the subsystems to each other would not be sufficient to create a functioning micro-plant. Therefore, the configuration architecture needed to be researched.
At last, the basic embodiment. To integrate a defined system scale and configuration architecture, the subsystems needed to be adapted. In this basic embodiment design stage, I could also implement my subsystem design suggestions and embed the newest technology insights of ZEF. With this embodiment the bill of materials and costs of the conceptual integration design would be defined.

A system scaling analysis was new to me and I did not find relevant literature on the topic. Therefore, I had to develop my own approach and methodology. At first, I defined all variables that would be significant for the system scaling: components, start-up time, efficiency, safety, maintenance, assembly, installation, investments and development. I sorted the components scaling effects per subsystem, to explore the effects if certain systems would be scaled up, while other systems would be numbered up. Per variable I defined the effects of the system scaling in costs per ton methanol. Costs per ton methanol was chosen as unit to clearly compare the effects of different scaling sizes. For example, if one micro-plant would be used per three solar panels, instead of per single panel, then the absolute costs per micro-plant would increase. However, also the yield would increase, and it appeared that the costs per produced methanol would be lower. The scaling effect research per variable was grounded on some internet research, but mainly on discussions with ZEF. I combined the scaling effect findings and used this data to elaborate on the most favourable scenario. Although the output data was quantitatively presented in Euro per ton methanol production, the data could be better interpreted qualitatively due to the assumptions and uncertainties.

Subsequently , I focussed on the configuration architecture. This was basically a large puzzle, with several pieces (subsystems) that had their own rules. However, these rules were not all clearly defined. The known configuration demands served as a starting point of the ideation sessions. I started with drawing and claying configuration architectures and evaluated these designs. This way I developed initial configuration insights. Next, I modelled the potential designs and, together with ZEF, evaluated the 3D model on its operation potential. During these evaluation sessions new configuration demands became clear. This became an iterative process of ideation, modelling and evaluation. In time, I conceptualised potential ideas and evaluated these with a Harris profile. None of the concepts appeared good enough and I conducted another iteration round. Then I found a configuration architecture that fitted all the design demands and wishes. I made a 3D printed model of the micro-plant hanging on a solar pole with three panels, as a tool to communicate the findings.

The initial research , the scaling research and the configuration architecture research together provided me with a comprehensive system overview. With this overview I defined several favourable or indispensable subsystem modifications. Moreover, ZEF had further developed the technical subsystem prototypes. I used these insights for designing basic embodiments of each subsystem. Next to the micro-plant's defined subsystems I designed a basic embodiment for the casing and insulation, the tubing and control system of the micro-plant. With the basic embodiment I aimed to define the most important characteristics per system. I did not elaborate too much on the materialisation and detailing of the design. For me it was important to implement my findings from the integration research in these subsystem designs to make sure they would not get lost. Although I had a good system understanding, the designs I made were simplified as I was not an expert on each subsystem. ZEF and I did not experience this inaccuracy as a problem, because the basic ideas were clear, and the design insights could serve as an inspiration. This part of the graduation project was most directly related to the learnings at Industrial Design Engineering.

Consequently, I used the embodiment designs to design a scale 1:1 integration prototype. During my bachelor I followed the minor 'Advanced Prototyping', so I was familiar with different types of prototypes. This integration prototype however differed from the known prototypes, as the prototype would not function, it would not be used for user research and neither would it be used for experiments. This integration prototype was aimed to teach, inspire and mainly demonstrate what a future micro-plant integration would look like. In the prototype I envisioned all the connections between the different subsystems. This would support subsystem designers to understand how their system fits in the micro-plant. I decided not to implement the micro-plant's casing and insulation in the prototype and I positioned the subsystems in a transparent plate to minimise 'visual noise'. After delivering the prototype to ZEF it was beautiful to see how the prototype directly contributed to the overall system understanding and was used as an education tool.

After finalising the prototype, I finished the embodiment design phase. Now I had made an integration design, it would be very valuable to evaluate the concept's costs and to compare this to the initial design. Therefore, I used the defined bill of materials to calculate the capex costs of the micro-plant. To verify the found costs, I wanted to check it with a second costs evaluation method. Here I used the cost per kg analysis as suggested by ZEF. ZEF claimed that practically all complex products had a production costs of 10 euro per kg in mass production. I conducted a costs price analysis for three different cars and this very brief research supported the 10 euro per kg theory.

The conceptual integration design I made for this project will not be the same integration design as the one that will be implemented in several years. However, the learnings from this design will still be applicable when changes are made to the subsystems. Therefore, I ended the report with a series of design guidelines and recommendations. Future integration designers can use these guidelines for design iterations on this micro-plant integration.

CONTRIBUTIONS TO ZEF

My graduation research contributed to ZEF on three major topics. At first, it offered ZEF a realistic cost overview of the entire micro-plant. I handed over the complete bill of materials with the components' costs in an excel sheet. This sheet can be modified by ZEF when the systems change. The costs overview supported ZEF in defining focus components that need to be optimised or sourced at lower costs.

Secondly, the scaling research presented in this report made ZEF decide to change the micro-plant scale from one micro-plant per solar panel, to one micro-plant per three solar panels. This system dimensioning change is directly implemented in the subsystem research and development.

At last, the configuration architecture offers a thorough reasoning in the spatial orientations per subsystem. This defined integration, together with the design guidelines, can be used for further subsystem developments and future integration designs. The 1:1 prototype supports the understanding of these findings and offers a way to clearly communicate the micro-plant's characteristics to ZEF and visitors.

REFLECTION ON INDUSTRIAL DESIGN ENGINEERING

In my studies I have been educated as an integrated product designer and during this graduation project I have worked on a product's integration design. Therefore, this project appears to fit perfectly well within my studies. And I think the topic does neatly fit the job of an integrated product designer. However, the study Integrated Product Design at the TU Delft did not cover all the needed knowledge and skills for such a project.

I think there should be more emphasise on the materialisation of products in the master Integrated Product Design. There is no course that explicitly teaches the implementation of different production techniques. It is impossible to make producible integrated designs, without understanding how the products will be made. In my bachelor I learned some basic manufacturing principles, but as an integrated product designer it would be useful to better master this topic. The manufacturing knowledge should also be sufficient to calculate the production costs of the design. For the initial cost analysis in this project, I have consulted my supervisory team several times to make sure the methods and assumptions used would lead to a realistic outcome. Regarding costs, it would be very useful to educate different abstraction levels of costs analysis. For example, although scientifically not supported, a cost per kg analysis could be used to create a very quick costs estimation. Such a method will be very applicable for designers to evaluate early concepts on costs.

At Industrial Design Engineering we are educated as system designers, considering the interests of different parties. However, the aim is always on consumer products. There is a lot of focus on the user centred design, which is good. Yet, I think design skills are also very valuable for solving highly complex technological problems, like this integration design of a methanol micro-plant, that are less consumer focussed. The designer could stand at an abstraction level above the functional research in a technology driven environment. The designer's system vision can become the driving link between technology and a realised, usage centred product. Here, I specifically mention 'usage centred' design, as all products should be designed for usage, while a user centred approach is not always applicable. To me, usage centred design embeds the user interaction and experience, but also the technological functioning, maintenance, repair and end of life. I think that if this wide aimed entrepreneurial behaviour of designers is further embraced within the study of Industrial Design Engineering, then it will further support designers to tackle highly complex problems and become important changemakers. The faculty of Industrial Design Engineering should further embed the versatility of the use of industrial design skills in their educational program.

ACKNOWLEDGMENTS

As this graduation project is on the boundary of what I learned at Industrial Design Engineering, I am very grateful for the offered help along the project. I would like to thank my graduation chair Jos Oberdorf for his project guidance and support, mainly regarding the manufacturing principles, costs insights and product architecture suggestions. I would also like to express my gratitude to my graduation mentor Frido Smulders for his critical notes and his encouragement to consider the micro-plant on a more conceptual level. From my graduation company Zero Emission Fuels I received a lot of substantive support on micro-plant content related topics. I would like to thank the entire team for their enthusiasm for my graduation project. Furthermore, I would like to especially thank Hessel Jongebreur for his business and market insights, Jan van Kranendonk for his technological insights and for sanity checking my research. Ulrich Starke has also been indispensable for his daily enthusiasm and his ethical approach. I am thankful to my entire graduation board for being flexible, so that I could combine this graduation project with top level fencing. Next to my supervisory team I would like to thank my love, Henriëtte Hofman, for the daily energy she gives me, for being a sparring partner regarding this graduation research and for checking the report on grammar and language. To finalise I would like to thank my parents for supporting me throughout my entire study phase. Without all this support from all these people, this graduation thesis would not have been possible.

Delft, May 27, 2019.
David van Nunen

INDEX

A SYSTEM INTEGRATION FOR SOLAR POWERED METHANOL SYNTHESIS

D.B. van Nunen

INTRODUCTION

Rising CO_2 levels are observed as one of the main causes of climate change (Nasa, 2018). For a large extend this is caused by the burning of fossil fuels. Electric energy from renewable sources is part of the solution, but as two-thirds of all energy used is non-electric, it is necessary to further disrupt the fossil fuel market. Renewable synthetic fuels could contribute to this, without requiring a whole new infrastructure.

'Zero Emission Fuels' (ZEF) is developing a low-cost methanol (fuel) micro-plant, that uses a 300W solar panel for the needed power input. This micro-plant captures and filters air for the feedstock of CO_2 and water. Next, the water is fed to an alkaline electrolyser and is split into hydrogen and oxygen. The oxygen is released, and the hydrogen and CO_2 are led to a methanol reactor which converts the input to methanol and water. The output is separated by steaming the liquid, producing high-quality grade AA methanol.

ZEF aims to produce a standalone methanol production micro-plant to connect to a single 300W solar panel. The small system sizing reduces the needed investments, it enables numbering up the amount of micro-plants and mass-production becomes feasible to reduce costs. Solar costs are minimal as there is no connection to the power grid. The chemical methanol plant will be of small size and therefore can be handled as a product. A main challenge for the product is to be financially competitive within the existing methanol market.

Figure 2, Canadian Timber Structures (2011). Retrieved at 13 November 2018, from: http://canadiantimberstructures.com/wind_timber_structure_opportunity/wind_timber_structure_opportunity/steel_power_problems_files/BIGbfe-co2-090118br-2mb-.jpg.jpg

PROBLEM DEFINITION

At the starting point of this graduation project ZEF had a thorough understanding of the different subsystems. All subsystems had been developed, or were being developed towards working prototypes in lab environment. However, there was no system integration yet, and all subsystems only worked individually. The next phase was to integrate the subsystems into a single product. This integration is challenging due to the complexity of all the subsystems. The subsystems that need to be integrated are:

- A direct air capture unit, mainly consisting of a CO_2 and H_2O sorbent chamber, a desorption chamber, compressors, and a CO_2- and water buffer;
- An Alkaline electrolysis unit, mainly consisting of a degasser system for purifying the water, electrolysis elements and pressure casing;
- A Methanol synthesis system, mainly consisting of a methanol reactor and distillation unit;
- A control system, consisting of controllers, valves, piping, wiring, actuators and sensors;
- A 300W solar panel, including a racking system and solar farm design.

The individual subsystems were further developed simultaneously to this graduation project. This formed a communication and management challenge, to include all the subsystems' changing needs in the integrated design.

The integrated product must be competitive with the regular methanol industries and at the same time the carbon- and environmental footprint had to be minimised. The total product system should last for about twenty years, but possibly several subsystems need to be replaced more often. Decisions need to be made regarding possibilities to repair and maintain the product during the integration design.

DESIGN CHALLENGE

"Design a system integration and embodiment for ZEF's solar powered methanol plant."

The design must be used to formulate design guidelines and recommendations for next generation embodiments, i.e. when the subsystems are further developed.

Figure 3. ZEF (2017), Starting point integrated design. Retrieved at 13 November 2018, from: http://www.zeroemissionfuels.com/

1.
SYSTEM EXPLORATION

INTRODUCTION

In this chapter an understanding is created of the company Zero Emission Fuels, their methanol micro-plant design and the context in which the sustainable methanol synthesis developments are taking place.

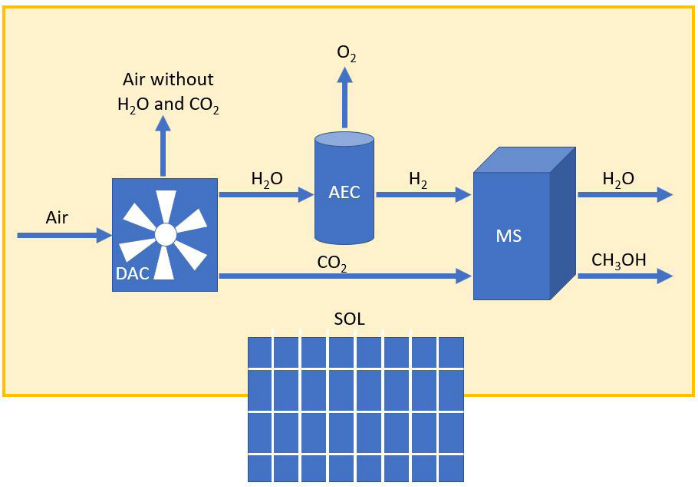


Figure 1.1, Basic schematic ZEF methanol micro-plant.

Figure 1.2, ToxTown 2017, Methanol. Retrieved at 2 December 2018, from: https://toxtown.nlm.nih.gov/chemicals-and-contaminants/methanol

ZERO EMISSION FUELS (ZEF)

THE ENTREPRENEURS

ZEF is a start-up company founded in July 2017, by three tech-entrepreneurs. H. Jongebreur, is an experienced CEO of technology start-ups, start-up advisory and the start-up selection processes. Within ZEF, Jongebreur is mainly involved in the business aspects of the development. J. van Kranendonk, mechanical/process engineer, is trained as innovation advisor at TNO, founded several start-ups and is the technical expert within the team. Ulrich Starke, mechanical/process engineer, is the founder of several technology start-ups and is mainly active on the HR management and engineering work on subsystems. This ambitious team sets its aims to disrupting the fossil fuelled methanol market by providing a competitive sustainable solution.

STUDENT TEAMS

To realise this ambitious goal ZEF embraces the expertise and working force of student teams of interns and graduate students of interdisciplinary backgrounds. The first ZEF student team worked from July 2017, until January 2018 on developing the first methanol micro-plant subsystems. The second team worked from January 2018 until July 2018 on analysing and iterating the systems developed by the former team and transforming these subsystems into individually working prototypes. In September 2018 the third ZEF student team started with the goal of further optimising the previously developed prototypes. I, David van Nunen, started my graduation project at team three. As I am working on my graduation thesis from September third 2018, until April fourth 2019, I will move from team three to team four in January 2019.

EXPERTS

Next to student teams, ZEF has gathered a team of academic and field experts supporting their developments.

Figure 1.3, ZEF (2018). ZEF team 3

WHY METHANOL?

ALTERNATIVE ENERGY SOURCES

Over 80% of all energy used is derived from fossil fuels (Goeppert, 2017). Electrical energy from solar, wind, hydro and geothermal sources are winning ground, but it is unlikely that they can disrupt the entire fossil fuel market in the foreseeable future. The two main promising alternative energy sources, solar and wind, have a main drawback of inconsistent power output. The sun's intensity differs over the year and only shines during the day, and wind speed can drastically change in one day. To level out these inconsistencies, power storage is needed. Storing energy in batteries is possible, but batteries have limited capacities, high costs and use scarce earth materials like lithium, which could cause future problems. Another storage possibility is converting the electrical energy to chemical energy, like hydrogen and methanol.

HYDROGEN

Hydrogen is a chemical bondage that can be derived by the electrolysis of water. This process is over one hundred years old and can function with an efficiency rate of 75-80% (Goeppert, 2017). When combusting hydrogen, energy is created together with water. Although this efficient water recycling is promising, there are several major drawbacks. Hydrogen gas has a very low volumetric density and requires a high pressure (350 to 700 bar) for efficient storage. Another storage possibility is liquefying hydrogen, which requires a temperature of -253°C, which requires a substantial amount of energy. At the same time hydrogen is explosive and highly flammable. Hydrogen can diffuse through commonly used metals and other materials. For these reasons hydrogen requires a very specific and tailor-made logistic structure that is of high cost (Goeppert, 2017).

AN INTRODUCTION TO METHANOL

Methanol (CH_3OH) is a chemical, that is liquid at common temperatures, its boiling and freezing points lie at 64.6°C and –97.6°C respectively (Methanol Institute, 2016). Generally, methanol is a save and convenient liquid, however it is toxic when digesting (Olah, 2005). Methanol can be used within logistic systems of piping and barrels that are widely available. Methanol is the simplest alcohol compound and due to its high octane rating it can be used as an additive to gasoline (named M3 to M99), or as a direct fuel (named M100). Methanol is suitable to use in modified diesel engines. Direct methanol cells could be used in transforming the methanol to electrical power at room temperature. Next to its fuel application, methanol is mainly used as a feedstock for several chemical compounds (Methanol Institute, 2018). All in all, methanol cannot only be used as a fuel to drive a car, truck, or ship, but it can also be used as chemical feedstock for producing solvents, antifreeze and refrigerants, as well as plastics, paints and furniture (figure 1.4).

WORLD METHANOL PRODUCTION

Currently 55% of all methanol is used for products, whereas 45% is used for fuels and for MTO (methanol to olefins) production (ZEF, 2018). There is an annual production of methanol of over 70 million tonnes (Goeppert, 2017). According to the Methanol Institute (2018), all 90 major methanol plants together have the production capacity of 110 tonnes annually.

THE FUTURE OF METHANOL

New technologies use methanol as a hydrogen carrier for fuel cells technology, for denitrification at waste water treatment and for fuelling electric power turbines (Methanol institute, 2018). Moreover, it is likely that methanol will be more extensively used as a (blended) fuel.

FUEL (BLENDING)

The EU renewable energy directive (RED) prescribes that all EU countries must use at least 10% of renewable fuels for their transport fuel supply by 2020 (European Union, 2009). Bio-fuels require extensive land usage and are unfavourable in terms of sustainability. Bio-ethanol from corn, the most common bio-fuel, has similar carbon dioxide emissions as gasoline from oil (Martin & Reilly, 2016). The awareness on the shortcomings of bio-fuels is growing and more and more organisations are looking for alternative, more sustainable sources. ZEF's completely renewable methanol could win ground here, and could even be double-counted for the renewable energy direction. A 5% renewable methanol compound would be sufficient for the RED, and economically favourable compared to bio-fuels (Jongebreur, H., personal communication, September 10, 2018). For the last forty years, China has been investing in methanol fuel implementations, for using more sustainable fuels and cost savings. China's methanol consumption for fuels grew from 20.000 barrels per day in 2000 to 500.000 barrels per day in 2015 (Hao, 2017). At the start of 2019 China had 7000 methanol fueled taxis. In 2019 this is projected to grow to 15.000 to 20.000 (Methanol Institute, 2019). Next to car fuel, methanol is also in development as a ship fuel.

ONE OF THE MOST USED CHEMICALS

Regarding the current developments it is likely that the (renewable) methanol market will grow in the coming years. Renewable methanol will likely be used as a convenient energy storage, a fuel and as a feedstock for synthesizing hydrocarbons for products (Olah, 2005). Anywhere in the world there are methanol production possibilities. Due to the fertility of production and usage possibilities, methanol it is one of the most used chemicals since 1800 and stated to be future-proof (Methanol Institute, 2018). The potential market for methanol and its applications can be viewed in figure 1.5.

Figure 1.4, Methanol usage, Methanol Institute (2018). Retrieved at 09-05-2018, from: https://www.methanol.org/about-methanol/

Application	Current Methanol Demand (2015E, -000-Tons)	Potential Market Demand (-000- Tons)
Alternative Fuels		
- Gasoline	11,571	40,000-50,000
- Biodiesel	1,197	25,000-40,000
- DME	4,970	10,000-15,000
- Power Generation & Others	>1	40,000-60,000
Fuel Cells	8	3,000-8,000
Methanol-to-Olefins	16,683	30,000-40,000
Methanol-to-Gasoline	250	15,000-35,000

Figure 1.5, Methanol demand and potential. Methanol Institute (2016). Retrieved at 09-05-2018, from http://www.methanol.org/wp-content/uploads/2016/06/MI-Combined-Slide-Deck-MDC-slides-Revised.pdf

METHANOL PRODUCTION METHODS

THE STANDARD WAY

The common way of producing methanol is by mixing natural gas and steam, this mixture is heated and passed to a catalyst in a steam reformer. Here the gas and steam are transformed to synthesis gas, which is a mixture of CO, CO_2 and H_2. The synthesis gas is pressurised and converted to methanol using a catalyst. Finally, this methanol Is distilled to remove water and pure methanol is yielded. The synthesis gas can be created from all feedstock that is, or ever was, a plant, but, due to price considerations, natural gas is most commonly used (Methanol Institute, 2018).

CARBON RECYCLING

This synthesis gas can also be produced by mixing CO_2 (from for example factory outlets) with green H_2, produced from electrolysis powered by renewable energy. This way methanol production acts as a carbon recycler. CO_2 based sustainable methanol is produced at large chemical plants. For the methanol hydrogen needs to be produced using renewable energy sources, which accounts for about 50% of the total cost. The hydrogen costs are this high due to the energy consumption and capital investment. These plants work with a high efficiency but have a long start-up time. Therefore, these plants must run 24 hours a day. When using solar power for these large plants, additional batteries would be needed to provide continuous operation.

PRODUCTION FUELS

In 2015 80% of the methanol production was powered by gas, 17% by coal and less than 1% could be called bio-methanol (Basile, 2018).

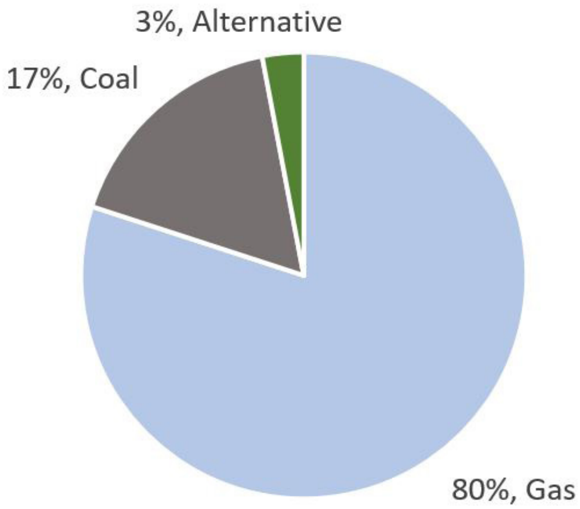


Figure 1.6, Market shares of different methanol production methods

Figure 1.7, Gas powered methanol plant. IVT (2007). Retrieved 21-05-2019, from: http://www.ivt.ntnu.no/ept/fag/tep4185/innhold/info.htm

MARKETING MIX

This section elaborates on ZEF's market position by emphasizing the product characteristics, the place at which the products will operate, the promotion and price.

PRODUCT

INTRODUCTION

ZEF's methanol synthesis plant only operates when the sun is sufficiently shining. This reduces capital costs, as no batteries are used. This is possible due to ZEF's small methanol plant size, which majorly reduces the start-up time. ZEF's methanol micro-plant transforms the traditional large scale chemical methanol factory, in an independent small-scale methanol micro-plant powered by solar panels (ZEF, 2017).

Furthermore, such a solar powered chemical micro-plant could also be used for producing hydrogen. However, as Jongebreur (2018) pointed out, the logistics system for hydrogen does not exist yet and the storage and transportation will therefore be way more expensive. A second benefit of methanol production compared to hydrogen, is that methanol 'cleans' the air by removing CO_2. This would not be the case for hydrogen.

PRODUCT FEATURES

The methanol micro-plant can be divided into several subsystems (figure 1.8)

- **The solar panel (SOL):** A 300W semi crystalline solar panel system, that provides electricity to power the other subsystems.
- **The direct air capture (DAC):** Here the feedstock for the methanol production is collected. A fan blows air through a system that captures the water and carbon dioxide out of the air. Next, the water and CO_2 is compressod to a pressure of over 50bar.
- **The alkaline electrolyser cell (AEC):** Here the water is purified and split into hydrogen and oxygen. The oxygen will be released back into the air.
- **The methanol synthesis system (MS):** Within this system the hydrogen reacts with the carbon dioxide, and methanol and water are produced. Next, the methanol is distilled from the water.

Figure 1.8 shows the basic schematic of the micro-plant. Appendix B1 further elaborates on the different subsystems' working principles.

The different subsystems are controlled by dynamic software to handle the fluctuating power input from the solar panels. *Note*

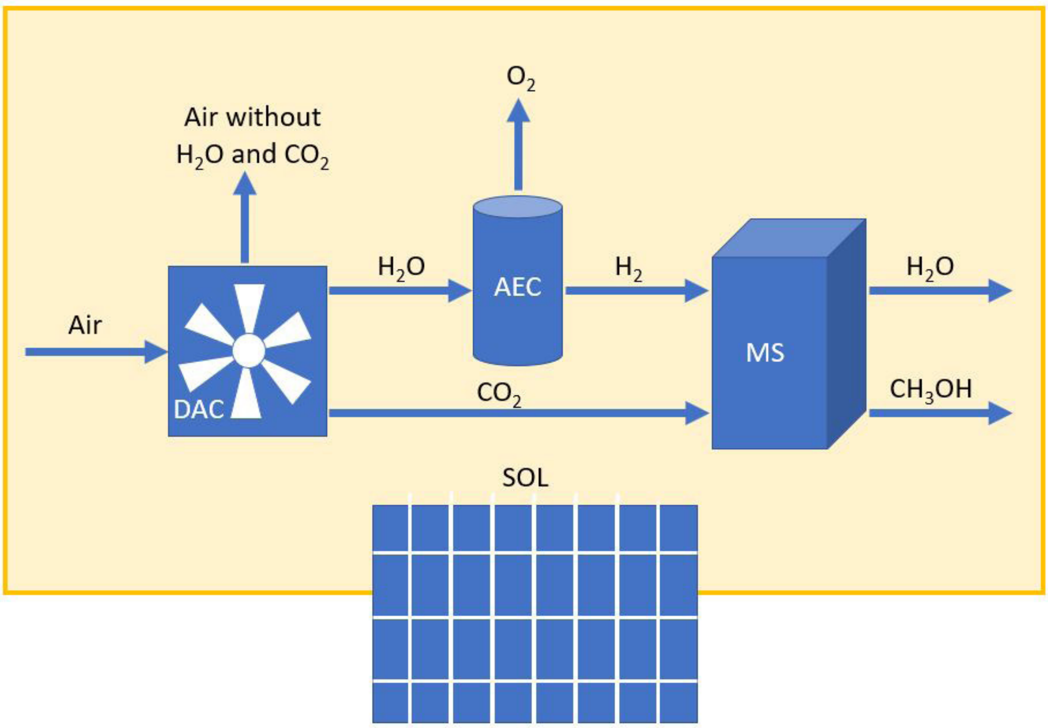


Figure 1.8, Schematic of ZEF's micro-plant working principle

SCALABILITY

Regular sustainable methanol factories need a developing time of about ten years and require high capital investments. Moreover, due to the available renewable energy source, a special location tailored design is also necessary. ZEF's methanol production system exists of one, or several solar panels together with one micro-plant. This scale-down enables mass manufacturing and upscaling, reducing the development time and requiring a lower capital investment. The upscaling will increase the number of products, instead of scaling up a single main plant (ZEF, 2017)

USER

The end-consumer's interaction with methanol entails, for example, fuelling a car or using a product for which methanol was used. The end-consumer will not get in contact with the methanol plant, as the plants will likely be implemented as a farm consisting of about 40.000 solar panels. The 'users' of the micro-plant can be defined as the assemblers and the operation and maintenance employees. The product will run automatically and only during the production and maintenance periods people are actively involved. It is still unclear what the installation, repair and maintenance will look like, as there is no data about the lifespan of different components yet. A feasible scenario would be that when a micro-plant breaks down, a signal is given to the maintenance centre. This signal could be communicated digitally, but also more physically, like a light burning on the micro-plant. The service staff will likely replace the entire micro-plant and the broken one will be sent to a centre for research and repair. If certain fluids or parts need to be replaced for common maintenance, the service staff could handle this on the spot.

TRANSPORTATION

The produced methanol will be sold to intermediate traders that take care of further retailing. In certain cases, the methanol can be directly transported to a nearby company that uses methanol. This will only be possible when logistics and natural conditions are suitable. In most cases the methanol will be transported to settled methanol storage locations (figure 1.9). From there the methanol can be further transported.

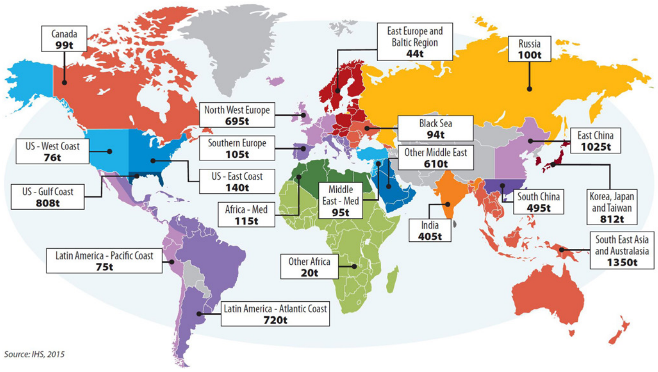


Figure 1.9, Methanol storage capacity estimate (thousand tons).

Figure 1.10, Assembly, Installation and maintenance workers are the user group of the methanol micro-plant.
Image: Ficero, L.C. (2016). Retrieved at December 2, 2018, from: https://news.stanford.edu/2016/12/05/stanford-unveils-innovative-solar-generating-station/

TECHNOLOGY READINESS

The state of the technology is a large determinant for the chance that the product will work sufficiently. Technology readiness levels are a common method used by NASA to define the state of technology. There are nine technology readiness levels (TRL), where numer one refers to a case where basic technology principles are observed and reported and TRL level nine refers to an in real-life set-up proven product or technology implementation (Mankins, 1995). The product development appears to be linear with the TRL levels. However, the product design is often an iterative process and sometimes it is necessary to go back in TRL levels to develop a more potential concept direction. The scale of the TRL levels are shown in table 1.1, together with the micro-plant's subsystems' current positions.

SUBSYSTEM TRL'S

The SOL subsystem is composed of already existing solar panels. Although not designed yet, the connection design with the micro-methanol plant will most likely not use special new technologies that need to be proven as a technology. The AEC subsystem is between TRL 3 and 4. The electrolysis system is validated in a laboratory setup. The AEC's degasser design is in the stage of being proved with laboratory studies. MS subsystem laboratory studies are delivering a proof of concept and the concept is being optimised. The DAC subsystem has just moved back in the TRL as the new continuous sorbent flow concept will be implemented. At this moment laboratory studies are running for proving the concept.

RISK ANALYSIS

The development of a solar powered micro-methanol plant is an undiscovered field of research. ZEF is a frontrunner in the field of direct air capturing and the productization of a chemical plant. Working in this new field offers opportunities, but also evokes risks and uncertainty, especially as most technologies are still at low technology readiness levels. For this graduation project there are also several risks to consider. Appendix B gives an overview of main company and personal risks and mitigation strategies

Table 1.1, Technology Readiness Levels

Subsystem	Technology Readiness Levels (TRL)
	TRL 1 Basic principles observed and reported
	TRL 2 Technology concept / application is formulated
AEC, DAC	TRL 3 Concept enabling phase, Laboratory studies to proof concept
AEC, MS	TRL 4 Component validation in laboratory setup
	TRL 5 Component validation in relevant environment setup
	TRL 6 Representative model prototype validation in real environment.
	TRL 7 Real size model prototype validation in real environment
	TRL 8 Actual system completed and tested in real environment
SOL	TRL 9 Actual system in operation

PLACE

INTRODUCTION
ZEF's methanol plants will not be placed at the consumers' homes, or at rural areas. Generally, in these area's the ground price will be way higher compared to dessert areas and the amount of sun hours will likely be lower. At these locations the micro-plants will not be economically viable. Another reason for centralising the micro-plants in a controlled farm is that all micro-plants are little chemical factories, that could cause harm when misused. Several natural factors need to be considered for determining potential ZEF farm locations.

ILLUMINANCE
The aim is to produce 200g methanol per day using a single 300W solar panel. In order to achieve this, the solar plants location needs to offer a mean of seven sun-hours daily without any curtailment (ZEF, 2017). ZEF's power plant will not be connected to the grid system. Therefore, energy curtailment will probably not cause any problems, as curtailment normally takes place when there is a power overflow in the grid system. Another reason for curtailment could be maintenance, however as the micro-plants only operate during sun shine, maintenance could take place after dark. The needed amount of solar irradiance can mainly be found around the equator (Figure 1.11). There will be a positive linear relation between the number of sun-hours and the methanol output. Dynamic software controls the differentiating power output, from illuminance fluctuations over the day.

TEMPERATURE
High temperatures negatively affect the solar panel's efficiency. The solar panel's efficiency is normally measured at 25°C. Every degree above this temperature causes a linear efficiency decrease, which is called the temperature coefficient. This can be found on a solar panel's specifications sheet. Temperature can negatively affect the output efficiency by 10-25% (Fox, 2017). Crystalline solar cells generally decrease about 0.5% in efficiency per degree temperature increasement above 25°C (Niclas, 2016).

DUST
Dust could block the solar panels from solar irradiation, or potentially be a problem for the DAC. Dust could block the fan, or even enter the system.

AIR COMPOSITION
The micro-plant uses CO_2 and H_2O captured at the DAC. Therefore, the carbon dioxide and water concentration in the air could influence the working efficiency. The CO_2 concentration differs world-wide from about 380ppm to 395ppm (NASA, 2014). At sea level there is the highest concentration of CO_2. Every 100 meters above sea level will cause the CO_2's ppm to decrease with about 1%. This creates a minor difference in the needed amount of airflow, but this will probably be of minor importance compared to the illuminance and temperature effects. Furthermore, the humidity changes depending

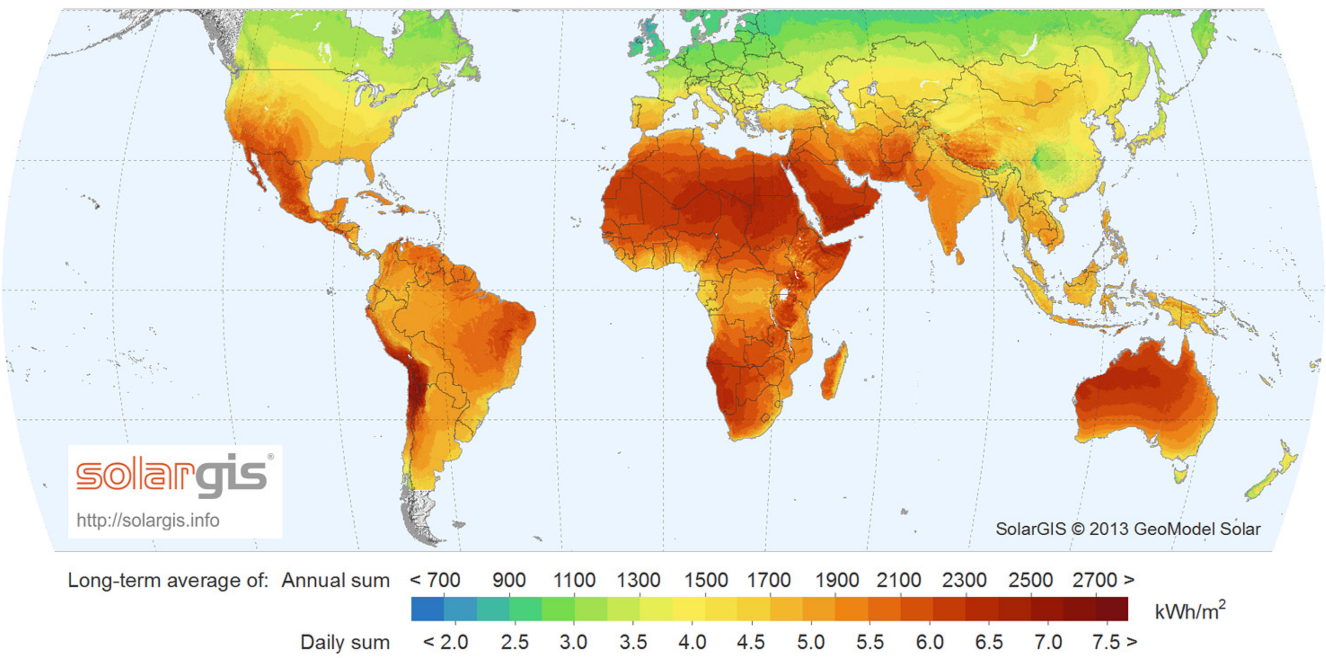


Figure 1.11, Global horizontal irradiance. Solargis (2018). Retrieved at September 7th 2018, from: http://www.ipsconnect.org/wp-content/uploads/2017/12/IPS-Connect-2017-Solar-Radiation-and-Solar-Programs.pdf

on variables like height, location on the globe, temperature, season, etc. According to Jongebreur (personal communication, 2018) it is calculated that, although the humidity level differs, there is practically always sufficient water in the air for the methanol micro-plant's functioning.

FLORA AND FAUNA

Next to methanol, the micro-plant also produces water. This water may have an effect on the environment in which the solar farm is located, regarding flora and fauna. Organisms around the solar farm could negatively impact the methanol output. Plants and trees could overshadow the solar panels and animals may dammage the systems. For example, certain insects and birds might choose to use a micro-plant for building a nest. The micro-plant design should minimise the chance of such undesired use. At the same time, solar farms could negatively impact the ground surface and biodiversity by blocking sunlight and rain (Straver, 2018). However, as the solar farms will likely be located in desert area's this is not a significant concern.

EXTREME WEATHER

Chances of extreme weather need to be considered. Typhoons, sandstorms, earthquakes and floods could cause major harm to the methanol farm.

POTENTIAL LOCATIONS

ZEF is developing a map of potential locations for methanol solar farms. This map will consider the factors: sunhours, transportation costs, labour costs, land costs and natural climate. It is likely that the solar methanol plants will be located in desserts in the sun regions. There the land price is low and there are at least 7 sun hours a day. Due to the importance of natural factors it will be unlikely that a ZEF plant can be located next to an existing methanol using facility. An intermediate party will conduct the logistics of selling and transporting the methanol.

PROMOTION

ZEF aims to sell the methanol to intermediate contractors. However, before this, investments are needed for development and the production of the first series. Promotion will mainly take place by writing funding proposals and holding pitches.

INVESTORS

When the product is developed and ready to be implemented in a zero series, an investor must be found to finance this series. Further investments will facilitate the developments of the first completed solar farms. Once the produced methanol is financially competitive with other renewable methanol sources, there will be a market for retail.

SUBSIDIES

When the first batches of methanol become available it is likely that subsidies can facilitate the process of bringing the methanol onto the market for a competitive premium price. Legislations will be very important for the available subsidies and for defining a competitive price in general.

EXPLOITATION

Methanol dealers will be the subcontractors to whom the produced methanol is sold. They will be responsible for the further retail.

As the product development is still in an early stage, the promotional activities cannot be clearly defined yet.

Figure 1.12, ZEF methanol retail station. In reality it is unlikely that there will be such a direct retail shop.

PRICE

ZEF METHANOL

The production price of the methanol is the main determent of the success of ZEF's methanol farms. ZEF's renewable methanol aims at a production cost of about €350 per ton. To be competitive, the retail price must be in a simillar range as bio-methanol, so around €600 per ton.

This methanol has the target market of fuel blending where the double counting rule applies, and cost benefits arise. A second target market is China, where currently similarly expensive methanol is produced from coal. As a third market the retail will be focussed on the production of dimethyl ether (DME), marine fuels and methanol to olefins (MTO) (ZEF, 2017).

THE SOLAR FARM

The solar farm's main costs consist of the solar panel itself, the solar mounting structure, the installation costs, civil costs for preparing the land, the development fees and land costs. The price of solar panels is nowadays about €0.32 per Wp and still decreasing (Schachinger, 2018). ZEF predicts to be able to buy 300W solar panels for €75 each at the production phase. The rack supply system is another major investment with a cost of about €25 per panel.

ZEF is a research and design company developing a methanol micro-plant. The development of the solar farms will be outsourced to EPC solar farm contractors. These contractors have experience and expertise in producing solar farms. Nowadays solar farms are the cheapest source of electricity with production prices of about €0.02 per kW. ZEF predicts this price, excluding energy conversion, to drop to about €0.01 per kW by 2030.

The solar angulation design is a determinant for the ground surface area that is needed. In appendix A. the needed land surface and rent is calculated for different inclination angles. In desert areas the land costs will not be significant to the other costs. In rural area's land costs would be considerable.

THE METHANOL MICRO-PLANT

The micro-plant is aimed to cost €100-200 per 300W power input. At this stage there is no clear view on the expenses per subsystem. Chapter 2 will further elaborate on the subsystem's costs.

Note

Solar costs €0.02/kW breakdown

*According to Marsh (2018), solar farms generally have an all-inclusive investment cost of €0.86/Wp (Watt peak). In this case a single 300W solar panel, including the installation process, is budgeted on €256. A 300W solar panel, in an area with seven sun hours per day, a running time of 365.25 days a year, running 20 years, would produce: 300*7*365.25*20 = 15.340Kw. This equals to an energy costs of 256/15340=€0.017 per kW. Interest rates are not considered in this calculation.*

COMPETITORS

GLOBAL MARKET PRICE

For the last ten years the global methanol market price has been about €350 per ton. This price, mainly based on coal and gas produced methanol, is about half of the market price ZEF aims for. Figure 1.13. shows the methanol market price's for different production methods. The methanol produced from fossil fuels will rise in price, if CO_2 taxes are applied in the future.

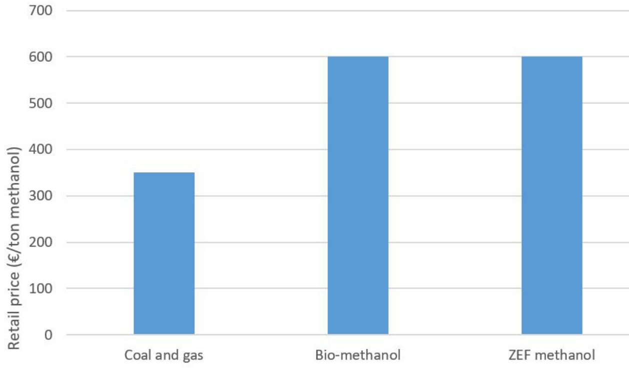


Figure 1.13, Approximate methanol retail costs from different types of methanol

BIO-METHANOL AND BIO-ETHANOL

Bio-methanol has a retail price of €500 to €700 per ton. A main competitor of bio-methanol is bio-ethanol. Bio-ethanol has a retail price of €500 to €600 per ton. Bio-ethanol also has a higher embedded energy of 27Mj/kg compared to 20Mj/kg for methanol. However, methanol reacts more efficiently in an engine and has a 1.08kg CO_2 emissions per kg compared to 1.51kg CO_2 emissions from ethanol.

RENEWABLE METHANOL FROM CO_2

The Islandic company Carbon Recycling International (CRI) is the first party producing renewable methanol from CO_2 (figure 1.14). They use the CO_2 emissions from a geo-thermal powerplant as feedstock for the methanol. The geo-thermal plant also provides energy for the methanol synthesis process. Growing plants like CRI is challenging as large investments are needed, and a constant renewable power supply for operation. Next to ZEF there are other start-up companies developing renewably powered methanol syntheses plants that extract methanol out of the air. Innogy is a German company that uses hydro-power from the lake Baldeney to produce methanol. Currently there is one excursion vessel fuelled by their methanol (Innogy, 2017). As they are using hydro-power as electricity source, scalability is limited and probably requires major investments. Also 'Swiss Liquid Future' and 'Antecy' develop CO_2 fuelled methanol synthesis, but all these companies require a continuous operation (ZEF, 2017)

SUN-TO-FUEL SYSTEMS

Some competitors are developing sun-to-fuel systems, like the company Soletair, which is developing chemicals using the air as feedstock and solar power for the electricity needed. They develop one fuel plant that works within a field of multiple solar panels (Soletair, 2018). The main difference between Soletair and ZEF is the focus on methanol and the scale per plant, as ZEF aims for one micro-plant per solar panel.

There are indirect competitors who develop subsystems that are also applied in the ZEF micro-plant. These competitors develop systems in the field of direct air capturing, electrolysers and direct conversion methods. The bio-methanol and bio-fuel market are also competing in getting a market share in the 'sustainable' fuel industry.

Figure 1.14, Carbon recycling international. Retrieved December 3, 2018, from: http://carbonrecycling.is/

STAKEHOLDERS

Due to the potential scale and impact of the ZEF micro-plant solar farms, many stakeholders are involved. All individuals, groups, companies and societies who have interests in ZEF, or who will potentially be influenced by the effects of ZEF's micro plant in a positive or negative way, are considered as stakeholders. The stakeholders can be divided into three main groups: the suppliers that provide (sub-)components and services, the methanol market, and (governmental) regulators and societies. All stakeholders have their own interests and influences (figure 1.15). It is important that all stakeholders' potential actions are carefully considered during the product design and development, to prevent surprises and wrong expectations. In this stakeholder analysis main parties are considered. The stakeholders' positions in the matrix are based on the author's expectation. For a complete overview, a more comprehensive stakeholder analysis, including stakeholder interviews and focus groups is advisable.

SUPPLIERS

Materials and some sub-components will be purchased for ZEF's micro-plant. The supplier companies have a high interest in ZEF's micro plant as the retail can be huge when the company scales. The same accounts for production and assembling companies. The solar field itself will be mounted by experienced EPC (engineering, procurement and construction) companies. Nearing production, a close relation with these companies needs to be established, as their choices impact the design of the solar fields. If these companies decide a certain, or a changeable solar panel angle to be most profitable, the micro-plants need to be suitable for these situations. The same accounts for the racks the solar panels and the micro-plants will be connected to. The land owners need to be involved for renting their area for the solar farm. A profitable price agreement needs to be made for both parties.

METHANOL MARKET

When the methanol is produced, it needs to be sold. ZEF will outsource this to methanol merchants. These merchants will arrange the transport, storage and sales. They may have demands regarding the plant's location, the methanol's content and purity, and the production volumes. In the end, they will sell the methanol to the final users. The methanol users have a large interest in sustainable methanol, because of regulations, niche markets, or sustainable image creation. Once ZEF's methanol has entered the market, it will be competing with other (renewable) methanol sources and possibly even fuels in general. ZEF's competitors may not be eager to welcome them as a competitive party and they could try to hinder market introduction, or scaling.

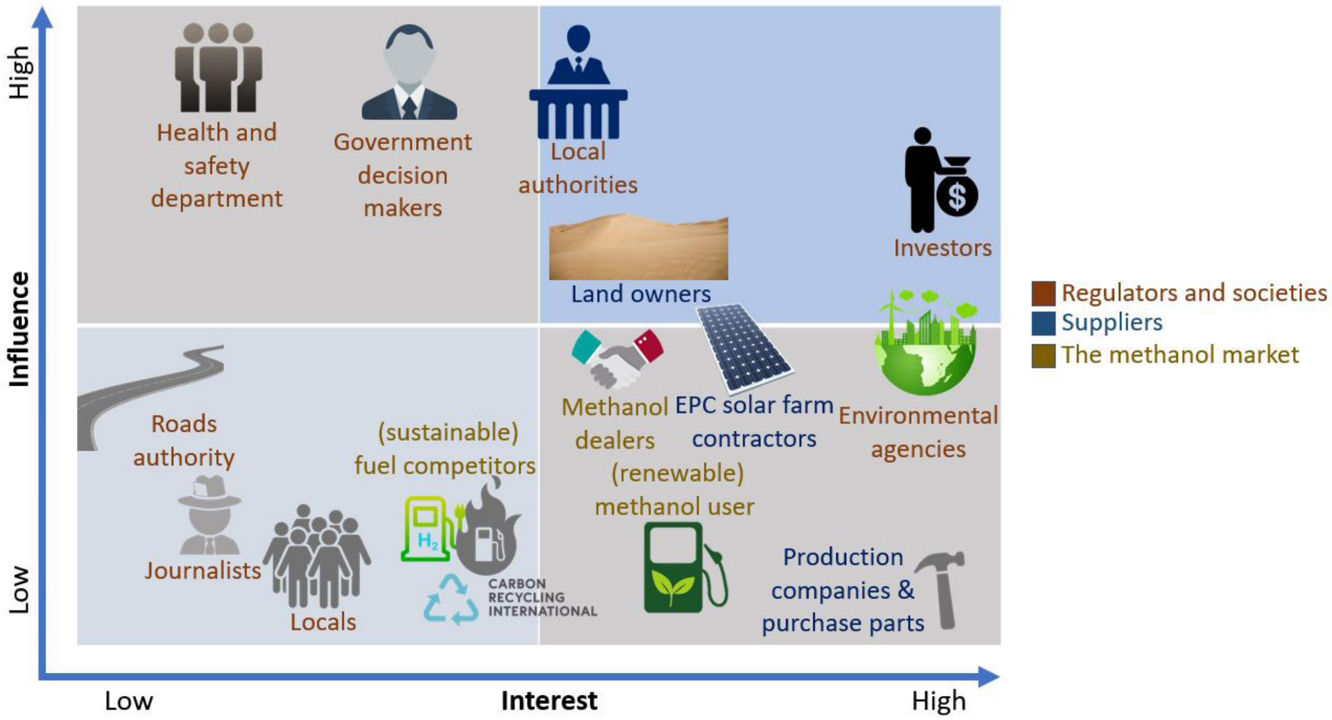


Figure 1.15, stakeholders interest/influence map

REGULATORS AND SOCIETIES

The governments that define large scale regulations will have major influences on the success of ZEF's methanol. These regulations include: the subsidies on renewable fuels, mandatory sustainable fuel contents in common fuel, whether the methanol will be counted double for fuel blending due to its CO_2 absorption at production, CO_2 emission taxes and more. Governments generally incorporate sustainability in their agenda, however this is more in the width and there might be limited specific interest in ZEF.

The local authorities of the location where the methanol farm will be located may have more interest as the farm will deliver labour opportunities for its civilians and tax incomes. A local municipality could use ZEF's methanol plant for gaining a sustainable image. On the other hand, local authorities could hinder the methanol's plant development when they are against the placement of the methanol farms. A governmental health and safety department might obstruct the construction of a methanol farm in case they fear for safety problems. Safety doubts could derive from the high pressure inside the micro-plant, the available chemicals as hydrogen and oxygen, or high temperatures.

Investors will have most interest in the commercial success of the methanol plants for financial reasons.

Environmental agencies may promote and support the development of the solar farms as it promotes an environmentally sustainable future.

Journalists could create or engage in public opinions on the methanol farms.

The local people themselves could, on the one hand, have interests in the solar farms due to new labour opportunities. On the other hand, locals could object to the construction of the farms due to visual obstruction of the area or fear for problems that come along with the farms. This could result in demonstrations and then it is up to the local government again what to do with the situation.

ENVIRONMENTAL ANALYSIS

All feedstocks for the methanol production are extracted from the air. With the extraction of CO_2, one could say that the methanol micro-plant is cleaning the air. When the methanol is incinerated, the CO_2 is re-emitted into the air. This forms a cycle in which the same amount of CO_2 is emitted when burned as adsorbed during the methanol production. If the produced methanol is used for producing products, the CO_2 is captured within these products.

CO_2 EMISSIONS

In this brief analysis the CO_2 emissions from ZEF's micro plant will be compared to the emissions from gas and coal fuelled methanol.

Note *In ZEF team 4 a graduate student dedicates his graduation project on developing an elaborate LCA on the micro-plant*

GREY METHANOL PRODUCTION EMISSIONS

The total annual CO_2 emission from methanol production is 100 million tons, for a market of 70-million-ton methanol (ZEF, 2017). This means that there is a mean emission of 1.4 kg CO_2 per kg methanol produced. 45% from the total emission is caused by coal powered methanol production, which only has a methanol production share of 17% (ZEF, 2017). This means that for each kg of methanol produced using coals, 3.8 kg of CO_2 is emitted. Most methanol is produced using gas. Methanol from gas production emits 0.85 kg CO_2 per kg methanol produced.

ZEF'S MICRO-PLANT

One methanol farm (40,000 units) has the potential to capture 3850ton CO_2 each year, to produce 2800 ton methanol (ZEF, 2017). For each micro-plant this comes down to an annual production of 70 kg methanol, and a capture of 96 kg CO_2 from the air. During the lifetime (20 years) of one methanol micro-plant, it will produce about 1400 kg methanol.

COMBUSTION EMISSIONS

Per kg of methanol, 1.34 kg of CO_2 is emitted during the combustion of methanol (Engineering Toolbox, 2009). This means, for example, that methanol from coal has a total CO_2 emission of 5.14 kg per kg methanol, from which 3.8 kg is emitted during production and 1.34 kg at combustion.

TOTAL EMISSIONS PER 1400 KG MEOH

At Combustion, 1400 kg methanol emits 1876 kg of CO_2 (1.34*1400). Producing 1400 kg methanol with coals would emit 5320 kg of CO_2. Together with the combustion emission, 1400 kg of methanol from coal is responsible for emitting 7196 kg of CO_2. For gas this number would be 3066 kg of CO_2 emission (1400*0.85+1876).

METHANOL MICRO-PLANT

Although the methanol production and combustion of ZEF's methanol itself will be circular and carbon neutral, the production of the solar farms need to be considered as well. The environmental impact of the production of solar panels are highly dependent on the manufacturer. The 2014 Solar Scorecard could be used for examining different production companies. Trina, Sunpower and yingli are at the top of sustainable production factories (Silicon Valley Toxins Coalition, 2014). To produce one kW polycrystalline solar panels, 1500-3000 kg CO_2 is emitted into the air (CES Edupack, 2018). For ZEF's 300W solar panels this would come down to 600-1200 kg. For this calculation a mean value of 900 kg CO_2 is used per panel. Next to the solar-panel, most CO_2 emissions will derive from the micro-plant. The micro-plant is aimed to weigh 10 kg. For this quick calculation it is assumed that the micro-plant is made of 5 kg stainless steel and 5 kg of 20-30% glass filled HDPE (table 1.2). Stainless steel has a production emission of about 7.3 kg CO_2 per kg and for HDPE the production emission is about 3 kg CO_2 per kg (CES Edupack, 2018).

Table 1.2, CO2 emission of the production per micro-plant and solar panel

Part	***CO_2 emission (kg)***
Solar panel 300W	900
Stainless steel (5kg)	36.5
20-30% glass filled HDPE (5kg)	15
Tot	**951.5**

BREAKEVEN POINT

For the production and fuel usage of 1400 kg of methanol, ZEF's micro-plant has a CO_2 emission of about 950 kg. This is more than seven times lower than the emissions from coal produced methanol and more than three times lower than gas produced methanol (table 1.3). The CO_2 breakeven point for ZEF's methanol micro-plants is about 6.5 years compared to gas fuelled methanol. This is at one third of the micro-plant's lifetime.

DISCUSSION

For these quick calculations assumptions are made regarding the CO_2 emissions for the production and the materials' compositions. Thereby, several factors are not considered, like the racking system of the solar panels, the piping system that lead the methanol to large bins, these bins themselves, transportation emissions, end of life recycling potentials, etc. For this reason, the breakeven point is just for getting a feeling regarding the carbon emissions of ZEF's methanol compared to traditional methods. The numbers themselves should be interpreted loosely. In the future, solar panel production emissions could decrease when the production and material mining power that is needed, is derived from renewable energy as well.

Table 1.3, Comparison of methanol production methods on CO_2 emission

Production method methanol	***CO_2 emission (kg) per 1400kg MeOH***	***CO_2 emission (kg) per ton MeOH***
ZEF's micro-plant	951	680
Coal	7196	5140
Gas	3066	2190

Figure 1.16, Auto Tech Review (2013). https://autotechreview.com/cover-stories/sustainable-fuel-a-fantasy

2.
SYSTEM DEFINITION

INTRODUCTION

In the previous section, the discovering phase, an overview of the status of ZEF's methanol synthesis micro-plant was created. This chapter will further elaborate on the micro-plant's component specifications and cost, to define the boundaries and demands that need to be considered for the system integration. At first, a complete bill of components of the micro-plant was created. Per component the costs and the characteristics were determined. Next, the data sets were discussed together with ZEF and bottlenecks were defined. With the found data, the program of demands was created.

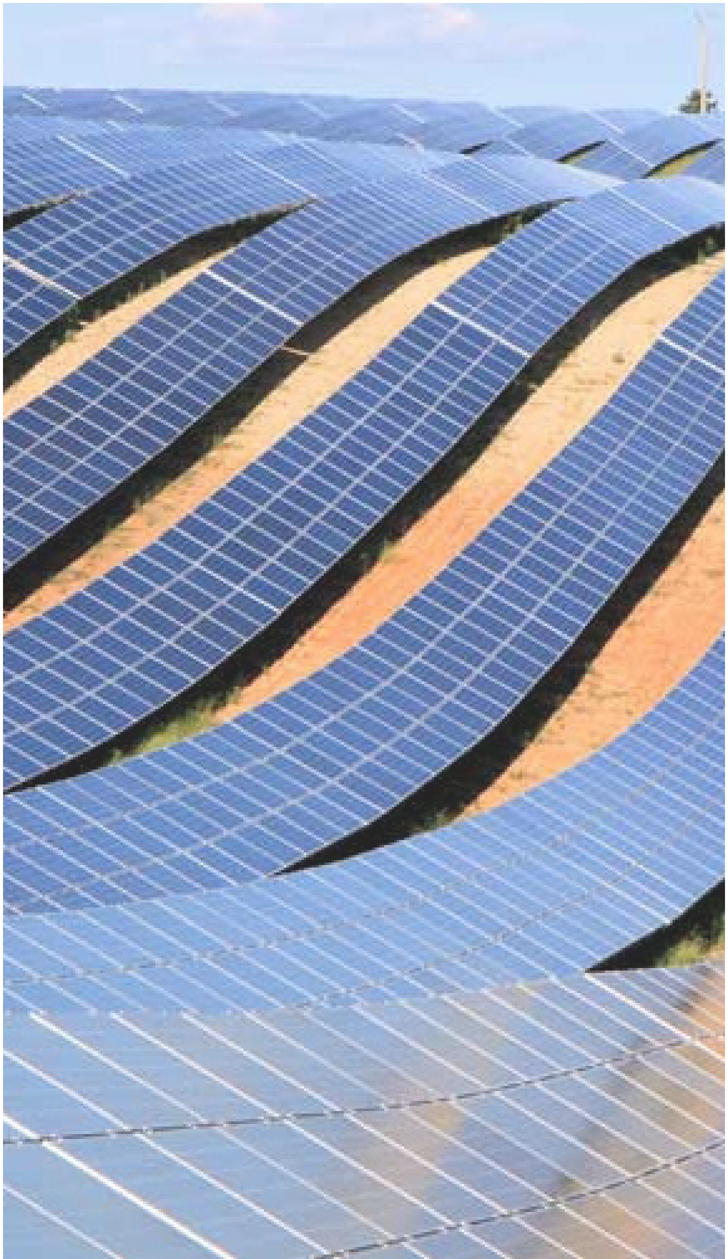


Figure 2.1, H. Roche (2011). Gigantic solar farm in Provence, Les Mées, France. Retrieved at 21 May 2019, from: https://www.alamy.com/stock-photo-gigantic-solar-farm-in-provence-les-mes-france-37858512.html

PROCESS FLOWS

A mathematical model is made to get an overview on the relationships between different system variables like: sun hours, solar panel output, compression rates, yields, dimensions, etc. (appendix D). Within this model the amounts of the available Wp are used to calculate the amount of methanol that could be produced, using the lower heating value of methanol, together with an overall micro-plant efficiency factor. This overall efficiency (exl. solar) depends on the efficiency per subsystem and is aimed at 50%. With the amount of methanol that could potentially be produced, the amount of hydrogen and carbon dioxide can be calculated using the moll fractions in the methanol reaction. Hereby, the amount of air capture and the amount of sorbent needed, can be calculated. These values can be used for determining the sizing of the absorption and desorption chambers. Consequently, the flow quantities determine the buffer sizes. Also, the needed wall thicknesses for holding the 50 bars of pressure can be calculated. Within this the model, the sizing of the electrolysis system, the power consumption needed for operation per component and the start-up time of the methanol synthesis system are all included. A simplified schematic representation of the mathematical model can be found in figure 2.2.

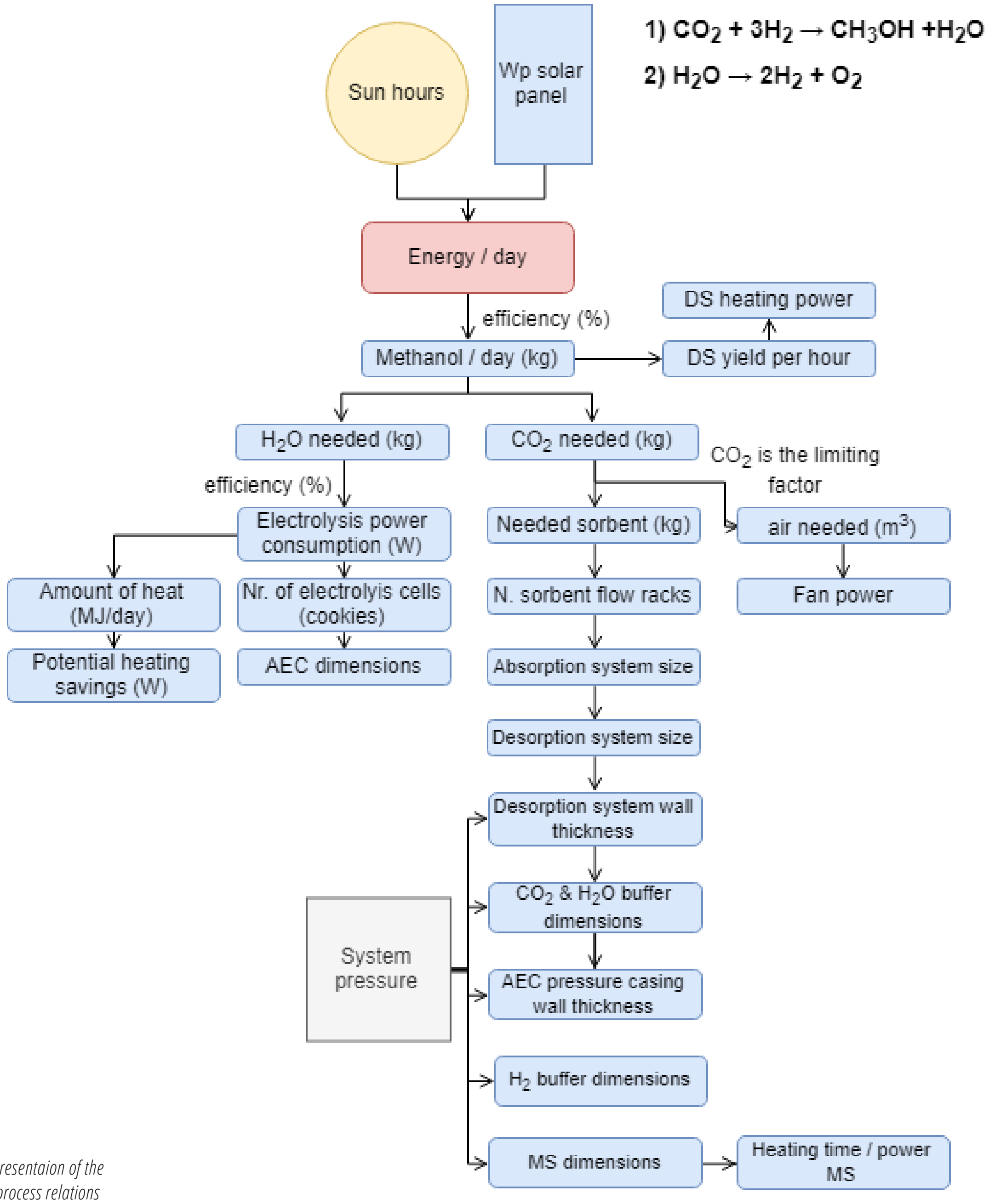


Figure 2.2, Schematic representaion of the mathematical model on process relations

PHYSICAL CHARACTERISTICS

INTRODUCTION

For integration purposes, the physical characteristics of the subsystems of the methanol synthesis device need to be considered. The chemical processes function at certain temperatures and pressures. Also, the sensors and other electronics need wiring to be connected. These more or less fixed characteristics will form the basis of the program of demands for the integration design. There are several other system characteristics that influence the yield capacity, power consumption and cost price, such as system sizing and heat buffering. To clearly define the system specifications, as well as the main influencing variables, a more specific subsystem division is needed.

SUBSYSTEM DIVISION

CURRENT SUBSYSTEM DIVISION

ZEF has divided the methanol micro-plant design into three main subsystems: DAC, AEC and MS. Next to this, there is a control subsystem, including the controllers, sensors and actuators. At last there is the solar system (SOL), which is of less concern for ZEF, as the panel design and racking will mainly be outsourced. For designing an integrated design, the DAC, AEC, MS, SOL and control division are not the most optimal. In each system there are new subsystems with different functionalities (figure 2.3).

NEW DIVISION

For integration purposes it will be better to consider each system with a specific function individually: 'functional subsystems'. For the functional subsystems the DAC will be divided into absorption, desorption, compressing and buffering H_2O/CO_2; the AEC will be divided into degassing, electrolysis and buffering H_2; MS will be divided into methanol synthesis and distillation. The control system itself is partly integrated within the other systems, but there needs to be a control chamber with the micro-controller and PCB. The integration design itself can be considered as a functional system too, as this system includes the heat buffering and general construction design. The integrated development of the entire solar farms is out of the scope, as this will be outsourced and other ZEF team members are working on this. However, it must be considered that the integrated micro-plant design needs to be connected to the solar panels.

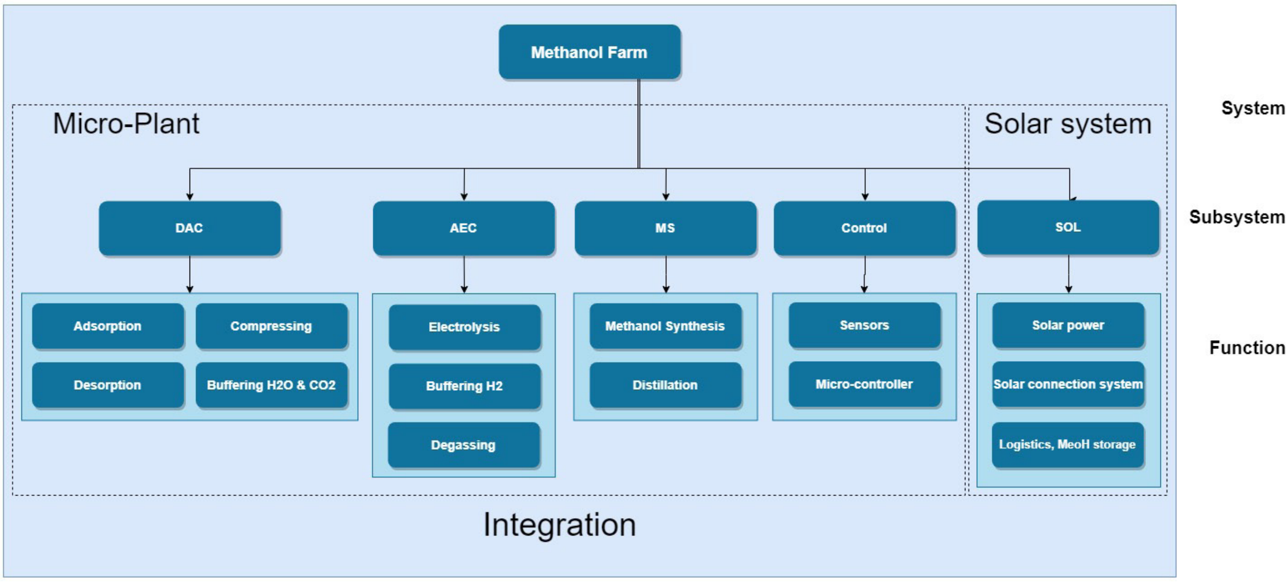


Figure 2.3, System, subsystem and function tree

MAIN PHYSICAL CHARACTERISTICS

In this section the main physical characteristics per subsystem are discussed. The working principles per subsystem can be found in appendix B1.

ABSORPTION:

sufficient CO_2 and water needs to be adsorbed for 'fueling' the consequent processes. This absorption is determined by the nutrient catching efficiency of the sorbent, together with the amount of air blown through the chamber by the fan. Inside the absorption chamber there can be no sunlight, or dust. There must be a way to determine when the sorbent is fully saturated and can move to the desorption system. If the flown down sorbent is not saturated, it must be redirected to the top of the chamber to further saturate. The amount of air and sorbent needed depends on the total system size and its overall efficiency.

DESORPTION:

The adsorbed CO_2 and H_2O need to be desorbed from the sorbent material, which is done in the desorption chamber. This desorption process happens at a temperature of 125°C under a vacuum of 0.1 bar. The sizing of the desorption chamber is related to the amount of CO_2 captured at the absorption chamber. The process of saturating sorbent with CO_2 and H_2O should take the same amount of time as the desorption of the previously saturated sorbent. The chamber size needs to be modified to this.

COMPRESSING:

From the 0.1 bar the pressure needs to rise to at least 51 bars. The compressor needs to bare the yield of both the CO_2 and water from the desorption chamber.

CO_2 AND H_2O BUFFER:

The direct air-capturing requires way less power than the electrolysis system and will therefore start working before and continuing after the peak sun hours. A buffer will store the chemicals until the electrolysis is ready. The buffer will have a pressure of 51 bars and a maximum temperature of 115°C. The buffer needs to be big enough to store CO_2 and H_2O for the hours that the electrolysis system is not working. The dimensions of the buffer are dependent on the sizing of the total system. The CO_2 gas has a volume of 0.55 liters per gram (Air Products and Chemicals, 2018), so the needed buffer volume can be calculated with:

*Volume CO_2,H_2O buffer = 0.55 / Compression ratio * gramsCO_2 + grams H_2O*

The compression changes along with the temperature. A safety factor of 2 needs to bare for these variations. The H_2O will come in liquid form, while the CO_2 is a gas. The pressure within this buffer needs to be a little higher than the pressure at the next stages to ensure the gases to flow.

DEGASSING:

Some of the CO_2 will be mixed within the water and this needs to be separated before the electrolysis stage. This will be done by a degasser. O_2 bubbles up through the poluted water and filters out the CO_2. The gravitational bubble flow orientation needs to be considered and it is necessary to build an outlet for the highly flammable O_2 and CO_2. The degasser functions at a pressure of 51 bar at 90°C. The water will only be led through the degasser when the electrolysis is active.

ELECTROLYSIS:

The electrolysis stage happens at a 50 bars pressure at 90°C. The electrolysis needs to have a specific orientation as the oxygen gases need to flow back to the degassing compartment on gravitational force. Moreover, the hydrogen gases need to flow to the hydrogen buffer. The electrolysis runs with an efficiency of 70%. The 30% 'loss' becomes heat. This heat needs to be redirected to the endotherm desorption and distillation processes. This system uses most power of the entire system and will only work when there is decent sunlight. It is assumed that this system works for 6 hours per day.

H2 BUFFER:

This buffer will store the H_2 before it is directed to the methanol synthesis. This is necessary during the heating period of the methanol synthesis system. The buffer will have a pressure of 50 bars and a temperature of 90°C. The buffer needs to be big enough to store hydrogen for the heating time of the MS system. The dimensions of the buffer are dependent on the sizing of the total system. Hydrogen gas has a volume of 12 liters per gram (Air Products and Chemicals, 2018). Therefore, the buffer size can be calculated through:

*Volume H_2 buffer = GramsH_2 buffered * 12 / compression ratio.*

The needed volume is also dependent on some other variables, like temperature. These effects should be managed by implementing a safety factor of two.

METHANOL SYNTHESIS:

The methanol synthesis happens at a temperature of 230°C, at 50 bar. The heating time, and thereby start-up time, of this system depends on its sizing. An optimum must be found between the system sizing and the heating time. If it takes too long to heat up, the efficient working time decreases too much, due to power fluctuations. When the system is too small, the yield is little compared to the materials needed for the system. The methanol synthesis system needs to be tilted a few degrees to stimulate condense flow within the piping.

DISTILLATION:

This system works at atmospheric pressure with a changing temperature throughout the system. Within this system capillary forces are used and therefore the middle tube of the distillation system needs to be horizontally oriented. Next to this, in order to vaporise methanol and water, the heat buffer integration needs to be connected to the heating block. Both sides, the 'hot' and ‘cold’ heating blocks, need to be oriented below the middle pipe so that only gases go into the connecting pipe and capillary forces redirect the condense back to the hot block.

SOLAR CONNECTION:

The methanol synthesis plant needs to be connected to the solar panel(s). The angle of the solar panels to the ground surface differs per location. The micro-plant needs to be adaptable to several solar panel angulations.
Integration: The integration design is the overlap between all functional systems. The integration design needs to exist of an efficient architecture for the heat buffer, general system connections, electrical components, and the design for assembly and maintenance. Main dependences will be the heat transfer efficiencies, strength and system robustness. Also wire management needs to be implemented.

BOM, THE BASE CASE

INTRODUCTION

At ZEF there was no complete overview of all the components of the micro-plant. Therefore, there was no clear idea of the micro-plant's production cost of when the product would be mass-produced. An overview of all materials and physical limitations is important for the development of an integrated design. Therefore, in this section a complete bill of components, with an estimation of the costs and physical characteristics per component are formulated.

The bill of materials and processes (BoM) can also be used to indicate the impact of design modifications on the micro-plant's cost.

MICRO-PLANT TARGET COST

The methanol micro-plant has a target cost price between €100 and €200 per piece, in a series of 100k micro-plants. The purchase components, the specific parts and the assembly will be the factors to determine whether the set goals are realistic.

INTRODUCTION

In order to find the impact of the design component improvements, it is important to set a base line of the methanol micro-plant and thereby to define the status quo. This is done by making the "BoM" of the prototypes currently made. The BoM includes purchase components, components from own production and the assembly. If the current prototypes would be mass-produced, more suitable machines would be used, and the efficiency would likely increase. However, for these variables there is hardly any data at hand, resulting in speculations and assumptions.

PURCHASE COMPONENTS

The purchased components for the current prototypes are mainly bought at AliExpress. AliExpress may not always be suitable for mass production, as this site can be considered as an 'outlet dump', and rates can differ quickly over time due to discounts. To check the cost relationship between AliExpress and European resellers a sample comparison research has been conducted (appendix C). Within this research the AliExpress rates were compared to half of the retail price (excl. VAT) from European retailers. The other half of the price was assumed to be profit for the retailing company, as in Europe it is common to double the purchase costs for retail (J. Oberdorf, personal communication, October 18, 2018). This way the purchase price of these retailers was estimated. As a result, it was found that there was a difference of about 20% between the rates from AliExpress and the calculated purchase costs for European retailers. This range fluctuated to both sides. It has been commonly accepted to have a 20% range in an early cost calculation, therefore the AliExpress rates are used.

AliExpress is an e-commerce-platform for mainly Chinese companies, to facilitate direct retailing to international markets. As middle-men are avoided costs stay low. *Note*

SELF DEVELOPED PARTS

For the components that fall under 'own production' the costs are estimated using the prices of the materials and the for the manufacturing. The market prices found on the internet were used for the material costs when available. If there was no access to market prices, the mean price per kilograms from the Cambridge Engineering Selector (2018) materials data base were used. These material rates were multiplied by the mass of the materials needed for production. These masses were derived from the Fusion 360 prototype models, adding waste materials from manufacturing techniques like machining. The manufacturing rates of the components were calculated using the 'Manufacturing costs build-up' sheet (Thomassen, 2015). According to Molcho (2014), costs estimations in the development phase could be based on either a comprehensive data sheet, for which component detailing is needed, or an expert could give an estimation based on manufacturing experience. In order to make this manufacturing costs breakdown, Prof. ir. Oberdorf J.E. was consulted as an expert to define expected costs and production times. The manufacturing costs exist of opex costs for machine-lines and molds, and apex costs for labour, machine usage and materials' usage. The labour costs are an important factor in defining the cost of the micro-plants. For this analysis a labour cost of €25 per hour is used. This number is based on the average Dutch wage (Thomassen, 2015). The wage could possibly lower when production is performed in low wage countries.

ASSEMBLY

All components need to be assembled to make it a uniform and working product. This includes the assembly of the subsystems, as well as the total product. Per subsystem only few data about component assembly is available. There is no design for assembling the different subsystems yet. It is assumed that when the subsystems are combined, the total assembly by one person will take another 15 minutes.

MAIN DECISIONS AND INFLUENCERS

ABSORPTION AND DESORPTION

The absorption chamber and desorption chamber are still conceptually changing. For these components data retrieved from the mathematical model (appendix D) is used within the current scenario of seven available sun hours per day and a 300W solar panel, with a methanol conversion efficiency of 50%. As a result, the absorption chamber needs to have a volume of about three liters. The desorption chamber needs to have a minimum size of about 0.15 liters. The absorption chamber needs to be able to endure rough weather circumstances. Based on the recommendations of Van Den Berg (2018) the casing material is chosen as PET45% glass filled. The sorbent racks have little specific physical needs and therefore polypropylene (PP) is chosen as material. The desorption chamber needs to be heated to 120°C. Plastics generally are not suitable for such high temperatures and therefore aluminum is chosen. The assumption is that the casing will be made with injection moulding, the sorbent racks will be stamped out of PP (polypropylene) sheet

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
1	€1-$	1.17641													
2	**Purchase components, excl. sol**		Ali/express		Regular		Mean	**Own production per component**							
3	**MeOH micro-plant**	**#**	**€ / piece**		**0.5price €**		**€**		**€ /kg**	**kg/piece**	**€**			**€**	**€**
4	Part	Quantity	purchase price	link	purchase price	link2	purchase total	Material	Material price	Weight	Material	Prod. Method	Rate	Manufacturing	Tot own prod.

Figure 2.4, Title segment of BoM

material and the aluminum block is CNC milled, just like the other metal components.

COMPRESSOR

The compressor casing is expensive due to its complexity, neat tolerances and large amount of materials that need to be removed. For the manufacturing time it was assumed that one casing from ZEF's second team would need a manufacturing time of five hours using a CNC machining device. The costs are mainly derived from the CNC devices, which cost €60 an hour for operation (Thomassen, 2015), together with the given €25 per hour for labour costs. Additionally, there are the material costs, a 1% defects-waste-factor and a 15% overhead factor. Of course, this component would never be manufactured using machining. With some design modifications, casting would also be possible. Casting is regularly done for engine blocks in the automobile industry. Conceptually these engine blocks could be compared with the compressor. Neat tolerances could be achieved by means of secondary manufacturing with machining.

AEC (BUFFERS, DEGASSER, ELECTROLYSIS)

The cookies used for the electrolysis also account for about €500 in component costs. The current cookie designs are based on machining. From personal communication with a member from ZEF team 3, Mr. Brouwer K. (Oktober 19, 2018), it was found that one cookie has a CNC milling time of about 2.5 hours on the pocket CNC device available. It was assumed that an industrial grade CNC machine could decrease the operation time tenfold, i.e. to fifteen minutes. However, there are twenty cookies within the system, which comes down to an operation time of five hours. Moreover, the labour and machine rates per hour again cause the costs to run high. By applying some design modifications, the cookies could be produced way faster and cheaper with injection molding. The same accounts for the down comers of the electrolyzer and the degasser cookie. The H_2O and CO_2 buffer, as well as the H_2 buffer have larger volumes than the cookies. Yet, these components are estimated to be less expensive, as the general shapes do not bring along complexities and tolerances are less neat.

MS (METHANOL SYNTHESIS)

The stainless steel MS block has a mass of about 2.8 kg according to the fusion model. Machining is used for the production and will increase the costs up to about €63. The MS tubing system is connected together with seven tri-clamps.

DS (DISTILLATION)

Similar to the MS block, are the machined DS blocks the largest costs for the DS system.

INTEGRATION

The sensors used in different subsystems are placed at this field in the BoM. The electronic wiring, micro-controller, physical integration design and some other components are considered at the integration category. There is no conceptual idea of the physical integration. These costs are assumed to be around €10.

P	Q	R	S	T	U	V	W	X	Y	Z	AA	AB
		mm										
	Low high	**l*w*h**	**€/kg**		**°C**	**bar**	**# wires**			**W**		**To next phase**
l costs	Accuracy	Dimensions	total price/kg	Orientation	Temp.	Pressure	Wiring	Limitations	Yield capacity	Power usage	Input	Output materials

Figure 2.5, cost diversion base-case per micro-plant

RESULTS

The complete bill of materials exists of about **363 components** and the micro-plant has a mass of about **20kg.** According to the excel sheet, the total cost would be around **€1700** per micro-plant, when 400.000 micro-plants would be made (10 farms)**.** This means that the cost should be cut about tenfold for achieving the aimed range. The total cost consist for €330 of purchase components, €1350 of components from own production and about €30 of assembly costs (figure 2.5). The AEC and compressor subsystems are most costly in the base-case (figure 2.6). The costs of the ten most expensive components are stated in table 2.1. These ten components together make up 84% of the total components' cost. The other sixty components account for about 16% of the costs of the components. Figure 2.7 shows this cost distribution.

Although most of the components used are purchased, the list with most expensive components exists for 80% of specific developed parts.

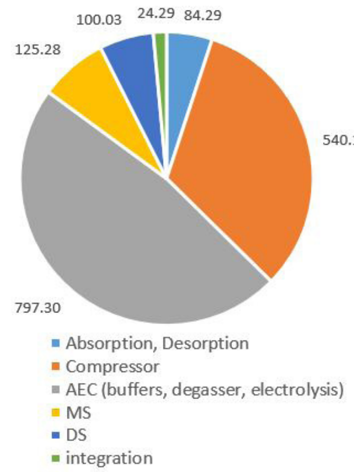


Figure 2.6, costs per subsystem division base-case

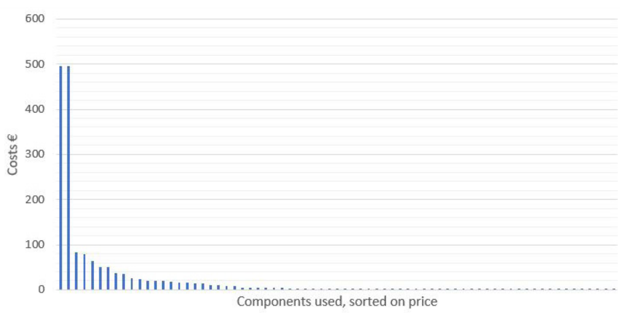


Figure 2.7, component cost distribution

Table 2.1, top 10 most expensive components in the base-case

	component	costs (€)	production
1	Compressor casing aluminium	496	Developed
2	Cookies, AEC	495	Developed
3	Valves	83	Purchase
4	Electrode	80	Purchase
5	MS block	63	Developed
6	Closing caps, pressure casing, AEC	50	Developed
7	Down comers, AEC	50	Developed
8	DS block cold	37	Developed
9	DS block hot	35	Developed
10	Degasser cookie, AEC	25	Developed

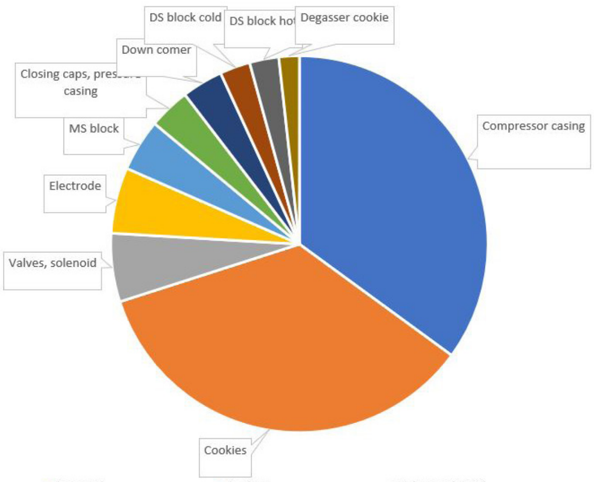


Figure 2.8, top 10 most expensive components in the base-case

DISCUSSION

Within this cost calculation, assumptions had to be made concerning the manufacturing time for the components under own production. Although this may cause the results to differ from reality, the magnitude of the costs per component and the cost division between the different components is clearly shown.

The top ten components are way too expensive for commercialisation. This mainly has to do with the non-optimised component designs for mass-manufacturing. The aluminum compressor casing and the cookies used for the AEC stand at the top of the cost list. These and most other expensive components are produced using machining. Small design modifications could enable more suitable mass production methods, like injection molding, casting, or forging. When possible, machining should be avoided as a manufacturing technique.

ZEF TEAM 2/3 PROTOTYPES IN MASS PRODUCTION

PURCHASE	*SPECIFIC DEVELOPED PARTS*	*ASSEMBLY*
€ 1350	€ 330	€ 30

TOTAL COST € 1700

THE BASE CASE

SCENARIO 2: MASS PRODUCTION FACILITATION

The previous cost analysis was conducted on the current prototypes that are not optimised for mass production. This section reviews the potential of the current design if mass manufacturing techniques could be applied. As the component designs are still in conceptual development, it makes no sense to optimise the current (October 2018) prototypes for mass manufacturing. Therefore, the following **conditions** are stated:

- The components have the same mass as the current prototypes
- The components are made of the same materials as the current prototypes
- The machined components are redesigned for injection molding, casting, forging, blow molding, or stamping.
- Conceptually the designs have not significantly changed in form or working principle compared to the base-case.
- Purchase components are the same as in the base-case BoM (only tri-clamps are left out).

PURCHASE COMPONENTS

All purchase components are the same as in the BoM base-case. Only the tri-clamps that are used for connecting the MS piping system is replaced by welding.

SPECIFIC DEVELOPED PARTS

Compared to the base-case the specific developed parts have different production techniques. In this scenario, the component masses are still similar. However, for several components the needed quantity of material decreases. In the base-case there was a lot of waste from the machining process, and more materials were necessary than for the components masses only. In this scenario the plastic components like the cookies and the buffers will be injection molded. The aluminum components will be sand casted. Some holes in the aluminum components have neat tolerances that will be achieved by secondary machining the casted components. Other feasible production methods for the metal components can be die-casting, or forging. For this quick cost estimation, a multiplication factor of 1.5 can be used for injection molding, sand or die-casting and forging, over the raw materials' price (J. Oberdorf, personal communication, October 18, 2018). The amount of secondary machining needed, and the related costs are depending on the future designs. As an assumption, a factor three over the material costs has been chosen when secondary machining is applied together with the primary manufacturing process of molding. For example: when an aluminum block with a material cost of €1.00 is casted and secondarily processed by means of machining, the total component cost will be €4.50, of which €1.00 material, €0.50 casting and €3.00 machining. In this calculation it is assumed that only the compressor casing needs such neat tolerances that secondary machining is necessary.

ASSEMBLY

In the base concept, the assembly of the MS piping system is done using tri-clamps. ZEF uses this method only for prototyping. Their plan is to weld the tubes together. MS and DS piping welding connections are added in the cost calculations. It is assumed that 4 MS systems can be welded per hour and 6 DS systems. Here, the welding machine costs are stated as €10 per hour with an hourly wage of €25 (Thomassen, 2015).

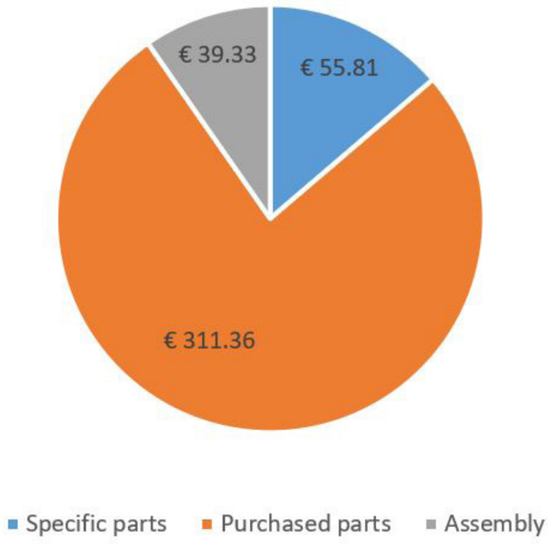


Figure 2.9, cost distribution mass-production scenario, per micro-plant

RESULTS

In this scenario the methanol micro-plant exists out of **356** components and has a total weight of **18.8kg.** The device will cost about **€410** for the stated production quantity of 400.000 micro-plants (10 farms). This cost is built up from €311 for purchased components, €56 for components under own manufacturing and €39 for assembly (Figure 2.9). The cost distribution between the subsystems can be seen in figure 2.10. The top ten most expensive components in this scenario are shown in figure 2.11. The top ten most expensive components are responsible for 75% of the total cost (±70 unique components). Figure 2.12 emphases this cost distribution.

The valves and electrodes are the most expensive components. Also notable are high expenses on the pressure casing, the MS block, and piping. The high costs come from the large quantities of stainless steel used. The seventh most expensive component is the integration embodiment design. The stated €10 is an assumption to make sure this integration is taken into account in the sheet. Real costs need to be determined later on. The complete list of components, sorted per subsystem can be found in appendix B2.

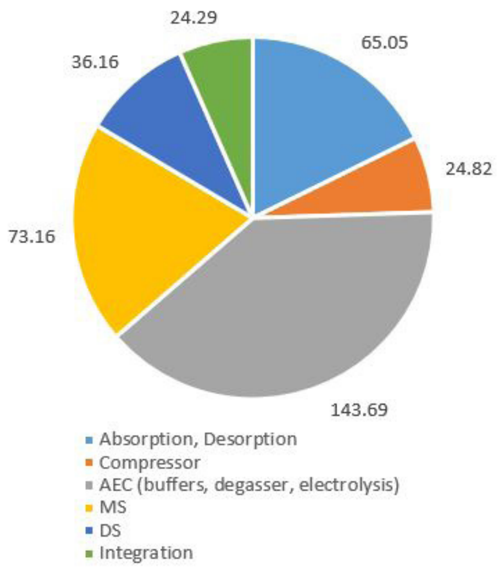


Figure 2.10, costs per subsystem division scenario

Table 2.2, top 10 most expensive components, mass-production scenario, per micro-plant

	component	costs (€)	production
1	Valves	83.20	Purchase
2	Electrodes	80	Purchase
3	Pressure casing	24.65	Purchase
4	MS block	20.83	Developed
5	Sorbent	19.13	Purchase
6	MS piping straight	13.68	Developed
7	Integration embodiment	10	Purchase
8	Electrode membrane	9.6	Purchase
9	Fan	8.29	Purchase
10	Compressor casing	6.34	Developed

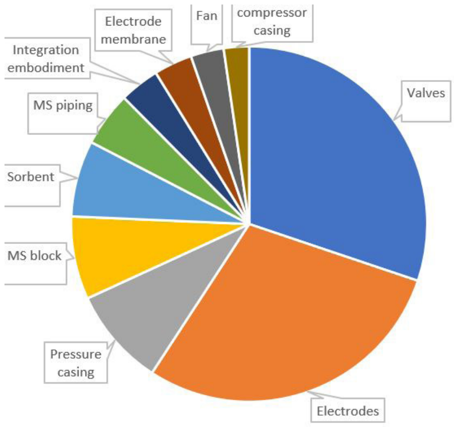


Figure 2.11, top 10 most expensive components, mass-production scenario, per micro-plant

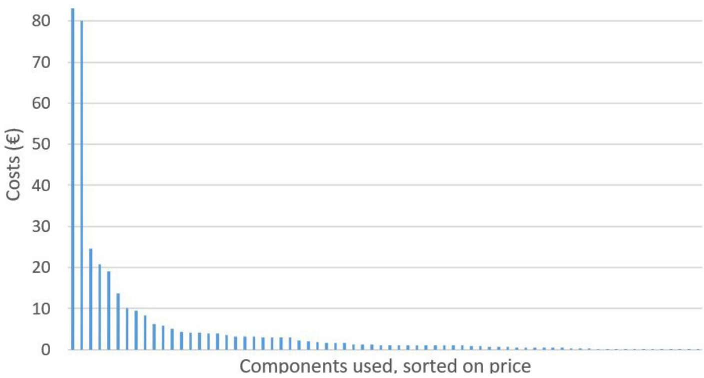


Figure 2.12, component cost distribution, scenario mass production

ZEF TEAM 2/3 PROTOTYPES MODIFIED FOR OPTIMISED MASS PRODUCTION

PURCHASE	SELF DEVELOPED PARTS	ASSEMBLY
€ 310	€ 60	€ 40

TOTAL COST

SCENARIO MASS MANUFACTURING

€ 410

DISCUSSION & RECOMMENDATIONS

The manufacturing rates used in this scenario are process specific, not component specific. Therefore, there might be some errors within the calculations. This is not observed as a problem as the outcomes are used to define the list of focus components that are too expensive. Component specific errors would not have had major influences on this list, or the total cost calculation. Similarly to the findings of the base-case, cheaper alternatives need to be found for the valves and the electrodes. The pressure casing, the MS block, the piping and the compressor casing need extra attention for cost reductions. These components are currently over-dimensioned. The pressure casing and piping costs, are based on AliExpress rates. Specific production would be possible too for these components. With the application of a factor 1.5 over the material costs, the final costs remain similar to the purchased parts that are used now.

COST REDUCTION

Costs could be cut by using cheaper materials, cheaper production methods, optimising the implemented system sizing, optimised weight design per component, and smart design that needs less components. Moreover, the components' sourcing could be made cheaper by shifting production to low wage countries.

The DAC team is researching the capabilities of the sorbent for the needed quantities. The costs of the sorbent have even more impact than shown in table 2.2, due to its degradation and the need for replacement in a currently unknown period. The fan and electrolysis membranes used are relatively expensive too. It could be researched whether there are more suitable alternatives in the market. These modifications together can have major impact on decreasing the micro-plant's cost. A smart system integration can also contribute to a cost decrease.

Table 2.3 shows a list of improvement possibilities for the most expensive components.

Table 2.3, recommendations

Pressure casing	**In scenario**	**Possible improvement**
Material	Stainless steel	Aluminum, Plastics: e.g. PVC 45%GF
Production	Extrusion	Rotation molding, Injection molding
Sizing	D50*2*600 2.9kg	Decrease in dimensioning wall thickness
Design	Open tube	Add electrolysis / buffer inserts, 1 down comer and one end side of the pressure casing may be molded together with the tube

MS block	**Currently**	**Possible improvement**
Material	Stainless steel	Brass, coated steel against oxidation, aluminum (probably maximum service temperature is not sufficient)
Production	Casting	Die-casting (not possible for steel)
Sizing	120*56.8*56.8 2.8kg	Decrease over-dimensioning and optimize usage of materials.
Design	Block with holes	Possibly the MS block design could be integrated with the MS tubing design

MS tubing	**Currently**	**Possible improvement**
Material	Stainless steel	Brass, coated steel against oxidation, aluminum (probably maximum service temperature is not sufficient)
Production	(purchase)	Die-casting (not possible for steel)
Sizing	D38.5*2	Decrease in dimensioning, wall thicknesses and optimize Diameter needed.
Design	Straight tube, or 90° bended tube	The straight and curved MS may be produced together as one part to prevent assembly. A way needs to be found to add the catalyst. In the optimal scenario the MS tubing could be integrated with the MS block in one part.

SCENARIO 3: MASS PRODUCTION, WITH LOGIC VALVE AND ELECTRODE RATES

The valve and electrode rates are modified in this scenario to more realistic values.

INTRODUCTION

In the bill of materials of the facilitated mass production scenario, the valves and the electrodes have by far the highest costs. To make the mass manufacturing scenario more realistic regarding costs it is of significance to implement better rates for these components.

VALVES

The currently used valves may be overpriced, with a cost of €7.56 per piece. The entire micro-plant uses eleven valves, so the costs rise up to €83 for the complete micro-plant. ZEF is now testing cheaper models and in the future only a specific part of the valves is necessary for functioning. This specific part may be ordered individually from the retailer when quantities rise. According to ZEF the future valves will cost about €1.50 per piece.

ELECTRODE

The coated electrodes appear to be a bottleneck. A requested quotation for 1.6 million electrodes (suitable for one methanol farm of 40.000 panels with 40 electrodes per micro-plant) showed the electrodes would cost €1.50 up to €2.00 per piece. For one electrolyzer this would mean that the costs would amount from €60 up until €80 for the electrodes. These costs are not acceptable within the cost aim of €100-200 per micro-plant. Therefore, other types of electrodes may need to be used, or the working efficiency needs to increase by design. Nickel electrodes without coating would cost 1.4 times the price of nickel (Permascand, personal communication). For the electrolysis unit this would mean a total cost of about €7.60, as forty electrodes weigh about half a kilogram and nickel has a kilogram price of about €10.90 (Nikkelprijs, 2018). This cost price is used in the next calculations.

The pure nickel electrodes will work with a lower efficiency then the ones with a coating. A ZEF team member will research the best electrodes to be used regarding costs and efficiency.

RESULTS

The device will cost about **€270** for the stated production quantity of 400.000 micro-plants (10 farms). These costs are built up from €172 for purchased components, €56 for components under own manufacturing and €39 for assembly costs (figure 2.13). The cost distribution between the subsystems can be seen in figure 2.14. The top ten most expensive components in this scenario are shown in figure 2.15. The top ten most expensive components are responsible for 60% of the total cost (±70 unique components). Figure 2.16. shows the cost distribution between all components.

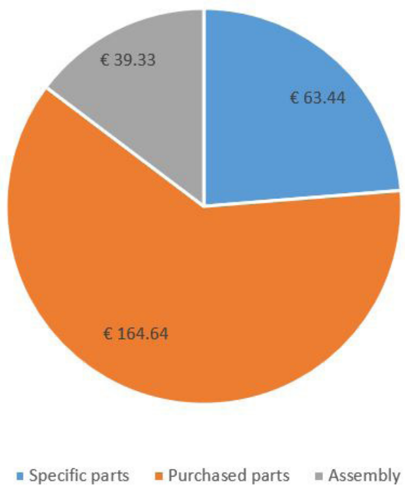


Figure 2.13, cost distribution mass-production scenario 3, per micro-plant

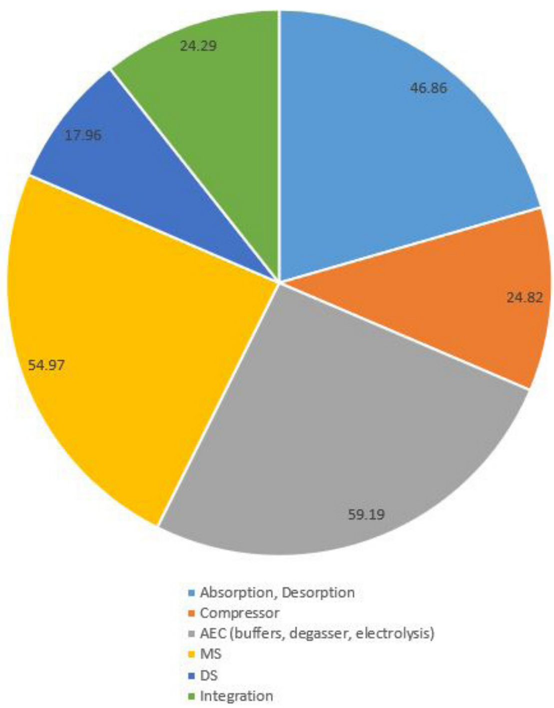


Figure 2.14, costs per subsystem division, scenario 3

Table 2.4, top 10 most expensive components, scenario 3, per micro-plant

	component	costs (€)	production
1	Pressure casing	24.65	Purchase
2	MS block	20.83	Developed
3	Sorbent	19.13	Purchase
4	Valves	16.50	Purchase
5	MS piping	13.68	Purchase
6	Integration embodiment	10.00	Developed
7	Electrolysis membrane	9.60	Purchase
8	Fan	8.29	Purchase
9	Electrodes	7.63	Purchase
10	Compressor casing	6.34	Developed

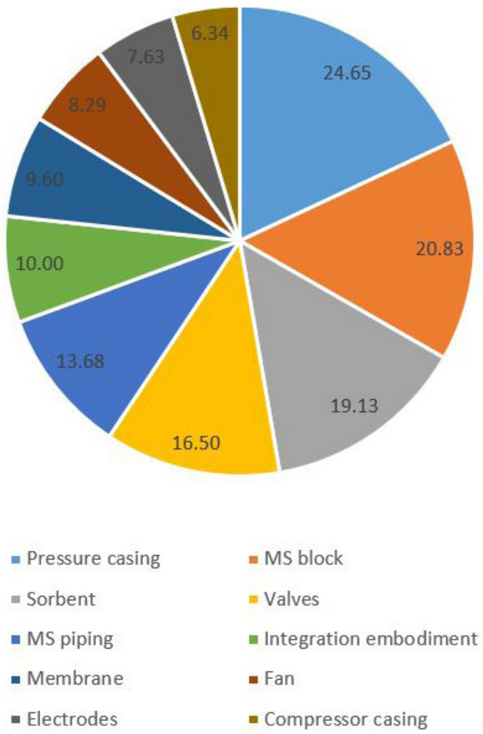


Figure 2.15, top 10 most expensive components, scenario 3, per micro-plant

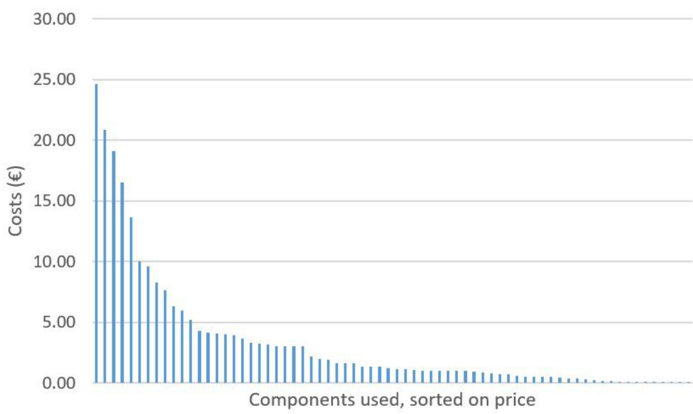


Figure 2.16, component cost distribution scenario 3

ZEF TEAM 2/3 PROTOTYPES MODIFIED FOR OPTIMISED MASS PRODUCTION WITH IMPROVED VALVE AND ELECTRODE RATES

PURCHASE	SELF DEVELOPED PARTS	ASSEMBLY
€ 170	€ 60	€ 40

TOTAL COST **€ 270**

SCENARIO 3, MASS MANUFACTURING, REALISTIC RATES

DISCUSSION

The results of scenario three, with the realistic rates for the valves and electrodes, deliver a view on the status of the methanol micro-plant. Considering that all optimisations and mass-manufacturing facilitations are done, the micro-plant has a current realistic cost of about €270. This is not yet within the range of €100-200, but it is close enough to varify the feasabillity of the cost aim. Cost decreases can be made by optimising the designs to decrease weight and by chosing cheaper materials. With general design improvements also costs could be further lowered. It should be noted that as the electrodes have changed and therefore the efficiency output also changes for an unknown number. Whether efficiency decreases are acceptable and how it effects the cost per kg methonal must be further examined by ZEF.

'BOM, THE BASE CASE' & SCENARIO 3

In the base case the total cost per micro-plant was €1700. With the production, electrode and valve optimisations considered in scenario 3, the cost is brought back to €270. In figure 2.17. the costs differences per subsystem can be found. The differences are highest for the components that switch production techniques from machining to more feasible methods like casting.

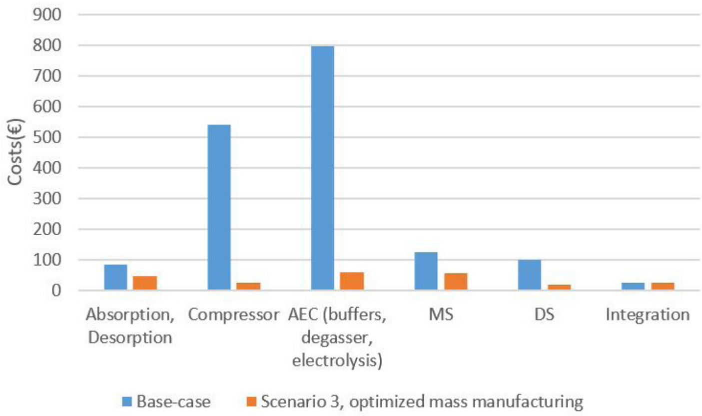


Figure 2.17, cost comparison: Base-case & Scenario 3

PROGRAM OF DEMANDS FOR INTEGRATION DESIGN

The program of demands for integration was formulated based on the defined physical characteristics and variables per subsystem for integration. Exploring scaling potential is one of the design challenges for the integration design. Therefore, ZEF's currently aimed input and output values cannot be directly implemented. The demands are formulated in a way that supports design modifications. For example, the methanol must not exceed a cost of €350 per ton. This way there is no absolute cost limit per micro-plant, and scaling is possible. The complete program of demands can be found in appendix E.

Note

Note: This program of demands is aimed on integration design. For specific subcomponents and the entire methanol farm additional demands should be considered that are not listed in this section.

REDEFINED PROJECT BRIEF

October 22, 2018

VISION

I started this graduation project with the design brief that can be found in appendix M. During the discovering and defining phases it became clear that the general aim of this graduation project needed some modification to bring this project to its highest potential. Initially I planned to integrate the prototypes that should be finished by Christmas 2018, by ZEF team 3. The ideal result of this graduation project would be a working integration design.

Along the way I challenged the potential of the integration design and, together with ZEF, I concluded that integrating the Christmas 2018 prototypes would make me too dependent on uncertain output. Even if the prototypes would be fully functional, the integration potential would be questionable as these prototypes are iterations and not final designs. To a large extend the effort taken on the integration would only be applicable on this specific iteration. For this reason, the decision is made to take a step higher in abstraction levels and to work conceptually on the integration design. Figure 2.18 shows several abstraction levels applicable to this project. Within this redefined project brief I will work more towards the conceptual side of the micro-plant's system. Developing working prototypes are out of the scope.

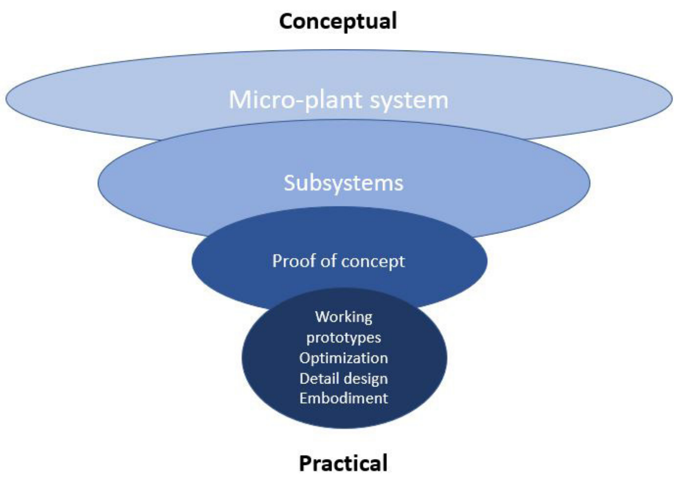


Figure 2.18, abstraction levels

PROBLEM DEFINITION

The problem definition presented in the design brief of appendix M is still applicable. In addition to this definition it should be noted that although ZEF has in depth knowledge of the subsystems working principles, the sizing of the subsystems may not be optimal. There is little knowledge about the influences of scaling the subsystems. For example, the one on one relation of solar panels and micro-plants may not be optimal. Even within the micro-plants it might be beneficial if certain subsystems are sized differently.

> *"Design a conceptual system integration of the ZEF methanol micro-plant, that is based on optimised system sizing, product architecture and basic embodiment.*

DESIGN GOALS

The integration design focusses on three main questions

1) **System sizing:** research the influences of systems sizing on the methanol micro-plant and use the most efficient sizings for a conceptual integrated methanol-plant design.
2) **Product architecture:** research the influences of different product architectures and implement the most promising architecture in a conceptual integrated design.
3) **Basic embodiment:** research and define a potential embodiment concept for the different subsystems, considering conceptual design, materialisation, assembly and maintenance.

This project aims to take first steps in optimising the integrated system of the ZEF methanol micro-plant regarding costs and efficiency. This project will be carried out in parallel to team ZEF 3 and 4. Results may indicate recommendations for (sub)system modifications. The results gained from this integration project will be used to define recommendations for future subsystem and integration developments. A visual showcase model will be made for the product architecture and embodiment.

APPROACH

To achieve the design goal, the project can be separated into three consequent phases: system sizing design, integrated architecture design and embodiment design. Finally, an evaluation phase will follow in which recommendations are defined. Although this process looks linear, there will be an overlap between the phases, and thus iteration steps need to be done based on the findings. The project approach is schematically represented in figure 2.19.

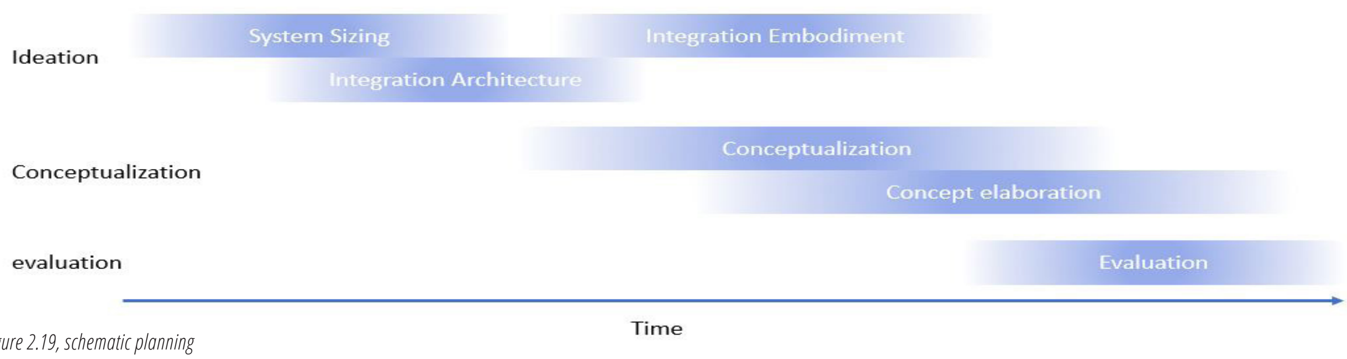


Figure 2.19, schematic planning

INTEGRATION RESEARCH

INTRODUCTION

The research conducted in chapter one and two provide an understanding of the system demands and working principles. This chapter handles the system sizing and integration design analyses. The ideation section is divided in 'system scaling' and 'product architecture', respectively defined as:

System scaling:
researching an optimal sizing for the micro-plant.

Product architecture:
searching for potential subsystem arrangements, considering the program of demands.

In many aspects the system sizing and product architecture are interlinked. A brief representation of the topics handled per category is shown in figure 2.20.

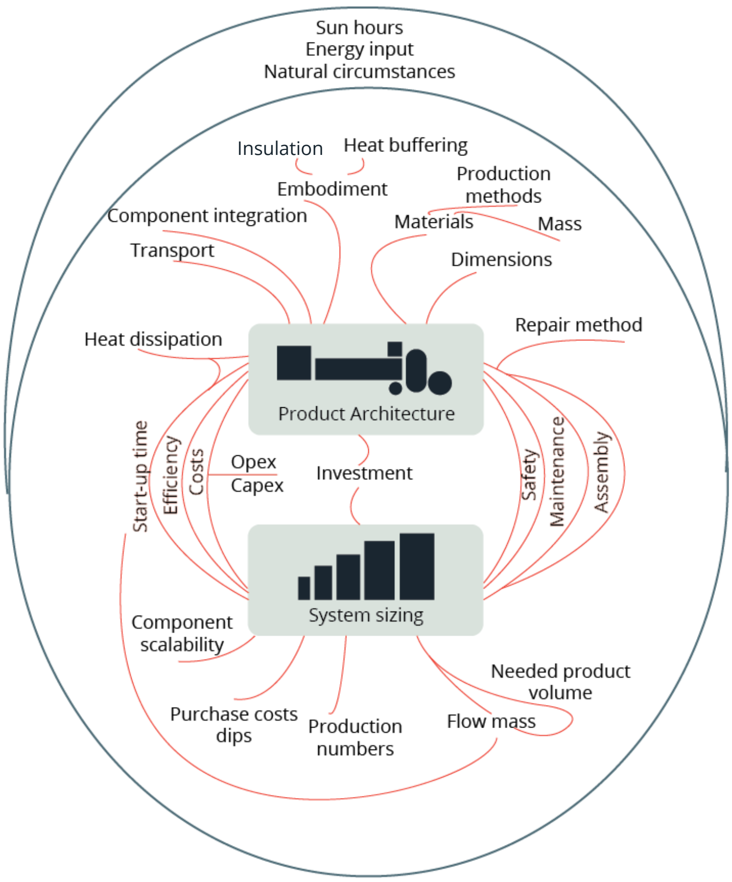


Figure 2.20, System sizing and product architecture relations.

3.
SYSTEM SIZING

During this graduation project the methanol micro-plant's scaling concept, used by the sub-teams was mainly based on the principle of having one micro-plant per 300W solar panel. Although this is an appealing concept, it might be more efficient to use a different system sizing. Possibly it would be more profitable if the entire system would be changed in size, or if certain subsystems are designed to work for multiple micro-plants. This section elaborates on the expected effects of system sizing.
The component boundaries and expected scaling effects are discussed with the ZEF sub-teams and entrepreneurs. The mathematical model (appendix D) was used for quantitatively analysing the influences of scaling. Effects of different system scaling's are considered relating to the capex per ton methanol, start-up time, efficiency, safety, maintenance, assembly, installation and investments.

When researching scaling potential, a factor 10 is considered as a maximum. Larger sizes are not considered as it would not fit the ZEF company vision and business model of numbering-up. Note

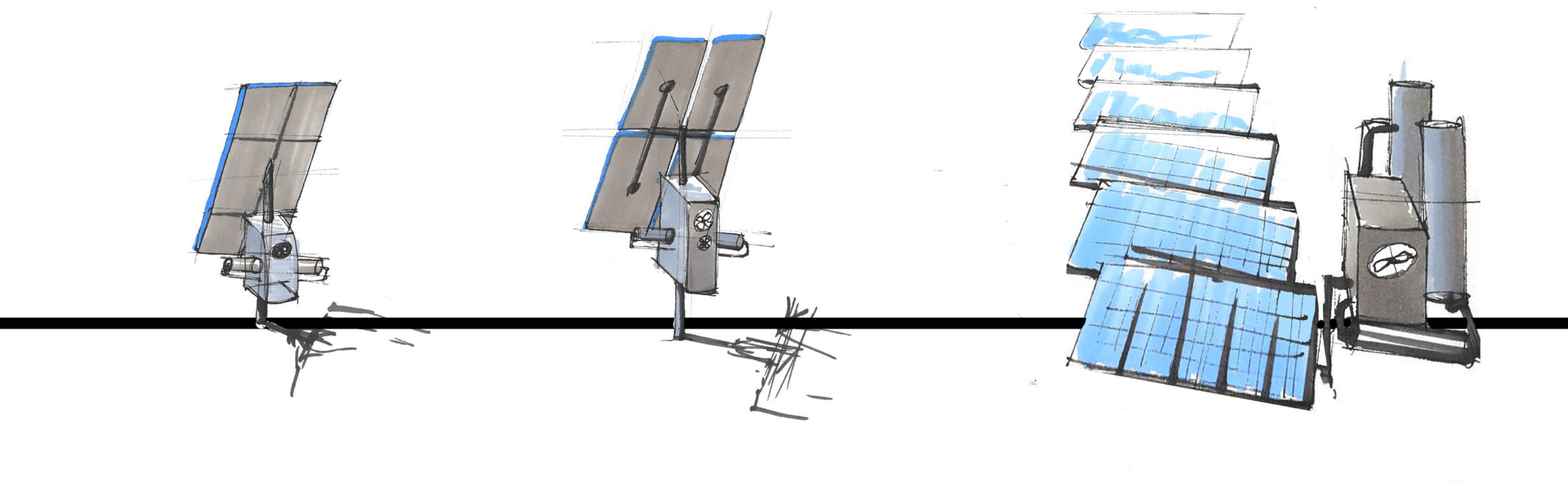


Figure 3.1, System sizing possibilities

COMPONENT COST-SCALING RELATION

All the components in the bill of materials presented in chapter two are qualitatively analysed on the effects of system scaling. For the costs at scale one, the values from 'scenario 3: mass production, with logic valve and electrode rates' are used. For the components under own production, system scaling would generally mean to enlarge the current components' design. For the purchased components, scaling could possibly mean purchasing alternative components that fit the needs of a certain system size or increasing the number of the same component. The expected cost and system sizing relations were explored and formulated in a system sizing analysis session together with J. van Kranendonk. Generally, the system's components could be organised into two categories: components that scale proportionally and components that scale non-proportionally relating to the costs per system size. Components that scale proportionally have minor cost influences on the micro-plant. The components that scale non-proportionally do have influence on the final cost per ton methanol. The system's components and their effects on scaling can be found in appendix F.

PROPORTIONALLY SCALING

The components that continue doubling in cost along with the system size, have a proportional cost-size relationship. The costs per kilogram methanol does not change because of these components (figure 3.2). The components with a proportional cost-size relation are mainly components that have a specific capacity or reaction speed. For example, the amount of sorbent is dependent on the amount of CO_2 that needs to be captured. If the absorption efficiency of the sorbent increases, less sorbent will be needed but the scaling still changes proportionally. The same accounts for the air fan and filter, for which the number-up quantity depends on the required airflow. However, for some components, like the fan, there are both the options of numbering up (proportionally), or scaling up by using larger fans (figure 3.3). The more expensive industrial fans may in the end better suit the needs of a larger system than a series of computer fans, due to less assembly costs and a more homogenous airflow. Next to this type of purchased components, most components derived from own development also increase about proportionally in cost when sizing increases. If, for example, more hydrogen is needed, the electrolysis system increases in size by numbering up the electrolyis cookies, or by increasing the cookies diameter. The electrode surface remains proportional to the needed hydrogen output.

All costs are calculated to €/ton methanol production. For this calculation the estimated costs from scale one are divided by the estimated amount of methanol that one (scale one) micro plant produced over its entire lifetime (1.4 ton). €/ton = Costs at scale 1 / 1.4 — Note

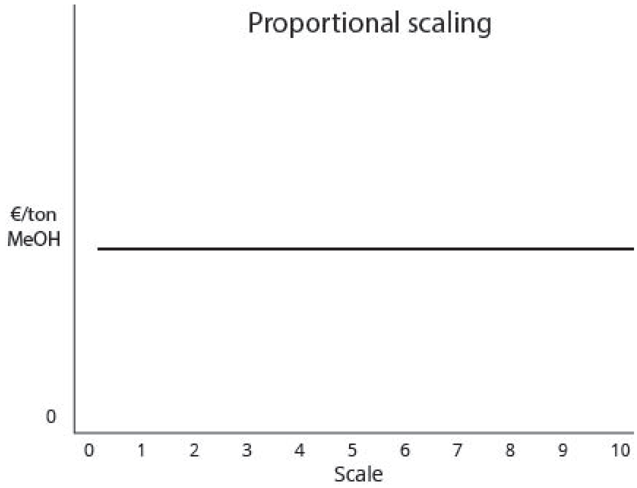


Figure 3.2, Proportional scaling

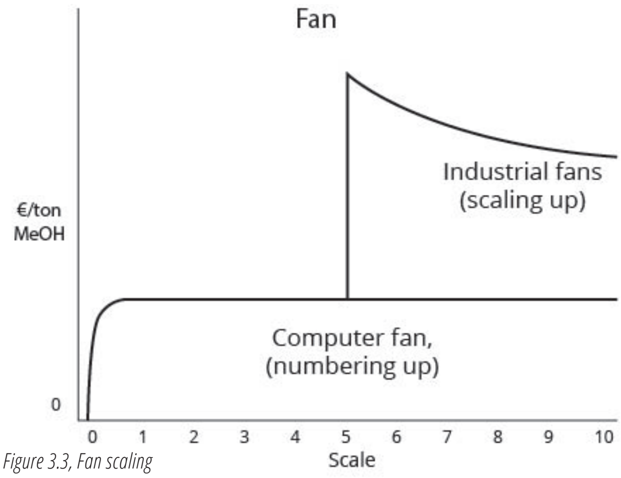


Figure 3.3, Fan scaling

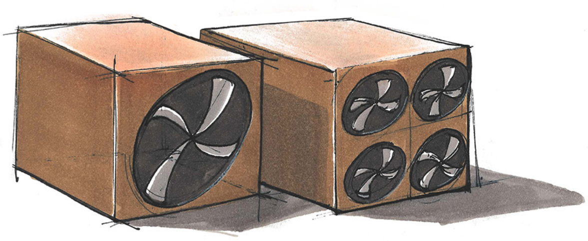


Figure 3.4, Fan scaling. Scaling up (left), numbering up (right)

Note

Scaling up:	*increasing the dimensions of the component*
Numbering up:	*using multiple components of the same type*

NON-PROPORTIONALLY SCALING

The goal of system scaling is to find more viable and cheaper options for the methanol micro-plant. For this reason, components that scale non-proportionally are most interesting to analyse.

SAME COMPONENTS AT DIFFERENT SCALES

In principle all sensors scale non-proportionally. When the system changes in size, the same sensors are still needed. Therefore, the relationship of costs per kilogram methanol can be written as:

$$\frac{Costs}{kgMeOH} = \frac{1}{scale} * \frac{€}{kgMeoH(scale\ 1)}$$

As a result, the cost curve can be seen in figure 3.6.

STEPWISE SCALING

Other components, like the valves, scale stepwise. The valves could probably bare a system size of four times its current size without changing. Next, a larger and more expensive valve needs to be used and so on (figure 3.7).

20% COST DECREASE PER DOUBLING SIZE

A third way in which components scale non-proportionally, is by decreasing about 20% in cost when doubling the system size. Such scaling effects will occur at for example the compressor. The costs per ton methanol decrease as the larger systems have a lower complexity, and relatively less secondary manufacturing is needed. This relationship also exists in for example the methanol synthesis and distillation blocks. In figure 3.8 the general cost curve of this system can be found.

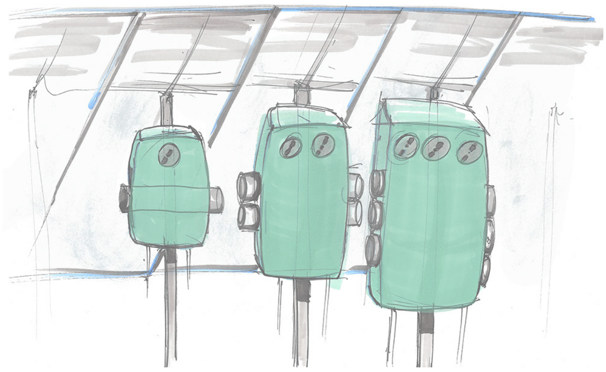


Figure 3.5, Scaling ideation

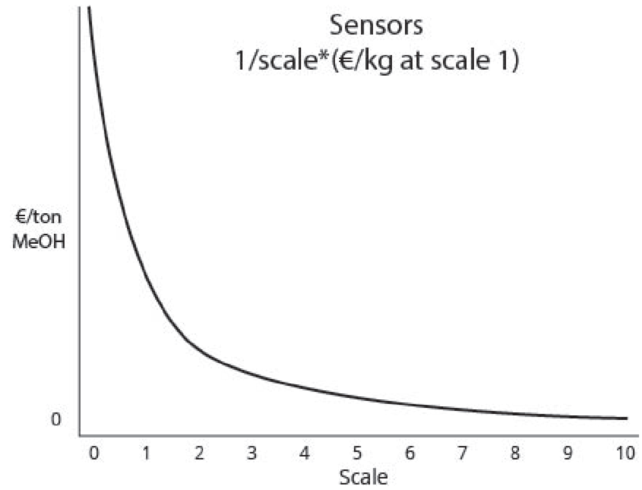


Figure 3.6, Sensors scaling, non-changing components

Figure 3.7, Stepwise scaling

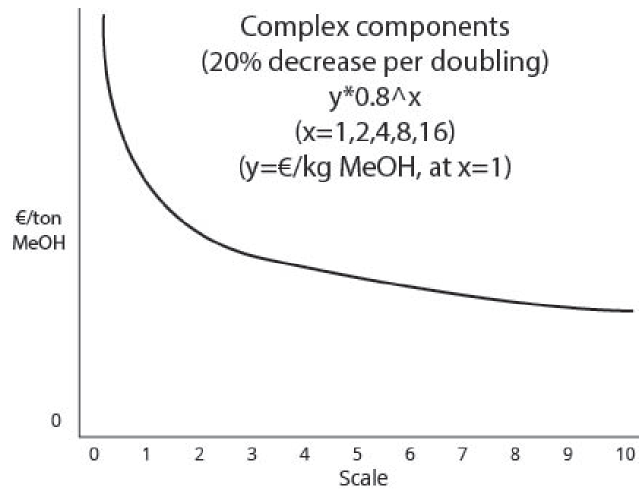


Figure 3.8, Complex component scaling, 20% cost decrease per doubing size

SUBSYSTEM SCALING COST

The cost impact needs to be determined per subsystem or subsystem group, as these could possibly scale individually. The subsystem groups considered are: absorption and desorption, the compressor, the AEC (two buffers, degasser and electrolyzer), the MS, the DS and the control system.

ABSORPTION AND DESORPTION

Most non-proportional components within the absorption and desorption chambers stay the same when scaling. The sorbent pump will likely decrease with 20% in cost when the size is doubled. Also the valves will lower in cost.

COMPRESSOR

Notable in this graph is the cost behaviour of the gearings. Around a scale of one there is a peak that shows the transition from plastic bearings to metal ones. Next, the cost will decrease with about 20% per doubled size. The drone motor and motor drivers used at the current scale (scale 1) will function until a scaling multiplication of three. Furthermore, several motors need to work in parallel, or a stronger motor is needed.

AEC (buffers, degasser and electrolyzer)

Except for the valves to be used all non-proportional absolute component costs stay similar when scaling.

MS

The MS block costs will decrease with about 20% per system size doubling. The heat pipes show similar scaling behaviour.

DS

Like the MS blocks, the two DS blocks show 20% cost decrease per system size doubling.

CONTROL

All non-proportional scaling components for the control system remain the same when scaling, as one does not need to add sensors and actuators. Yet, there will be a maximum system size for which the Arduino micro-controller is a suitable option. For larger sized systems people to control the systems may need to be employed, which is most likely too expensive.

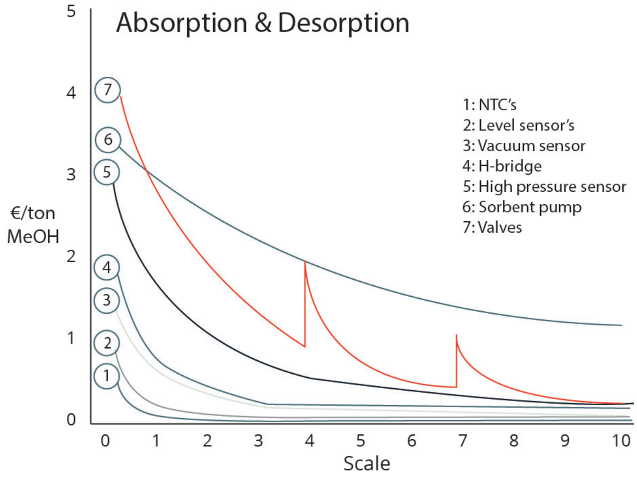


Figure 3.9, Scaling absorption and desorption

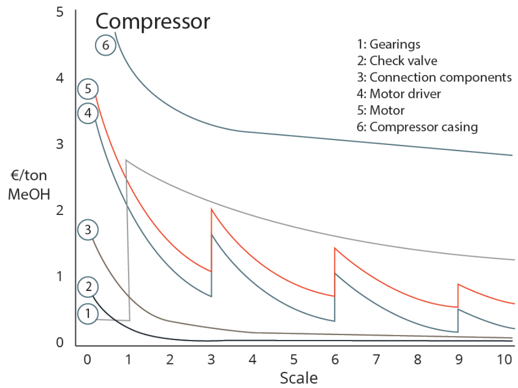


Figure 3.10, Scaling compressor

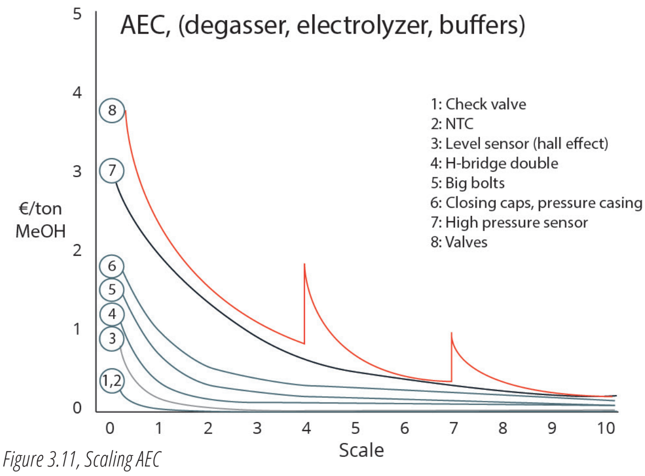


Figure 3.11, Scaling AEC

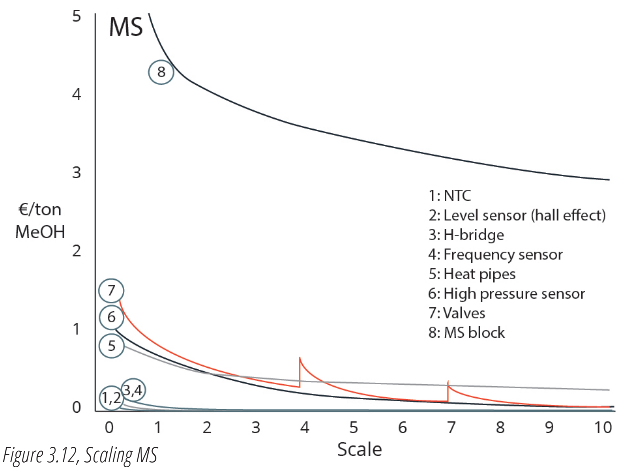


Figure 3.12, Scaling MS

SUBSYSTEM COSTS AND SCALING

Figure 3.15 shows the non-proportional cost sum per subsystem when scaling. Generally, it can be observed that the cost drops down when scaling increases. In this figure it seems as if there are only advantages to upscaling. However, the reality is somewhat more complex.

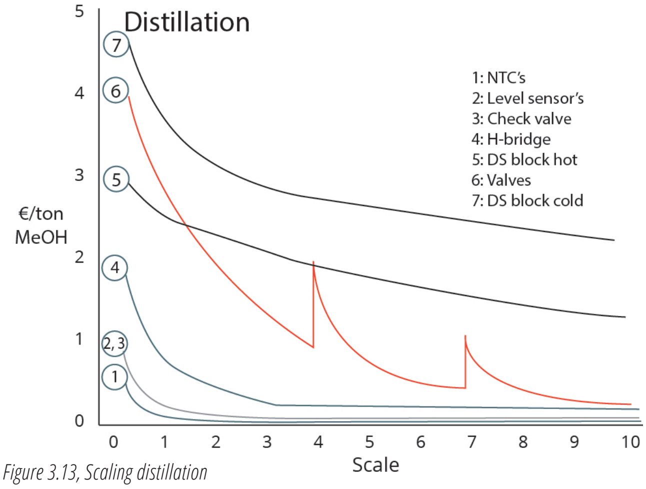


Figure 3.13, Scaling distillation

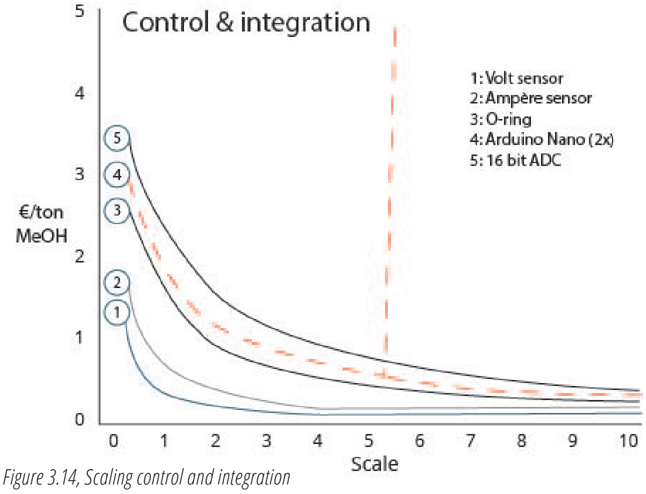


Figure 3.14, Scaling control and integration

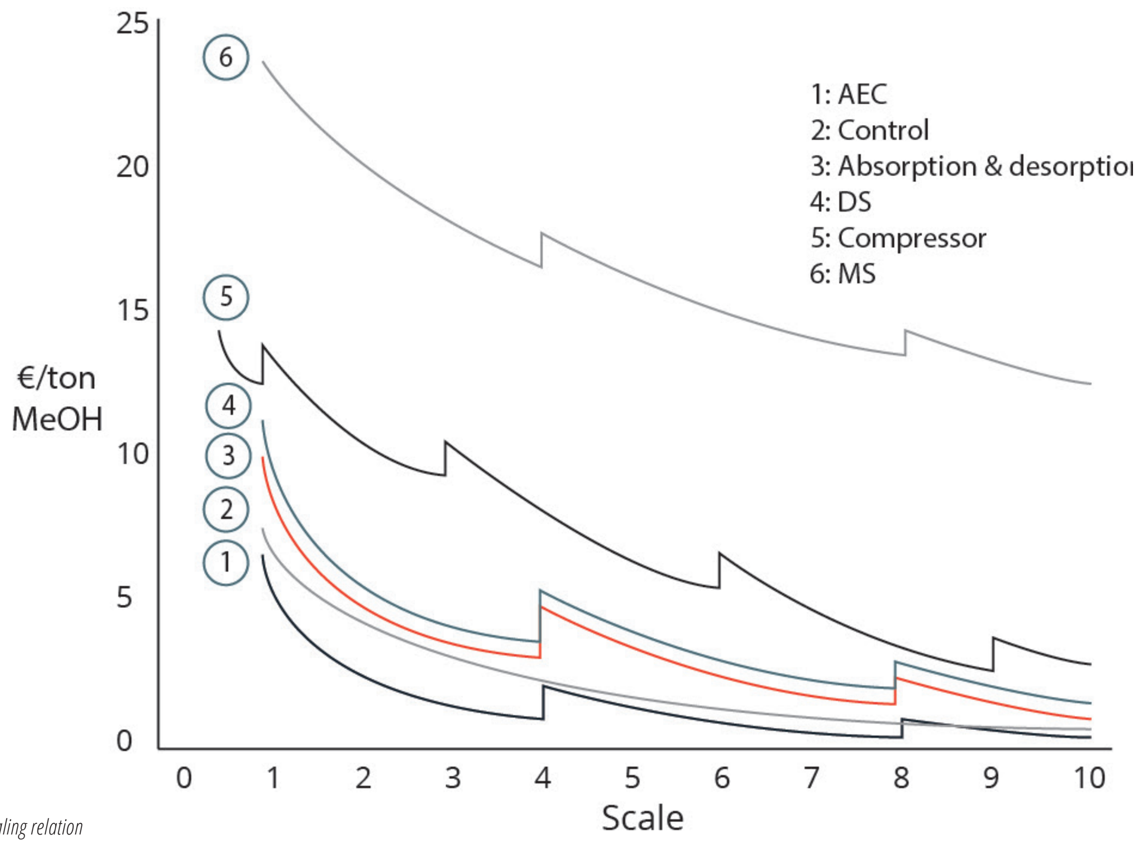


Figure 3.15, subsystem costs – scaling relation

PRICE DIPS

The graphs in figures 3.9 to 3.14 show nicely curved lines. In theory these lines are correct, but in reality, several price dips could be found for commonly used components. For example, this is clearly visible for brushless DC motors, where a specific type of motor is way cheaper than alternatives. The same accounts for specific sizes of fans, valves and some other components. For this reason, it would be best to make a design specifically for the price dips within the market. This way standardised and widely used components are used. Apart from cost decrease, commonly used parts also decrease the risks of failure as much data will be available.

Note — *When ZEF would produce several up to hundreds of micro-plant farms, ZEF would also be able to create its own price dips for its tailor-made components.*

START-UP TIME

ZEF's methanol synthesis device does not have a constant power supply and therefore the operation is not homogeneous. This is no problem if the system is able to start-up within a short time period, so that efficiency losses are minimised. Larger systems, however, will require longer start-up times. The MS subsystem's scale size has most influence on the system start-up time, as this part requires the highest temperatures. A tube needs to be heated to a temperature of 230°C (figure 3.16). Consequently, the heat needs to be transferred to the moving gases inside the MS system. In appendix G several calculations are shown, aimed at defining the system start-up at different scales. However, the thermo-dynamic system is complex, containing several heat sources, a stainless-steel tube, insulations and moving gases. The calculations done were not satisfying and were based on large simplifications. For this reason, Van Kranendonk was consulted about his expectations on start-up time. According to Van Kranendonk the system start-up will insignificantly be prolonged, untill a system scaling of four. The system sizing mainly influences the heating or conduction time of stainless steel components. Stainless steel conducts heat about 10 times slower than, for example, aluminum. The effects of scaling on start-up time can be decreased by choosing better conducting materials.

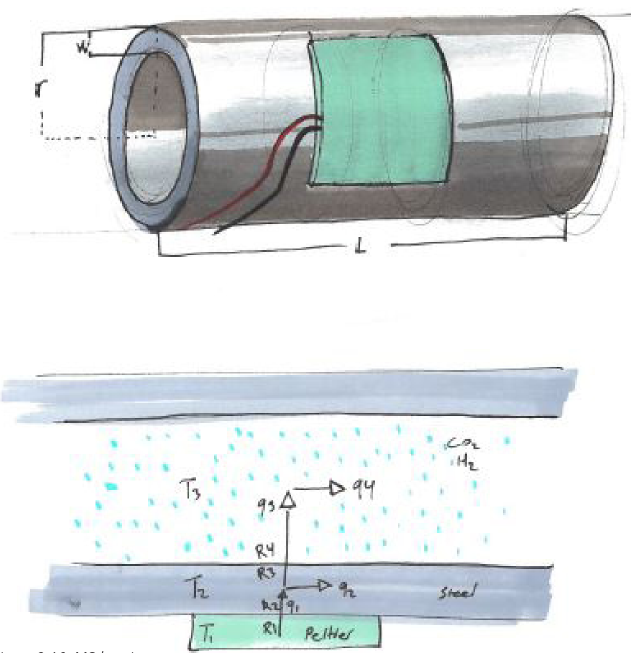


Figure 3.16, MS heating system

EFFICIENCY

The total system efficiency is aimed at 50% from the electricity produced by the solar panel, to the production of methanol. Potentially this efficiency can be lifted up even more by increasing the system size. Efficiency losses are the result of resistances and heating in (thermal) electrical systems. Larger system sizes can work with higher efficiency. According to Van Kranendonk (personal communication, December 2018) the efficiency can increase with about 10% compared to its initial value when the scale is ten times larger. The efficiency increases when larger, more efficient components and a more efficient insulation can be used.

In figure 3.17 the efficiency scaling relationship is shown. The production of methanol increases along with the efficiency increase. The 10% efficiency increase at scale ten (3kW system) would produce an extra 2.78ton methanol production over the 20 year lifetime. (A 3kW system would totally produce 16.64 ton MeOH, when functioning with a 60% efficiency). If this methanol would be sold for €500 per ton, then about €1400 extra turnover could be made per scale 10 micro-plant. This may be translated to an extra €1000 profit, which equals to about €60 per ton methanol, at a system scale ten. Per scaling the extra profit per ton methanol can be calculated by:

€/ton MeOH = 60 Log (x)

Here, 'x' stands for the chosen scale.

Note — *Electrical efficiency increases only occur when scaling up. When the same components are numbered up, little efficiency increase can be achieved.*

Note — *The additional amount of methanol to be produced depends on the aimed value at scale one. An efficiency of 50% is used as reference. However, this target has not been proven feasible yet.*

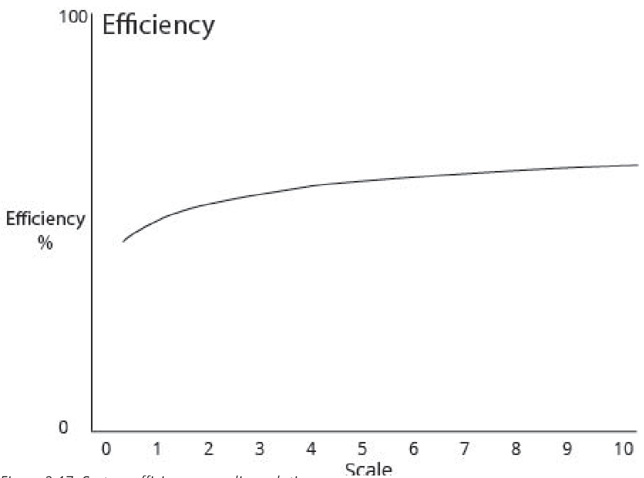


Figure 3.17, System efficiency – scaling relation

SAFETY

Dangerous chemicals, like hydrogen, are produced in the methanol micro-plant. Besides, there are high pressures in the little factory. When scaling to larger system sizes, the amount of potentially harmful sub-stances increases. At a certain point, a specialised control employee needs to constantly, or at least regularly, check the factories. Moreover, all installation and assembly procedures should be done by three people together, one operator and two persons checking the work done. This will be the point from which further scaling becomes too expensive. There will be norms and regulations for when safety checks are needed. These regulations may differ over different countries and exploring these is a study on its own. The exact tipping point from where safety employees are needed is uncertain but assumed to be at a scaling of four (figure 3.18).

Further scaling is possible, but the saved costs do not outweigh the costs of safety checks. Similarly, common large scale methanol plants are designed to prevent safety costs. For this reason, regular methanol factories operate under atmospheric pressure. Due to this, the opperating efficiency decreases by 7%, compared to a high pressure (50 bar). This 7% efficiency decrease outweighs the alternatively needed safety checks.

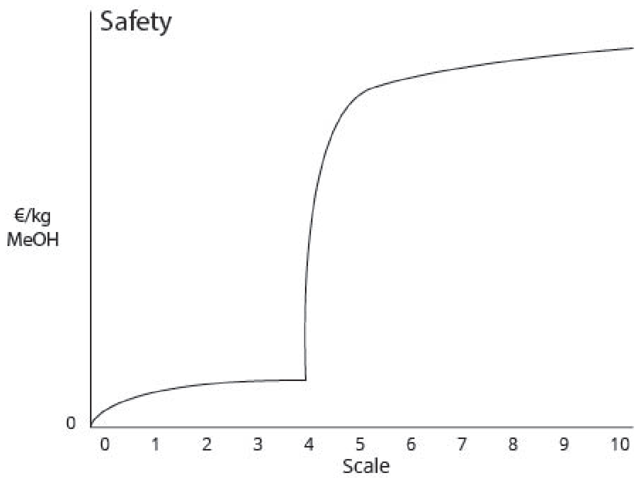


Figure 3.18, Safety costs – scaling relation

MAINTENANCE

When the system size increases, less individual micro-plants need to be maintained. However, when a micro-plant breaks down, there are more losses per time unit. It is unlikely that broken micro-plants will be repaired on the spot as this requires expertise and a specific maintenance environment. Possibly, the broken part is disassembled and returned to the factory, while the missing part will be replaced.

Regular maintenance, like adding new sorbent, should be done on the spot. For all other tasks the broken part will be returned to the factory, or a workplace. When the system becomes too large, the micro-plant becomes too heavy for a single person to carry and additional tools would be needed, or the maintenance would become a two-man job. How much weight a single person is allowed to carry depends on factors like the needed body movement, the distance to move the object and the frequency of moving such objects. In the Netherlands the maximum weight an employee is allowed to carry under optimal circumstances is 23kg (Ministerie van Sociale Zaken en Werkgelegenheid, 2018). The carrying will likely not be in optimal circumstances and it is assumed that 20kg will be the maximum carrying value for one person.

The field employees cannot get in contact with the pressurised areas at any time in the field. All pressurised parts need to be replaced without allowing the compression to escape.

ASSEMBLY

The assembly costs will likely lower when the micro-plant scales, as the number of components would not change too much. However, at a certain scale the components get too heavy, or too big to handle easily. At that point the assembly costs will increase as additional tools and machines are needed. This will probably happen at a scaling factor of about five. Next, the costs will lower again (figure 3.19).

INSTALLATION TO THE SOLAR SYSTEM

In the end the micro-plant needs to be connected to the solar panel. There are many different types of solar panel racking systems and for different systems different integration methods may be needed. The system sizing majorly influences the way the micro-plant is connected. At a small scale the aim is to position the micro-plant under an angled solar panel so that the plant will mainly be located in the shadow. However, if the solar panel lays horizontally, there may be insufficient space for the micro-plant. In this case, the methanol micro-plants can be placed externally next to the solar panel. Therefore, there are little design limitations for system sizing related to the solar and connection system. However, the installation costs will rise when the micro-plant exceeds a weight of 20kg. Above this weight two people need to carry together or a lifting machine needs to be used. When the micro-plant exceeds a weight of 50kg, manually carrying is no longer allowed, independent of the number of carriers (Ministerie van Sociale Zaken en Werkgelegenheid, 2018). With the assumption that one micro-plant can be installed in 20 minutes for an hourly wage of €25, then the installation costs at scale one would be €8.30, so about €6.00 per ton methanol. The expected scaling potential is shown in figure 3.20.

The scale of the micro-plant does not have to affect the type of solar panels that will be used. Note

The amount of needed micro-plant connection tubes with a methanol storrage tank would decrease when scaling-up. This tubing is outside the scope as it is outside the micro-plant itself. Note

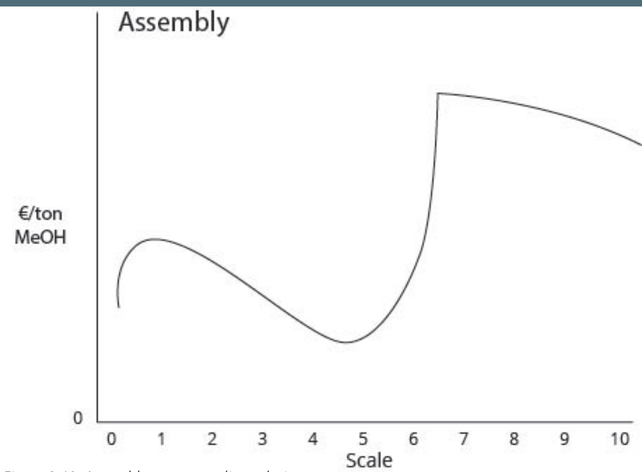


Figure 3.19, Assembly costs – scaling relation

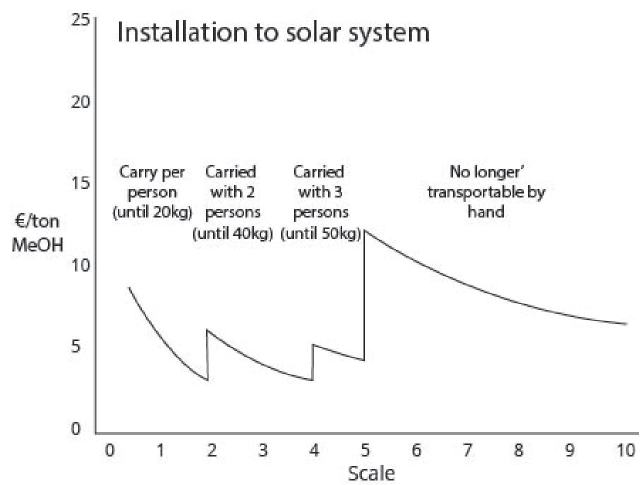


Figure 3.20, Installation to solar system costs – scaling relation

FIRST FARMS

A downside of scaling up subsystems is that the product series sizes decrease. For the first batches of the micro-plant this can be a problem, as the return on investment is reached later. The moulding costs are higher for the larger components, while the batch sizes decrease. When scaling-up too much, mass production methods are no longer feasible, and custom made, or in series produced parts will be needed. This would correspond to the design of current chemical factories and the numbering-up advantages of ZEF would disappear.

For a rough estimation for quantifying the results of upscaling on the first farms, the following assumptions are made:

- There are twenty components in the micro-plant that need a mould;
- The mean mould costs are €10.000 at scale 1, so per micro plant €200.000 investment is needed on moulding. For 40.000 micro plants, that produce 1.4 ton methanol over their entire life-time the costs would come down to €3.6 per ton methanol;
- Per doubling in size, the mould costs multiply by 1.5.

The moulding investment costs per produced ton methanol is calculated as:

€/ton MeOH = Investment / n. micro-plants / ton methanol per plant (lifetime)

MICRO-PLANT DEVELOPMENT

The development, prototyping and testing of the first series of the methanol micro-plant happen in the labs of Delft University of Technology. For ZEF it is important to be able to launch the product as fast as possible. Larger system sizes contain larger volumes of hydrogen and other compressed gases. This would increase safety issues during the development. According to Van Kranendonk a system scaling of about two would still be possible internally. For larger scales alternative developing locations, and safety employees may be needed.

Table 3.1, Mould investments - scaling relation

Scale	1	2	3	4	5	6	7	8	9	10
Investment (€)	200k	300k	375k	450k	510k	570k	625k	675k	720k	760k
N. micro-plants	40k	20k	15k	10k	8k	7k	6k	5k	4.7k	4.4k
Ton MeOH per plant	1.4	2.8	4.2	5.6	7	8.4	9.8	11.2	12.6	14
€/ton MeOH	3.6	5.4	6.0	8.0	9.1	9.7	10.6	12	12.2	12.3

RESULTS

Based on the findings some advantages and disadvantages of system scaling can be formulated.

Advantages of system scaling
- Lower components capex cost (€/ton methanol);
- System efficiency increases;
  - Component complexity decreases;
- Component failures are less likely to happen;
- Assembly, installation and maintenance quantity decreases.

Disadvantages of system scaling
- The system start-up takes longer. This becomes problematic at scalings larger than 4;
- Operation safety costs become problematic at scalings larger than 4;
- Development safety issues may become problematic at scalings larger than 2;
- Assembly, installation and maintenance components are larger and heavier;
- Larger investments need to be made;
- At too large scales supply parts may no longer excist.

Note — *At scale 1, the compressor and MS system could be rated less favourable. The compressor is of high complexity, which risks of malfunctioning. Increasing the scale goes together with increasing robustness. The MS system is probably oversized at scale 1 due to minimal required tube sizing.*

COST REPRESENTATION

Based on these findings, the scaling potential is represented in table 3.2. Here the scaling dependent costs per ton methanol are stated. It is clearly visible that a scaling from two to four is favorable for the subsystems. It is possible for the systems to scale independent of each other. A scaling of five is unfavourable due to the safety limitations for the compressed systems and due to the higher costs for the valves for the non-compressed systems.

In figure 3.21 the sum of the non-proportional costs per ton methanol is plotted for different scalings. A significant cost decrease of about €53 per ton methanol can be observed from scale one to two. Next, the scaling to scale three and four bring along smaller cost benefits of about €18 and €10 respectively. This is mainly caused by the logarithmic efficiency increasement and vastely dropped assembly costs from scale one to two. However, at scale three the device will weigh over 20kg and at least two people need to assemble and install the device together.

Figure 3.21, Non-proportional costs per ton methanol. (neglecting efficiency)

Table 3.2, Non-proportional costs per ton methanol

		Scaling, €/ton MeOH									
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
System	**Start-up time**	0	2	4	8	Not possible for MS					
System	**Safety**	-	-	-	-	Not possible for compressed systems					
System	**Assembly**	28	15	11	10	10	15	30	25	22	20
System	**first farm**	4	5	6	8	9	10	11	12	12	12
System	**Installation**	6	3	6	4	5	12	10	9	9	8
System	**Efficiency**	0	-18	-28	-36	-42	-47	-51	-54	-57	-60
Components	**MS**	24	19	17	16	18	16	15	14	15	14
Components	**Compressor**	14	12	10	10	7	6	5	4	3	4
Components	**DAC**	10	7	5	4	5	4	3	3	4	3
Components	**DS**	11	6	4	3	4	3	3	2	2	2
Components	**AEC**	7	4	3	2	3	2	1	1	2	1
Components	**Control/integration**	8	4	3	2	2	2	1	1	1	1
	Sum	**112**	**59**	**41**	**31**	**21**	**23**	**28**	**17**	**13**	**5**
	Sum, (neglecting efficiency)	**112**	**75**	**69**	**67**	~~**63**~~	~~**70**~~	~~**79**~~	~~**71**~~	~~**70**~~	~~**65**~~

POTENTIAL SCALING

With the results explained above, three main potential scaling options can be defined:
1) Implementing a scaling factor of two on all systems;
2) Implementing a scaling factor of three on all systems;
3) Implementing a scaling factor of four on all systems.

Benefits of factor two
Inhouse development at the Delft University of Technology remains possible. Moreover, the device will likely be less than 20kg which means that one single person would be allowed to carry the system. This way the assembly and installation will be less complex then at a system scaling of three.

Benefits of factor three
An additional amount of about €18 may be saved per ton methanol compared to scale two. The chosen motor and its driver operate at their maximum at this sizing.

Benefits of factor four
An additional amount of about €10 may be saved per ton methanol compared to scale two. The valves will operate at their maximal scale in this sizing.

SYSTEM SIZING DECISION

Together with ZEF the decision is made to design a system integration with a scaling factor of three. This means that the required volumes and flows are threefold compared to the aimed (ZEF team 3) designs. Design and system knowledge is important in this development stage for ZEF. A design for a system sizing of three will likely deliver more interesting insights than a design for a system scaling of two. At the same time a scaling factor of three is near the financial optimum. A scaling of four would be riskier, as safety issues might already be present at this scale. Also, it is questionable whether a scaling of four would eventually produce cheaper methanol. The cost decrease of a ten euros between scale three and four might turn out significantly different if the efficiency changes appear to be different. Neglecting the efficiency increase, a cost saving of only two euros would be possible. When the variables turn out differently, scale four might actually be more expensive compared to scale three.

The next design phases will be conducted for one micro-plant per three 300W solar panels.

SCALE 3 MICRO-PLANT CAPEX COSTS

In Chapter 2 the production costs of the **scale one** micro-plant were calculated to be €270 when optimised (scenario 3). For the 1.4ton methanol production in 20 years this would equal to **€195 per ton methanol**.

From the €195 about €112 are variable to the system sizing (table 3.2), this means that €83 is non-variable. The variable capex costs at **scale three** are lowered to €69 per ton methanol. This would result in a micro-plant capex costs of **€152 per ton methanol.**

The **scale three**, 900W, solar powered micro-plant system would produce about 4.6 ton methanol over its lifetime. 4.6 times €152 capex costs per ton methanol equals to **€700 per micro-plant.** This saves €110 compared to three 300W (scale 1) micro-plants.

SCALE 3 MICRO-PLANT OPEX COSTS

Next to capex savings extra margins will be made from the efficiency increase by 4.7%. The improved efficiency at a scale three micro-plant is responsible for an aditional 391kg methanol production in its lifetime. If ZEF would sell the methanol for €350/ton to sub-contractors, then €136 turnover can be gained over the micro-plant's operational period.

MICRO-PLANT COSTS PER TON METHANOL

The capex savings and opex extra turnover cause lower costs per ton methanol.

The variable costs at **scale three** including the efficiency increasy are lowered to €41 per ton methanol. This would result in a micro-plant costs of €124 per ton methanol. Compared to scale one this offers a saving of about **€71 per ton methanol.**

SYSTEM SCALING THREE, 900W, capex costs

TOTAL COSTS **€ 700**

FROM 3 TIMES SCALE 1, €270 X 3 = €810. CAPEX SAVINGS: €110

DISCUSSION

NOT CONSIDERED ELEMENTS

This scaling analysis points out to have a more optimal sizing at a scaling factor of two up to four. Not considered is the impact of the costs of maintenance. Too little information is available to make a sound estimation on maintenance costs at different scales. The regular maintenance will decrease in costs as less devices need to be maintained, but the replacement costs will increase when several employees are needed to de-install and carry the micro-plant.

The additional costs for the first methanol micro-plant are considered in the calculations. However, when multiple farms are installed, these costs will be neglectable and scaling becomes even more profitable.

Interest rates are not considered in these calculations. Generally, in order to decrease the effects of interest it would be beneficial to keep the investment low.

Possibly, the plant layout will be more complicated as the solar panel configuration needs to embed three solar panels. Generally, three solar panel configurations are common.

DATA ACCURATENESS

The costs and technical behaviour per subsystem are formulated in a personal discussion between the designer and Van Kranendonk. Most likely, this qualitative approach is decent for defining general cost curves and system boundaries, but it is hard to assign accurate cost values per scaling size. More extensive research per component is needed for more accurate system sizing elaborations. This research could be conducted by ZEF in the future, when more data is available regarding the subsystem designs. At that stage also intermediate system scaling sizes like '2.5' could be researched.

SAFETY

The safety (regulations) factor is only superficially considered in this analysis. However, safety could turn out to be a major determinant for system scaling potential. For now, a maximum scaling of four is chosen for systems with a pressure of 50bar to avoid the need of safety control employees. More extensive research on legislations may point to a different maximum scaling.

SAVINGS AT SCALE THREE PER TON METHANOL

(€/ton MeOH at scale three minus €/ton MeOH at scale one)

START-UP TIME	**MINUS**	€4.-
SAFETY		-
ASSEMBLY		**€17.-**
FIRST FARM	**MINUS**	€2,-
INSTALLATION		€0.-
EFFICIENCY		**€28.-**
MS		€7.-
COMPRESSOR		€4.-
DAC		€5.-
DS		€7.-
AEC		€4.-
INTEGRATION		€5.-

SYSTEM SCALING THREE, 900W

COST SAVINGS PER TON METHANOL **€ 71**

COMPARED TO SCALE 1

4.
CONFIGURATION ARCHITECTURE

INTRODUCTION

In the previous chapter a system scaling of one micro-plant per three solar panels appeared to be optimal for the methanol micro-plant. The way the subsystems are organised and related to each other determines the overall quality of the micro-plant. The product architecture must optimise the material flows, pressure relations, spatial requirements between components and heat integration. These together will optimise the system efficiency and thereby costs per kilogram methanol.

In this chapter the defined program of demands was used as boundary conditions to search for the subsystem's most promising configurations. System configuration ideation sessions were done and followed by conceptualisation steps. In this phase a high number of iterations were conducted to find a promising architecture design.

SUBSYSTEM DEFINITION

The subsystem division as formulated in Chapter 2, System Definition, Subsystem Division, is used for the configuration architecture research. The only difference is that the degasser is incorporated in the electrolysis system. This decision is made as it appears certain that these two systems will be located within the same pressure casing.

SOLAR CONNECTION SYSTEM

The way the micro-plant is connected to the solar panel influences the needed product architecture. For different racking systems, different types of connections and micro-plant architectures would be most suitable (figure 4.1). The ZEF solar farms will be standing on the ground. For this reason, roof and canopy structures are outside the scope. Two main types of ground based solar mounting systems are: single posed and double posed mountings (figure 4.2). For both types there are many variations in shape and material.

ORIENTATIONS

The angle and height of the solar panel mainly determines whether there is space available to connect a methanol micro-plant to the racking system. Generally, the panels are lifted from the ground, but the distances from the solar panels to the ground and the orientation angles vary. There are also solar panels with a solar tracking system (single, or double axis), that move over the day. For different locations different types of racking systems will be used.

MICRO-PLANT CONNECTION DESIGN

As the ZEF solar farms racking systems are not defined yet and will likely differ per farm. For each racking type a different micro-plant design could be made, or one single design should be adaptable for the different solar systems. The second option is favourable as there are no product variations

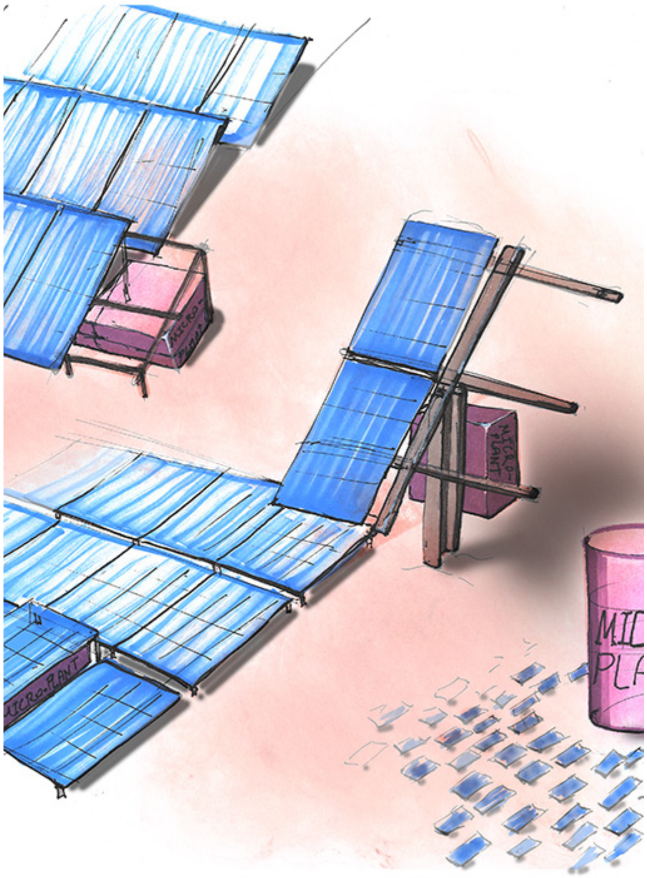


Figure 4.1, different types of connections and micro-plant architectures

Figure 4.2, Ground mountings. Double posed mountings (left) and single posed mountings (right)

needed.

The micro-plant design should support the implementation below a single, or double posed racking system. As suggested by Picarelli (2018) mounting the micro-plant to the longitudinal axis of the racking system is most favourable, as it vertically supports the micro-plant. Thereby, a connection to the longitudinal axis will be most sturdy, as the lowest momentum is created by the micro-plant's mass, compared to connections to horizontal, or diagonal beams. In the scenario that there is no space to attach the micro-plant to the longitudinal axis, the micro-plant will be located as a self-standing system next to the solar panels. This system must stand straight on the floor as the micro-plant's subsystems rely on orientation. Figure 4.3 shows an overview of the micro-plant's connection methods.

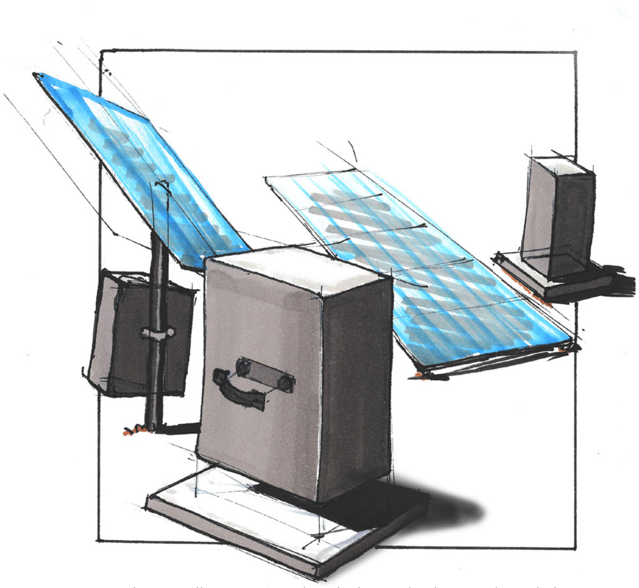


Figure 4.3, Micro-plant installation: mounted on the longitudinal axis and stand alone

SOLAR HEAT INTEGRATION

One may argue that either at large, or at small scale it would be efficient to include heat transfer from the solar panels to the micro-plant. However, the outdoor temperature will be at most around 45°C. and the lowest heating temperature needed within the micro-plant system is over a hundred degrees. For this reason, there are little power savings on heating to be achieved by solar heat integration. It will be more efficient to transfer the 90°C excess heat from the electrolysis system to the other systems.

Solarus

An interesting alternative could be to implement a Solarus' PowerCollector instead of regular solar panels (figure 4.4). These PowerCollectors create heat and electricity. There are both solar panels facing upwards and downwards. The downward facing solar panels receive light from the installed mirrors. Water flows through the double paned solar panels. This way the panels are cooled and can work with an efficiency that is up to 40% higher. through this heated water is obtained. This heated water can get a temperature of 80 up to 90 degrees Celsius (Brinkman, 2018). The system has a peak electrical power of 270W and a peak heating power of 1350W (Solarus, 2018).

For the micro-plant most of the energy needs to be electrical, for the electrolysis. With a PowerCollector an overload of heating energy would be created, which would make the system inefficient. An option would be to have one PowerCollector combined with several regular solar panels. However, this would cause the system complexity to increase.

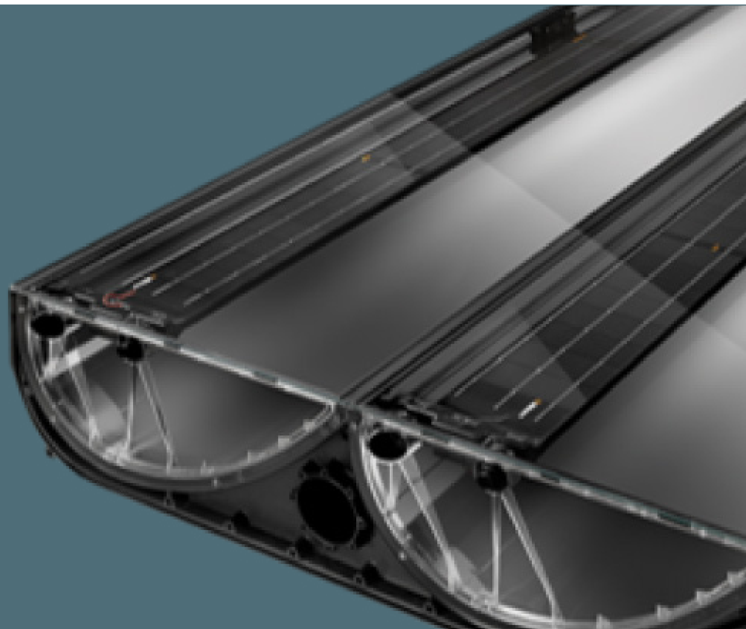


Figure 4.4, Solarus solar system

SUBSYSTEM DIMENSIONING

As the micro-plant will be dimensioned to deliver three times the yield of the original sizing, all subsystems also need to handle three times the amount of material flow. The effects on dimensioning differ per system and are analysed with the maple system model (appendix D). The results from this section can be found in appendix 2C.

COLLAGE

A collage was made as a source of inspiration for the configuration architecture.

Figure 4.5, Collage for product architecture

CONFIGURATION ARCHITECTURE DEMANDS

The program of demands (appendix E) embeds all demands that should be considered for an integrated methanol micro-plant design. From these, the configuration demands are defined below and shown in figure 4.5.

- The **absorption chamber** needs to be oriented **vertically**, as gravitational forces direct the sorbent flow;
- The **desorption** system must be **below the absorption** chamber, gravitational flow;
- The **desorption and DS** systems must be close to and **above the electrolyzer**, as a heat pipe transfers the electrolyzer's heat to the desorption and DS;
- The **compressor tubes** must be oriented **vertically**;
- The **Compressor inlet** must be positioned **below**, or on similar height as the **desorption** tube’s outlet, to direct fluid flow;
- The **Compressor's** first and last stage should be **near the desorption** chamber;
- The **CO_2 and H_2O buffer** needs to be located **below the compressor's outlet**;
- The **CO_2 and H_2O buffer** needs to be **above the electrolyzer**, to direct the water flow;
- The **Electrolyzer** needs to be oriented **horizontally**, as gases need to go to the top of the chamber;
- The **MS** system needs to be **tilted** a few degrees so that condensed gases move downwards by gravitational forces;
- The **DS tube** must be oriented **horizontally** for the capillary flow, and the DS blocks must be on similar height;
- The **micro-plant** must be connected to the **longitudinal beam** of the solar panel.

INSULATION

Thermal efficiency is key for the overall efficiency of the micro-plant. Therefore, certain systems need to be insulated, while other parts need to be cooled. Figure 4.6 shows which area's should be insulated.

Insulation needed	**Cooled (by environmental temperatures)**
Desorption system	Absorption chamber
Electrolyzer	Compressor
Hot part MS	Cold side MS (after last heat exchange stage)
DS tube and hot block (H_2O side)	DS block (methanol side)

Note

In appendix H the subsystem relations regarding material flow, pressure and heat are shown in design system matrices. These matrices helped to create a system understanding and to define integration demands.

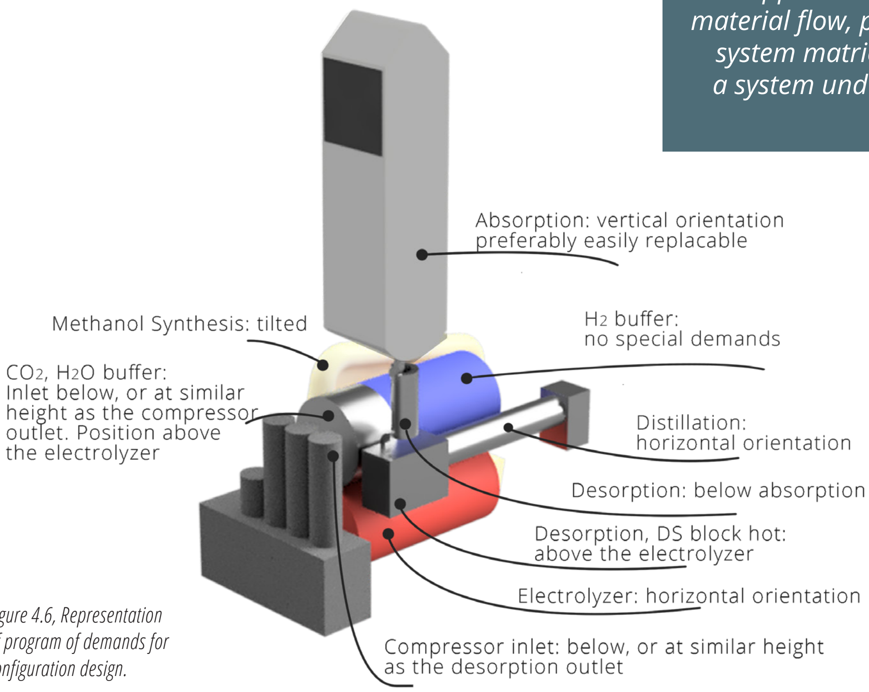


Figure 4.6, Representation of program of demands for configuration design.

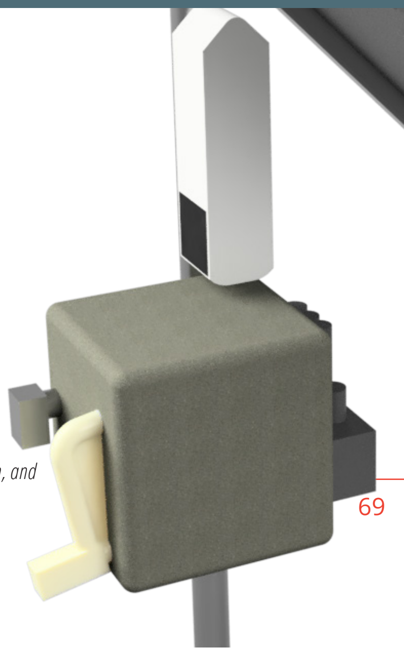


Figure 4.7, systems in, and outside insulation

IDEATION

Several ideation methods and tools are used to discover potential methanol micro-plant configurations. On these pages some of this ideation process is shown.

Primarily methods such as ideation claying, drawing and computer modelling were used. The level of detail dependeds on the aimed goal of the ideation. Generally, the designs went from rough to more detailed.

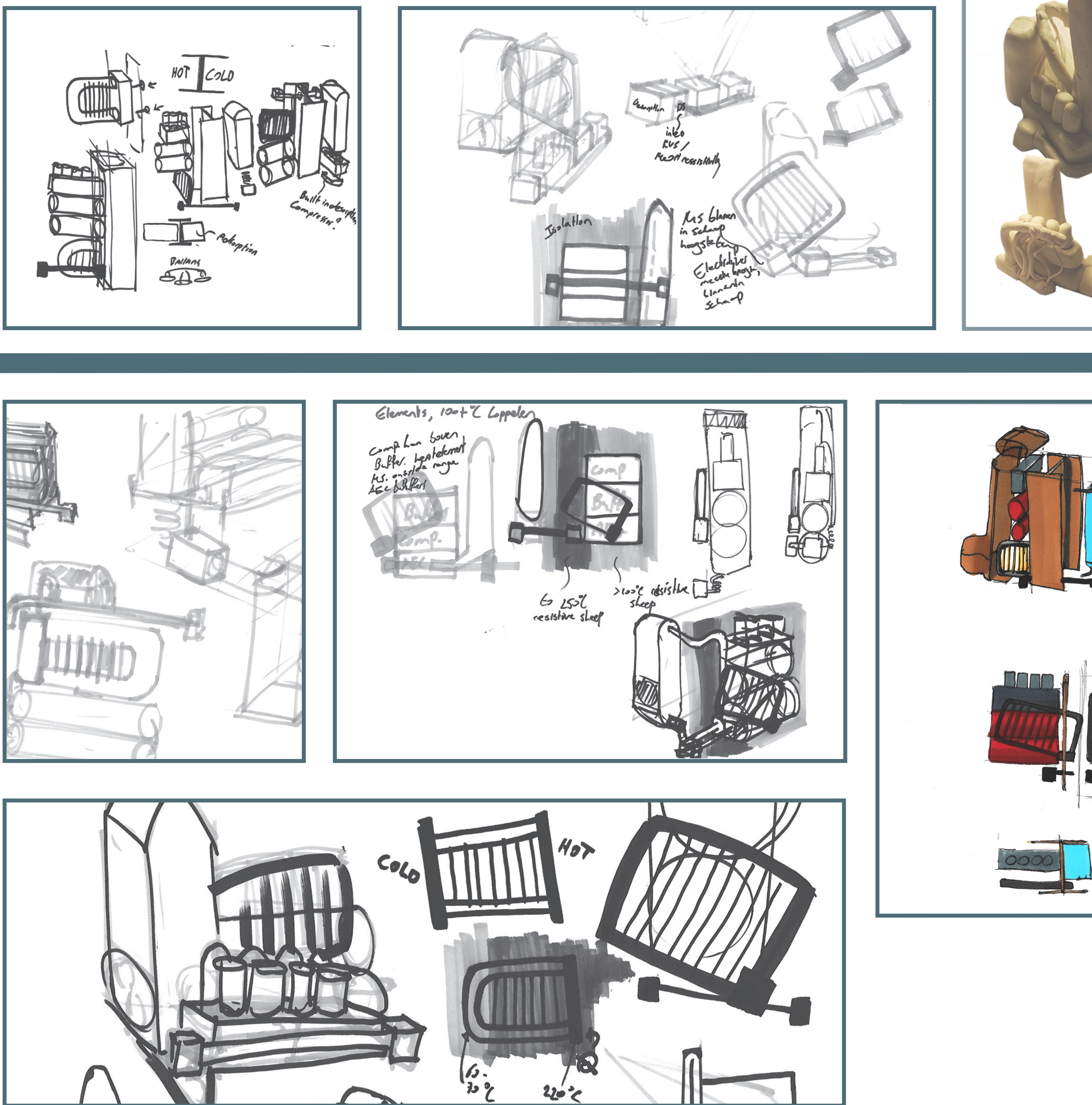
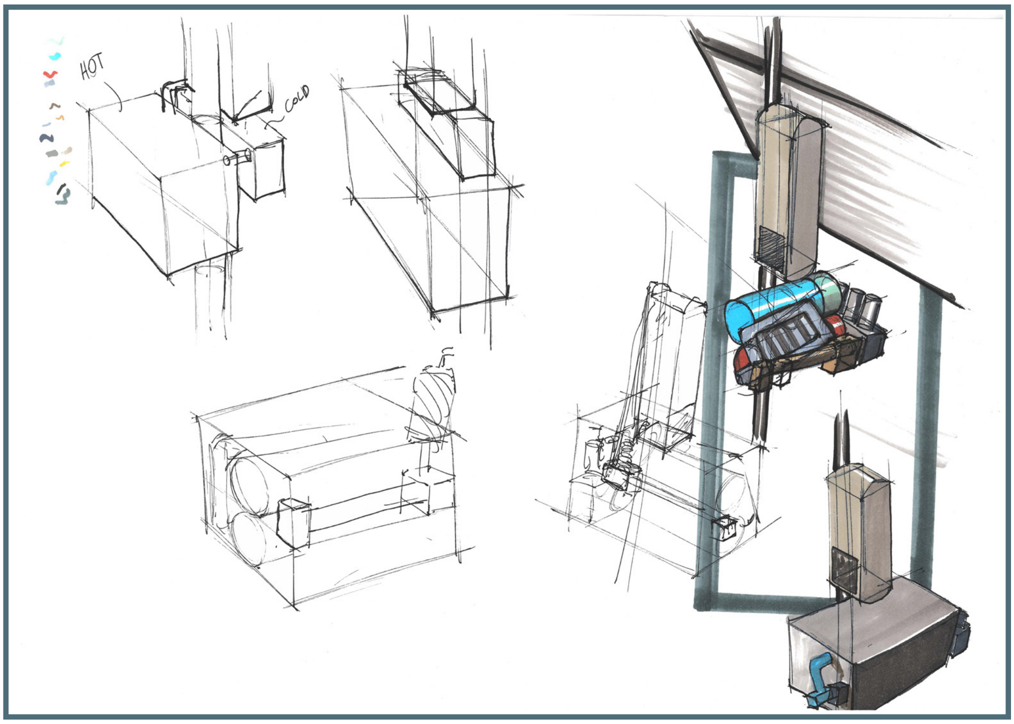
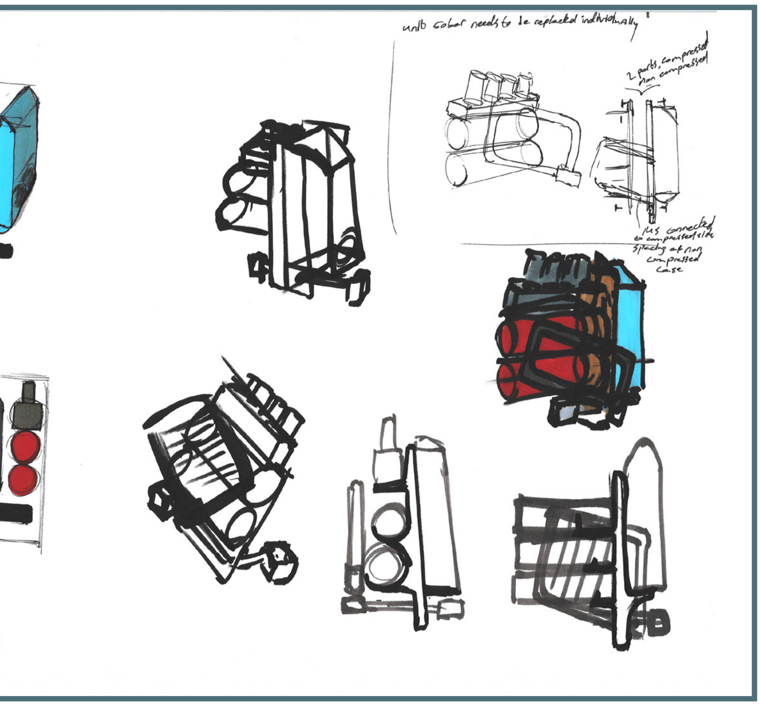
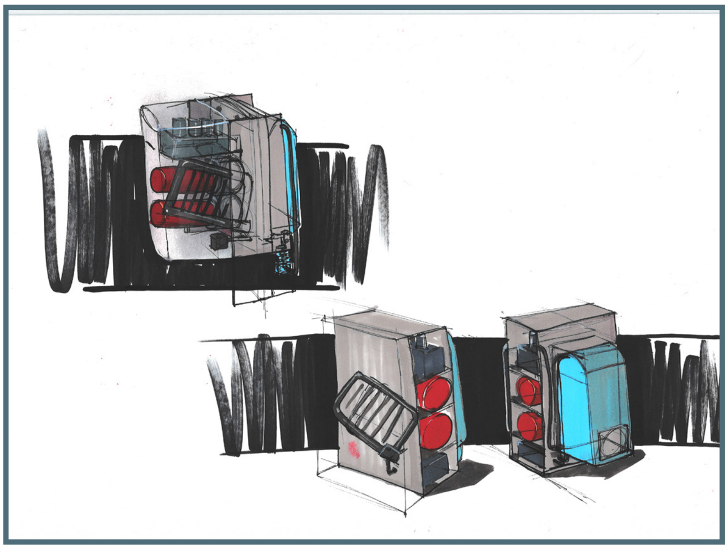


Figure 4.8, Ideation


HOT
COLD


needs to be replaced individually
2 parts, compressed
non compressed
spacing of non
compressed
case



COMPUTER AIDED DESIGN (CAD)

CAD program Fusion 360 was used for the 3D modelling of configuration and architecture ideas and concepts. Figure 4.9 shows some of the concept development over time. After each iteration the designs were examined on 'pros and cons' and a new iteration round started. Some of these comments are stated within the figure. The iteration rounds resulted in several concepts. These were further evaluated and compared.

In the figure the pros written in green and the cons are written in red. The model evaluations are presented in chronological order from left to right

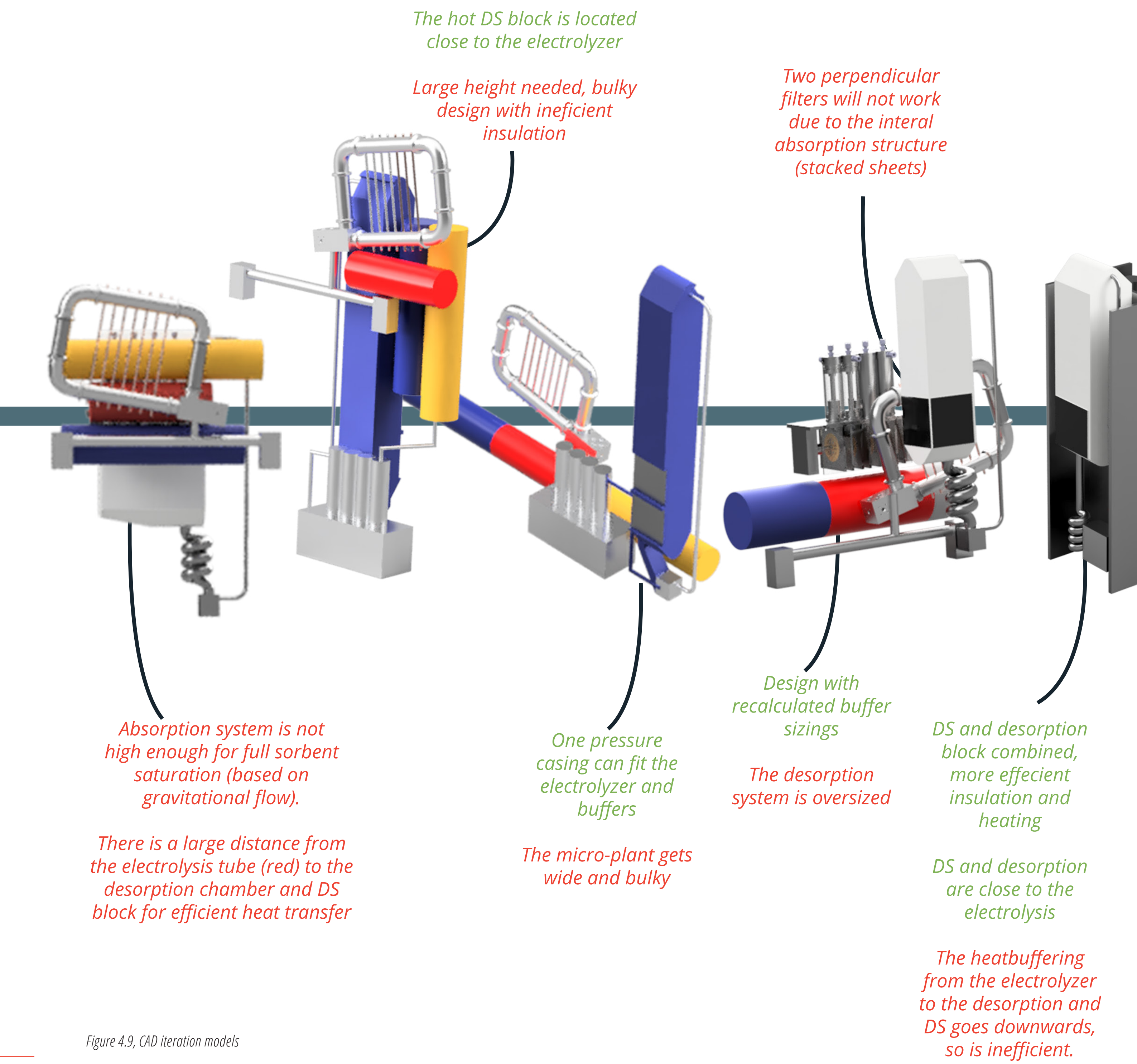


Figure 4.9, CAD iteration models

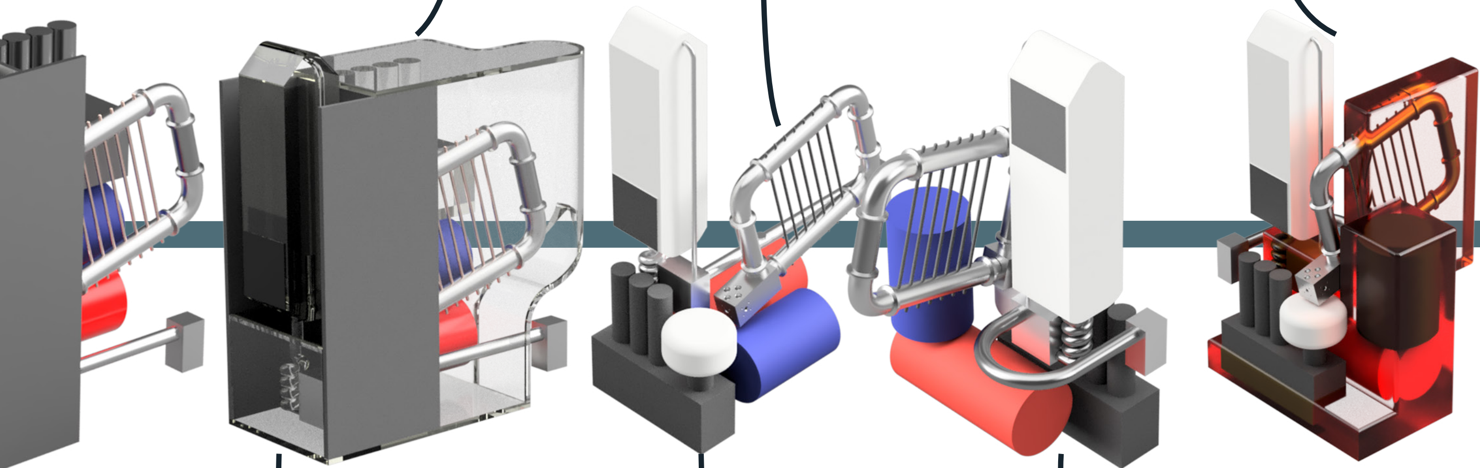
The concepts presented are to analyse the expected effects of different configurations. The structural embodiment will be designed in the next steps. Note

The compressor should be cooled by outside temperatures and needs to located below the desorption system, as there is gravitational fluid flow

The DS pipe is next to the MS system. Undesired heat transfer may occur

Possible casing design. The design is vulnerable with its' many casing corner pieces

The CO_2 buffer is close to the MS inlet



Solid, but bulky and massive design. The casing is oversized

The CO_2 buffer is located on top of the compressor's last stage (here there is no need for a cooling stage)

Curved DS pipe for a more compact design

The subsystems are so close to each other that there is no space for insulation

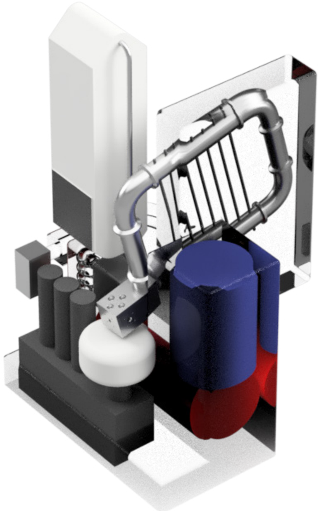


Figure 4.10, Concept 1

Figure 4.11, Concept 1

Figure 4.12, concept 1, scenario

CONCEPT 1, FEEL THE HEAT

INTRODUCTION

This configuration concept was mainly based on the needed heat buffering. The electrolyzer is the lowest system in the configuration. From there, heat pipes buffer the heat towards the desorption and distillation systems. The desorption and distillation systems are combined within one block to minimise the heat loss.

CHARACTERISTICS

- All subsystems fit within one casing;
- The parts that need cooling are exposed to the outside air;
- The CO_2/H_2O buffer is on top of the compressor;
- The H_2 buffer is standing on top of the electrolyzer;
- The electrolyzer heat transfer moves upwards.

EXPECTED PROS

- The MS block is near the two buffers, piping is minimal here;
- The micro-plant can easily be assembled as most components are inside one casing;
- The absorption chamber is not fixed to the casing and may be replaced easily;
- The coiled desorption chamber decreases the needed height, therefore the electrolyses can be placed below;
- The heat pipe from the electrolyzer moves upwards towards the D, and desorption.

EXPECTED CONS

- MS points relatively far backwards, this may hinder at the installation;
- The casing does not fully match the components, too much space is used and insulation is not applied efficiently.

CONCEPT 2, ONE TUBE

INTRODUCTION

Decreasing the micro-plant system complexity will likely be coherent with the concept's viability. In this concept, 'One tube', the buffers are located in front of and behind the electrolyzer. This way fewer parts are needed, as only one pressure casing is used. The tubing system itself will also increase in firmness as all connections are inside the tube. On the other hand, this may cause a more complicated internal assembly. To minimise the momentum on the solar pole, the subsystems are located on different sides of it. Although this concept was aimed at creating uniformity and extra firmness, besides the pressure casing the subsystems do not have a solid structure.

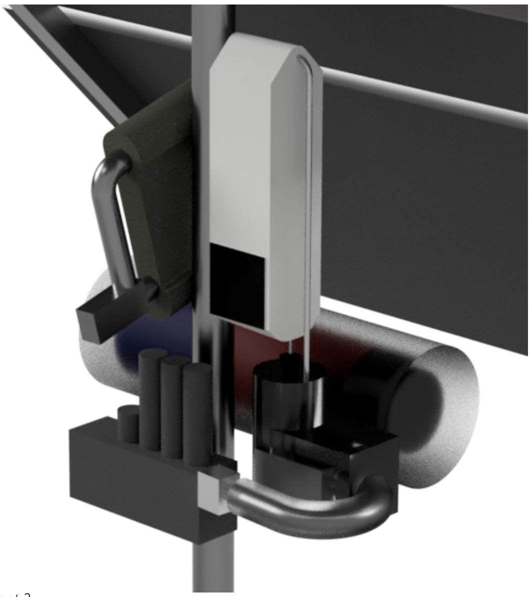


Figure 4.13, Concept 2

CHARACTERISTICS

- The electrolyzer and the two buffers are combined within one pressure casing and insulation tube;
- The DS block and desorption block are combined;
- The absorption, the desorption and DS, the compressor, the buffers and electrolysers and MS can be shipped separately. The assembly will be done at the installation phase. The subsystems are separately connected to the vertical solar beam;
- The desorption chamber consists of a straight tube.

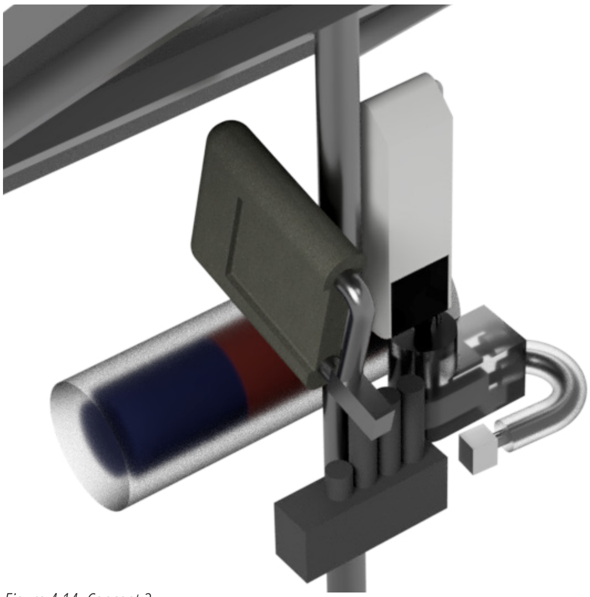


Figure 4.14, Concept 2

EXPECTED PROS

- The insulation shape exactly matches the subsystems' needs;
- No weight bearing construction is needed between the several subcomponents.

EXPECTED CONS

- Large distance between the buffers and the MS;
- The tube is wide and therefore there is a relatively large momentum;
- The on site installation will be time consuming and thereby costly;
- Tubing between the subsystems need separate insulation;
- The heat pipe from the electrolyzer needs to go through the pressure casing.

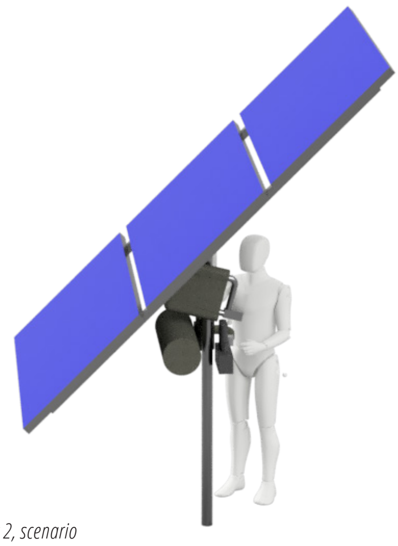


Figure 4.15, concept 2, scenario

CONCEPT 3, FIT AND FIRM

Figure 4.16, Concept 3

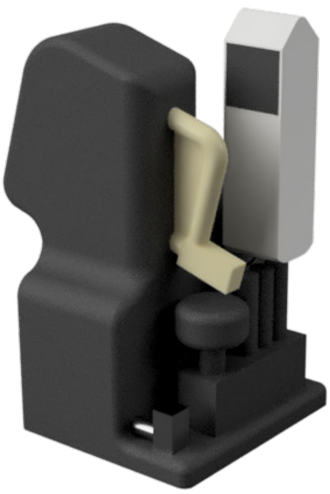


Figure 4.17, Concept 3

Figure 4.18, concept 3, scenario

INTRODUCTION

Contrarily to the previous concepts, this concept was designed to think of a more uniform configuration design. The hydrogen buffer was located on top of the electrolyzer, the MS was relocated to the side of the two buffers and a better fitting casing design direction was developed. The micro-plant's casing will envelop the solar pole for extra structural firmness.

CHARACTERISTICS

- All subsystems are fit within one casing;
- The desorption chamber consists of a straight tube;
- The hydrogen buffer is laying on top of the electrolyzer;
- Part of the micro-plant is in front of the construction tube and a part is behind the tube. The micro-plant envelops the pole;

EXPECTED PROS

- The micro-plant design is compact;
- Most systems are within the casing, creating a kind of firmness;
- The absorption chamber can be disassembled individually;
- The insulation is applied where needed;
- The design is balanced on the front and back side of the vertical construction tube;
- The fan cools the MS system.

EXPECTED CONS

- The heat pipe from the electrolyzer goes downwards to the DS and desorption block;
- It will be hard to dissipate heat from the heat pipe to the straight desorption tube.

CONCEPT EVALUATION

The concepts are compared on several aspects to determine which one bears most potential to continue with. A Harris profile (figure 4.19) is used to visually represent the concepts' outcomes on the different aspects. The attributes are ordered from the top down on relevance, so that the first attribute is most important and the lowest one is least important.

Configuration concept comparison attributes

1 **Weight:** The foreseeable micro plant embodiment is low in weight;
2 **Firmness:** The configuration design is firm and can survive extreme weather;
3 **Insulation:** The configuration supports efficient insulation and cooling;
4 **Heat buffer:** The heat pipe length from the electrolyzer to the desorption moves upwards and is small;
5 **Connections:** The configuration will likely support efficient subsystem connections (tubing, wiring, bearing structure);
6 **Assembly:** The configuration will likely be easy to assemble and install;
7 **Maintenance:** The configuration will likely be easy to disassemble or repaired.

Note *A 'Harris Profile' is used to evaluate the different concepts. Here the designs are qualitatively reviewed on the mentioned attributes. Next they are ranked from '- -', very bad, to '++', very good on a four point scale.*

Feel the Heat

Concept 1	--	-	+	++
Weight			■	
Firmness			■	
Insulation		■		
Heat buffer			■	■
Connections			■	
Assembly			■	
Maintenance			■	

One Tube

Concept 2	--	-	+	++
Weight			■	
Firmness		■		
Insulation		■		
Heat buffer		■		
Connections	■	■		
Assembly		■		
Maintenance			■	

Fit and firm

Concept 3	--	-	+	++
Weight			■	
Firmness			■	■
Insulation			■	
Heat buffer		■		
Connections			■	
Assembly			■	
Maintenance			■	

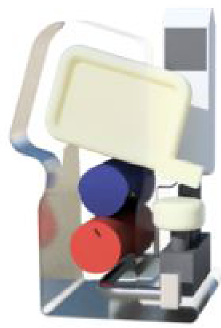


Figure 4.19, Harris Profile

FINDINGS

In the Harris Profile concept one and three are leaning in the positive direction, concept two leans in the negative direction. Concept one and three have several configuration similarities. However, concept one scores better on heat buffering as the desorption chamber is coiled and the heat pipe can move upwards from the electrolyzer to the DS and desorption block. Concept three's casing is better shaped to the subsystems and therefore has a more efficient insulation. The compact design of concept three, will also likely be firmer.

Concept two will not be favourable. It will be troublesome to direct the wiring and tubes between the separated subsystems, as there is no real casing. This makes the product less firm, may cause insulation difficulties, and installation will be more troublesome as all parts are installed separately.

An observed benefit of concept two is that the CO_2/H_2O buffer is installed within the pressure casing, next to the hydrogen buffer and electrolyzer. In concept one and three a separate buffer tank is used on top of the compressor. Likely a separate buffer tank will be somewhat more expensive as it needs separate insulation and additional unique parts. This buffer could be located next to the hydrogen buffer. The compressor's length can decrease a few centimetres when the buffer is separated.

In all concepts the MS is located on top of the other subsystems. This way the MS requires almost a complete own casing and insulation. A better configuration design must be found.

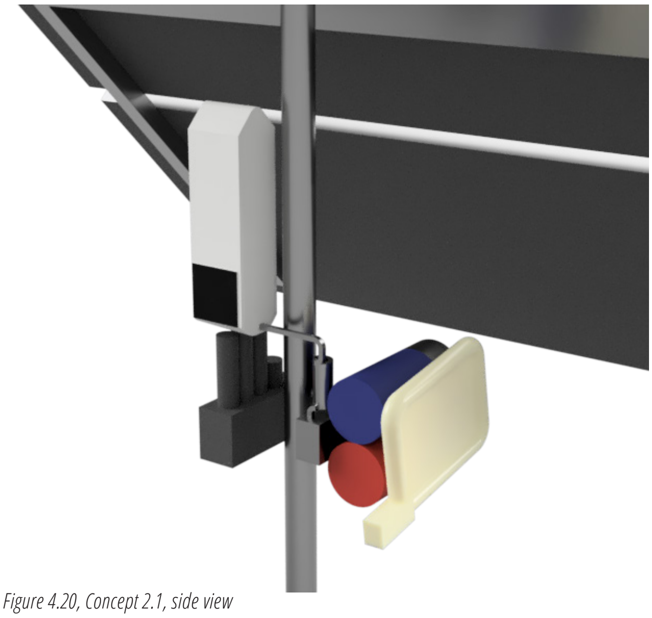


Figure 4.20, Concept 2.1, side view

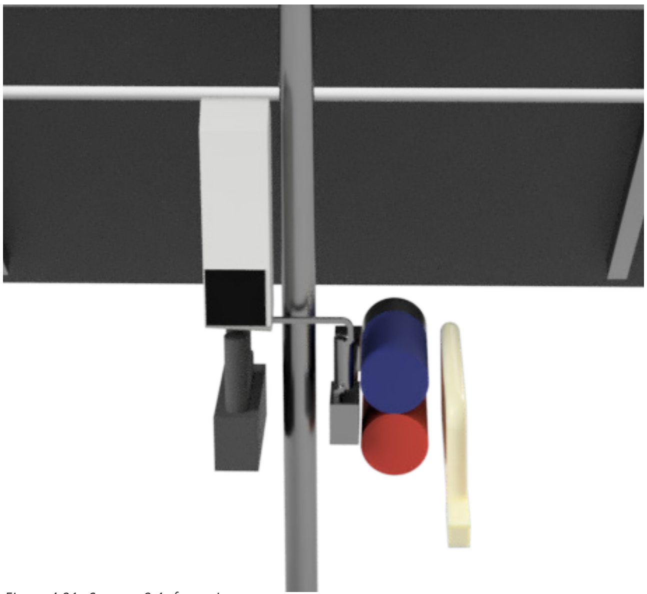


Figure 4.21, Concept 2.1, front view

Figure 4.22, concept 2.1, scenario

CONFIGURATION CONCEPT ITERATION

None of the discussed concepts were fully satisfactory. Therefore, next iterations were performed based on these findings. From the new designs two potential configurations concepts were chosen. In both new concepts some modifications were made similarly:

- The CO_2 buffer was located next to the H_2 buffer, for more efficient insulation and a more compact design;
- The desorption chamber was coiled with a square section, which creates a large contact area with the heat pipe
- The DS tube was chosen to be straight, the simplest and thereby cheapest option;
- The heated DS block was moved to similar height as the electrolyzer, so that the heat pipe would not need to transfer heat downwards;
- The MS system is located next to the pressure casings, so that insulation can be shared;

CONCEPT 2.1, HOT AND COLD

INTRODUCTION

This concept is an iteration of concept 3, ‘Fit and Firm’. The previously mentioned modifications were applied, and this concept was designed to separate the mainly heated and cooled systems on two sides of the solar pole. This way the masses also became better balanced. The absorption, the compressor and the casing with the other systems can be firmly connected to the longitudinal pole.

CHARACTERISTICS

- The compressor and absorption chamber are on one side of the installation pole, the other subsystems on the other side;
- During installation the main body and absorption chamber will be installed separately. Subsequently the tubing is installed;
- The MS and DS cold sides are both on the opposite sites.

EXPECTED PROS

- The masses can be balanced on both sides of the pole;
- The absorption chamber and compressor are far away from the heated elements;

EXPECTED CONS

- During the installation phase the main body, the compressor and the absorption need to be assembled individually;
- There will be several tubes outside the casings (more vulnerable).

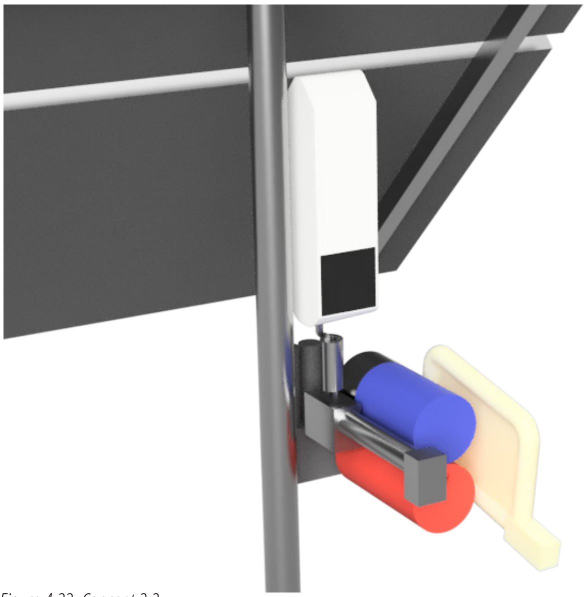


Figure 4.23, Concept 2.2

CONCEPT 2.2, ONE BOX

INTRODUCTION

This concept is mainly an iteration of concept 1, 'Feel the Heat'. All subsystems are installed inside or connected to the outside of a solid casing. This casing will be connected to one side of the solar pole. As all systems fit one casing, the installation at solar fields will require less time, tubing outside the casing is minimised and therefore the micro-plant is less likely to be damaged.

Note — *As the micro-plant hangs on one side of the solar pole, the masses are not balanced. As assumed this will not be a problem for the structural solar pole. To clarify, three 300W solar panels weigh about 70kg and the methanol micro-plant weighs less than 50kg. The forces applied on the pole during a storm by the solar panels will be much higher than those applied by the micro-plant, as the panels catch way more wind.*

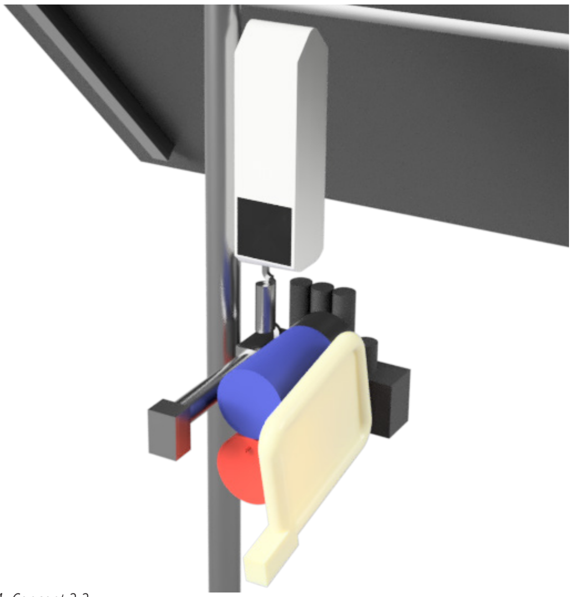


Figure 4.24, Concept 2.2

CHARACTERISTICS

- All systems except the absorption are together within one casing;
- The micro-plant assembly can completely happen within the factory;
- The system is installed as one unit.

EXPECTED PROS

- The micro-plant can easily be assembled and disassembled;
- The desorption block is very close to the buffer and compressor;
- The design is compact.

EXPECTED CONS

- There is a large distance from the MS block to the DS block;
- All weight is on one side of the connection pole.

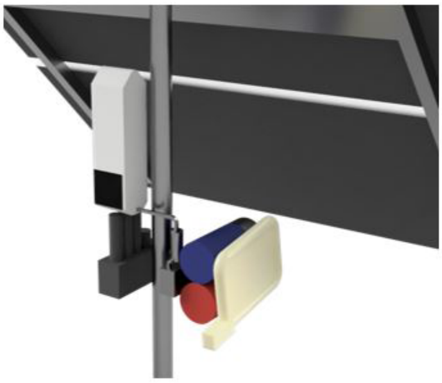

Figure 4.25, concept 2.2, scenario

2. CONCEPT EVALUATION

The Harris profiles (figure 4.26) display that concept 2.2 is likely favourable over concept 2.1. In most cases the base construction of solar panels is sturdy enough to hold the weight. Therefore, separating several components will only further complicate the design, likely cause a less firm construction, cause the installation to take longer and there will be more tubing and wiring outside the main casing.

Hot and cold

Concept 2.1	--	-	+	++
Weight			■	■
Firmness		■		
Insulation		■		
Heat buffer			■	■
Connections		■		
Assembly		■		
Maintenance		■		



One box

Concept 2.2	--	-	+	++
Weight			■	
Firmness			■	■
Insulation			■	■
Heat buffer			■	■
Connections			■	
Assembly			■	■
Maintenance			■	

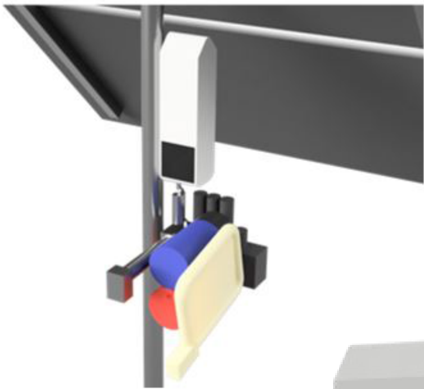


Figure 4.26, Harris Profile of the second concept iteration round

Note

As stated at 'Solar connection system' the micro-plant must be able to be installed as a stand alone unit, or connected to the longitudinal pole of the solar racking system. When functioning as a stand alone unit, the micro-plant can be connected to a detached longitudinal pole to ensure the needed orientation.

Figure 2.27, Micro-plant design as a stand alone unit.

5.
CONCEPT EMBODIMENT

INTRODUCTION

The previous chapter concluded with an integrated configuration design concept. Based on this configuration design concept a scale 1:20 demonstration prototype was made (figure 5.1). In this chapter the subsystems are further elaborated, resulting in conceptual product designs.

In appendix 2D the subsystem embodiment process and designs are presented. This subsystem embodiment design stage served to implement ZEF's newest technology, the designer's insights and the needed scaling in the subsystems. These subsystem designs are used for the development of a 1:1 prototype. The main dimensions of the micro-plant are presented in figure 5.2. In the next chapter, based on these designs, a final cost analysis is conducted.

This chapter finnishes with some thoughts and explorations on what a ZEF methanol farm will look like and how each micro-plant could contribute to a large methanol yield and possibly fresh water supply.

Figure 5.1, 3D printed configuration prototype considering the integration architecture

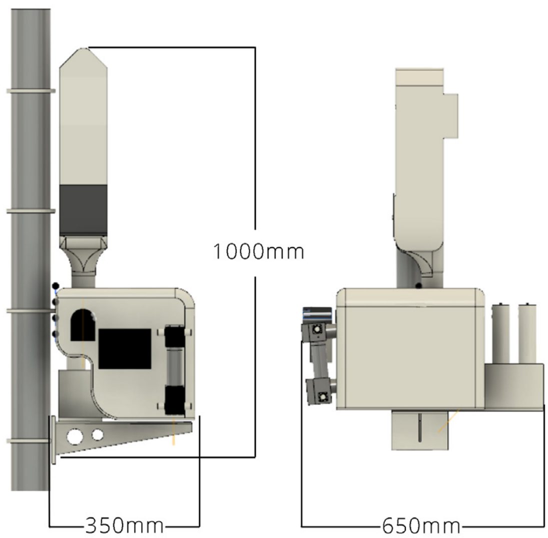


Figure 5.2, Micro-plant main dimensions

INTEGRATION PROTOTYPE

The basic subsystem embodiment designs for the 900W micro-plant were prototyped on a scale 1:1. This prototype is mainly intended to communicate the system's sizing, design and architecture. This prototype does not function as a methanol reactor.

WIRING

In appendix I the number of needed wires was defined per subsystem and component. However, the number of wires can differentiate, as for example the ground cables could be interlinked. In the integration prototype the wires aim to visualise the wiring logistics from the subsystems to the control chamber. The number of wires per subsystem will be higher in functional designs.

> *The main goal of the integration prototype is to bring the 900W methanol micro-plant to reality. The real sized model is aimed to inspire, teach and communicate the micro-plants integration design.*

PROTOTYPE PURPOSES

- Facilitate the creation of a system understanding: create an understanding of the 900-watt methanol micro-plant design. A real size model is more comprehensible than a CAD model and hand drawings;
- Bridge the gap from subsystem to system: the integration prototype can be used to create an understanding of how subsystems fit within in the complete micro-plant. This relates to the needed tubing, wiring and architecture;
- Validate the made integration design decisions: Building the integration design prototype will likely create findings regarding the integration quality of the set design and future design improvements could be formulated.

APPROACH

The 900W micro-plant's integration design is attached to a two meters high solar pole. The three 2x1m solar panels are not added.

It is important that the subsystem architecture is visible. Therefore, the micro-plant's casing is not embedded in the prototype. The subsystems are attached in a transparent plate and connected with steel tubing. The subsystems were mainly made from foam, polymer tubes and PLA 3D prints. Some purchase components are directly implemented in the prototype to increase the accurateness.

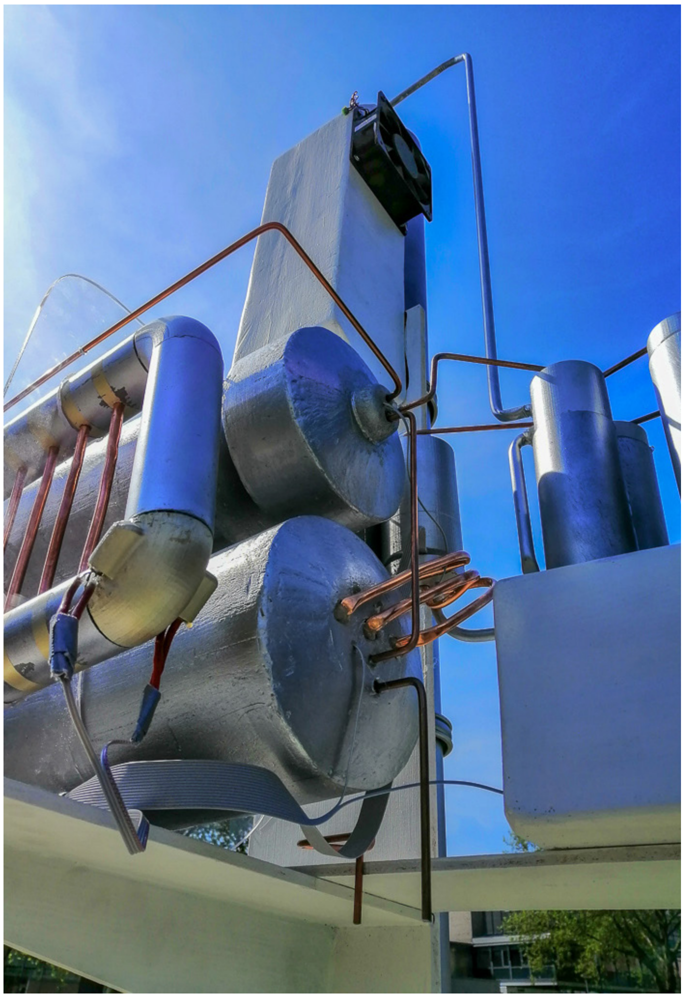
TUBING

The subsystems are inter connected with 4mm steel tubes / rods. These tubes show how the material flows are directed through the micro-plant.

Figure 5.3, Prototyping process pictures

RESULT, PROTOTYPE IMAGES



RESULTS

The main goal of the prototype was to **inspire**, **teach** and **communicate** the working principle of the 900W micro-plant. The quotes presented on this page demonstrate the prototypes reception and confirm that the prototype serves its aimed functions.

Since the prototype is in the office it is directly used for introducing new ZEF members to the micro-plant's subsystems and technology. For the ZEF entrepreneurs and team members the prototype supports to create a system understanding. With this prototype, the methanol micro-plant is no longer merely an idea. This prototype visualises the direction ZEF is heading for.

DESIGN INSIGHTS FROM PROTOTYPING

Designing and manufacturing the integration prototype delivered some insights that should be incorporated in future designs.

- The connection between the micro-plant and the solar beam needs to be solid. The previously suggested hose clamps may not be sound enough. A tube clamp, or saddle clamp needs to be used for the connection;
- The water and carbon-dioxide buffer, or electrolyzer needs to have a valve to control the water input for electrolysis;
- In the prototype the bended heat pipes from the electrolyzer to the desorption and distillation systems happened to kink. Heat pipes have large minimal bending angles with their thin wall thicknesses. This needs to be considered in future integration designs.
- The wiring from the MS valves hang outside the casing and therefore become vulnerable. Future integration designs should include a more sound wire management.

> *"After two years it is finally here, the complete scale 1:1 micro-plant design." (J. van Kranendonk)*

> *"This morning I sent a picture to my girlfriend, now she can finally see what I'm actually working on." (U. Starke)*

> *"Now I get a way better feeling of the sizing, than from the analysis on paper" (H. Jongebreur)*

> *"That device eases my life so much" (U. Starke, after explaining the system to a potential ZEF member)*

> *"Now we know what we are working on" (ZEF team 4 member)*

ZEF PLANT DESIGN

All previously conducted architecture and embodiment research was scoped at individual micro-plants. Each micro-plant is connected to three solar panels in a solar farm of about 40.000 solar panels. The methanol outputs need to be brought together for collection and there is the water output as by-product from methanol production. In this section the scope is enlarged from the micro-plant to an entire solar farm. Some methanol farm design suggestions are named.

Note The meta design of the ZEF farm is generally outside the scope of this report. Regardless, it is insightfull to share a glance on the future implementation of the product and to consider the implementation context.

FARM CONTROL AND MAINTENANCE

The micro-plant's operation data needs to be measured within each micro-plant, as each plant operates individually. This information could be transferred to a central computer either wirelessly or by a wired connection. If an operation error occurs at a micro-plant, then this will be noticed to the operation manager and the specific micro-plant can be checked for the needed maintenance, or repair. Malfunctioning micro-plants can be turned off on the spot and either some small repairs can be done in the field, or the micro-plant is replaced and the broken one sent to a repair centre.

A second control option would be to keep the monitoring local per micro-plant. An error light could start blinking on the control chamber of the plant, when problems occur. In this scenario the farm operator would need to check the micro-plant's error lights periodically. For data management and control, central (wireless) communication will be favourable.

METHANOL OUTPUT.

Each 900W micro-plant produces about 750 millilitres (600g) of methanol daily. This means that one solar farm of 40.000 solar panels would produce about 10.000 litres of methanol daily. Tank trucks typically have a volume of 5.500 to 11.600 US gallons (Zidolider, 2019). This equals to at most 44.000 litres. Therefore, once every four or five days the methanol needs to be collected by a single large truck. For the solar farm, the methanol storage could be done in a tank of about 50.000 litres. The methanol output tube of each micro-plant could be directed to a larger connection tube, that subsequently leads to the storage tank (figure 5.4). The inter-micro-plant tubes could either be attached to the racking system, similarly to the cabling of a grid-connected solar farm, or laying on the ground surface.

WATER OUTPUT

Per methanol farm (40.000 solar panels), there will be a water output of about 4700 litres per day. This water is separated from the methanol in the distillation system. There are several usage possibilities for the water output:

1. The water is collected, processed and used for (urban) farming;
2. The water is collected, processed and used as drinking water;
3. The water can be used for automatically cleaning the solar panels;
4. The water can be dropped below the micro-plant as waste;

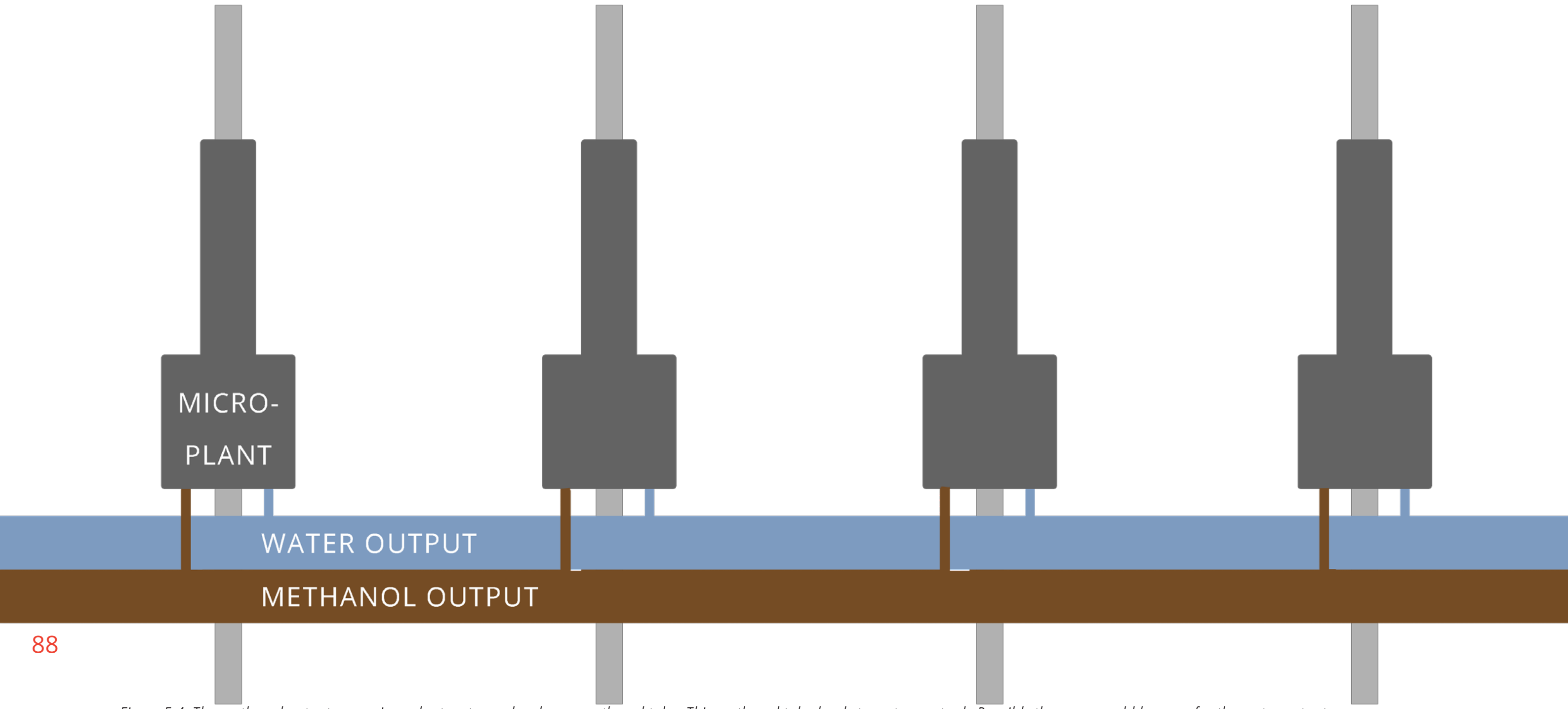


Figure 5.4, The methanol outputs per micro-plant go towards a larger methanol tube. This methanol tube leads to a storage tank. Possibly the same could happen for the water output

1: DRINKING AND IRRIGATION WATER

As the methanol solar farm will be located in dessert like areas with a lot of sun, water scarcity is likely a problem for the surrounding residents. ZEF's methanol farm could be a solution to this problem when its water output is made to drinking water or used for farming. According to the United Nations (2010) 50 litres of water is needed daily for personal usage to ensure most basic needs to be met. This includes drinking, cooking and personal hygiene. One methanol solar farm of 40.000 panels could provide about 90 residents with their daily water needs. When using the water for irrigation the farming potential depends on the grown crops and the farming practice type (e.g. urban farming can be more water efficient. Before the water output from the micro-plants can be used it needs some treatment.

2: WATER TREATMENT, DRINKING & IRRIGATION WATER

It is assumed that the water output from the distillation is almost pure water with a tiny bit of methanol pollution. The methanol can be separated by a biological active carbon filter. Likely a little bit of phosphate should be added to the water before passing the filter as nutrients for the biological filtering system. Also, nitrogen and oxygen should be available in the water. Oxygen can simply be added by exposure to the atmosphere. Costs of these types of water treatment should be low (Hofman, R., personal communication, November 2018).

3: SOLAR PANEL CLEANING WATER

The solar panels' efficiency drops when they are partly covered by dust. The water output per micro-pant could be used for cleaning its' three connected solar panels. To do this the water should be stored in a small tank and then once there is enough it could be released over the solar panels. The methanol solar farm's location determines whether solar panel cleaning is needed.

4: WATER AS WASTE

Dropping the water output below the micro-plant does not require additional tubing and costs. Therefore, this may be a favourable option in certain scenarios. The dropped water could cause grass and small plants to grow underneath the micro-plants.

CONCLUSION

The possible types of water usage in ZEF's methanol solar farms need to be further researched. A cost breakdown could show the potential of each scenario. The optimal water usage system is likely location specific (e.g. if there are no residents around the farm, then drinking water is no longer a potential option).

Figure 5.5, Possible ZEF methanol farm

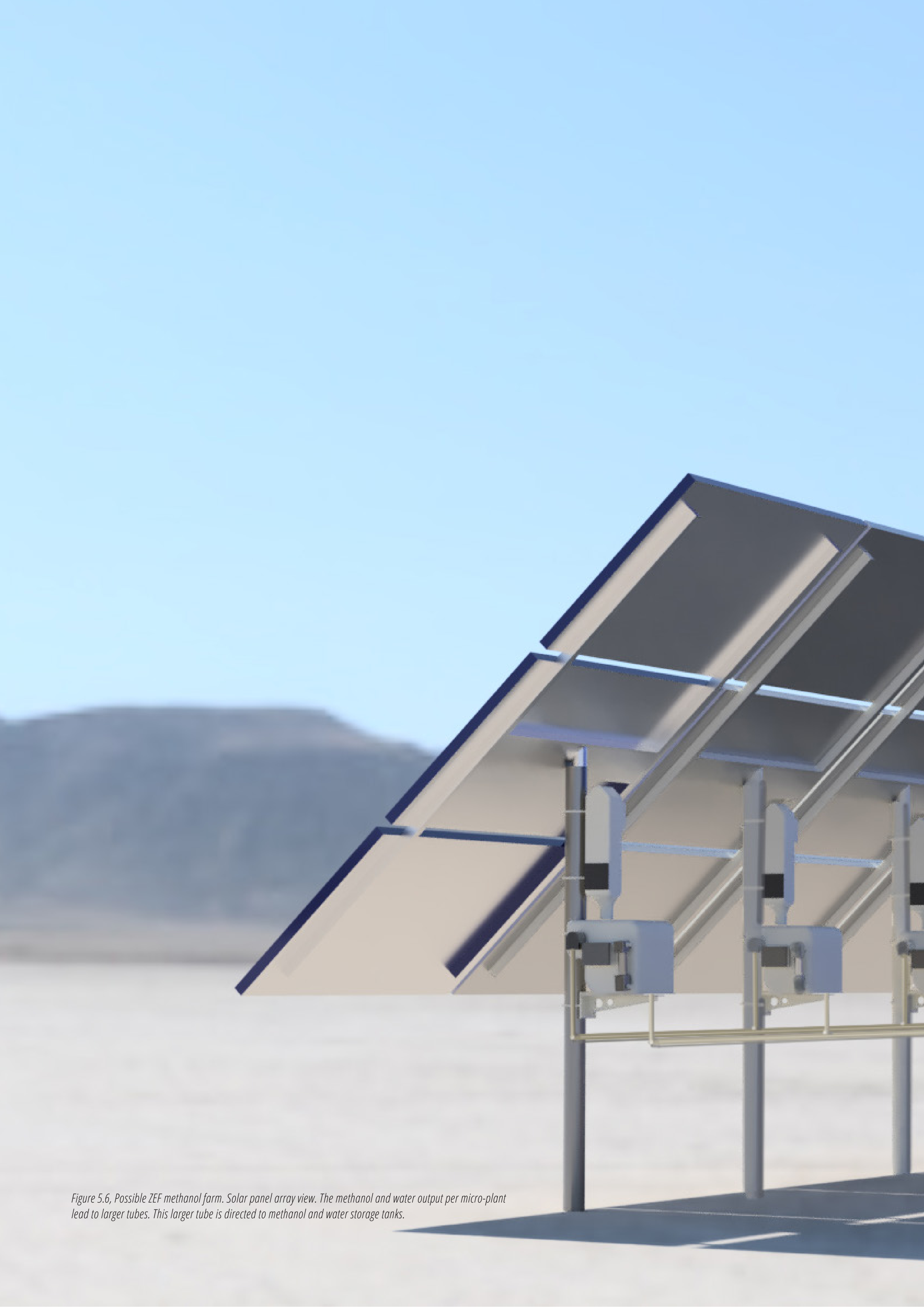
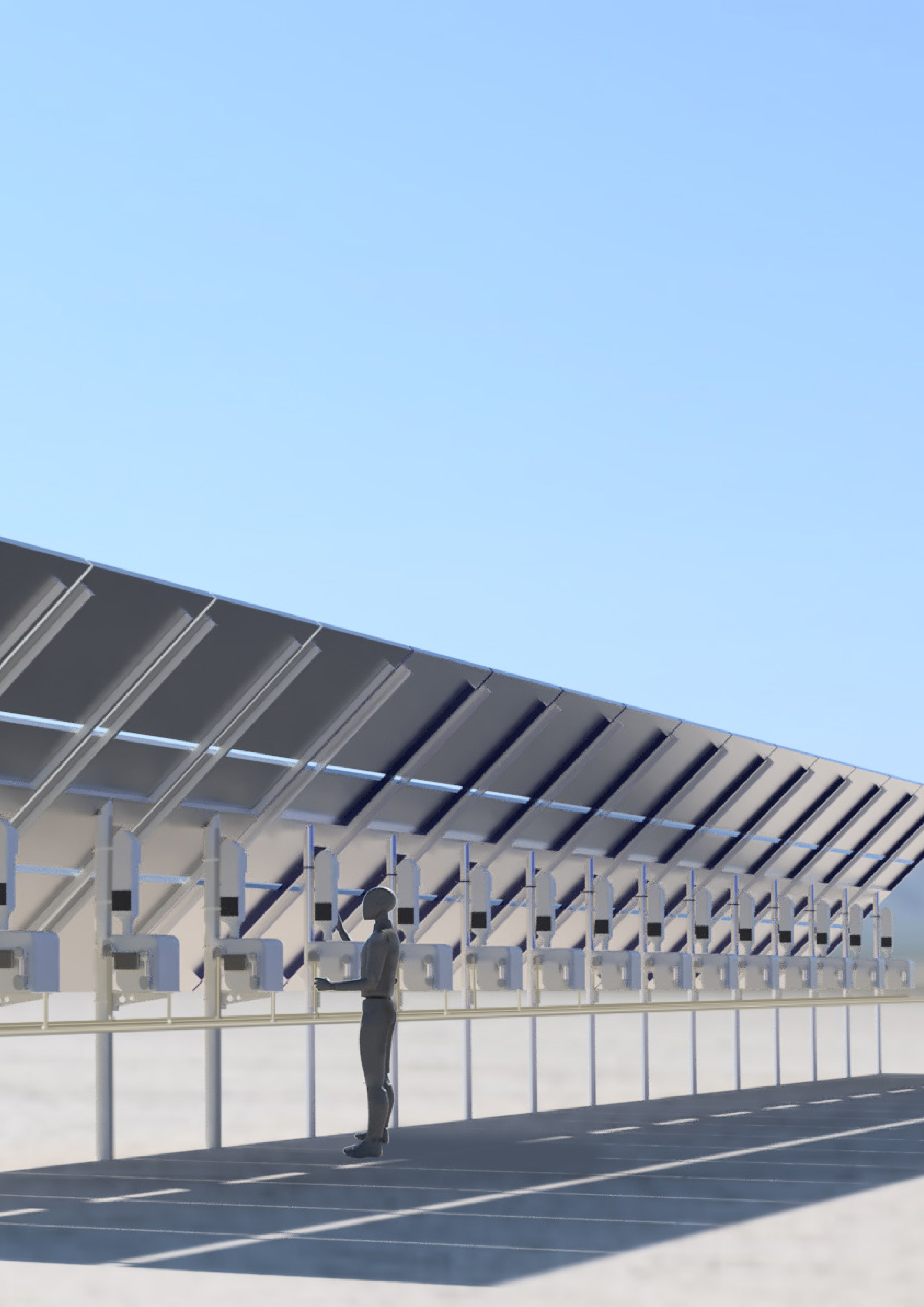


Figure 5.6, Possible ZEF methanol farm. Solar panel array view. The methanol and water output per micro-plant lead to larger tubes. This larger tube is directed to methanol and water storage tanks.



6.
EVALUATION

INTRODUCTION

The previous chapter defined the design of a mass-producable integrated micro-plant concept. This concept is evaluated on costs in this chapter. The cost results are compared to the base-case to evaluate the concept's impact. Next, based on the integration research, design guidelines and recommendations are defined. In future ZEF micro-plant integration designs these guidelines and recommendations can be used as a reference.

COST ANALYSIS

INTRODUCTION

In chapter two, the bill of materials and cost calculations of the ZEF team 3 prototype was made and optimised. Next, in chapter three, the likely cost of a micro-plant with a system scaling of three was calculated. The previous chapter updated the subsystem designs with the latest technology and modifications for mass-production and integration. The BOM derived from these systems is used to determine the capex costs of the complete 900W micro-plant. The BOM and cost analysis can be found in appendix 2D. The BOM is scoped at a micro-plant production quantity of about 130.000 plants (10 farms of 40.000 solar panels)

APPROACH

The in chapter four defined subsystem embodiment designs were used to calculate the component's weight and thereby calculate the materials costs. Next, the manufacturing process was defined, and a manufacturing costs multiplication factor was added over the material costs. For injection moulding, casting and extruding this factor was chosen to be 1.5. For components with neat tolerances that need secondary production a factor of 4.5 over the material costs was used. The determined factors are shown in the bill of materials.

ASSEMBLY

Per subsystem the assembly costs were calculated and added to the total subsystem's capex costs. The assembly costs were estimated based on earlier assembly research from ZEF, calculated welding time and the designer's intuition. Some assumptions were made:

- A mean welding speed of 400mm per minute can be achieved (PRRE Lastechniek, 2010). Including positioning the weld speed is assumed to be 200mm per minute;
- A €25 / hour wage was used for the assembly calculations;
- For the welding of the MS and electrolyzer an additional cost of €10 per hour is used for the machine and material costs of welding. The other systems have way less welding area and material costs are neglected;
- Next to welding, the tool and location usage costs for assembly were neglected.

INSTALLATION

As mentioned in chapter 3, system sizing, a micro-plant with a weight between 40kg and 50kg needs to be carried by three persons due to regulations. With an assumed installation time of 20 minutes by three persons with a wage of €25 / hour, the installation would cost €25. In practice a carrying device may be used that influences the installation costs.

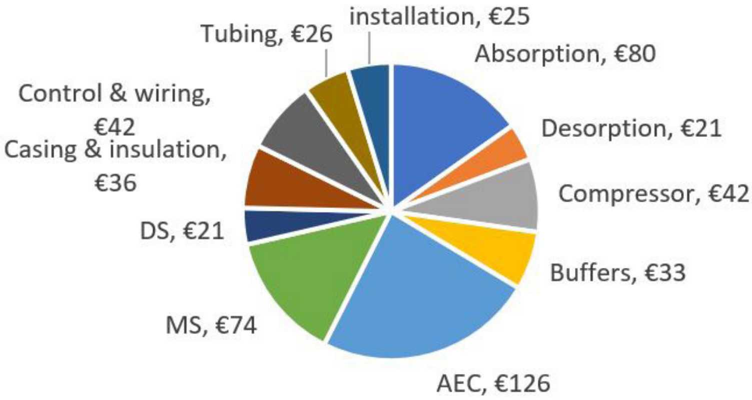


Figure 6.1, costs per subsystem division. 900W micro-plant design

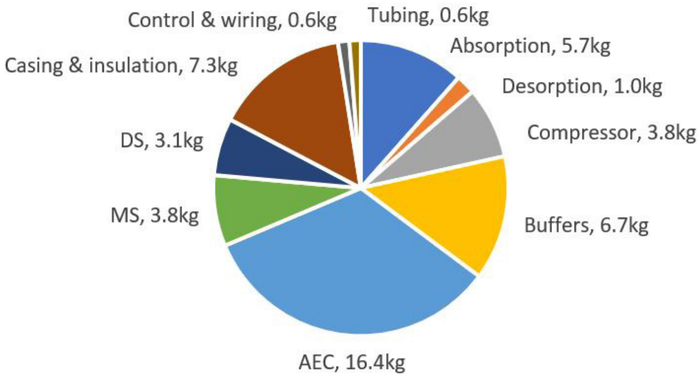


Figure 6.2, Mass distribution per subsystem. 900W micro-plant design

RESULTS

The 900W micro-plant design exists of about **530 components** and has a total mass of **49kg**. The total capex costs are calculated to be **€525** per plant. The cost and mass structure can be found in table 6.1 and in figures 6.1 and 6.2. The 900W system is aimed to produce 4.6ton methanol during its operational period. This brings the capex costs to **€114 per ton** methanol.

The top ten most expensive components in the 900W micro-plant are shown in table 6.2 and in figure 6.3 These 10 components are responsible for 46% of the total micro-plant's costs. Figure 6.4 shows the components cost distribution within the micro-plant.

Table 6.1, capex costs structure and subsystem mass

	Production (€)	Assembly (€)	total capex costs (€)	Total mass (kg)	cost (€)/kg
Absorption	75.85	4.17	80	5.7	14
Desorption	18.99	2.50	21	1.0	21
Compressor	34.45	7.50	42	3.8	11
Buffers	32.69	0.80	33	6.7	5
AEC	118.42	7.09	126	16.4	8
MS	56.68	16.92	74	3.8	19
DS	17.88	3.00	21	3.1	7
Casing & insulation	23.10	13.33	36	7.3	5
Control & wiring	16.83	25.00	42	0.6	69
Tubing	13.97	12.42	26	0.6	43
installation			25.00		
Sum	**404.74**	**92.71**	**527**	**49.0**	**10.8**

Number	Component	Costs (€)
1	Absorption sorbent	46.75
2	Pressure casing Electrolyzer	36.80
3	Electrolysis membrane	32.00
4	MS heat pipes	27.44
5	Electrodes	25.18
6	Pressure vessel hydrogen	24.91
7	Fans (absorption system)	17.60
8	heat pipes, desorption and DS	14.40
9	Micro-plant main Casing	9.54
10	Compressor gear box	8.71

Table 6.2, top 10 most expensive components, 900W micro-plant design

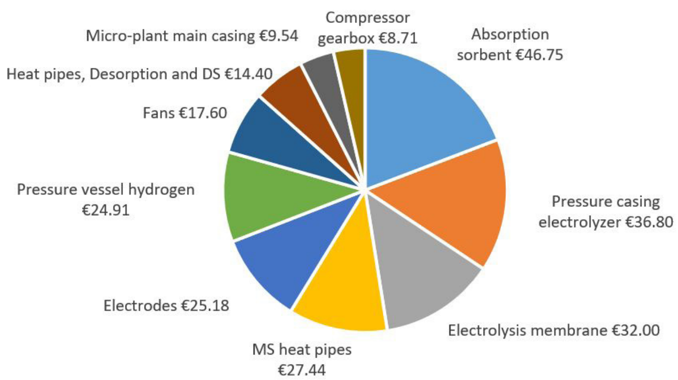


Figure 6.3, top 10 most expensive components, 900W micro-plant design

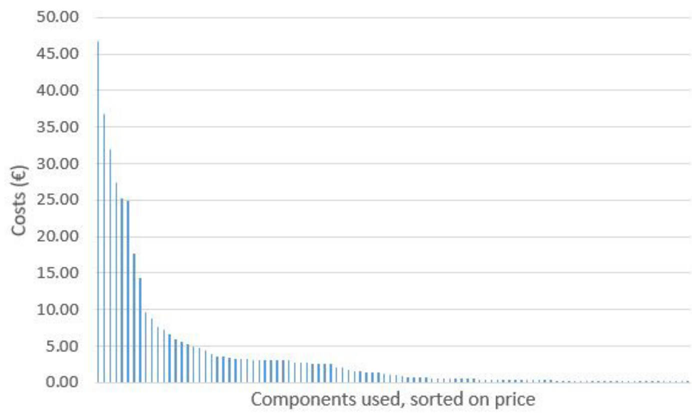


Figure 6.4, component costs distribution, 900W micro-plant design

PRODUCTION

€ 405

ASSEMBLY

€ 95

INSTALLATION

€ 25

TOTAL COST

€ 525

900W EMBODIMENT DESIGN, MICRO-PLANT

COST VALIDATION

COST PER KG ANALYSIS

To evaluate whether the micro-plant's cost is realistic a kg cost analysis is conducted. A production cost of €10 per kg is to be expected for a mass-produced micro-plant, as this is a regular value for large mass-produced technological products. Appendix L elaborates on the €10 per kg breakdown.

The last column of table 6.1 shows the cost per kg calculations per subsystem. The complete micro-plant has a production cost of €10.80 per kg. This is close enough to €10 per kg to state the total micro-plant cost is realistic.

SUBSYSTEM KG COSTS

When analyzing the cost per kg per subsystem the 'control and wiring' is notably high with €69/kg. Although this is high, it is realistic, as it mainly includes purchased electronics with relatively high costs per kilogram. Also, the tubing system has a relatively high kilogram price, as these tubes are very thin, they have little weight, but require quite some manufacturing. The MS and desorption systems are relatively expensive per kilogram due to the purchased heat pipes. In the absorption system the sorbent increases the kilogram costs. The buffers and the casing and installation are low in costs per kilogram. This is because these systems do not use expensive materials or require much manufacturing.

COST EVALUATION

EMBODIMENT DESIGN, COST DECREASE

The new concept's capex costs is considerably lower (with €525), than in chapter three's cost calculation for a 900W system of €700. The differences come from the implemented design modifications of chapter five.

LOWERED COSTS

The main costs decrease, with €110, can be explained by the previously over dimensioned methanol reactor. The initial 300W MS design would likely be able to produce the yield for a 900W system. The rest of the cost reduction can be explained by several smaller design modifications like:

- the electrolyzer's pressure casing was over dimensioned and thereby overpriced, €25, for the 300W system. In this 900W system the pressure casing costs €37.
- The MS block was over dimensioned and is changed in two blocks in the 900W system. These blocks are made of a methanol resistant type of aluminum for improved heat transfer. These aluminum blocks are lighter and way cheaper.
- The number of valves is decreased from eleven to eight by the implementation of mechanical valving techniques.
- The DS blocks are changed in material from stainless steel to methanol resistant aluminum. This decreases the weight, material costs and increases thermal conductivity.

ADDED COSTS

Compared to chapter two's base-case costs analysis, several components are added, and some assumptions were modified. For example, it was assumed that the assembly of the compressor would take 4 minutes. Further system insights increased this number to 15 minutes. In the earlier costs calculation there was no design for the thermal conductivity from the heat pipes. Therefore, there are three heat pipes added in this design. Also, the tubing and casing were minorly incorporated in the base case bill of materials.

UNCERTAINTIES

The purchase components costs are highly dependent on the sourcing company. For several components (like the sorbent, electrodes, electrolyte, heat pipes and catalyst) the purchase costs are subject to significant changes, either positive, or negative. These components are available in quite a wide cost range and it is unsure which ones suits best. Future tests by ZEF will give new insights in the needed parts.

NON-EVALUATED COSTS

Repair and maintenance costs are not incorporated within this analysis. In time, new sorbent needs to be added and several components could break down. The embodiment design does support disassembly and repair, but the break down frequency and logistics are unknown and would require elaborate analysis to make sound assumptions. Therefore, this cost analysis solely handles the micro-plant's capex costs.

The transport costs are not incorporated in the capex costs, as production and farm locations and logistics are not defined.

DESIGN GUIDELINES FOR INTEGRATION

This section summarises the design guidelines that should be considered for the micro-plant integration design. Most of these guidelines are also presented in previous chapters, this section delivers the overview. Design guidelines are formulated for the four main segments of this report: system sizing, configuration architecture, subsystem embodiment and cost analysis.

SYSTEM SIZING

Initially the aim was to connect one methanol micro-plant to one 300W solar panel. Research showed that the cost per produced unit of methanol would lower, when the micro-plant system was up-scaled. The most favourable system sizing appeared to be one micro-plant per three 300W solar panels (Chapter 3, System Sizing).

Possibly, the most optimal micro-plant system sizing changes when design insights change. In that case the scaling research of chapter three can be modified with the new data. The scaling analysis embeds the following:

1: How does scaling impact the methanol costs regarding:

- Subsystem components → Proportional scaling
  → no influence;
  → Non-proportional scaling
  → estimate costs for different scaling sizes;
- Start-up time → Will the start-up time be problematic at a certain scaling?
- Efficiency → How does the operation efficiency change when scaling?
- Safety → At what scale will safety issues become problematic?
- Maintenance → How do maintenance costs relate to system scaling?
- Assembly → How do assembly costs relate to system scaling?
- Installation → How do installation costs relate to system scaling?
- Investments → How do the needed investments relate to system scaling?
- Development → Is ZEF able to develop it, will development costs change?

2: Integrate the scaling effects in the same unit (e.g. cost per ton methanol);

3: Analyse the scaling effects for different system dimensions and define the scale that has the highest potential. It could be possible that some subsystems should number up while other subsystems scale up.

CONFIGURATION ARCHITECTURE

Most subsystems' orientations are dependent on gravitational flows. This defines the configuration architecture design demands. Sub chapter 'Configuration Demands' in chapter 4 shows the configuration needs per subsystem. Figure 6.5 shows how the guidelines are implemented in the integration prototype and how the material flows move. For the configuration architectures it is important to thoroughly understand the subsystems' configuration demands and the material flows. Also, the thermal properties per subsystem need to be well considered to optimise insulation and thermal buffering.

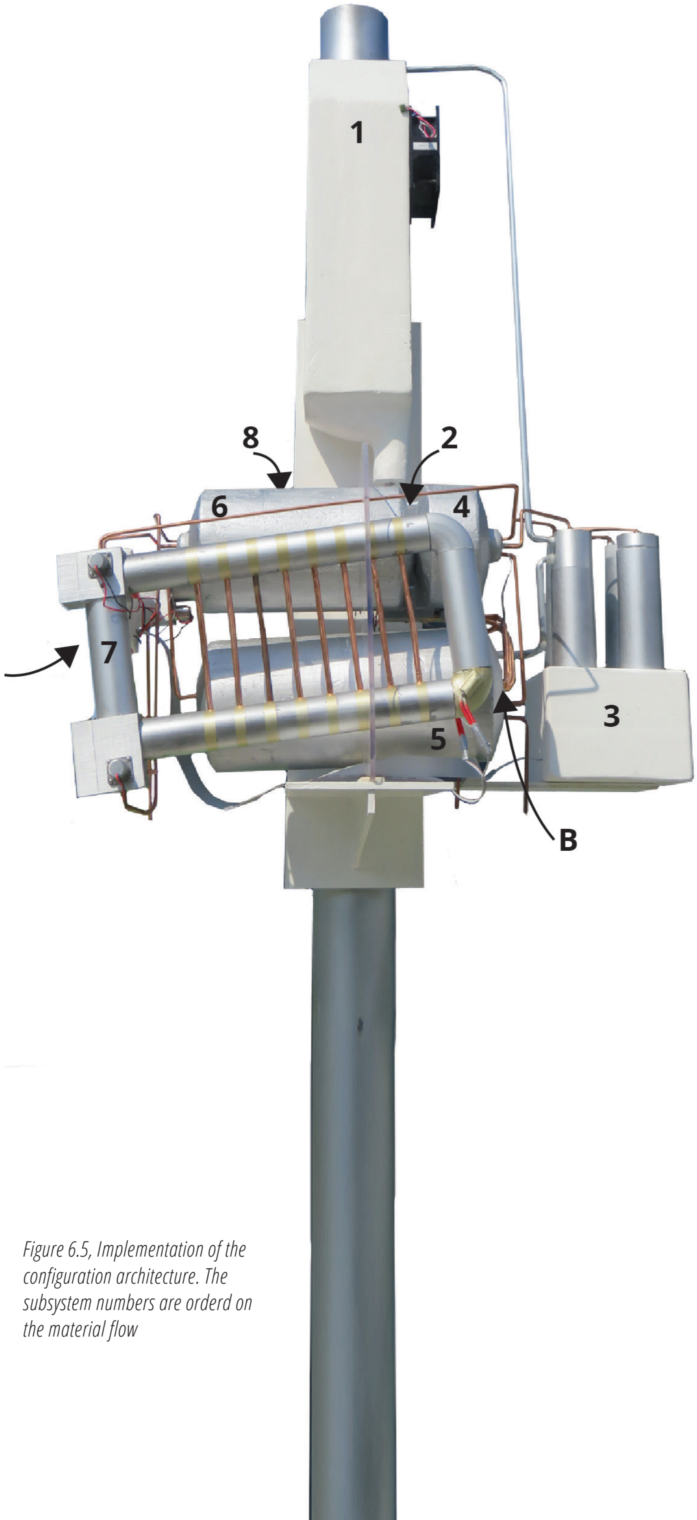


Figure 6.5, Implementation of the configuration architecture. The subsystem numbers are orderd on the material flow

1: ABSORPTION

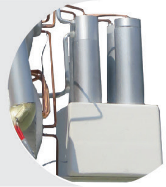
Air is fanned in and water and carbon dioxide are absorbed in a sorbent. This sorbent flows down the absorption system on gravity.

2: DESORPTION

Water and carbon dioxide are desorbed from the flown down sorbent. The desorption's gas outlet is above the compressor's inlet

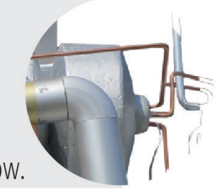
3: COMPRESSOR

The compressor creates the vacuum in the desorption system and compresses the water and carbon dioxide to about 55 bar



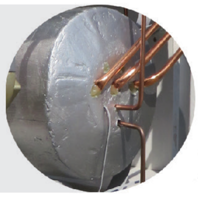
4: CO_2 & H_2O BUFFER

The compressed carbon dioxide gas and liquid water are buffered here. This buffer is located above the electrolyzer for gravitational water flow.



5: Electrolyzer

The water goes through an electrolysis process and becomes hydrogen. This system embeds a degasser to purify the water input.

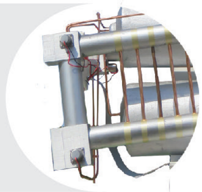


6: H_2 BUFFER

The produced hydrogen is buffered. This buffer is located above the electrolyzer. The hydrogen gas can move upwards.

7: METHANOL SYNTHESIS (MS)

Carbon dioxide and hydrogen react to methanol and water. This system is tilted a few degrees to stimulate flow.

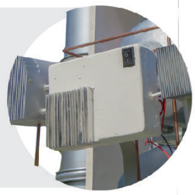


8: DISTILLATION (DS)

Methanol is distilled from the water. The DS works on a low pressure and can therefore be located above the MS outlet. The middle tube is horizontal.

A. CONTROL

The main electronics are located in the control chamber. This system is cooled by the atmosphere and the location is chosen to minise wire lengths.



B. HEAT INTEGRATION

From the electrolyzer, heat pipes move to the desorption and distillation systems. The heatpipes move upwards for optimal heat flow.

SYSTEM EMBODIMENT FOR MASS PRODUCTION

In this report the system embodiment designs mainly served to implement the latest design modifications and the designer's insights in the prototype and cost evaluation. For the system embodiment it is most important to consider that the components will be mass manufactured. The materials used need to be suitable for the chemicals that they will be in contact with. However, it needs to be considered that materials that appear not to be suitable in the first place, may function with a specific surface treatment and be favourable. For example, aluminum normally corrodes with methanol and therefore stainless steel is used in prototypes, but certain material treatments could potentially make it resistant. Then, aluminum will be beneficial due to weight, costs and thermal characteristics. Generally, design for mass reduction should be the aim when designing subsystems.

COST ANALYSIS

One of the main challenges is to produce methanol at a competitive price. Therefore, design directions and modifications should be examined based on their cost. It is important to consider the mass-production costs of the the product, as prototyping costs are not representative. Based on the needed cost accurateness different cost analysis methods could be used:

Quick (€/kg analysis):

A very quick way to analyse the production costs in mass production would be to examine the system's mass and multiply this by €10/kg.

About accurate (BOM)

A more accurate cost analysis could be done by creating the complete bill of materials of the system. The purchase component costs can be added and the self-developed part costs can be estimated with the weight, the material costs and the production method. The Excel sheets used for this report's cost analysis could be modified with the design changes.

About accurate (Expert consult)

Another more accurate option would be to consult an expert to discuss mass production costs estimations. This could be done in parallel with the BOM analysis.

Accurate (quotations)

When the micro-plant's design is getting optimised and production is nearing, more accurate cost analysis would be needed. Part quotations should be inquired from potential manufacturers. For an accurate cost analysis, the transportation costs need to be considered as well.

INTEGRATED MICRO-PLANT DESIGN RECOMMENDATIONS

Throughout the entire integration process findings led to the definition of micro-plant design recommendations. At several sections some recommendations have already been mentioned. This section gives the overview of recommendations, sorted per category.

SYSTEM RECOMMENDATIONS

GENERAL

- Achieving a high system efficiency is the most important for producing competitively priced methanol. Therefore the main focus of ZEF should be on system efficiency optimisation;
- It may be interesting to designate a graduation project on the usage of the micro-plant's water output. Within this project the mentioned possibilities can be further evaluated;
- The lifespan and maintenance requirements per subsystem must be further formulated, in order to make an optimal integrated design suitable for maintenance.

MATERIALS

- Tests must be done to show whether the chosen materials will function for the 20 years life span in the subsystem's environment;
- It must be researched how aluminum could be made resistant to methanol.

SUSTAINABILITY

- The recycling potential per system must be determined (will materials degrade by the present chemicals?).

SUBSYSTEM RECOMMENDATIONS

ABSORPTION

- The sorbent racks should be designed as a stack to be easily inserted into the absorption system. One by one insertion would be costly and increase the chances of errors.
- The absorption chamber design needs to be modified to embed two 'price dip' computer fans to get the needed airflow for a 900W micro-plant.
- The sorbent sheet's durability must be researched. (will it stand 20 years of operation)

DESORPTION

- It must be examined whether it is favourable to put a heat pipe through the inside of the desorption system. (having the heat pipe inside the system could over complicate the design)

COMPRESSOR

- The compressor should be designed to have the first and last stage next to each other (The first stage is the gas inlet, the last stage the gas outlet and the sorbent inlet and outlet. Bringing these stages next to each other minimises tube length).

ELECTROLYZER (+ DEGASSER)

- The heat flow through the electrolyzer must be further researched to design an optimal heat buffering system, e.g. heat pipe connection;
- A valve system must be designed to regulate the water input and degassers output;
- The electrodes used are a main variable for the electrolyzers efficiency. The efficiency must be linked with the costs to find optimal electrodes (currently in research by ZEF);
- The heat buffering distance from the electrolyzer to the desorption and distillation system must be minimised to lower heat buffer (pipe) costs and operate at maximum efficiency.

BUFFERS (H_2O/CO_2 & H_2)

- The buffer's and electrolyzer's pressure casings are possibly over-dimensioned. Possibly costs could be saved here;
- The safety regulation regarding hydrogen buffering must be researched.

MS

- The catalyst costs for the methanol reaction has some uncertainty. On the internet similarly looking catalysts are sold within a cost range of €5-170/kg. A cost of €20/kg was used for the calculations. ZEF could further analyse the differences between the catalysts;
- The heat pipe distance must be minimised for improving the heat transfer efficiency;
- The corner pieces could be casted to prevent a minimum bending angle;
- The catalyst tube could be enlarged in diameter to decrease the needed height (and thereby heat pipe length);
- Potential mass producible heat pipe connection methods must be further researched.

DS

- The needed middle tube diameter should be further researched for the 900W micro-plant

system. Possibly it is over dimensioned in the designs of this report;
- The DS block designs should be optimised for mass reduction;
- The DS and desorption system are located next to each other for optimal heat buffering, possibly casing parts of the desorption and the hot side of the distillation block could be combined;

TUBING
- The needed tubing diameter sizing must be further optimised based on tests and calculations;
- The tubing shape must be further optimised for the design for assembly;
- It must be researched how the DS output tubes are attached to a central methanol tube.

CONTROL
- It must be further researched how malfunctioning micro-plants are reported to the farm manager.
- It must be researched whether pasive cooling is sufficient for the control system, or that a fan is needed.

CASING
- The structural subsystem connection design within the casing must be further researched.
- It must be researched whether cellulose fill would decently insulate the micro-plant over its lifetime.

SOURCES

Air Products and Chemicals (2018). Hydrogen Weight and Volume Equivalents. Retrieved at October 5, 2018, from: http://www.airproducts.com/products/Gases/gas-facts/conversion-formulas/weight-and-volume-equivalents/hydrogen.aspx

Alberico, E., & Nielsen, M. (2015). Towards a Methanol Economy Based on Homogeneous Catalysis: Methanol to H2 and CO2 to Methanol. Chemical Communications, 51(31), 6714-6725.

Basile, A., Dalena, F., Methanol Science and Engineering. Amsterdam, The Nethlands: Elsevier.

Browning, T. R. (2001). Applying the Design Structure Matrix to System Decomposition and Integration Problems: a review and new directions. IEEE Transactions on Engineering management, 48(3), 292-306.

CES Edupack (2018). Power System – Low Carbon, PV, Poly-Silicon [Computer Software]. Cambridge (UK), Granta Headquarters

Dewhurst, P., & Boothroyd, G. (1988). Early Cost Estimating in Product Design. Journal of Manufacturing systems, 7(3), 183-191.

Engineering ToolBox (2009). Combustion of Fuels - Carbon Dioxide Emission. Retrieved at September 20, 2018, from: https://www.engineeringtoolbox.com/co2-emission-fuels-d_1085.html

European Union (2009). Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the Promotion of the Use of Energy from Renewable Sources and Amending and Subsequently Repealing Directives 2001/77/EC and 2003/30/EC. Official Journal of the European Union, 5, 2009.

Fox, S. (2017). How Does Heat Affect Solar Power Efficiencies. Retrieved September 7, 2018, from: https://www.civicsolar.com/support/installer/articles/how-does-heat-affect-solar-panel-efficiencies

Goeppert, A., Olah, G. A., & Prakash, G. S. (2017). Toward a Sustainable Carbon Cycle: The Methanol Economy. In Green Chemistry (pp. 919-962).

Hoa, F. (2017). Could Methanol Replace Diesel?. Retrieved September 9, 2018, from: https://www.chinadialogue.net/article/show/single/en/10129-Could-methanol-replace-diesel-

I.P.J. Carels (2018), Dynamic Model and Preliminary Design of a Small-Scale Renewable Methanol System. Mechanical Engineering, Delft University of Technology.

Innogy (2017). Innogy Presents Alternative to Oil. Retrieved September 11, 2018, from: https://news.innogy.com/innogy-presents-alternative-to-oil/

J. Brinkman (2018). Lunch Lecture Solarus. Retrieved from Delft University of Technology, Delft Sustainable Energy Association

Klaus, U. (2016). Big Car Makers, Big Profits?. Retrieved April 11, 2019, from: https://www.dw.com/cda/en/big-carmakers-big-profits/a-19480709

L.W. Picarelle (2018), Reinventing the Chemical Industry. Industrial Design Engineering, Delft University of Technology.

Landau, C. R. (2017). Optimum Tilt for Solar Panels. Retrieved September 12, 2018, from: http://solarpaneltilt.com/

Mankins, J. C. (1995). Technology Readiness Levels. White Paper, April, 6.

Marsh, J. (2018). Solar News. Retrieved September 13, 2018, from: https://news.energysage.com/solar-farms-start-one/

Meister, P. (2018). How Much Does it Cost to Make a Car? Retrieved April 11, 2019, from: https://carfromjapan.com/article/industry-knowledge/how-much-does-it-cost-to-make-a-car/

Methanol Institute (2016). Compatibility of Metals & Alloys in Neat Methanol Service. Retrieved March 1, 2019, from: http://www.methanol.org/wp-content/uploads/2016/06/Compatibility-of-Metals-Alloys-in-Neat-Methanol-Service.pdf

Methanol Institute (2016). Physical Properties of Pure Methanol. Retrieved at September 5, 2018, from: http://www.methanol.org/wp-content/uploads/2016/06/Physical-Properties-of-Pure-Methanol.pdf

Methanol Institute (2018). Feedstock Supply. Retrieved September 5, 2018, from: https://www.methanol.org/feedstocksupply/

Methanol Institute (2018). The Methanol Industry. Retrieved September 5, 2018, from: https://www.methanol.org/the-methanol-industry/

Methanol Institute (2018). What is Methanol. Retrieved September 5, 2018, from: https://www.methanol.org/about-methanol/

Methanol Institute (2019). Methanol Fuel Blending in China. Retrieved April 2, 2019, from: https://www.methanol.org/wp-content/uploads/2019/02/6.-Kai-Zhao-Methanol-Fuel-Blending-in-China.pdf

Ministerie van Sociale Zaken en Werkgelegenheid (2018). Tillen en Dragen. Retrieved November 14, 2018, from: https://www.arboportaal.nl/onderwerpen/tillen-en-dragen

Mishra, S. (2016). What Happens to Boiling Point of Water in Vacuum?. Retrieved 20 February, 2019., from: https://www.quora.com/What-happens-to-boiling-point-of-water-in-vacuum

Molcho, G., Cristal, A., & Shpitalni, M. (2014). Part Cost Estimation at Early Design Phase. Cirp annals-manufacturing technology, 63(1), 153-156.

NASA (2014). NASA Computer Model Provides a New Portrait of Carbon Dioxide. Retrieved September 7, 2018, from: https://climate.nasa.gov/news/2190/nasa-computer-model-provides-a-new-portrait-of-carbon-dioxide/

NASA (2018). Climate Change: How do We Know?. Retrieved at November 21, 2018, from: https://climate.nasa.gov/evidence/

Niclas, D.W. (2016). Measuring the Temperature Coefficient for a PC Module. Retrieved at December 2, 2018, from: https://sinovoltaics.com/solar-basics/measuring-the-temperature-coefficients-of-a-pv-module/

Nikkelprijs (2018). Live Nikkel Prijs Koersen. Retrieved at October 19, 2018. From: https://www.nikkelprijs.eu/

Olah, G. A. (2005). Beyond Oil and Gas: the Methanol Economy. Angewandte Chemie International Edition, 44(18), 2636-2639.

OJ Insulation (2018). What are Different Types of Insulation?. Retrieved 19 December, 2018., from: https://www.ojinc.com/different-types-of-insulation/

Pimmler, T. U., & Eppinger, S. D. (1994). Integration Analysis of Product Decompositions.

Schachinger, M. (2018). Module Price Index. Retrieved September 12, 2018, from: https://www.pv-magazine.com/features/investors/module-price-index/

Silicon Valley Toxins Coalition (2014). 2014 Solar Scorecard. Retrieved at September 20, 2018, from: http://www.solarscorecard.com/2014/2014-SVTC-Solar-Scorecard.pdf

Solardat (2018). Sun Path Chart Diagram. Altitude: 1.3169, longitude 36.854, UTC +3, retrieved September 12, 2018, from: http://solardat.uoregon.edu/SunChartProgram.php

Solarus (2018). The New Power to Fuel Our Future. Retrieved November 29, 2018, from: https://solarus.com/wp-content/uploads/2018/06/18SOL002-Technische-Brochure-Update-LRv1.pdf

Soletair (2018). The Soletair Concept. Retrieved September 11, 2018, from: https://soletair.fi/

Straver, F. S. (2018). De Aanleg van Weides Vol Zonnepanelen Kan Grote Gevolgen Hebben Voor het Leven in en op de Bodem. Trouw, 25 juni 2018. Retrieved December 2, 2018, from: https://www.trouw.nl/groen/ecologen-zonneparken-zijn-funest-voor-de-natuur~af9edb6b/

The Engineering Toolbox (2018). Carbon Dioxide – Density and Specific Weight. Retrieved September 7, 2018, from: https://www.engineeringtoolbox.com/carbon-dioxide-density-specific-weight-temperature-pressure-d_2018.html

Thomassen, E.J. (2015). Manufacturing Costs Build-up.

United Nations (2010). The Right to Water. P8. Retrieved April 25, 2019, from: https://www.ohchr.org/Documents/Publications/FactSheet35en.pdf

Van den Berg, R.W. (2018). Designing a Direct Air Capture Unit for Methanol Synthesis. Delft University of Technology, graduation project.

Wiefferink (2018). Gasbuffer. Retrieved at 26 February, 2019, from: https://www.wiefferink.nl/gasbuffer/

ZEF (2017). Business Case Air to Methanol. Retrieved September 6, 2018, from: personal communication

Zeng, K., & Zhang, D. (2010). Recent Progress in Alkaline Water Electrolysis for Hydrogen Production and Applications. Progress in Energy and Combustion Science, 36(3), 307-326.

Zidolider (2019). Tankwagen. Retrieved April 24, 2019, from: http://zidolider.com/article/tankwagen

APPENDIX

APPENDIX A, SOLAR ELEVATION ANGLE

One of the price determinants is the ground rental price of the solar farms. ZEF plans to use 300W solar panels with dimensions of 1.96m in length and 0.99m in width. One solar farm will exist of 40.000 solar panels. The most efficient tilting angle of the solar panels differs per region. Around the equator, with generally the most sun hours in the world, a tilt angle around 0° tilt is most optimal in spring and autumn. In summer and winter, the most optimal angle is larger and can go up to plus, or minus 25°. Figure A1 shows the optimal solar panel angulations for city Nairobi in Kenya, which is located near the equator.

In the first scenario (1) when installing the solar panels flat on the ground area, the highest density of solar panels can be achieved. In this case a solar farm with 40.000 panels would need a ground surface of:

(1) 40.000 * 1.96 * 0.99 = 77616 m2

In the second scenario (2) when the solar panels are placed with a tilt angle of 22° (like in summer in Nairobi), the solar panel density needs to be decreased to prevent the panels from overshadowing each other. In summer in Nairobi there will be a solar elevation angle of about 65°at 12AM (Solardat, 2018). In this case a solar panel uses a row width of 2.05m (figure A2). This would come down to a ground surface of 81180m2. For a matter of scale, this corresponds to 12.7 soccer fields.

(2) 40.000 * 2.05 * 0.99 = 81180 m2

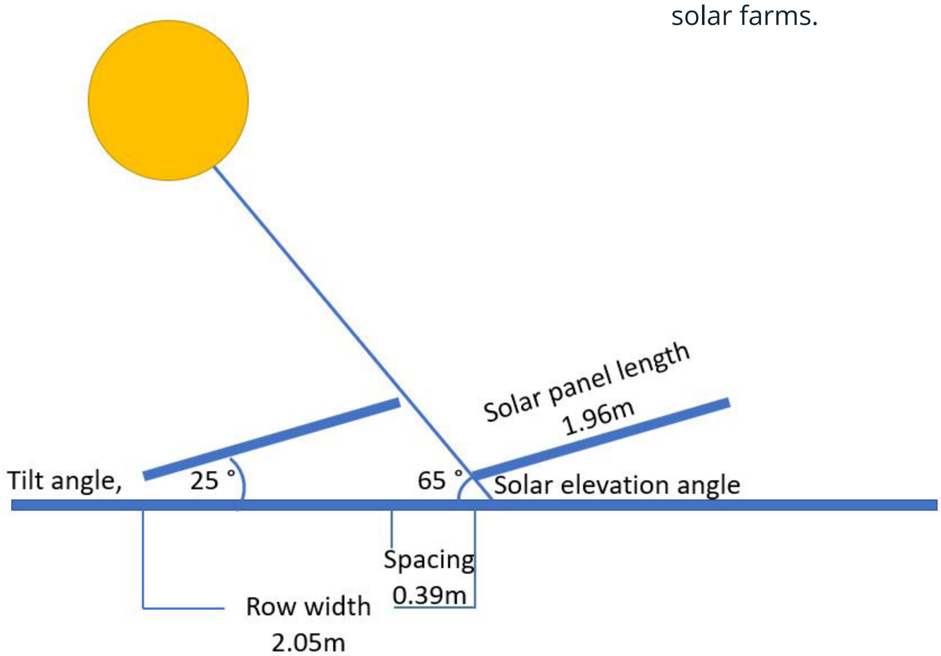


Figure A2, Tilt- and solar elevation angle

Figure A1, Optimal solar panel angle Nairobi, Kenya. http://solarelectricityhandbook.com/solar-angle-calculator.html

In the case of a rental price of €0.8 m2 per year, in scenario (1) the total rental would be €62,000 per year, with €0.005 per W. In scenario (2) the rental increases to about €65,000 per year and a €0.005 per Wp installed. In the case that another location is chosen, where a solar elevation angle of 20° is applicable, with a tilt angle of 25°, the rental costs per Watt would increase to €0.009 per installed Wp, as more spacing is required.

SOLAR TRACKING RACKING SYSTEMS

A possibility would be to make the solar panel's angle adjustable by adapting the racking system manual or automatically. This would require a more complicated racking design and man hours for the transmission, but when changing the system for summer and winter, the solar capturing efficiency increases from about 72% to 76% (Landau, 2017). A system that moves along with the sun could theoretically catch a 100% efficiency. Additionally, extensive racking costs are needed in such a system. Moving solar systems are hardly used in commercial solar farms.

APPENDIX B, RISK ASSESMENT

The development of a solar powered micro-methanol plant is an undiscovered field of research. ZEF is a frontrunner in the field of direct air capturing and the productization of a chemical plant. Working in this new field offers opportunities, but also evokes risks and uncertainty, especially as most technologies are still at low technology readiness levels. For this graduation project there are also several risks to consider. Table B1 gives an overview of main company risks and mitigation strategies (Risk and mitigation data from ZEF, 2017), and personal graduation risks and mitigation strategies. The severity and likelihood of the risks is loosely shown based on the authors perspective with a one to five scale, where one means unlikely and five very likely. When the product is further developed a more concrete likelihood analysis can be conducted. The main risk for ZEF is not being able to sell their methanol for a competitive market price.

Table B1, Risk assesment Zero Emission Fuels

Risks ZEF	Likelihood	Severity	Mitigation strategy
Not achieving 50% efficiency target	4	4	Iterative design, with consultations of an (academic) advisory board. Computer simulations to predict behaviour .
Not achieving a competitive micro-plant cost price	3	5	Iterative design, with consultations of an (academic) advisory board. The downscaling of a chemical plant enables mass-manufacturing and thereby cost reduction. Scaling requires ‘little’ investments
Not achieving a 20 years’ lifetime	3	3	Parts need to be designed for repair, maintenance and replaceability.
Price increasements of solar power	1	3	Solar power prices are steadily decreasing, and sev-eral solar panel technologies exist.
Product develop-ment delays	3	3	Product development is done in an agile way with many iterations. This way a decent development speed is set.
Safety (leaking chemicals) problems with the micro-plant	2	4	The chemical processes are known, and data is available for determining demands. Lab tests pro-vide safe test setups, to research the system.
Alternative renewable methanol suppliers appear with lower production costs.	2	3	The methanol market is probably large enough to allow several market players. Competitors will probably build large scale chemical factories that are hard to scale up.

Table B2, Risk assesment graduation project

Graduation risks	Likelihood	Severity	Mitigation strategy
The amount of in-formation is over-whelming, and I lose overview	3	2	Use a result-oriented approach with clear research points and goals and an iterative approach. Diverge large questions into smaller researchable questions.
Subsystems might change to an extend that my preliminary research is no longer usable	2	2	Depending on the available time, either I will conduct another iteration round to explore and implement the new subsystem design, or I will continue with the previous one. It is unlikely that all systems change, so my integration design will still be of value.
Subsystem variables are not clear enough for an integrated design	3	2	Use the known variable domains to formulate as-sumption values or make the design adjustable to changing variables.
Integration complex-ity prevents me from integrating all sub-systems	3	1	Be up for changing my design assignment to narrow down the field of research or simplify the complexi-ty of the systems.
The integration de-sign will be too ex-pensive to be competitive.	3	2	I make a total cost breakdown per subsystem as a start to see where I could combine integration designs and lower the costs. Otherwise, next generation integrations can work on further costs optimizations.
Communication with subsystem teams is not streamlined	3	3	Define a clear goal per interview, or meeting. I can deliver the questions in advance so that the team can think of their answers in advance.
I miss iteration steps on the subsystems	2	3	Daily SCRUM meetings will keep me up to date.
Lacking time for report writing	2	3	Directly write down the parts of each research and design phase when results are found.

APPENDIX C, ALIEXPRESS COST VALIDATION

The retail rates on AliExpress may differ from feasible mass production retail rates. The rates on AliExpress may express dump prices or sharp discounts that only account for limited time. In this section a sample comparison is made between the rates from AliExpress and the European retailers 'Conrad', 'Mouser Electronics' and 'Open Circuit' (figure C1). The links to the websites stating the prices are added in the bill of materials cost price excel document, that can be found at the TU Delft repository. Within this comparison the costs of the products from European retailers are halved to deduct profit margins. Also the European prices excluding taxes are used, as this could be deducted. At AliExpress the retailer pays the taxes and this cannot be deducted by a Dutch company.

Table C1 points out that the AliExpress prices found regularly fall within a 20% range compared to the prices available at 'Conrad', 'Mouser', or 'Open Circuit', when 50% is deducted. Compared to AliExpress, the Arduino Nano has a price which is 28% higher when calculated from European retailers. This may be explained by a specific dump price on AliExpress. Still, this difference only slightly influences the cost calculation. The valves from the European retailers appear to be 21% cheaper, in this case this can be explained by the fact that no completely similar valves have been found. All in all, it can be concluded that the AliExpress rates can be used for the initial bill of materials and costs.

Table C1, AliExpress' rates compared to half of the European rates (excl. VAT)

	AliExpress €	Alternative half price €	Factor
Arduino Nano Atmega A328P	1.6	2.05	1.28
Atmega A328 chip	1.09	1	0.92
Valve	7.57	6	0.79
Peltier element	1.34	1.18	0.88
Brushless drone motor	4.13	4.13	1
Fan	8.28	8.1	0.98

APPENDIX D PROCESS RELATIONS

Process relations, a mathematical model

> *restart*;

Co2 + 3 H2 = CH3OH + H20
2H2O -> 2H2 + O2
It is assumed that CO2 is the determining factor for the amount of air needed to circulate through the DAC unit.

> *Totalpowerconsumption* := *PFan* + *Pperistalicpump* + *PheatingPEI* + *PCompressor* + *P_AEC* + *PcontinuousMS* + *PheatingDS*; #W
PstartMS; #W
Heatbufferpotential := *Ppotential*; #W

Totalpowerconsumption := 1060.018681
PstartMS
Heatbufferpotential := 240.1360751 **(1)**

General values

> *WpSolar* := 0.90 : #kW
Sunhours := 7 :
MeOHeff := 0.547 :
Toutside := 40 :#degrees celcius
DACsorbenteff := 0.25 :
LHVMeOH := 19.9 : # $\frac{in\ MJ}{kg}$
MwMeOH := 32.04 : # $\frac{g}{mol}$
MwCO2 := 44.01 : # $\frac{g}{mol}$
MwH2 := 2.0158 : # $\frac{g}{mol}$
dH2 := 0.09 :# $\frac{kg}{m^3}$
MwH2O := 18.01528 : # $\frac{g}{mol}$
MwAir := 28.97 : # $\frac{g}{mol}$
dCO2inAir := $\frac{400}{1 \cdot 10^6}$: #ppm
dAir := 1.3 : # $\frac{kg}{m3}$

Desired CH3OH, H20, CO2

> *Esolar* := *WpSolar*·*Sunhours*·3.6; #MJ
Esolar := 22.680 **(3.1)**

> *kgMeOH* := $\frac{Esolar}{LHVMeOH}$ ·*MeOHeff* ; #kg produced per day
tMeOHlifetime := $\frac{kgMeOH \cdot 365.25 \cdot 20}{1000}$;
ProductionkgH2O := $\frac{MolMeoH \cdot MwH2O}{1000}$;#kg H2O
kgMeOH := 0.6234150751
tMeOHlifetime := 4.554047124
ProductionkgH2O := 0.3505304974 **(3.2)**

> *MolMeoH* := $\frac{kgMeOH}{\left(\frac{MwMeOH}{1000}\right)}$; #perday
MolCO2 := *MolMeoH*; #perday;
MolH2 := 3·*MolMeoH*;
mCO2 := *MolCO2*·*MwCO2*; #gram input
mH2O := *MolH2*·*MwH2O*; #gram input
mH2 := *MolH2*·*MwH2*; #gram hydrogen produced

MolMeoH := 19.45739935
MolCO2 := 19.45739935
MolH2 := 58.37219805
mCO2 := 856.3201454
mH2O := 1051.591492
mH2 := 117.6666768 **(3.3)**

Absorption

> *RunningtimeDAC* := *Sunhours* + 1;
#I assume that the fan works 1 more hour than the amount of sun hours, as it can function with little power input
Mairneeded := $\frac{\frac{MolCO2}{dCO2inAir}}{DACsorbenteff} \cdot \frac{MwAir}{1000}$; #kgAir
Vairneeded := $\frac{Mairneeded}{dAir}$; #m3
RunningtimeDAC := 8
Mairneeded := 5636.808592
Vairneeded := 4336.006609 **(4.1)**

Fan

> *Vsec* := $\frac{Vairneeded}{RunningtimeDAC \cdot 3600}$;# $\frac{needed\ m^3}{second}$,
CMM := *Vsec*·60;# $\frac{m3}{minute}$
Fan := 45; #Pa $\frac{mmWg}{0.1}$ internal pressure at fan specs sheet·(excel link)
Faneff := 0.1;
PFan := $\frac{Vsec \cdot Fan}{Faneff}$;#W
Vsec := 0.1505557850
CMM := 9.033347100
Fan := 45
Faneff := 0.1
PFan := 67.75010325 **(4.2)**

PEI, (3H2O, 1CO2 relation needed)

> *PEIratio* := 0.14;
#g H2O+CO2 per gram PEI, this process takes 2 hours, ideal H20 CO2 relation
Absorptiontime := 1;
#hours. This is the important influencing factor defining the amounts of PEI needed
Absorptionmass := *mCO2* + *mH2O*; #grams to be adsorpted per day
AbsorptionPEI := $\frac{\frac{Absorptionmass}{PEIratio}}{\left(\frac{RunningtimeDAC}{Absorptiontime}\right)}$; #gPEI needed at adsorption
Desorptiontime := 0.1;#hours, according to Jan (6min)
DesorptionPEI := $\frac{AbsorptionPEI}{\left(\frac{Absorptiontime}{Desorptiontime}\right)}$;
#The PEI that is at the desorption chamber per time unit.
PEIneeded := *AbsorptionPEI* + *DesorptionPEI*;#gPEI needed
DensityPEI := 1.09;# $\frac{KG}{L}$;
lPEI := $\frac{PEIneeded}{DensityPEI} \cdot 10^{-3}$;#liters PEI
FlowspeedPEI := 0.1; #mm per second (Mrigank)
Absorptionheight := *Absorptiontime*·3600·*FlowspeedPEI*;
#mm adsorption height needed to fully saturate PEI in one flow down
PEIratio := 0.14
Absorptiontime := 1
Absorptionmass := 1907.911637
AbsorptionPEI := 1703.492532
Desorptiontime := 0.1
DesorptionPEI := 170.3492532
PEIneeded := 1873.841785
DensityPEI := 1.09
lPEI := 1.719120904
FlowspeedPEI := 0.1
Absorptionheight := 360.0 **(4.3)**

> *sizePEIrack* := 0.12 ·0.40 ; #m^2 I took the fan size as depth times·(m) height
Layerthickness := 0.0005;#m PEI
PEIperrack := *sizePEIrack*·*Layerthickness*·2·1000;
#liters PEI per rack, both sides of the rack have PEI flowing, ·1000 as from m3 to liters
nracks := $\frac{lPEI}{PEIperrack}$;
Spacingracks := 2·*Layerthickness* + 0.00225;
#m 2 times layer thickness PEI, as PEI is on both sides. There is 2mm air inbetween the sheets. 0.25mm paper flow sheet thickness
LengthAbsorption := *nracks*·*Spacingracks*; #m
volumeAbsorption := *LengthAbsorption*·*sizePEIrack*·1000; #liters

sizePEIrack := 0.0480
Layerthickness := 0.0005
PEIperrack := 0.04800000
nracks := 35.81501883
Spacingracks := 0.00325
LengthAbsorption := 0.1163988112
volumeAbsorption := 5.587142938 **(4.4)**

Peristalic pump

> *Pperistalicpump* := 3.6; #W
Flowperistalicpump := $\frac{DesorptionPEI}{Desorptiontime \cdot 60}$;# $\frac{ml}{minute}$
Pperistalicpump := 3.6
Flowperistalicpump := 28.39154221 **(4.5)**

Desorption

> *volumeDesorptionchamber* := $\frac{\frac{DesorptionPEI}{DensityPEI}}{1000}$;
#liters, minimal volume of desorption chamber. (divided by 1000 as from ml, to l)
volumeDesorptionchamber := 0.1562837185 **(5.1)**

Peltier element

> *Desorptiontemp* := 125 :#degrees celcius
dTdesorption := *Desorptiontemp* − *Toutside* :
theatingPEI := 15·60 :#seconds desired heating time PEI at adsorption
DesorptionPEIperDay := *DesorptionPEI*·$\left(\frac{RunningtimeDAC}{Desorptiontime}\right)$;# $\frac{g}{day}$
cPEI := 2.8 :
specific heat PEI $\frac{KJ}{kgK}$ maybe lower is more logical? https://tinyurl.com/y9pkmdfj
cCO2 := 0.918 :#` $\frac{KJ}{kgK}$ https://www•engineeringtoolbox•com/carbon−dioxide−d_974•html
cH2O := 4.184 :#` $\frac{KJ}{kgK}$ https://water•usgs•gov/edu/heat−capacity•html
QPEI := *cPEI*·*DesorptionPEIperDay*·*dTdesorption*; #heating energy (J)
QCO2 := *cCO2*·*mCO2*·*dTdesorption*;
QH2O := *cH2O*·*mH2O*·*dTdesorption*;
QheatingPEI := *QPEI* + *QCO2* + *QH2O*; #total heating energy (J)
PheatingPEI := $\frac{\frac{QheatingPEI}{RunningtimeDAC}}{3600}$;#Watt

$DesorptionPEIperDay := 13627.94026$

$QPEI := 3.243449782\ 10^6$

$QCO2 := 66818.66095$

$QH2O := 373987.9983$

$QheatingPEI := 3.684256441\ 10^6$

$PheatingPEI := 127.9255709$ **(5.2)**

Wall thickness desorption chamber

> $rdesorptionchamber := 2.5;$ #cm radius, assume the chamber is a tube

$Ldesorptionchamber := evalf\left(\left(\frac{DesorptionPEI}{\mathrm{Pi}\cdot rdesorptionchamber^2}\right)\right);$

cm length desorption chamber

$rdesorptionchamber := 2.5$

$Ldesorptionchamber := 8.675816222$ **(5.3)**

> $Pd := 10\cdot 100000 :$ #Pa, 10 as there is a pressure of 0.1bar. dpressure is 10 times

$Rd := rdesorptionchamber :$ #outside diameter (assumption)

$Sd := 200\cdot 10^6 :$#Pa yield strength Aluminum

$Ed := 1 :$#tube welding factor seemless

$pd := 0 :$#corrosion allowances, (HDPE does not corrode)

$Safetyfactor := 4;$

$minimalAECWallthickness := \frac{Pd\cdot Rd}{2\ Sd\cdot Ed - 0.6\cdot pd}\cdot Safetyfactor;$#cm

$Safetyfactor := 4$

$minimalAECWallthickness := 0.02500000000$ **(5.4)**

Compressor

> $effcompressor := 0.3;$#assumption

$RCO2 := 0.1889;$ #gasconstant co2

$Compressionrate := 55 ;$

$PCompressor := 34 ;$#Watt, according to Jan

$effcompressor := 0.3$

$RCO2 := 0.1889$

$Compressionrate := 55$

$PCompressor := 34$ **(6.1)**

CO2 & H2O buffer

H2O and CO2 buffer size

>

> $dH2O := 1 :\#\frac{1kg}{l}$

$dCO2gas := 1.977\cdot 10^{-3} :\#\frac{kg}{l}$

$VbufferH2OCO2 := \frac{\left(\frac{mH2O\cdot 10^{-3}}{dH2O} + \left(\frac{mCO2\cdot 10^{-3}}{dCO2gas\cdot Compressionrate}\right)\right)}{RunningtimeDAC};$ #liter buffer tank

$VbufferH2OCO2 := 1.115860747$ **(7.1)**

> $lengthBufferCO2H20 := \frac{VbufferH2OCO2\cdot 1000}{\mathrm{Pi}\cdot r^2};$#cm

$rxvolume := \frac{\mathrm{sqrt}(lengthBufferCO2H20\cdot \mathrm{Pi}\cdot VbufferH2OCO2\cdot 1000\cdot x)}{lengthBufferCO2H20\cdot \mathrm{Pi}};$

#cm, ·1000 as liters to ml.

plot(rxvolume, x = 0 ..100, labels = ["x(volume multiplication)", radius(cm)]);

#x is the multiplication factor of the VbufferH2OCO2 volume (l)

$Vmaterial := \mathrm{Pi}\cdot rxvolume^2\cdot lengthBufferCO2H20 - \mathrm{Pi}\cdot r^2\cdot lengthBufferCO2H20;$

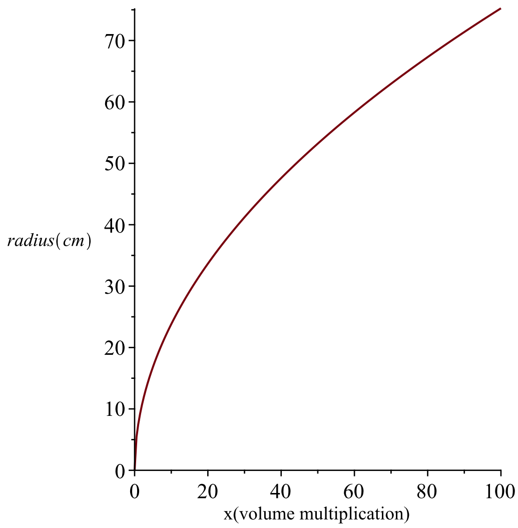
#cm³ how much material is needed **for** the tube when the length is set.

plot(Vmaterial, x = 1 ..100, labels = ["x(volume multiplication)", material volume (cm³)]);

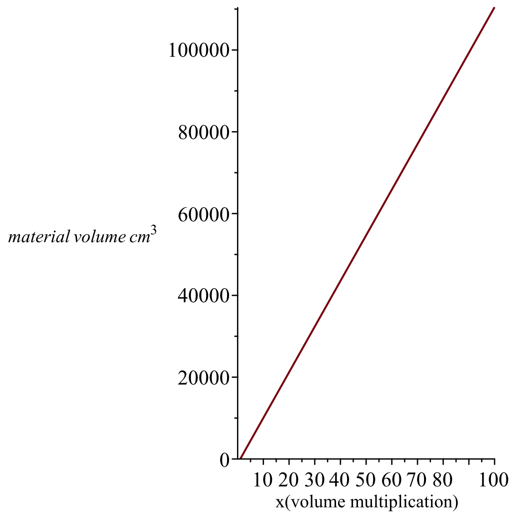
#material volume appears to increase linearly with increased wall thickness.

$lengthBufferCO2H20 := 6.273159949$

$rxvolume := 7.524660035\ \sqrt{x}$



$Vmaterial := -1115.860747 + 1115.860746\ x$



Wallthickness

> $P1 := Compressionrate\cdot 100000 :$ #Pa

$R1 := r + 1;$ #cm outsideinternal radius tube, 1 cm radius above electrolyte radius

$S1 := 41.4\cdot 10^6 :$#Pa yield strength 30% glassfilled HDPE

$E1 := 1 :$#tube welding factor seemless

$p1 := 0 :$#corrosion allowances, (HDPE does not corrode)

$minimalAECWallthickness := \frac{P1\cdot R1}{2\ S1\cdot E1 - 0.6\cdot p1}\cdot Safetyfactor;$#cm

$R1 := 8.524660037$

$minimalAECWallthickness := 2.265006290$ **(7.2)**

Electrolysis

AEC, energy used

> $LHVH2 := 120 :\#\frac{Mj}{kg}$ source : https :// h2tools • org / hyarc / calculator − tools / lower − **and** − higher − heating − values − fuels

$AECeff := 0.70 :$#%

$AEC\_runningtime := 7;$ #to be checked:

$AEC\_runningtime := 7$ **(8.1)**

> $E\_AEC := \frac{mH2\cdot 10^{-3}\cdot LHVH2}{AECeff};$ #Mj per day

$P\_AECday := \frac{E\_AEC}{3600}\cdot 10^6;$ #Wh per day

$P\_AEC := \frac{P\_AECday}{AEC\_runningtime};$ #W of AEC

$E\_AEC := 20.17143031$

$P\_AECday := 5603.175086$

$P\_AEC := 800.4535837$ **(8.2)**

The electrolysis process is exotherm, the heat emitted need to be transported to the systems that need heating

> $Heatemitted := (1 - AECeff)\cdot E\_AEC;\ \#\frac{MJ}{day}$

$Ppotential := \frac{Heatemitted}{3600\cdot AEC\_runningtime}\cdot 10^6;$ #W

$Heatemitted := 6.051429093$

$Ppotential := 240.1360751$ **(8.3)**

Sizing electrolysis, number of cells needed

> $Usolar := 30;$#V assumption avarage voltage output solar panel (UMPPT)

$Ielectrolysis := \frac{P\_AEC}{Usolar};$ #Amps

$ElectrodeAcm2 := 0.3;$ #mean amps of electrode per square centimeter, experimental

$Aelectrode := \frac{Ielectrolysis}{ElectrodeAcm2};$#cm2 per electrode

$Acookie := Aelectrode\cdot 2;$

#according to the current designs the electrode is about half of the size of the entire cookie.

$MinUH2 := 1.23;$

#This is the minimal voltage needed to produce H2, here there is a 100% efficiency, but 0 output

$Ucell := \frac{MinUH2}{AECeff};$#voltage per cell

$ncells := \frac{Usolar}{Ucell};$#number of cells for electrolysis

$equ1 := solve(\mathrm{Pi}\cdot rcookie^2 = Acookie, rcookie);$

$r := evalf(subs(equ1[1]));$ #radius cm, electrodes

$widthcell := 1.5;$#cm assumption

$Welectrolysis := widthcell\cdot ncells + 3\cdot widthcell;$

cm Width electrolysis, top and bottom cookie, degasser

$AECvolume := \frac{Welectrolysis\cdot Acookie}{1000};$

#liters Electrolysis + degasser volume. (This is calculated only with the electrode surface. The electrode will be embedded in a system, so the total diameter should increase to about 14cm. That brings the AECvolume at scale 3 to 2.3 liters.

$Usolar := 30$

$Ielectrolysis := 26.68178612$

$ElectrodeAcm2 := 0.3$

$Aelectrode := 88.93928707$

$Acookie := 177.8785741$
$MinUH2 := 1.23$
$Ucell := 1.757142857$
$ncells := 17.07317073$
$equ1 := 7.524660037, -7.524660037$
$r := 7.524660037$
$widthcell := 1.5$
$Welectrolysis := 30.10975610$
$AECvolume := 5.355880482$ **(8.4)**

H2 Buffer

H2 buffer size, H2 to be stored for one hour after working AEC. So 1/sunhours*mH2, When P < 0.385SE.t=\frac{PR}{SE-0.6P} When P < 1.25SE.t=\frac{PR}{2SE+0.4P}
https://www.johnpaulhandrigan.net/minimum-design-wall-thickness-cylindrical-pressure-vessel-asme-section-viii-div-1/

> $VbufferH2 := \frac{\frac{mH2 \cdot 1e-3}{dH2 \cdot 1e-3}}{Sunhours \cdot Compressionrate}$; #liter buffer tank
$P := Compressionrate \cdot 100000$; #Pa
$R := r + 1$; #cm outsideinternal radius tube, 1 cm radius above electrolyte radius
$S := 41.4 \cdot 10^6$;#Pa yield strength 30% glassfilled HDPE
$E := 1$;#tube welding factor seemless
$p := 0$;#corrosion allowances, (HDPE does not corrode)
$minimalAECWallthickness := \frac{P \cdot R}{2\,S \cdot E - 0.6 \cdot p} \cdot Safetyfactor$; #cm
$lengthBufferH2 := \frac{VbufferH2 \cdot 1000}{Pi \cdot r^2}$;#cm

$VbufferH2 := 3.395863689$
$P := 5500000$
$R := 8.524660037$
$S := 4.14000000\ 10^7$
$E := 1$
$p := 0$
$minimalAECWallthickness := 2.265006290$
$lengthBufferH2 := 19.09090910$ **(9.1)**

Total length AEC (buffers + electrolysis)

> $LAEC := lengthBufferCO2H20 + lengthBufferH2 + Welectrolysis$
$LAEC := 55.47382515$ **(9.2)**

Methanol Synthesis

The MS system needs to be heated to 230 degrees celcius. The starting (heating) time determines the functional hours. A larger system with a higher heating time however could have a larger yield per time.

> $mMS\_heating := 1$;#kg the weight of the elements to be heated
$specificHeatMS := 500$;# $\frac{J}{kg}$ **for *Stainless Steel*** $\cdot (CES)$
$TMS := 230$; # degrees celcius
$dTMS := TMS - Toutside$;
$EheatingMS := dTMS \cdot specificHeatMS \cdot mMS\_heating$;#J needed for start-up heating
$PstartupMS := 30$;#W the power of one 60W peltier element (50% eff.)
$TstartMS := evalf\left(\frac{EheatingMS}{PstartupMS}\right)$; #t needed for heatup
$PcontinuousMS := 20$; #W needed for continuous operation. assumption

$mMS\_heating := 1$
$specificHeatMS := 500$
$TMS := 230$
$dTMS := 190$
$EheatingMS := 95000$
$PstartupMS := 30$
$TstartMS := 3166.666667$
$PcontinuousMS := 20$ **(10.1)**

Wall thickness MS based on inside pressure

> $P2 := Compressionrate \cdot 100000$; #Pa
$R2 := \frac{3.48}{2}$; #cm outsideinternal radius tube, 1 cm radius above electrolyte radius
$S2 := 250 \cdot 10^6$;
#Pa about avarage yield strength stainless steel, asutentic, 316 CES (used in current prototype)
$E2 := 1$;#tube welding factor seemless
$p2 := 0$;#corrosion allowances, (HDPE does not corrode)
$minimalMSWallthickness := \frac{P2 \cdot R2}{2\,S2 \cdot E2 - 0.6 \cdot p2} \cdot Safetyfactor$;
#cm wall thickness needed, based only on pressure

$P2 := 5500000$
$R2 := 1.740000000$
$S2 := 250000000$
$E2 := 1$
$p2 := 0$
$minimalMSWallthickness := 0.07656000000$ **(10.2)**

Yield

output

> $DSrunningtime := Sunhours + 1$;#hours per day
$DSyieldMeOH := \frac{kgMeOH}{DSrunningtime}$;# $\frac{kg}{hour}$
$DSyieldH2O := \frac{ProductionkgH2O}{DSrunningtime}$;# $\frac{kg}{hour}$

$DSrunningtime := 8$
$DSyieldMeOH := 0.07792688439$
$DSyieldH2O := 0.04381631218$ **(11.1)**

Heating

> $ThotDS := 100$;#degrees celcius
$dTDS := ThotDS - Toutside$;
$QDSH2O := cH2O \cdot ProductionkgH2O \cdot dTDS \cdot 1000$; #Joule for heating fluid H2O per day
$cMeOH := 2.49$;# $\frac{kJ}{kg} K$
$QDSMeOH := cMeOH \cdot kgMeOH \cdot dTDS \cdot 1000$; #Joule for heating fluid methanol per day
$QtotalDS := QDSH2O + QDSMeOH$;#total heating energy per day
$PheatingDS := \frac{\frac{QtotalDS}{DSrunningtime}}{3600}$;

$ThotDS := 100$
$dTDS := 60$
$QDSH2O := 87997.17606$
$cMeOH := 2.49$
$QDSMeOH := 93138.21222$
$QtotalDS := 181135.3883$
$PheatingDS := 6.289423206$ **(11.2)**

APPENDIX E, PROGRAM OF DEMANDS FOR INTEGRATION

Below one can find the program of demands that need to be considered for the integration design of the micro-plant. There are general system demands and specific demands per functional subsystem. The demands are formulated in a way that supports design modifications. For example, the methanol must not exceed a production costs of €350 per ton. This way there is no absolute cost limit per micro-plant and scaling is possible.

This program of demands is aimed on integration design. For specific subcomponents and the entire methanol farm additional demands should be considered that are not listed in this section. *Note*

CONTEXT

- The mean ambient temperature is 40°C;
- The methanol micro-plants will be installed in desert area;
- There is a mean of seven sun-hours per day available;
- The system will be installed in a 'farm' with 40.000 solar panels of 300W (1956x992x50mm);
- The energy price of the solar panels is about €0.02 / kWh.

SYSTEM INTEGRATION DEMANDS

FINANCIAL

- The methanol should be produced at a maximum of €350/ton;
- The micro plant can cost at most €143 (200/1.4t) per ton methanol produced;

TECHNICAL

- It must be possible to manually power-off the micro-plant system;
- An optimum must be found regarding the thermal insulation and costs;
- An optimum must be found for the system sizing and the system's processing time, so that all systems have a maximum operating time and efficiency;
- Heat pipe lenghts must be minimised to optimise the efficiency;
- The methanol micro-plant must work with industry standard ((1956x992x50mm)) solar panels;
- After twenty years, the methanol micro-plant must operate with at least 80% of its initial efficiency;
- The methanol micro-plant's design must facilitate mass-production (40.000-4.000.000 units).

ASSEMBLY, DISASSEMBLY AND INSTALLATION

- The assembly of the subsystems that contain high pressure must happen in factory environment.
- It must be possible to disassemble the micro-plant;
    - Design for assembly and disassembly principles need to be considered.
- The subsystems that contain high pressure can not be individually disassembled in the field
    - In a factory environment the disassembly of subsystems that contain high pressure should be possible

LOCATION

- The embodiment design must be able to stand temperatures between -20°C and 60°C;
- The embodiment design, including maintenance, must still be functioning after twenty years with seven sun-hours per day;
- The embodiment design must be able to withstand daily dust and rainfall;
- The embodiment design must be robust enough to stand extreme weather like sandstorms and heavy rainfall.

SUSTAINABILITY

- Methanol from ZEF must have a lower carbon footprint than fossil fueled methanol;
- The methanol micro-plant cannot use chemicals banned from C2C certified list;
- The integration design enables disassembly for cost effective reuse, remanufacturing, or recycling;
- 90% of the micro plant's parts/materials must get a second life cycle;
- No potentially harmful chemicals can be leaked into the environment.

LOGISTICS

- The methanol micro-plant, must be transported by ship and truck;
- When a product breaks down, it must be transported back to the factory for research.

SAFETY

- The methanol micro-plant must not cause harm to operators, or maintenance workers;
- The methanol micro-plant's design must show its intended maintenance operation by design 'use-cues';
- The methanol micro-plant must ensure that operators and maintenance workers will not touch hot (>60°C) areas on the micro-plant;
- For all trained personal it must be clear how to connect, disconnect and transport the methanol micro-plant;
- Except for air, water and oxygen, chimicals cannot leak out of the micro-plant.

SUBSYSTEMS

ABSORPTION

- No dust larger than 1 micrometer can enter the absorption chamber;
- No sunlight can enter the absorption chamber;
- The sorbent cannot clock in the valves;
- The absorption chamber must be positioned in such a way that the sorbent flow through the chamber is led by gravitational forces;
- Maintenance workers need to be able to insert new sorbent to the absorption chamber within twenty seconds;
- The absorption chamber design should allow the air-filters to be changed;
- When the sorbent is at the bottom of the absorption chamber, it must be recirculated, or led to the desorption chamber;
- Per desired gram of methanol output, 1.37g. of CO_2 needs to be absorbed together with 0.22g. H_2O;
- The temperature of the sorbent should be below 40°C when contacting air (O_2);
- Sufficient air flow is needed to get the needed 'nutrients' inflow (depending on the absorption efficiency rate).
- The air fan must be located at the top side of the absorption chamber (air flow goes from the bottom up)

DESORPTION

- At least 80% of the adsorbed CO_2 and H_2O needs to be desorbed from the sorbent material;
- The desorption chamber must operate at a vacuum of 0.1 bar;
- The bottom of the desorption chamber must be heated to 125°C;
- The top of the desorption chamber must be heated to 60°C;
- There must be thermal insulation between the different wall temperatures of the desorption chamber.
- The desorbed H_2O and CO_2 gases must flow to the compressor;
- The process of saturating sorbent with CO_2 and H_2O should take the same amount of time as the desorption time of the previously saturated sorbent;
- The desorption chamber must be located below the absorption chamber.

COMPRESSING

- A compression ratio of 510 needs to be achieved, from 0.1 bar to 51 bar;
- The compressor needs to bare the output yield from the desorption chamber;
- The compressing system should not exceed a temperature of 107°C (glass temperature PTFE), or other materials need to be used that can withstand higher temperature;
- The gases need to flow through the cooling chambers from the bottom up (gravitational);
- The compressor must only compress gases, liquids must escape out of the chambers.
- The compressor input must be located on the same height, or below the gas output of the desorption chamber

BUFFERING CO_2 H_2O

- The buffer needs to bear a temperature of 115°C;
- The buffer needs to bear a pressure of 51 bar;

- The buffer needs to have a higher pressure than the degassing and electrolysis stages;
- The buffer needs to be big enough to store all CO_2 and H_2O until the AEC starts operating, and after the AEC has finished operating (1 hour);
- The CO_2 and H_2O buffer needs to have a tank size of
  Buffer volume (l) = 0.55/compression ratiogCO_2 + gH_2O;*
  (CO_2 as a gas has a volume of 0.55 litres per gram (Air Products and Chemicals, 2018).)
- The buffer input must be located at the same height, or below the output of compressor, as there are fluids in the system;
- The buffer must be located above, or on the same height as the electrolyzer to direct the water flow.

DEGASSING

- The degassing stage needs to bear a temperature of 115°C;
- The degassing stage needs to bear a pressure of 51 bar;
- The CO_2, O_2 and excess H_2O need to be released into the air;
- The degassing stage needs to have an orientation that facilitates the bubble flow.

ELECTROLYSIS

- The 'gas chambers' need to be located on top of the electrolysis system, so that gravitational forces lead the hydrogen towards the buffer;
- The electrolyzer tube needs to lay horizontally;
- The electrolysis system needs to maintain a temperature of 90°C;
- The power conversion to heat at the electrolysis phase, needs to heat the desorption and DS system with an efficiency of at least 50%;
- No KOH can leak out of the electrolysis chamber;
- The electrolyte cells need to be connected in series;
- The materials used for the buffer system need to be resistant to H_2O, H_2, O_2 and KOH.

BUFFERING H_2

- One sixth of the daily needed H_2 needs to be buffered, so that the methanol synthesis can continue for one hour after power has dropped to the level at which there is no longer sufficient power available for the electrolysis;
- The materials used for the buffer system need to be resistant to H_2O, H_2, and O_2;
- The H_2 buffer needs to have a minimal tank size of:
  *Volume H_2 buffer = GramsH_2 buffered * 12 / compression ratio.*
  (H_2 as a gas has a volume of 12 litres per gram (Air Products and Chemicals, 2018).)

METHANOL SYSNTHESIS (MS)

- The hot side of the MS needs to operate at 230°C;
- The cold side of the MS needs to be 60°C;
- The MS needs to operate at 50 bar;
- The MS system needs to be tilted a few degrees;
- The MS outlet needs to be at the lowest part of the MS system;
- An efficient (90%) heat transfer is needed to provide passive heating and cooling;
- The heat pipes have a maximum length of 20cm;
- The MS system must have an external (electric) heater;
- There must be an outlet (check valve) when CO, CO_2, and H_2 gases are putting too much pressure on the system;
- The materials used for the MS system need to be resistant to H_2O, H_2, CO_2, CO and CH_3OH;

DISTILLATION

- The produced methanol must be AA grade, i.e. have a purity of 99.85% (by weight);
- The middle tube with the capillary cloth needs to be horizontally oriented;
- The DS blocks need to be vertically oriented;
- The heat buffer should provide most of the needed heat;
- The heated DS block needs a temperature higher than 100°C;
- The 'cold' DS block needs to be cooler than 100°C (colder is better);
- The middle tube and hot block need to be insulated;
- A wick through the connection of the hot and cold side must provide sufficient capillary flow;
- The materials used for the DS system need to be resistant to CH_3OH and H_2O.

SOLAR CONNECTION

- The micro-plant should not obstruct the solar panels from receiving sun at any moment;
- The methanol micro-plant must be assembled or disassembled to the solar system within 10 minutes;
- The micro-plant must offer a connection method to the longitudinal axis of the solar racking system;
- The micro-plant must facilitate to be implemented as a stand-alone system, next to the solar panels.

WISHES FOR INTEGRATION DESIGN

- The weight of the micro-plant should be minimised ;
- The number of needed components should be minised;
- As little as possible heat should get lost;
    - The exothermal MS process should heat the desorption and DS as efficient as possible;
- The spatial proximity between the subsystems is as close as possible;
- The assembly of the micro-plant happens within the factory (not in the field);
- The in the field installation must be as fast as possible;
- The absorption chamber can be replaced in the field;
- The assembly time of the micro-plant is as low as possible.

APPENDIX F, SCALING EFFECTS PER COMPONENT

In table F1 all the components from the bill of materials, scenario mass production, are elaborated regarding scaling. There is a division between components that scale proportionally and components that do not scale proportionally. The non-proportional components have most impact on scaling potential. For these components, an explanation is provided regarding the type of scaling. Also, per component it is stated whether price dips are applicable.

Absorption, Desorption	Component cost	Proportional scaling	Non- proportional scaling	Cost dips possible?	Explanation	Additions Constraints
Air filters	3.16	X		X	Scales with airflow, if the fan remains the same size but fans fast-er, then still more air filtering is needed	
Sorbent	19.13	X				Clogging may become less likely when tubing increases in diameter
Fan	8.29	X		X	Multiple fans could be placed next to each other.	Non-proportional when different fans are used.
Peltier element	1.02	X		X	Proportional when the cheapest design is numbered up.	scaling range min 40x40mm, max 200x200mm per ele-ment. Output is proportional with size
Level sensors	0.20		X		Same sensors for dif-ferent system sizes	Costs/kgMeoH= 1/scale * € (at scale 1), till 10
High pressure sensor AEC	3		X		Same sensors for dif-ferent system sizes	Costs/kgMeoH= 1/scale * € (at scale 1), till 10
Vacuum sen-sor	0.91		X		Same sensors for dif-ferent system sizes	Costs/kgMeoH= 1/scale * € (at scale 1), till 10
NTC	0.09		X		Same sensors for dif-ferent system sizes	Costs/kgMeoH= 1/scale * € (at scale 1), till 10
Sorbent pump	4.25		X	X	about 20% less costs/kg MeOH, per system size doubling	
Valves,	22.70		X	X	The base-case valve works until about 4 times the system size, then a larger valve for the next 4 system sizes is needed, and so on.	
H-bridge double	1.02		X	X	Proportional with valves. Per two sole-noid valves one H-bridge is needed	Absolute costs remain similar when scaling
Sorbent flow racks	1.06	X				proportional with the sorbent
absorption chamber	1.91	X			about proportional	mathematically scales with square root size, neglecting wall thickness, materials etc.
desorption chamber	1.32	X			about proportional	mathematically scales with square root times the size, neglecting wall thickness, materials etc.

Table F1, Scaling effects per component

Compressor	Component cost	Proportional scaling	Non- proportional scaling	Cost dips possible?	Explanation	Additions Constraints
Brushless Drone Driver	3.66		X	X	Numbers up with drone motor. Scaling up with larger drivers is about similarly priced.	one motor is sufficient till about 3 times scaling, numbering up is possible
Brushless Drone Motor	4.14		X	X	1-10 times max scaling, with numbering up. Next larger motors are needed.	one motor is sufficient till about 3 times scaling, numbering up is possible
Bearings	1.11	X			Bearing sizes and costs increases about proportionally	
Gearing sys-tem	4.00		X		plastic, metal bounda-ry, around 1, next 20% decrease per doubling.	
Check valve (umbrella)	0.30		X	X	Same for different system sizes	Costs/kgMeoH= 1/scale * €(at scale 1), till 10
Casing Al	6.34		X		20% off / kg MeOH per doubling in size	Complexity decreases with size increase, mass decreas-es, so more important
Pistons Brass	0.38	X			Material increases proportionally	
Piston sliders PTFE	0.77	X			Material increases proportionally	The pistons can never compress the fluid water, only gas.
Connection parts	1.12		X		1/scale * base case. / kgMeOH	

AEC, (buffers, degasser, electrolysis)

Buffer H20, CO2	0.36	X			Material increases proportionally	
Membrane	9.60	X			Proportional with electrodes	
Level sensor (hall effect)	0.13		X		Same sensors for different system sizes	
High pressure sensor AEC	3.00		X		Same sensors for different system sizes	
NTC	0.05		X		Same sensors for different system sizes	
Valves	15.13		X	X	The base-case valve works until about 4 times system size, then a larger valve for the next 4 system sizing's is needed, and so on.	

AEC, (buffers, degasser, electrolysis)	Component cost	Proportional scaling	Non- proportional scaling	Cost dips possible?	Explanation	Additions Constraints
H-bridge double	0.51		X	X	Proportional with valves. Per two valves one H-bridge is needed	
Check valve	0.10		X	X	Same for different system sizes	Costs/kgMeoH= 1/scale * € (at scale 1), till 10
Wiring	1.00	X				little less due to assembly
Small bolts (in between cookies	1.60	X			Proportional with nr. Electrodes	
Big bolts	1.00		X		Same for different system sizes	Costs/kgMeoH= 1/scale * € (at scale 1), till 10
Electrode	80.00	X			Proportional with H2 output	
Electrolyte	1.62	X			Proportional with nr. Electrodes	
Cookies	2.18	X			Proportional with nr. Electrodes	
Degasser cookie	0.11	X			Size increases with nr. Cookies	
Buffer H2	0.60	X			Proportional with flow and scale	
Down comer	0.73	X			Only 2 down comers are needed, but wall- thickness increases	
Closing caps, pressure cas-ing	1.32		X		Only 2 closing caps are needed, 50 bar needs to be held	
Pressure cas-ing	24.65	X			Material increases pro-portionally	Possibly price dips could be found.

MS	Component cost	Proportional scaling	Non- proportional scaling	Cost dips possible?	Explanation	Additions Constraints
Catalyst, $CuZnOAl_2O_3$	1.60	X			Proportional with MS size	
Peltier ele-ment	1.34	X		X	Size is proportional with heat energy needed	max 200x200mm
Frequency sensor	0.43		X		Same for different system sizes	Costs/kgMeoH= 1/scale * € (at scale 1), till 10
Level sensor (hall effect)	0.07		X		Same for different system sizes	Costs/kgMeoH= 1/scale * € (at scale 1), till 10
High pressure sensor MS	3.00		X		Same for different system sizes	Costs/kgMeoH= 1/scale * € (at scale 1), till 10
NTC	0.05		X		Same for different system sizes	Costs/kgMeoH= 1/scale * € (at scale 1), till 10
Valves, sole-noid	22.70		X	X	The base-case valve works until about 4 times system size, then a larger valve for the next 4 system sizing's is needed, and so on.	
H-bridge double	1.02		X	X	Proportional with valves. Per two sole-noid valves one H-bridge is needed	
Heat pipes	3.27		X	X	Probably 20% less materials per doubling	20 cm, max, capillary limit
Piping curved	5.18	X			There is a minimum due to the catalyst sizing. Probably this minimum is larger than what's needed for the yield of a 300Wp panel. Fur-thermore, the sizing moves proportional	Possibly the wall thickness could differ over the tube. Only the catalysts has a min-imal width
Piping straight	13.68	X			There is a minimum due to the catalyst sizing. Probably this minimum is larger than what's needed for the yield of a 300Wp panel. Fur-thermore, the sizing changes linearly	Possibly the wall thickness could differ over the tube. Only the catalysts has a min-imal width
MS block	20.83		X		Complexity, 20% decrease / doubling	

DS	Component cost	Proportional scaling	Non- proportional scaling	Cost dips possible?	Explanation	Additions Constraints
Electric heater	0.72	X		X	Nr. proportional with heat needed	
Check valve	0.10		X	X	Probably 20% costs decrease per size doubling	
Level sensor (hall effect)	0.13		X		Same sensors for different system sizes	
NTC	0.09		X		Same sensors for dif-ferent system sizes	
Valves	22.70		X	X	The base-case valve works until about 4 times system size, then a larger valve for the next 4 system sizing's is needed, and so on.	
H-bridge double	0.51		X	X	Proportional with valves. Per two valves one H-bridge is needed	
Piping T shape	1.18	X			Material increases proportionally	
DS Piping straight	0.82	X			Material increases proportionally	
Wick	0.06	X			Material increases proportionally	
DS block cold	5.95		X		Complexity, 20% / doubling	
DS block hot	3.89		X		Complexity, 20% / doubling	

Control and integration

Arduino nano	3.20		X	X	Same hardware, but more complexity, more safety needed, opera-tors at certain scale?? Safety	
O rings	2.00		X		1/scale times costs	
DC-DC con-verter 5V??	0.48	X		X	More expensive, be-cause out of dip	
16 bit ADC	4.08		X	X	1/scale times costs	
Cable harness	3.00	X			Proportional with wire lengths	
Ampère sen-sor	1.02		X		Same sensors for dif-ferent system sizes	
Volt sensor	0.52		X		Same sensors for dif-ferent system sizes	
Integration embodiment, aim	10.00	X			About proportional	

APPENDIX G SYSTEM HEATING TIME

Before the methanol micro-plant functions, the individual subsystem-processes need to heat up. This heat-ing time will increase along with the system size. To get a feeling on the relationship between the system's size and the start-up time the process is modelled.

MS heating time
The system is modelled as a tube with a radius (r) and wall thickness (w). This piping system is heated by a heating element of 40x40mm (figure G1). The heating time of the tube can be calculated with:

*E_needed = C *m *dT*
t-heating = E_needed / P_available

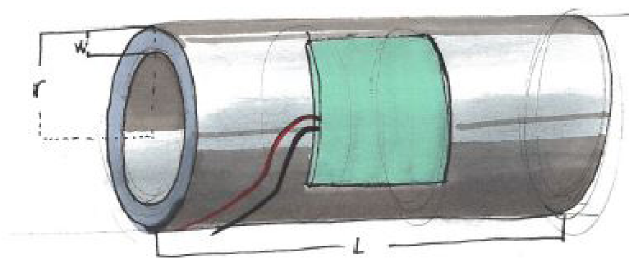
In the formula, C stands for the specific heat, 'm' for the mass and 'dT' is the temperature difference. The P_available is the power of the heating element.

The MS system will linearly increase in weight compared to its yield. Because of this, the power needed during the start-up time will also increase linearly if the start-up time cannot change (table G1). For the start-up larger heating elements are needed, but according to these formula, heating a larger system should not be a problem.

Table G1, Heating time

Wp	MS mass to be heated	P needed at start-up	Heating time (to 230°C)
300	1kg	53W	30 minutes
600	2kg	106W	30 minutes
1200	4kg	211W	30 minutes
2400	8kg	423W	30 minutes

The previously shown formulas are far from reality as it only considers the heating time of the steel. The conduction is not considered. For a more realistic model the conduction should be considered, as well as the heating of the CO_2 and H_2. This calculation can be seen in the maple file presented below. Still, these results contain too large errors to use. Undesired thermal conductivity to the parts that do not need to be heated is not considered, neither is the fact that the gases flow through the tube, so the dynamic system is represented statically. For these reasons the obtained results only give insight in the influencing factors for the start-up time. No clear data can be retrieved from the results.



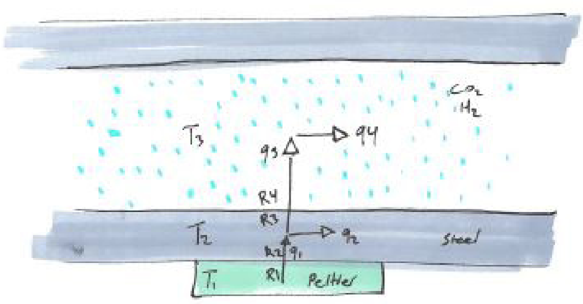


Figure G1, MS heating system

> restart;
x := 1;#scaling factor

$x := 1$ (1)

> q1 := q2 + q3;
rtube := 0.025; #radius pipe
ltube := x·0.2;
L1 := 0.0025;#half thickness peltier element
L2 := 0.001;#half thickness pipe, normal 2mm
k1 := 17;# $\frac{W}{M}$ Celcius thermal conductivity steel
k2 := k1;#assumption material peltier element is same as tube
h3 := 50;
#https://www.engineersedge.com/heat_transfer/convective_heat_transfer_coefficients$_{13378.htm}$
A1 := x·0.04·0.04;#surface area peltier element
A2 := x·2·Pi·rtube·ltube :
A3 := A2 :
Csteel := 500;# $\frac{J}{kg}$ specific heat capacity steel
CH2 := 14000;# $\frac{J}{kg}$ specific heat H2 https :// en • wikipedia • org / wiki / Heat_capacity
CCO2 := 839;# $\frac{J}{kg}$ specific heat CO2 https :// en • wikipedia • org / wiki / Heat_capacity
mSteel := $(\mathrm{Pi}\cdot rtube^2 - \mathrm{Pi}\cdot(rtube - 0.001)^2)\cdot ltube\cdot 7850$;
#diameter times length times mass stainless steel per density
mH2 := $x\cdot\frac{0.038}{7}$;# $\frac{kg\ H2}{hour}$ heated
mCO2 := $x\cdot\frac{0.261}{7}$;# $\frac{kg\ CO2}{hour}$ heated
Tpeltier := 230;#degrees

$q1 := q2 + q3$
$rtube := 0.025$
$ltube := 0.2$
$L1 := 0.0025$
$L2 := 0.001$
$k1 := 17$
$k2 := 17$
$h3 := 50$
$A1 := 0.0016$
$Csteel := 500$
$CH2 := 14000$
$CCO2 := 839$
$mSteel := 0.2416827228$

$mH2 := 0.005428571429$
$mCO2 := 0.03728571429$
$Tpeltier := 230$ (2)

> $R1 := \frac{L1}{k1\cdot A1}$;
$R2 := \frac{0.5\ L2}{k2\cdot A2}$;
$R3 := R2$;
$R4 := \frac{1}{h3\cdot A3}$;

$R1 := 0.09191176469$
$R2 := 0.0009362055475$
$R3 := 0.0009362055475$
$R4 := 0.6366197723$ (3)

> $equ1 := \frac{(Tpeltier - Tsteel(t))}{R1 + R2} = mSteel\cdot Csteel\cdot diff(Tsteel(t), t) + \frac{(Tsteel(t) - Tgas(t))}{R3 + R4}$; #

$equ1 := 2477.167776 - 10.77029468\ Tsteel(t) = 120.8413614\ \frac{d}{dt}\ Tsteel(t) + 1.568489725\ Tsteel(t) - 1.568489725\ Tgas(t)$ (4)

> $equ2 := \frac{(Tsteel(t) - Tgas(t))}{R3 + R4} = mH2\cdot CH2\cdot diff(Tgas(t), t) + mCO2\cdot CCO2\cdot diff(Tgas(t), t)$;

$equ2 := 1.568489725\ Tsteel(t) - 1.568489725\ Tgas(t) = 107.2827143\ \frac{d}{dt}\ Tgas(t)$ (5)

> $equ3 := mSteel\cdot Csteel\cdot diff(Tsteel(t), t) + mH2\cdot CH2\cdot diff(Tgas(t), t) + mCO2\cdot CCO2\cdot diff(Tgas(t), t) \le 30$;

$equ3 := 120.8413614\ \frac{d}{dt}\ Tsteel(t) + 107.2827143\ \frac{d}{dt}\ Tgas(t) \le 30$ (6)

> ics := Tsteel(0) = 30, Tgas(0) = 30;

$ics := Tsteel(0) = 30, Tgas(0) = 30$ (7)

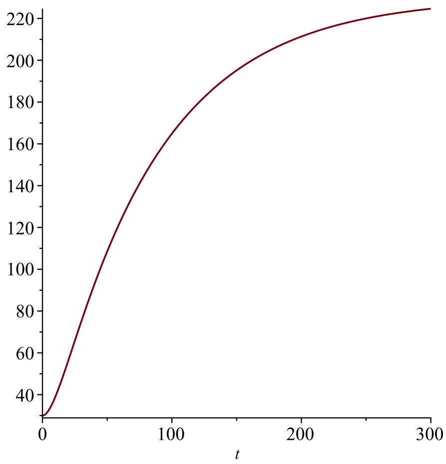
> sol := dsolve({equ1, equ2, ics}, {Tsteel(t), Tgas(t)}, type = numeric, output = listprocedure, maxfun = 50000000);

sol := [t = **proc**(t) ... **end proc**, Tgas(t) = **proc**(t) ... **end proc**, Tsteel(t) = **proc**(t) ... **end proc**] (8)

> Tgas := rhs(sol[2]);

Tgas := **proc**(t) ... **end proc** (9)

> plot(Tgas(t), t = 0 ..300)



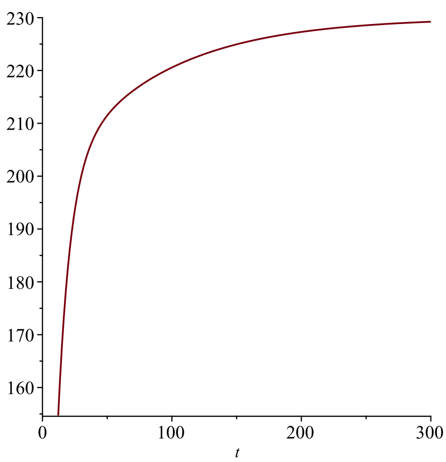
> Tgas(300);

224.659121579627 (10)

> Tsteel := rhs(sol[3]);

Tsteel := **proc**(t) ... **end proc** (11)

> plot(Tsteel(t), t = 0 ..300)



Heating time when thermal resitances and conduction times are neglected and only direct material and gas heating is considered.

> dT := 210; #degrees
$Eneeded := mSteel\cdot Csteel\cdot dT + mH2\cdot CH2\cdot dT + mCO2\cdot CCO2\cdot dT$;
Pavailable := 30;
$Tneeded := \frac{Eneeded}{Pavailable}$;

$dT := 210$
$Eneeded := 47906.05590$
$Pavailable := 30$
$Tneeded := 1596.868530$ (12)

> Q := 30;# $\frac{j}{s}$
$T(t) := \frac{Q\cdot t}{mSteel\cdot Csteel + mCO2\cdot CCO2 + mH2\cdot CH2} + 20$;
T(0) := 20;

$Q := 30$

$T := t \mapsto \frac{Q\ t}{mCO2\ CCO2 + mH2\ CH2 + mSteel\ Csteel} + 20$
$T(0) := 20$ (13)

> plot(T(t), t = 0 ..3000);

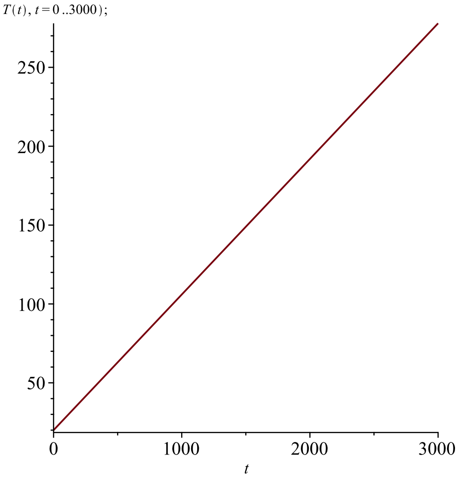


Figure G2, heating time

APPENDIX H, DESIGN SYSTEM MATRIX

The design system matrix (DSM) can be used to represent and analyse the system architecture in terms of relations between constituent components (Browning, 2001). For the methanol micro-plant's architecture, a DSM will be used to represent integration architecture dependencies and sequences.

All subsystems are evaluated on the material flow, compression and heating relations. Whenever two subsystems are related, the connecting cell is filled with a '1'.

The evaluation means can be described as follows:
Material: a flowing material type of interaction
Pressure: a pressure relation exists (the pressure is transported to the consequent system)
Heat: There is a thermodynamic interaction. Heating, or cooling from different systems are used.

Table H1, DSM's, material flow, pressure, heat

Material flow	'1' = Receives material flow			'-1' = Delivers material flow						
System	1	2	3	4	5	6	7	8	9	10
1 Outside system, solar panel		-1	0	0	0	1	0	0	0	1
2 Adsorption chamber	1		-1	0	0	0	0	0	0	0
3 Desorption chamber	0	1		-1	0	0	0	0	0	0
4 Compressor	0	0	1		-1	0	0	0	0	0
5 Buffer (CO2 + H2O)	0	0	0	1		-1	0	0	-1	0
6 Degasser	-1	0	0	0	1		-1	0	0	0
7 Electrolysis	0	0	0	0	0	1		-1	0	0
8 Buffer (H2)	0	0	0	0	0	0	1		-1	0
9 Methanol synthesis	0	0	0	0	1	0	0	1		-1
10 Distillation	-1	0	0	0	0	0	0	0	1	

Pressure	'1' = pressure relationship									
System	1	2	3	4	5	6	7	8	9	10
1 Outside system, solar panel		1	0	0	0	0	0	0	0	1
2 Adsorption chamber	1		1	0	0	0	0	0	0	0
3 Desorption chamber	0	1		1	0	0	0	0	0	0
4 Compressor	0	0	1		1	0	0	0	0	0
5 Buffer (CO2 + H2O)	0	0	0	1		1	0	0	0	0
6 Degasser	0	0	0	0	1		1	1	0	0
7 Electrolysis	0	0	0	0	0	1		1	0	0
8 Buffer (H2)	0	0	0	0	0	1	1		1	0
9 Methanol synthesis	0	0	0	0	0	0	0	1		0
10 Distillation	1	0	0	0	0	0	0	0	0	

Heat relation	'1' = Heating			' -1' = Cooling						
System	1	2	3	4	5	6	7	8	9	10
1 Outside system, solar panel		0	0	0	0	0	0	0	0	0
2 Adsorption chamber	-1		1	0	0	0	0	0	0	0
3 Desorption chamber	0	-1		0	0	0	1	0	0	0
4 Compressor	-1	0	0		1	0	0	0	0	0
5 Buffer (CO2 + H2O)	0	0	0	1		1	0	0	0	0
6 Degasser	0	0	0	0	1		1	0	0	0
7 Electrolysis	0	0	-1	0	0	1		1	0	-1
8 Buffer (H2)	0	0	0	0	0	0	1		1	0
9 Methanol synthesis	-1	0	0	0	0	0	0	1		1
10 Distillation	-1	0	0	0	0	0	0	0	1	

APPENDIX I, TUBE AND WIRING CONNECTIONS

Table I1 gives an overview over the needed material flow tubing connections between the different subsystems. Table I2 shows the amount of wires that are needed per subsystem and and electrical component within the methanol micro-plant

Table I1, tubing connections

From system:	To system:	Details
Desorption	Compressor last stage	Sorbent pump
Desorption	Compressor first stage	Vacuum, 0.1 bar
Compressor	CO_2, H_2O buffer	>50 bar
Compressor	Absorption	Sorbent pump flow
CO_2, H_2O buffer	Electrolyzer	Only the fluid level
Electrolyzer degasser	Atmosphere	Umbrella valve followed by an outlet tube (on top of the electrolyzer)
Electrolyzer	H_2 buffer	Direct connection, >50 bar
H_2 buffer	MS	>50 bar
CO_2, H_2O buffer	MS	>50 bar
MS	Atmosphere	Flute sensor, no tube needed
MS	DS	>50 bar (pressure is released here)
DS hot side	Atmosphere	Water release in atmosphere, or collection
DS cold side	MeOH tube / tank	Lead the methanol to a larger tube, or bin

Table I2, Required wiring

SUBSYSTEM	Wires entire subsystem	COMPONENT	Amount	NR. OF WIRES (total)
Absorption	3	Fan	1	3
Desorption	6	Peltier element	1	2
		NTC?	2	4
Compressor	11	Drone motor	1	3
		Drone driver	1	3
		Vacuum sensor	1	5
CO_2 H_2O buffer	13	High pressure sensor	1	3
		NTC	1	2
		Valve	1	2
		H-bridge (combined with Electrolyzer)	1	6
Electrolyzer	14	NTC	3	6
		Level sensor	2	6
		Valve (output degasser)	1	2
H_2 buffer	5	NTC	1	2
		High pressure sensor	1	3
MS	32	Valve	4	8
		H bridge	2	12
		Electric heater	1	2
		Level sensor	1	3
		NTC	2	4
		High pressure sensor	1	3
DS	22	Valves	2	4
		H bridge	1	6
		Peltier element	1	2
		Level sensor	2	6
		NTC	2	4
Total nr. wires:	**106**			

APPENDIX J, HEAT INTEGRATION

The methanol micro-plant must work at its highest potential efficiency to become economically viable. Therefore, Inter-subsystem heat integration is needed. The electrolysis process is exotherm and produces 'waste' heat of about 90°C. The desorption and distillation processes are endotherm processes and need a temperature of about 125°C. A heat pipe is located inside the electrolysis system and collects the 'waste' heat. Next the heat pipe moves upwards to the desorption and distillation systems. Here the temperature will be bridged from 90°C to 125°C using a peltier element.

POWER SAVING POTENTIAL

The calculation sheet from appendix D is used for this analysis.

The electrolyzer utilises most of the produced power from the solar panels. From the 900Wp available (from three solar panels), the electrolyzer will use about 640Wp if it could run with a 70% efficiency. The 30% loss will be transformed to heat.

Electrolyzer power consumption: 730Wp
Electrolyzer power efficiency loss to heat: 220W

Heating power needed desorption: 120W
Heating power needed at DS: 6W

If we assume the electrolyzer's waste heat can be utilised for the desorption and DS system with an efficiency of 50%, then about 110W of heating power can be saved. Figure J1 visualises the electrolyzer, desorption and DS thermal relationship.

Note The power need at the desorption stage is much higher than at the distillation phase. This is caused by the large amount of sorbent that needs to be heated.

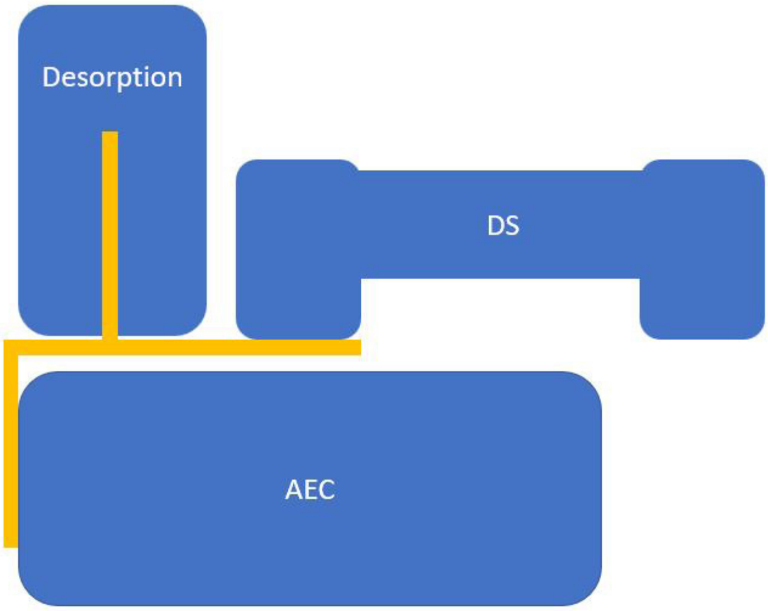


Figure J1, heat pipe integration schematic

APPENDIX K, INSULATION

DIFFERENT TYPES OF INSULATION

Insulation materials are materials that reduce the heat transfer between objects of different temperatures. These materials have a low thermal conductivity (k) value, or they reflect radiative heat. Insulation types can be separated into: loose-fill, blankets, foam and reflective isolation (OJ Insultation, 2018).

Loose-fill
A material is blown inside an existing form. The material is injected inside the casing of the micro-plant. This is an easy one size fits all solution, however if the fill material hardens as foam, then removal is hardly possible.

Blanket insulation
An insulation blanket, e.g. glass wool, would could be connected to flat, or easily shaped surfaces.

Rigid, or casted foam
Rigid foam insulation comes in the form of plates, or it can be expanded to fit a specific mould. With this type of insulation, the material can be used most effectively, when the design is made to optimise thermal properties.

Reflective insulation
Reflective insulation can be used to minimise radiative heat from the sun or other sources. This type of insulation may be used within the micro-plant for the components that should be low in temperature. The casing colour of the components that are exposed to sun impacts the reflectiveness as darker colours absorb sunlight and lighter colours reflect.

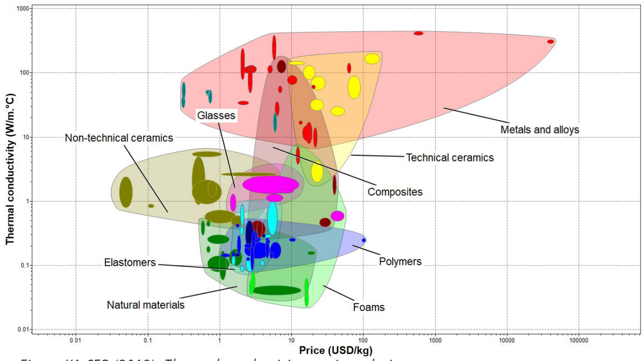


Figure K1 CES (2018), Thermal conductivity – price relations

Common insulation materials
- **Fiberglass** is widely used within the building sector and can be used to be blown into cavities, or as a blanket.
- **Cellulose** is generally the most environmentally friendly option for insulation as it can be produced from recycled and bio-based materials.
- **Radiant barrier insulation** is a common reflective type of insulation.
- **Polystyrene** is a commonly used material for rigid insulation blocks.

In figure K1 the thermal conductivity of different material categories is plotted to the price. Yet, more factors need to be considered, like operation temperatures, manufacturability, density and sustainability. Several possible insulation materials are examined on these factors (table K1).

	Thermal conductivity (W/m.°C)	Cost (USD / kg)	Density (kg/m3)	Max working temperatures (°C)	Sustainability
Glasswool sheet	0.04 (2)	1.5-15 (2)	12-100 (2)	230-540 (2),(5)	Less good (6)
Rock wool sheet	-	-	132-250 (1)	760 (5)	-
Cellulose loose fill	0.04 (4)	1.33 (4)	24-160 (1)	255 (3)	Good (6)
Rigid Polystyrene	0.034-0.064 (7)	15.3-16.9 (7)	170-470 (7)	77-167 (7)	Non-recyclable (7)
Phenolic foam	0.02 (7)	6.6-7.5 (7)	32-38 (7)	150 (5)	Non-recyclable (7)
Ceramic foam	0.5-0.7 (7)	35-53 (7)	392-670 (7)	1200-1800 (5), (7)	-

Table K1, insulation material examination, The numbers are indications found from different sources. Further research may show some more divergence. Sources:

(1) P. Norton (2019). Types of insulation. Retrieved 31 March 2019, from: https://www.energy.gov/energysaver/weatherize/insulation/types-insulation http://www.wbdg.org/guides-specifications/mechanical-insulation-design-guide
(2) National Industrial Co (date unknown). Glasswool (fibre glass) insulation. Retrieved 31 March 2019, from: http://www.natindco.in/insualting-products/glasswool
(3) P. Rantuch, T. Chrebet (2013). THERMAL DECOMPOSITION OF CELLULOSE INSULATION. Retrieved 31 March 2019, from: http://www.cellulosechemtechnol.ro/pdf/CCT5-6(2014)/p.461-467.pdf
(4) Ecomerchant (2019). Thermofloc Loose Fill Cellulose Insulation 12kg. Retrieved 31 March 2019, from:https://www.ecomerchant.co.uk/thermofloc-loose-fill-cellulose-insulation-12kg.html
(5) Engineering ToolBox (2005). Insulation Materials - Temperature Ranges. Retrieved 31 March 2019, from: https://www.engineeringtoolbox.com/insulation-temperatures-d_922.html
(6) ApplegateInsulation (Date unknown). Performance and Safety Factors. Retrieved 31 March 2019, from: http://www.applegateinsulation.com/Product-Info/Technical-Pages/249460.aspx
(7)CES Edupack (2018). [Computer Software]. Cambridge (UK), Granta Headquarters

APPENDIX L, COST PER KILOGRAM CALCULATIONS

According to ZEF, the production costs of large mass-produced technological products can be approached by the products mass, multiplied by €10 per kg. There was no literature found to support this statement. Therefore, in this section a sample research is conducted to determine the production cost per kg for three different models of cars.

CAR PRODUCTION COSTS

According to Meister (2018) 57% of the total costs per car go into the production of the car. The other 43% of the costs go into research, advertisements, dealership rates and taxes. The total car production costs can be calculated with:

*(1) Production costs: (Retail price - mean profit per car) * 57%*

CASE STUDIES

Toyota C-HR

The Toyota C-HR model has a retail price of €30.950,- (Autokopen.nl, 2019). According to Klaus (2016) Toyota makes a mean profit of €1602 per sold model. Using formula (1), this brings the production costs to: €16.728,-.

The Toyota C-HR has a mass of 1395kg. This brings the production costs per kg to:
€12/kg

Figure L1, Toyota C-HR. Retrieved April 11, 2019, from: https://www.autokopen.nl/voorraad-nieuw/toyota/c-hr/8179743-toyota-c-hr-18-hybrid-executive-nwpr-ac-36890?sqid=5fef5839f26440259af42bf1668d6ad7#autogegevens

Volkswagen Caddy 2.0

The Volkswagen Caddy has a retail price of €17.490,- (Autokopen.nl, 2019). According to Klaus (2016) Volkswagen makes a mean profit of €801 per sold model. Using formula (1), This brings the production costs to: €9512.

The Volkswagen Caddy has a mass of 1351kg. This brings the production costs per kg to:
€7/kg

Figure L2, Volkswagen Caddy. Retrieved April 11, 2019, from: https://www.google.com/search?hl=nl&q=vw+caddy&tbm=isch&tbs=simg:CAQSkwEJ5yge9uL-280ahwELEKjU2AQaAAwLELCMpwgaYgpgCAMSKLwGlQKWApcCmwK7Br0GvgaYApoC1zK4MrcmrSaEJv8lvjLoILImuTIaMBbA2sSc0q6n1nSYsTV-W2e06Oed5N9e0FdrocF_1hyvGoLBYWhnGDU9fzha0I-qU4CAEDAsQjq7-CBoKCgglARIEOdwQOgw&sa=X&ved=0ahUKEwik0u36stLhAhUJL1AKHfHMBBYQwg4IKSgA&biw=1707&bih=838&dpr=1.13#imgrc=ECT_fTyvSfebAM:

Ford Focus

The Ford Focus has a retail price of €24.160,- (Ford, 2019). According to Klaus (2016) Ford makes a mean profit of €1652 per sold model. Using formula (1), this brings the production costs to: €12830.

The Ford Focus has a mass of 1322kg. This brings the production costs per kg to:
€10/kg

Figure L3, Ford Focus. Retrieved April 11, 2019, from: https://www.ford.nl/alle-modellen/focus

CONCLUSION

This research shows a range from €7/kg to €12/kg in car production costs. These samples show that using the by ZEF recommended €10/kg target price will likely deliver a close cost approximation for a mass-produced micro-plant.

DISCUSSION

The Toyota C-HR has the highest production costs per kilogram. This may be explained by looking at the yearly number of produced cars (table L1). The Toyota C-HR has a yearly production of 130k cars, where the Volkswagen Caddy has a yearly production number of 490k. Prices drop when the production numbers increase. For the Ford Focus there was no production number found for the new model.

Car	Retail (€)	Production (€)	€/kg	Production / year
Toyota C-HR	30950 (3)	16728	12	130k (1)
Volkswagen Caddy	17490 (4)	9512	7	490k (2)
Ford Focus	24160 (5)	12830	10	-unclear

Table L1, €/kg car samples

(1) Toyota Europe Newsroom (2016). Toyota C-HR production starts in Europe. Retrieved April 11, 2019, from: https://newsroom.toyota.eu/toyota-c-hr-production-starts-in-europe/

(2) Volkswagen (2017). Volkswagen Commercial Vehicles. Retrieved April, 11, 2019, from: https://annualreport2017.volkswagenag.com/divisions/volkswagen-commercial-vehicles.html

(3) Autokopen.nl (2019). Toyota C-HR. Retrieved April 11, 2019, from: https://www.autokopen.nl/voorraad-nieuw/toyota/c-hr/8179743-toyota-c-hr-18-hybrid-executive-nwpr-ac-36890?sqid=5fef5839f26440259af42bf1668d6ad7#autogegevens

(4) Autokopen.nl (2019). Volkswagen Caddy 2.0. Retrieved April 11, 2019, from: https://www.autokopen.nl/voorraad-nieuw/volkswagen/caddy/7845467-volkswagen-caddy-20-tdi-55kw75pk-bmt-highline-vsb3657?sqid=ea3af4daeea147ffa8837fb4b2197e83#autogegevens

(5) Ford (2019). De nieuwe Ford Focus. Retrieved April 11, 2019, from: https://www.ford.nl/alle-modellen/focus