T.S. Hacking

Department: Process and Energy; Faculty 3mE
Frontcover image by David van Nunen

Graduation Committee:

Prof.dr.ir. W. de Jong
Dr.ir. G. Korevaar
Prof.dr.ir. C. A. Ramirez Ramirez
Dr.ir. G. A. Tsalidis
Ir. J. van Kranendonk

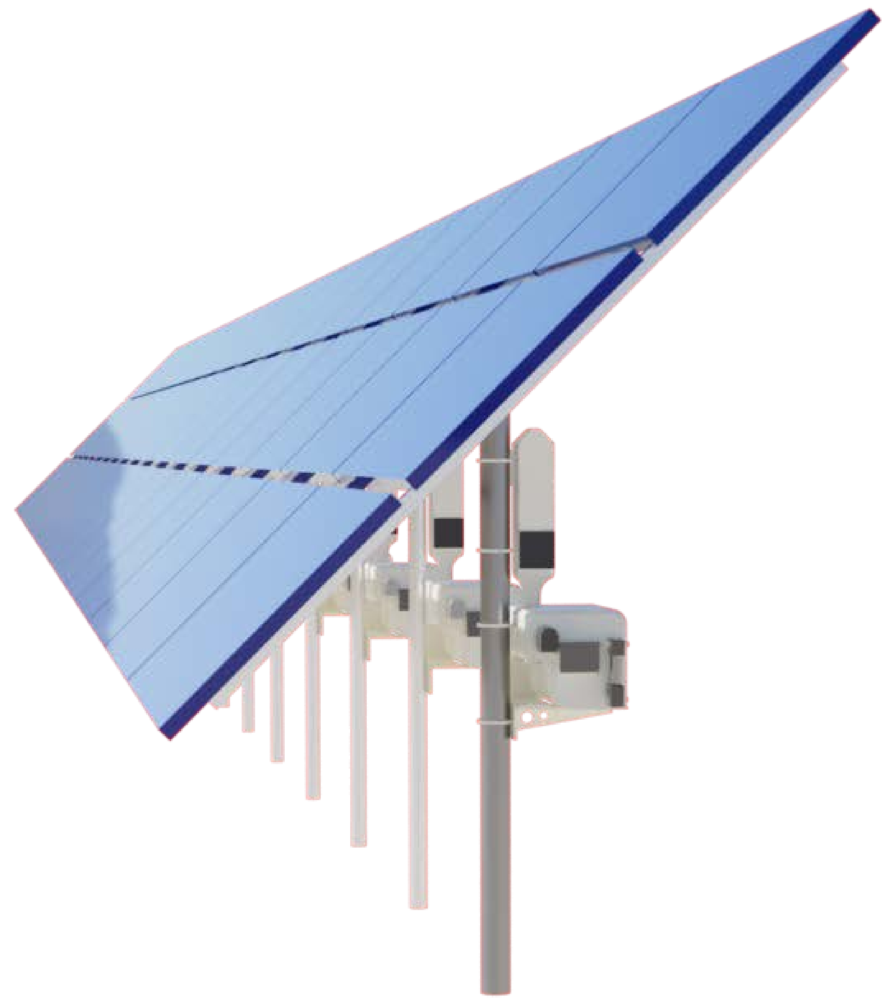
Challenge the future

The Environmental Impact Of A Solar Powered CO_2 To Methanol Farm

Technische Universiteit Delft

The Environmental Impact Of A Solar Powered CO_2 To Methanol Farm

T.S. Hacking



Challenge the future

The Environmental Impact Of A Solar Powered CO_2 To Methanol Farm

by

Tim Sander Hacking

to obtain the degree of Master of Science
at the Delft University of Technology,
to be defended publicly on September 4, 2019 at 1 PM.

Student number:	4293002	
Project duration:	January, 2019 – September, 2019	
Thesis committee:	Prof. dr. ir. W. de Jong,	TU Delft, 3mE || Chair
	Dr. ir. G. Korevaar,	TU Delft TPM
	Prof. dr. ir. C. A. Ramirez Ramirez,	TU Delft TPM
	Dr. ir. G. A. Tsalidis,	TU Delft TPM
	Ir. J. van Kranendonk,	ZEF

This thesis is confidential and cannot be made public until September 2021.

TU Delft

Acknowledgements

First, I want to thank Ulrich Starke, Jan van Kranendonk, & Hessel Jongebreur of ZEF for their help and guidance throughout this project. I had a great time working with ZEF and want to thank all members of ZEF team 4.

From the TU-Delft, I want to thank George Tsalidis. He helped me with the project and was always there to answer my questions. Also, I want to thank Wiebren de Jong & Gijsbert Korevaar for their supervision throughout the project.

Furthermore, I want to thank my brother Jasper Hacking for providing feedback on the report, and Tim de Joode & Stef Koomen for checking the grammar of the report. A special thanks to the men of Verserdam who made sure there was food on the table, and Hub Hacking & Renée Portz for supporting me since high school. Lastly, I want to thank my brother Bas Hacking and my friends for supporting me throughout the process.

Tim Hacking
Rotterdam, August 2019

Abstract

Zero Emission Fuel (ZEF) has the goal to create affordable high-grade methanol, produced from absorbed carbon dioxide and water from the air. The methanol is produced in a solar methanol (MeOH) farm, consisting of 13225 micro-plants which are powered by PhotoVoltaic solar panels (PV panels). The solar capacity of the solar MeOH farm is 12 MW and produces 7.8 tons of grade AA methanol per day (grade AA methanol has a purity of 99.8%). One of the main goals of ZEF is to produce methanol with a smaller environmental impact compared to the currently commonly used production methods. A part of the research focuses on an advice for the type of PV panels to use. The main goal of the research is to determine the environmental impact of methanol produced by the solar MeOH farm. The results lead to an advice for ZEF concerning reducing their environmental impact, also the research advises on further research.

To determine the environmental impact a life cycle assessment (LCA) is performed according to ISO 14040 and ISO 14044 standards, using the ReCiPe 2016 method. The midpoint impact categories researched are the global warming potential (GWP), the mineral resource scarcity, and the fossil resource scarcity. The functional unit of the LCA is one ton methanol. A set of assumptions is made concerning the solar MeOH farm, which are tested in the sensitivity analyses. A second LCA is performed, which compares different PV technologies. This LCA focuses on the endpoint impact categories, and the goal of this LCA is to show which PV technologies have the least environmental impact. The PV technology with the smallest environmental impact, polycrystalline silicon PV panels, is used in the LCA concerning the solar MeOH farm.

One ton of methanol produced by the solar MeOH farm has a GWP of -835 ± 50 (6.5%) kg CO_2 equivalent, proving that the methanol produced by ZEF absorbs CO_2. When the end-use of methanol is included, approximately 40% of the methanol produced by ZEF should be used for the production of plastic and chemicals to produce zero-emission methanol. After 7.9 ± 0.8 years of production, the solar MeOH farm has reached the CO_2 break-even point. The mineral resource scarcity of one ton methanol produced by the solar MeOH farm is 10.7 ± 0.7 (6.3%) kg Cu equivalent, the fossil resource scarcity is 127 ± 13 (10%) kg oil equivalent, and the energy payback time (EPT) is 6.9 ± 0.7 years of methanol production. The most crucial factor that influences the environmental impact is the amount of equivalent sun hour (ESH), therefore, the solar MeOH farm should operate on a location with a high amount of ESH to decrease the environmental impact. A 1% decrease of micro-plant efficiency increases the environmental impact with more than 1%. The recommendation is to focus on lifetime and efficiency when designing new subsystems, since lifetime is a more important factor than the materials used.

Contents

List of Figures

List of Tables

Nomenclature

Glossary

Micro-plant	A micro-plant that produces methanol
Modular MeOH system	The micro-plant including photovoltaic panels and mounting system
Solar MeOH farm	A farm consisting of 13225 modular MeOH systems

Abbreviations

a-Si	Amorphous Silicon
AEC	Alkaline Electrolytic Cell
BOS	Balance Of System
CdTe	Cadmium Telluride
CIGS	Copper Indium Gallium Selenide
DAC	Direct Air Capture
DALY	Disability Adjusted Life Year
DS	Distillation
ESH	Equivalent Sun Hours
GWP	Global Warming Potential
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MS	Methanol Synthesis
PV	PhotoVoltaic
USD	United States Dollars
ZEF	Zero Emission Fuels

Units

J	Joule
kWh	Kilowatt hour
W	Watt
Wp	Watt-peak

Chemical compounds

CH_3OH	Methanol
CO	Carbon monoxide
CO_2	Carbon dioxide
COS	Carbon oxysulfide
H_2	Hydrogen
H_2S	Hydrogen sulfide
H_2O	Water
KOH	Potassium hydroxide
MeOH	Methanol
N_2	Nitrogen
PEI	PolyEthyleneImine
PET	PolyEthylene Terephthalate
PPS	PolyPhenylene Sulfide
Si	Silicon

1 Introduction

1.1. Context

In December 2015, 174 countries and the European Union signed the Paris agreement [1]. A part of this agreement is to keep the global temperature rise in the 21st century well below 2 °C compared to pre-industrial levels, and to pursue efforts to limit the temperature increase even further to 1.5 °C [2]. The leading cause of global warming is the increase in greenhouse gasses in the atmosphere. Greenhouse gasses like CO_2 are emitted during the burning of fossil fuels like coal, gas, and oil. In figure 1.1, the primary energy supply is depicted. This figure shows a growth in primary energy use as well as a growth in the amount of fossil fuel used. In the year 2017 the number of greenhouse gasses emitted increased by 1.3% [3]. To reach the goals of the Paris agreements more renewable energy generation needs to be implemented.

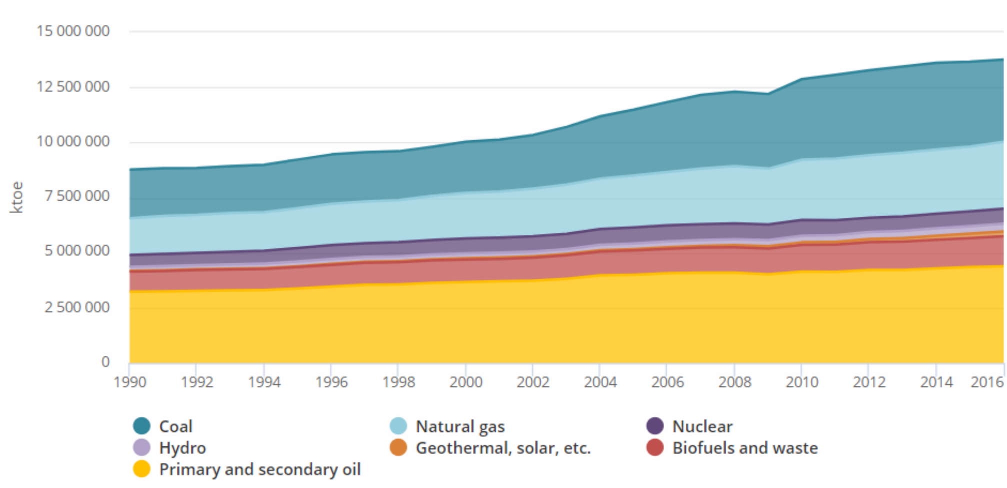


Figure 1.1: Worldwide total primary energy supply from 1990 to 2016 [4].

To become fully sustainable and reach the Paris agreement, not only renewable electrical energy sources are needed. In 2016, around 19% of the primary energy supply was used to produce electricity. However, the oil consumption was 41%, and the gas consumption 15% of the total primary energy use. The main end-use for oil is the use of fuels, while gas is mainly used as a chemical feedstock and for heating [4]. These percentages indicate the energy and chemical dependency on hydrocarbons. This dependency means new methods for sustainable production of hydrocarbons, or chemicals that replace hydrocarbons, are necessary to become fully sustainable. An example of a hydrocarbon that can be used as fuel and feedstock is methanol. The focus of this research is the production of renewable methanol by using solar power. Section 1.2 discusses the pros and cons of producing methanol over other chemicals.

1.2. Methanol

Zero Emission Fuels (ZEF) is a company that uses solar power and air to create chemical substances, methanol to be precise. The company of ZEF and how they produce methanol is discussed in section 1.3. This section elaborates on the main reasons why the chemical methanol is selected for production. Methanol is a chemical with the molecule formula CH_3OH, figure 1.2 depicts the skeletal formula. It is the simplest hydrocarbon that is liquid at room temperature [5]. This results in less energy required to form the molecule in comparison with other, more complex, hydrocarbons. The main technical reason for choosing methanol over other hydrocarbons is the low amount of energy required for production and thus the relatively high conversion efficiency. Methanol is a liquid at room temperature, making it easy to store. The energy content of methanol at standard conditions is around 20 MJ/kg, which translates to around 16 MJ/L. 20 MJ/kg is the lower heating value [6].

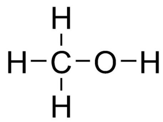


Figure 1.2: The flat skeletal formula of methanol [7].

Methanol is mostly used as a chemical solvent, a fuel, or as a precursor in the production of plastics [7]. This means that there is an existing market for methanol, which also means the infrastructure to transport and store methanol is already present. The methanol market is the second reason methanol is chosen, the capacity of the methanol market was 110 million tons in 2017, produced by 90 plants. This is interestingly enough not equal to the total methanol demand, which was equal to 97 million tons in 2017 [8]. Almost 200,000 ton of methanol is used daily for feedstock or fuel [9]. The price of one ton of methanol in the first quarter of 2019 was 350 € [10]. In figure 1.3 an overview of the end products of methanol is shown.

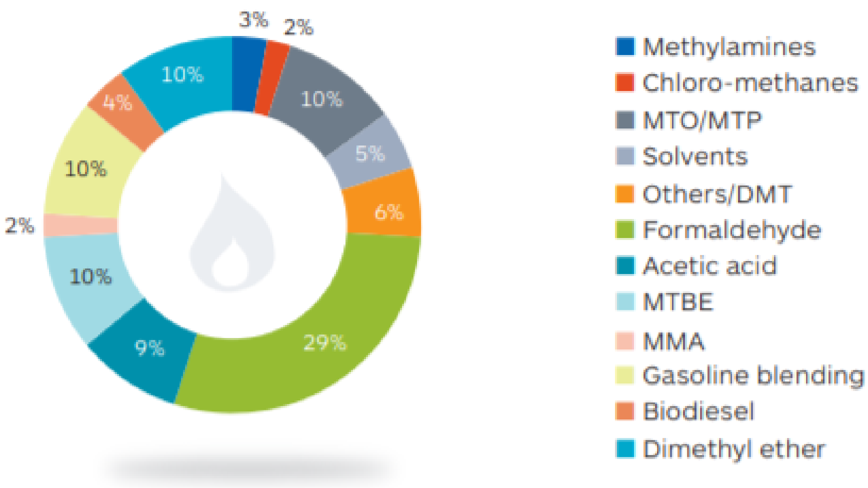


Figure 1.3: An overview of the methanol market based on end-use of methanol [11].

The main disadvantage when using methanol as a fuel in comparison with other hydrocarbons is the energy density. As mentioned above the energy density of methanol at standard conditions is 16 MJ/L. For the main fuels gasoline, diesel and kerosene these values are 34 MJ/L, 38.5 MJ/L and 36.5 MJ/L respectively [12]. So to store the same amount of energy more than two times the volume is needed.

The two main feed materials for methanol production are natural gas and coal, where the first accounts for around 90% of the methanol production. Coal is mostly used in regions where no natural gas sources are available [13]. The scope of this research includes only these two production methods. Biomass is not discussed in this research for multiple reasons. The first being that it is not in the scope of interest of ZEF. The second reason is that the subsidies for food-based biofuels are being cancelled in the European Union [14]. The third reason is that methanol can be produced from numerous routes when using biomass as a feed [15]. Because there are so many different production routes the scope of this research would become too broad when including biomass.

1.3. Zero Emission Fuels

ZEF is a start-up with the goal to produce sustainable and affordable grade AA methanol (grade AA methanol has a purity of 99.8%). ZEF is developing a conceptual solar methanol (MeOH) farm, with a solar capacity of 12 MW and a targeted methanol production of around 7.8 ton per day. The production rate is based on the assumption that the solar MeOH farm operates on a location where 7 equivalent sun hours (ESH) are present. One ESH is equal to a solar irradiation of 1 kWh/m^2. A visualisation of this solar MeOH farm is depicted in figure 1.4.

Figure 1.4: A visualisation of the ZEF solar MeOH farm designed by Van Nunen [16].

A **solar MeOH farm** consists of 13225 **modular MeOH systems**, of which a schematic overview is given in figure 1.5. The modular MeOH system is modular and consists out of PhotoVoltaic (PV) solar panels and a **micro-plant**. The capacity of the PV panels is 900 Watt-peak (Wp). The modular MeOH systems are connected using pipelines, which flow to a storage vessel. The farm operates without electrical storage, meaning the farm only produces methanol when energy is delivered from the PV panels.

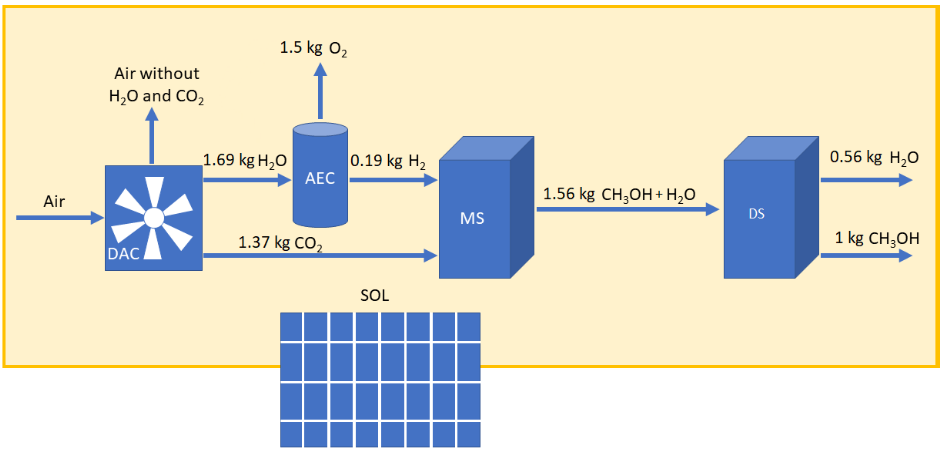


Figure 1.5: A schematic and simplified overview of the modular MeOH system. DAC means the Direct Air Capture, AEC means alkaline electrolytic cell, MS means methanol synthesis, DS means distillation and SOL means solar panels [16].

Some processes in the micro-plant operate at elevated temperatures, meaning that the micro-plant has a start-up time. If power is interrupted this can significantly reduce efficiency.

A more detailed explanation and assumptions made about the solar MeOH farm and the modular MeOH system are given in chapter 3.1.2. Because of confidentiality reasons, not all details of the different components are discussed.

The **Direct Air Capture** (DAC) unit absorbs CO_2 and H_2O from the air, using a sorbent. The air is filtered and blown into the absorption chamber by a fan, in which the sorbent is spread out over different plates to increase the reaction surface. The sorbent releases the CO_2 and H_2O at low pressure and high temperature, which is done in the desorption chamber at vacuum pressure and elevated temperatures.

The synthesis of methanol should be performed at high pressures and temperatures, this is achieved by compressing absorbed CO_2 and H_2O with a **compressor** from 0.1 bar to at least 51 bar. Compressing the mixture of H_2O and CO_2 is more efficient than compressing hydrogen. The pressurised solution is pumped into a buffer, in which H_2O is in liquid state and CO_2 is in gas state, enabling the separation of CO_2 and its consequent usage in the methanol synthesis.

The **Alkaline Electrolytic Cell** (AEC) splits H_2O into H_2 and O_2 through electrolysis at a pressure of at least 51 bar and a temperature of 90 °C. The electrolyte used is potassium hydroxide (KOH). The anode and cathode are separated by a membrane. The H_2 produced is used in the methanol synthesis.

The **Methanol Synthesis** (MS) occurs in the methanol reaction chamber. The operation conditions are a temperature of approximately 230 °C and an absolute pressure of at least 51 bar. In this chamber, the compressed CO_2 from the DAC and the H_2 from the AEC are mixed. The two main chemical reactions occurring in this chamber are reaction 1.1 and reaction 1.2. Reaction 1.1 is the desired reaction. Reaction 1.2 is called the water gas shift reaction and is unwanted because this reaction consumes CO_2 and does not produce methanol.

$$CO_2 + 3\,H_2 \rightleftharpoons CH_3OH + H_2O \tag{1.1}$$
$$CO_2 + H_2 \rightleftharpoons H_2O + CO \tag{1.2}$$

The reaction side of the chamber is warmed to 230 °C, the other side is passively cooled by environmental temperatures. The cool side leads to condensation of water and methanol. The methanol and water mixture is fed into the distillation unit.

The methanol and water is a mixture that needs to be separated, which is done in a capillary micro **Distillation Unit** (DS). The distillation leads to the desired methanol purity of 99.8%. The distilled water can have small quantities of impurities like methanol and dissolved CO_2.

1.4. Life Cycle Assessment

As mentioned before, ZEF has the goal to produce sustainable, zero-emission, methanol. The main focus of the research is on CO_2 emissions, which should optimally be zero or below zero, but at least lower than the main production methods. To assess the environmental impact of a product, a life cycle assessment (LCA) is conducted. An LCA is a systematic set of procedures for compiling and examining the inputs and outputs of materials and energy and the associated environmental impacts that are directly attributable to the functioning of a product throughout its life cycle [17]. In the case of ZEF, the product is methanol. In this research, an LCA is conducted to determine the environmental impact of methanol produced by ZEF. Conducting an LCA is explained in more detail in chapter 2.1.

An impact category is defined as where the environmental impacts are addressed. Different methods exist to interpret the environmental impact. The method used in this research is the ReCiPe 2016 model. This method was developed by the Dutch National Institute for Health and Environment, Radboud Universiteit Nijmegen, Leiden Universiteit and the company PRé sustainability [18]. The ReCiPe model defines 18 different environmental midpoint impact categories. The goal of the ReCiPe model is to link the emissions and material consumption during the life cycle to these 18 impact categories [19]. The ReCiPe model converts the 18 different impact categories by aggregating them to three end categories, which are damage to human health, damage to the ecosystem, and damage to resource availability. There are two main advantages of the ReCiPe model over other interpretation methods. The first advantage is that the ReCiPe model has the broadest set of midpoint impact categories. Secondly, the impact is assessed on a global scope [19]. These advantages are the reason for using the ReCiPe model in this research.

Three midpoint impact categories are interesting for ZEF. These are the global warming potential (GWP), mineral resource scarcity, and the fossil resource scarcity. The first category, GWP, measures the global warming potential for the next 100 years in kilograms of CO_2 equivalent. This is interesting to research for ZEF because they want to produce zero emissions methanol. The mineral use shows how much minerals are used, this category compares different minerals based on kilograms of copper equivalent. Sustainability does not only look at the amount of CO_2 emission, but also at the amount of rare minerals used. The latter can limit the upscaling of the ZEF methanol project. The last impact category is fossil resource use, which is directly linked to energy use. For the comparison of different PV panels the endpoints impact categories are used. The impact categories and endpoints are discussed in more detail in chapter 2.1.4.

1.5. Research Questions

The first section of this chapter discussed the need for sustainable fuels and feedstock. Section 1.3 explained how the ZEF solar MeOH farm produces sustainable methanol. However, the environmental impact of the conceptual solar MeOH farm is not yet determined. This means that it is not known how sustainable the methanol produced by ZEF is. Section 1.4 explained how the environmental impact can be assessed by using an LCA. This research will determine the environmental impact of the conceptual solar MeOH farm by conducting an LCA. The results of the research can help in making decisions to decrease the environmental impact and making sure sustainable methanol is produced. The main research question of this research is:

Research question: What is the environmental impact based on global warming potential, mineral use, and fossil fuel use, for methanol produced by the ZEF solar MeOH farm?

To answer and substantiate this question, the following five sub-questions are researched:

1. What type of PV panels have the lowest environmental impact?
2. What are the main contributors to the environmental impact?
3. How does the environmental impact of ZEF methanol production compare with the main production routes of methanol?
4. How do different locations of operation influence the environmental impact?
5. How do uncertainties influence the final result?

1.6. Goals

To answer the formulated research questions certain research goals are formulated:

1. Advice ZEF which type of PV panel has the least environmentally impact. This advice is substantiated by a comparative LCA concerning different PV panels.
2. Advice ZEF on the key parameters for decreasing their environmental impact. This advice is based on a cradle-to-gate LCA of the methanol produced by the solar MeOH farm.
3. Advice ZEF on further research that reassures certain assumptions made in the LCA.

1.7. Structure of the Report

The second chapter discusses results from a literature study. The chapter first focuses on how to conduct an LCA and elaborate on why the three impact categories, GWP, mineral use, and fossil fuel use are the only categories assessed. The second part focuses on the environmental impact of different types of PV panels. The last part of the chapter discusses the main production methods for methanol. Chapter three describes the stages of the two LCA's conducted. The first LCA conducted is used to advise on PV panels. The second LCA focuses on the solar MeOH farm itself. It first explains the goal and scope, which includes all assumptions made and explain how uncertainties are assessed. The second part of the chapter discusses the inventory used and elaborates on the Simapro model. The fourth chapter discusses the main results from both LCA's. Chapter five gives a sensitivity analyses of the assumptions made in chapter three. The last chapter presents a conclusion of this research.

2
Literature

This chapter discusses the results of the conducted literature study. The first section elaborates on the life cycle assessment. This section also explains the ReCiPe model in detail. The second section focuses on different PV technologies and the environmental impact of these techniques. The main production methods of methanol and their environmental impact are elaborated in the last section. The results of the literature study are used for comparisons and advice.

2.1. Life Cycle Assessment in General

This section discusses the framework of a life cycle assessment based on the International Organisation for Standardisation (ISO). ISO has published two guidelines for LCA, namely the ISO 14040:2006 [17] and ISO 14044:2006 [20]. These guidelines describe four different phases which are discussed in this chapter. In figure 2.1 the ISO framework is illustrated. The first phase is the description of the goal and scope of the research. The second phase is the inventory analysis, the third phase is the impact assessment, and the last phase is the interpretation. However, as can be seen in the figure, these phases are iterative. The following sections elaborate the different phases.

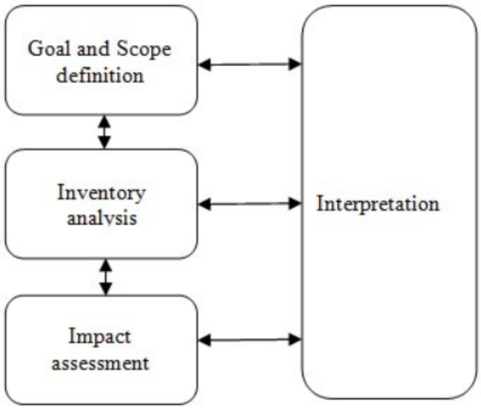


Figure 2.1: Life cycle assessment framework [17].

2.1.1. Goal & Scope Definition

The goal and scope of an LCA shall be clearly defined and shall be consistent with the intended application. Due to the iterative nature of LCA, the scope may have to be refined during the study [20].

Goal

The following points determine the goal of the study [21]:

- Range of application: What is the objective of the study?
- Interest of realisation: Why is the LCA study conducted?
- Target group(s): For whom will the LCA study be conducted?
- Publication or other accessibility for the public: are comparative assertions intended in the study?

Scope

The first step in determining the scope is to determine the functional unit. The definition of a functional unit is a certain amount of product or service. The functional unit is defined in such a way that different products can be compared, based on the environmental impact that follows from the LCA [22]. For example, the functional unit of a methanol plant could be in the units of tons of methanol. With this functional unit the difference in for example greenhouse gas emission, between different methanol plants, per ton of methanol produced can be determined.

The second step is determining the product system and setting the system boundaries, which follows from a well-described functional unit. Based on the functional unit, the different flows of the system are described [21]. The best manner of presenting all the flows of the system is by a flowchart, which is called a product tree. Figure 2.2 shows an example of such a product tree.

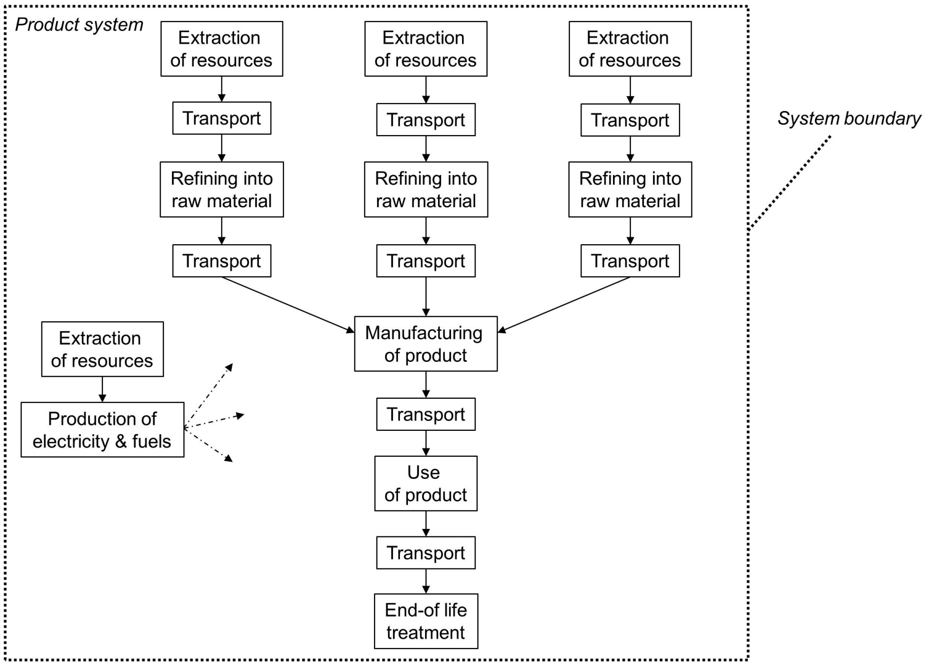


Figure 2.2: An example of a product tree, showing the product system and system boundaries [23].

This product tree gives an overview of the boundary of the system and all the processes that are in the scope. One box in the product tree is called a unit process. When a unit process is outside the system boundary, it is not included in the environmental impact. In this example, the environmental impact for the extraction of resources is taken into account. This is not necessary when comparing two systems that consume the same resources. In that case, the extraction would contribute the same amount to both systems. Setting the boundary is very important for the LCA; the boundary determines the scope.

The scope describes different sets of boundaries. These boundaries are, for example, geographical boundaries and the time horizon. The time horizon can be defined as the present and future environmental impact. One way to define the time horizon is to assume the environmental impact of the product during the next 100 years [24].

Other subjects that are discussed in the scope are allocation, the interpretation method, and assumptions. Allocation is necessary when multiple products are produced. The environmental impact should be allocated between the different products. The method of allocating the environmental impact needs to be mentioned in the scope [17]. The interpretation method used in this research is discussed in section 2.1.4.

2.1.2. Inventory Analysis

The life cycle inventory phase (LCI) is based on materials and energy. It is an accounting of everything involved in the product system. This phase gives more detail to the product tree using input and output used for certain products. The LCI is built up using unit processes. A unit process is the smallest element considered in the life cycle inventory analysis for which input and output data are quantified [17]. Some examples of unit processes are printing, transportation, or deforming the metal. These unit processes can consume or produce energy, materials, or both.

Next step in the LCI is the energy analysis, this is important because environmental problems are frequently coupled with energy consumption. In this phase, energy consumption or production is linked to the unit processes. When electricity is consumed the electricity mix of the location of electricity consumption is used for the assessment. This location is described in the geographical boundaries in the scope.

The LCI leads to results, for example, greenhouse gas emissions, energy use, and water consumption. The impact assessment uses these results.

2.1.3. Impact Assessment

The life cycle impact assessment (LCIA) converts the results of the LCI to potential environmental impacts. These environmental impacts support the interpretation phase, where the questions posed in the goal definition are answered [25].

The mandatory parts of a LCIA according to ISO 14040 [17] and ISO 14044 [20] are:

1. Selection of impact categories, category indicators, and characterisation models.
2. Assignment of LCI results to the selected impact categories (classification)
3. Calculation of category indicator results (characterisation).

The 2^{nd} and 3^{rd} parts can be modeled using the Simapro software and selecting an interpretation method. This is discussed in more detail in section 2.1.6. The following section elaborates the impact categories, category indicators, and characterisation models.

2.1.4. Impact Categories

The impact category is defined as where the impacts are addressed. These categories are selected in accordance with the goal. An example would be climate change or ecotoxicity. For each impact category, the necessary components of the LCIA include [20]:

- Identification of the category endpoints
- Definition of the category indicator for given category endpoint(s)
- Identification of appropriate LCI results that can be assigned to the impact category, taking into account the chosen category indicator and identified category endpoint(s)
- Identification of the characterisation model and the characterisation factors

The category endpoint can be one of the following three categories [18]:

1. Damage to human health
2. Damage to the ecosystem
3. Damage to resource availability

These are general categories and to better specify them midpoint impacts are used. These focus on a single environment problem, e.g., climate change. The climate change midpoint can be converted to endpoints, this is shown in figure 2.3. Appendix A discusses an example of how to use the terms impact categories, category indicators, and characterisation models.

This research uses the ReCiPe 2016 model [18] as interpretation model. This model is developed by the Dutch National Institute for Health and Environment, Radboud Universiteit

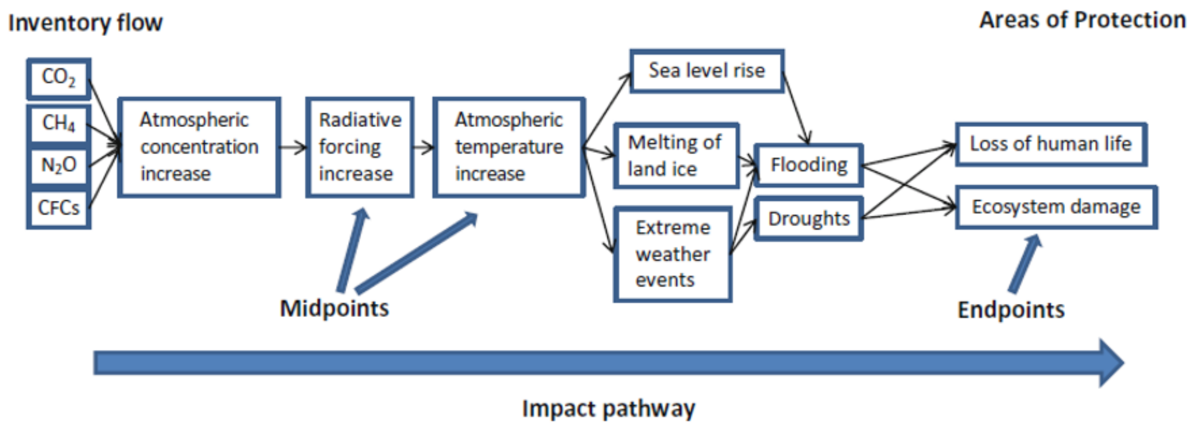


Figure 2.3: Simplified overview of midpoint and endpoint impact categories [25].

Nijmegen, Leiden Universiteit and the company PRé sustainability [18]. The ReCiPe model defines 18 different impact categories on the midpoint level and three impact categories on the endpoint level. The ReCiPe model converts the 18 different impact categories by using weighing to the three endpoint impact categories, this is explained in more detail in appendix A. This research uses the endpoint impact categories for comparing different PV panels, which are explained in the next sections. The methanol production is assessed on the three selected midpoint impact categories, which are also explained in the following sections.

Damage to Human Health

To measure the endpoint of damage to human health DALY is used. DALY is an abbreviation for Disability Adjusted Life Year. DALY measures the difference between the standard life expectancy in perfect health with the actual situation [26]. This can be written as in equation 2.1:

$$\text{DALY} = \text{Years Lived with Disability (YLD)} + \text{Years of Life Lost (YLL)} \tag{2.1}$$

Some examples of damage to human health due to environmental pollution are dead due to heatwaves, or an increase in infectious diseases due to an increase in temperature. The unit of DALY is in years of life lost.

Damage to the Ecosystem

The endpoint of damage to the ecosystem is measured as the local species loss over time or species.year [27]. An example is that due to global temperature increase species lose their natural habitat and become extinct. Another example is that species become extinct locally, due to the poisoning of their habitat.

Damage to the Resource Availability

The last endpoint is the damage to the resource availability. Due to the extraction and consumption of both mineral and fossil resources the availability of these resources decrease. The decrease in availability leads in general to an increase in the extraction difficulty, which leads to an increase in extraction cost. This increase in cost is measured using the value of Unites States dollar in 2013 (USD2013) [28].

Global Warming Potential

The GWP measures the global warming potential for the next 100 years in kilograms of CO_2 equivalent. The emissions obtained in the LCI are converted to CO_2 equivalent. For example, in the ReCiPe method one kilogram of methane emitted is equal to 34 kilograms of CO_2 equivalent emitted [28]. The category endpoints to which the GWP contributes are damage to human health and damage to the ecosystem. One of the most used impact categories is GWP [29].

One of the goals of ZEF is to reduce worldwide greenhouse gas emissions. This is the main reason this category is selected. The category shows the amount of greenhouse gasses emitted during the production of the solar MeOH farm and the amount that is absorbed from the air when methanol is produced. The GWP determines if ZEF has a net emission of zero. The main focus of the research is on the GWP.

Mineral Resource Scarcity
The mineral use shows the amount of mineral consumed in the process. Not all minerals are as easy to extract as others, and some are more abundant than others. This category compares different minerals based on these factors in kilograms of copper equivalent. The endpoint of this category is damage to the resource availability [18].

This category is selected because of scalability. If a resource used in the construction of the plant is rare it influences the scalability of the plant. To become more sustainable the use of (very) rare minerals should be limited.

Fossil Resource Scarcity
The last impact category is the fossil resource scarcity, which compares the fossil fuel use. It takes the following resource into account: crude oil, natural gas, hard coal, brown coal, and peat [18]. This is directly linked to energy use because these fuels are used for generation of electricity or heat. The unit in which the fossil resource scarcity is compared is oil equivalent. An oil equivalent is a normalised unit of energy. The unit normalises the energy content of different fossil fuels based on their higher heating value [28]. The endpoint of this category is damage to the resource availability.

This category is selected because fossil fuels are burned to extract energy, which creates CO_2 and other greenhouse gasses. These emissions are already taken into account with the GWP but can show hot spots for energy consumption. Reduction in energy consumption contributes to becoming more sustainable.

2.1.5. Interpretation

This is the last phase of the assessment. In this phase, conclusions are added to the results from the LCI and LCIA phases, which leads to recommendations.

ISO 14040 [17]: *Interpretation is the phase of LCA in which the findings from the inventory analysis and the impact assessment are considered together. The interpretation phase should deliver results that are consistent with the defined goal and scope and reach a conclusion, explain limitations and provide recommendations.*

The ISO 14044 states three steps for the interpretation phase:

1. Identification of the significant issues based on the results of the LCI and LCIA phases of LCA
2. An evaluation that considers completeness, sensitivity and consistency checks
3. Conclusion, limitation, and recommendations

One of the sub-questions is concerning a sensitivity, or uncertainty, check. This check results in an estimation of the uncertainties of the LCA. A sensitivity check allows to change different parameters and document the influence on the final result [21]. The consistency check provides a reference to the goal and scope. The objective of the consistency check is to determine whether the assumptions, methods, and data are consistent with the goal and scope [20].

2.1.6. LCA in Simapro

To conduct the LCA Simapro software is used. Different databases form the backbone of this program. The main database used is called the Ecoinvent database. The version used is the Ecoinvent 3.4, which was compiled in November 2017 [30]. This database contains data from different processes with this data and Simapro the environmental impact can be assessed. How Simapro is used in this research is explained in the following example:

- The goal is to determine the GWP of manufacturing a steel and aluminium component in China and transporting this to Europe.
- The next step is to obtain the LCI. Using Simapro a process is created. This process includes the materials steel and aluminium from the Ecoinvent database. The database contains data for producing steel and aluminium in different locations. In this case, the location of the steel and aluminium manufacturing is in China. To this process, the production methods can also be added, for example, drilling of aluminium parts. The last step of finishing the process is to include the transportation from China to Europe. Using the database the mode of transportation is selected. The transportation is expressed as tonne-kilometr. One tonne-kilometr is defined as the transport of one tonne of material over one kilometer.
- The next step is the LCIA. Simapro is used to calculate the environmental impact based on an interpretation model. The impact assessment model used is the ReCiPe midpoint model, as explained before. Using this model the Simapro software calculates the impact of the 18 different midpoint impact categories. Simapro uses the method to convert emissions in the production to CO_2 equivalent. The goal was to determine the GWP, which is expressed in CO_2 equivalent emission. If the goal is changed, for example, to determining the damage to human health endpoint the only component that changes is the interpretation model. Now, the new ReCiPe endpoint model is used, this converts the CO_2 equivalent emissions to DALY.
- For the interpretation, the results from Simapro are used, but not the software itself. The uncertainty assessment is also conducted without the use of Simapro.

This simple example summarises how an LCA can be conducted using Simapro. In chapter 3, a detailed description of the Simapro inputs is presented.

2.2. Literature Results PV Panels

The goal of this section is to obtain environmental and performance parameters for different types of PV panels. These parameters are used to advise ZEF concerning the PV panels with the least environmental impact. This advice is written based on the conceptual design made by Van Nunen [16]. The capacity of the PV panels is 900 Wp. 900 Wp or Watt-peak means that the PV panels produce 900 Watts under standard test conditions. The standard test conditions are an irradiance of 1000 W/m^2, a cell temperature of 25°C and an air mass of 1.5. The air mass is the ratio between the path light has travelled through the atmosphere and the path length of the atmosphere vertical upward [31]. A longer path length through the atmosphere means more absorption of light. An air mass of 1.5 results in a specific light spectrum.

Two different types of commercially available PV panels are discussed in the next sections, namely silicon crystalline, and thin film. The first subsection of the chapter discusses silicon crystalline PV technologies. Almost 95% of the market share consists of crystalline PV panels, as can be seen in figure 2.4. The second subsection of the chapter analyses different thin-film technologies. Every subsection first describes the technology and state the advantages and disadvantages of that technology. Followed by the production method. The last part of each subsection discusses efficiencies and CO_2 equivalent emissions. At the end of the chapter, the costs are briefly discussed, and the results are summarised. The PV panels discussed are within the scope of ZEF, which means affordable and produced on a large scale.

From literature, an estimate of the environmental impact of the PV panels can be determined. Many factors influence the environmental impact, e.g., location of production and technologies used for production. The main focus is the GWP of the production of the panels. The results do not include the environmental impact of installing the PV panels. However, the results include the environmental impact of the casing of the PV panels. The results lead to an average range of CO_2 equivalent that is used later in this research. Another important note is that ZEF not only wants the lowest amount of greenhouse gasses but also wants to produce the solar MeOH farm as cheap as possible. This leads to a trade-off between cheaper

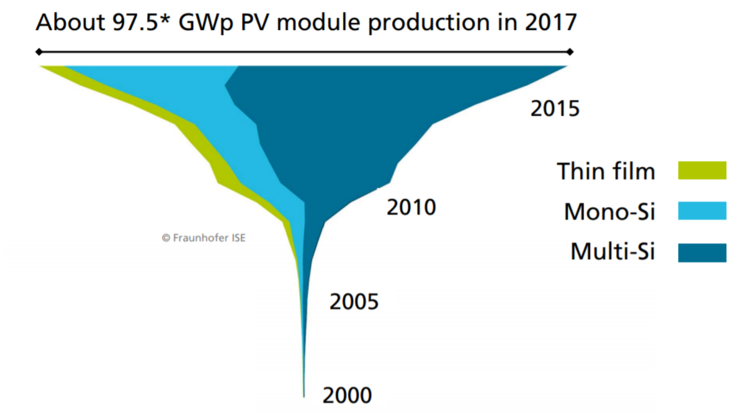


Figure 2.4: Overview of the global annual production of different PV technologies [32].

PV panels from, for example, China but a higher environmental impact, or more expensive PV panels and lower environmental impact.

2.2.1. Silicon Crystalline PV Panels

A silicon crystalline PV panel consists of connected PV cells. These cells are made out of either monocrystalline silicon or polycrystalline silicon. The type of cells in the panel determines whether the PV panel is monocrystalline or polycrystalline. From figure 2.4 it is clear the most dominant technique on the moment, around 60%, is polycrystalline (multi-crystalline). The main reason polycrystalline has the biggest market share is because of lower costs. Both PV panels have a long guaranteed lifetime (20-25 year); the lifetime is discussed in detail in section 2.2.5. The next two sections elaborate on the two different types of silicon crystalline PV panels in more detail. The third section summarises the results.

Polycrystalline PV Panels

Polycrystalline PV panels, in general, have a lower efficiency[1] than monocrystalline PV panels, but the production of the silicon is less energy-intensive. The polycrystalline PV panels are cheaper in general. There are two main techniques for making polycrystalline PV panels.

The first technique is casting and sawing. The process starts with metallurgic silicon that is melted. The molten metallurgic silicon is cast into an ingot. The ingot is cooled from one side to give an orientation to the crystals. With this technique, many separate silicon crystals are formed [35]. The ingot is cut with a saw which leads to silicon losses equal to the thickness of the saw.

The second technique is called string ribbon. This technique pulls two strings through molten silicon. The string moves upwards, and the silicon crystallises between the strings. Figure 2.5 illustrates this process. This process results in a thin ribbon of polycrystalline silicon that is cut into wafers for the cells. The advantage of this technique is that less silicon is wasted due to cutting. A disadvantage is that the silicon must be constantly heated, meaning this process consumes more energy than the casting process.

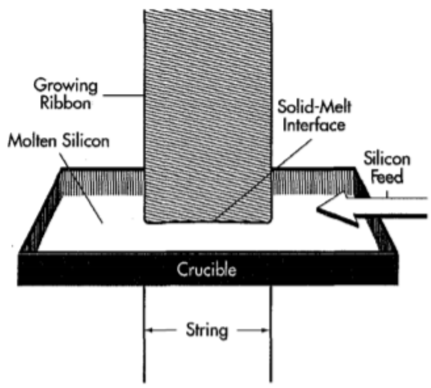


Figure 2.5: The string ribbon technique visualised [34].

[1] The efficiency of a PV panel is defined as the ratio between the energy output of the PV panel and the input of solar energy on the PV panel [33].

The average efficiency of polycrystalline PV panels varies between 12% & 18% [36]. Table 2.1 gives an overview of the results from literature research for polycrystalline PV panels. Appendix B shows how CO_2/m^2 is recalculated to CO_2/900 Wp.

Table 2.1: Results of studies regarding emissions of producing polycrystalline PV panels. Using the obtained efficiencies and the capacity of the ZEF plant, emissions of producing square meters of solar panel are recalculated to 900 Wp

Location of production poly-Si	**Europe [37]**	**Europe [38]**	**Europe [38]**	**U.S. [38]**
kg CO_2 eq./m^2	160	130	185	240
kg CO_2 eq./900 Wp	1100	1105	1380	1815
Location of production ribbon-Si	**Europe[37]**	**Europe [38]**	**Europe [38]**	**U.S. [38]**
CO_2 eq./m^2	130	95	120	150
CO_2 eq./900 Wp	980	920	1195	1460

As can be seen, ribbon-Si has the lowest environmental impact. The efficiency of ribbon-Si PV panels is slightly lower, which results in a larger surface area needed to reach the same capacity. The efficiency is lower because the crystals are less orientated in one direction than in the casting production method [37]. An extra advantage ribbon-Si based PV panels have is that they are more cost-effective [39]. Because the ribbon-Si production leads to less material lost, the assumption is made that the less expensive polycrystalline PV panels consist out of ribbon-Si. The difference in CO_2 emissions seen in table 2.1 is because the energy consumption for production in U.S. is higher than in Europe. Not only the energy consumption is higher, but the energy mix of U.S is less sustainable. This leads to more emission to generate the required energy in comparison to the European energy mix.

Monocrystalline PV Panels

Monocrystalline is the more efficient of the two silicon crystalline technologies and has a slightly longer lifetime. However, the monocrystalline PV panels are the more expensive technology [41]. Because of the higher capacity, the area the PV panels occupies will be lower than other technologies.

The reason the efficiency is higher than polycrystalline is that each cell is made up out of one single crystal of silicon. Production of monocrystalline silicon is mostly through the Czochralski process, which in short is the next process, a pure silicon crystal is put in molten metallurgic silicon. This seed expands slowly and is moved upwards until the crystal covers the entire ingot in one crystal [42]. The melting point of silicon is 1415 °C [43], meaning this process operates at this temperate. This results in much thermal energy needed to produce monocrystalline silicon. An example of such a monocrystalline silicon ingot is depicted in figure 2.6. This ingot is wire-sawed into thin wafers, that form the solar cells. Due to the sawing, a part of the silicon is wasted [44], namely the thickness of the wires.

Figure 2.6: A monocrystalline silicon ingot produced by the Czochralski process [40].

The average efficiency of monocrystalline PV panels varies between 16% & 22% [36]. In table 2.2 an overview of the results from literature research for monocrystalline PV panels is shown.

Table 2.2: Results of studies regarding emissions of producing monocrystalline PV panels on different locations.

Location of production	**China [37]**	**Europe[37]**	**Philippines[45]**	**Europe[45]**	**Norway[45]**	**Korea[45]**
Kg CO_2 eq./m^2	385	200	281	259	198	287
Kg CO_2 eq./900 Wp	2490	1290	1245	1140	885	1275

Overview Silicon Crystalline PV Panels

In table 2.3 an overview is given of the average efficiencies obtained from the literature study, the last column shows the deviation from the average. The average efficiencies are used in the rest of this research.

Table 2.3: Overview of efficiencies obtained from literature for the different silicon crystalline PV panels.

Production technology	Average efficiency	Deviation
Mono-Si	18%	± 4%
Poly-Si	16%	± 2%
Ribbon-Si	15.5%	± 2%

2.2.2. Thin-Film PV Panels

The previous sections discussed three types of PV panels that are based on crystalline silicon. As can be seen in figure 2.4 thin-film PV panels make up 5% of the currently produced PV panels. The three main produced thin-film PV panels are amorphous silicon (a-Si), Cadmium Telluride (CdTe) and Copper Indium Gallium Selenide (CIGS). The main advantages of these PV panels are that they are flexible, lighter, and easier to install. The efficiency of thin-film PV panels decreases less at higher temperatures in comparison with silicon crystalline PV panels. Thin-film PV panels have a lower efficiency; this affects the space needed to obtain the same capacity. In average two times more area is needed for the same capacity [46].

CdTe PV Panels

The cadmium telluride (CdTe) PV panel is the most dominant thin-film technology currently produced. CdTe panels have the lowest energy payback time of all PV technologies that are mass-produced [32]. The biggest disadvantage is that cadmium is a highly toxic metal [47]. Tellurium is a teratogenic substance and also a rare element [48]. CdTe panels are produced by chemical vapor deposition.

The efficiency of CdTe panels ranges between 9% and 11% [49]. In table 2.4 results from different studies are shown.

Table 2.4: Results of studies regarding emissions of producing CdTe PV panels.

Location of production	U.S. [50]	Southern Europe [50]	Southern Europe [50]	Malaysia [51]	U.S. [52]
kg CO_2 eq./m^2	61	57	45	36	-
kg CO_2 eq./900 Wp	765	765	490	360	292

Amorphous-Crystalline PV Panels

Amorphous-crystalline, as the name says, does not have a clear crystal structure. Hydrogen is added to reduce dangling bonds in the silicon. This creates hydrogenated amorphous silicon (a-Si:H) [53]. The thin-films are produced using so-called plasma-enhanced chemical vapor deposition (PECVD). In this process, Silane (SiH_4) is combined with oxygen to produce amorphous silicon [54]. This process operates at a temperature range of 250°C - 300°C.

One of the advantages of the panels is that they are cheaper to produce than mono and polycrystalline PV panels. The trade-off is that the area needed to reach the same capacity is approximately two times higher. Moreover, the a-si PV panels can generate electricity from diffuse and low-intensity light [55]. There are two main advantages of amorphous silicon over the other types of thin-film PV panels. Silicon is an extremely common element, around 25% of the earth crust is made up out of silicon. Silicon itself is non-toxic, contrary to Cadmium [56].

The average efficiency of the amorphous-crystalline PV panels is between 5% and 7% [49] [57] [58]. In table 2.5 results from different studies are shown. It needs to be noted that most studies are over ten years old.

Table 2.5: Results of studies regarding emissions of producing a-Si PV panels.

a-Si Operation location	Spain [59]	Rome [60]	Michigan [61]	Rome [62]
kg CO_2 eq./m^2	80	53	55	80
kg CO_2 eq./900 Wp	1330	950	835	1360

CIGS PV Panels

Copper indium gallium selenide PV cells (CIGS) is the last category of thin-film PV panel discussed. There are versions of this technology which do not use gallium. These panels are called copper indium selenide PV cells (CIS). The main difference is that during the production of CIGS PV panels, cadmium sulfide is used [63]. As discussed before cadmium is highly toxic. The advantage of this technology over CdTe is that it uses less cadmium. The main disadvantage is that CIGS is more expensive than the other thin-film technologies [64]. Another disadvantage is that one of the components of this PV panel is indium, which is both crucial in CIG and CIGS. Indium is very rare element [65].

The CIGS achieves the highest conversion efficiencies of the thin-film technologies [65]. The highest efficiency reached by produced panels is 19.2%. The average efficiency is in the range of 10% to 13% [49]. Table 2.6 shows the results from different literature studies regarding CIGS panels.

Table 2.6: Results of studies regarding emissions of producing CIGS PV panels.

Location of production	Japan [52]	Italy [66]	Germany [60]	Europe [67]	Europe [68]
kg CO_2 eq./m^2	148	112	121	84	98
kg CO_2 eq./900 Wp	1195	1250	1070	918	980

Overview Thin-Film PV Panels

In table 2.7 an overview is given of the efficiencies obtained from the literature study. These efficiencies are used in the rest of the research.

Table 2.7: Overview of efficiencies obtained from literature for the different thin-film PV panels.

Production technology	Average efficiency	Deviation
CdTe	10%	± 1%
a-Si	6%	± 1%
CIGS	11.5%	± 1.5%

2.2.3. Installation

To install PV systems more is needed than just the PV panels. For example, cables are needed to transport the energy, but also inverters, transformers, optional storage, and mounting are needed. This is called the balance of system (BOS) and consists of everything needed to construct a functional PV system. The results discussed in this chapter do not take the BOS into account. The modular MeOH system , however, does need a mounting structure. When the area of the PV panels increases so do the materials needed for the mounting structure. This increase in material use increases CO_2 emissions. Moreover, the cost of installing more area of PV panels are higher. More area needed would also mean the ZEF plant takes up more space, which is unwanted. Concluding that a larger PV panel area is not beneficial. These factors are taken into account in the final advise.

There are different ways of mounting PV panels. For commercial use, the PV panels are often mounted to the roof of a house. However, the plant of ZEF operates in a field. This means that a ground-mounted structure is used. Two main designs for the mounting system are considered in this study. The first design is an open ground mounting system, depicted in figure 2.7. The second design is an open ground pole mounting, depicted in figure 2.8. The main difference between the two figures is the metal frame and concrete use. The open ground mounting structure consumes more concrete, while the pole mounting consumes more steel and aluminium [69]. A recent trend in mounting structures is to construct a frame like depicted in figure 2.7, but using wood instead of metal [70]. This could lead to a more environmentally friendly way of constructing a PV mounting system. A disadvantage of using wood is that wood decreases the fire safety of the mounting structure. The report of Fthenakis et al.[69] describes materials that are used in the different mounting structure, values from this report are used in the sensitivity analyses.

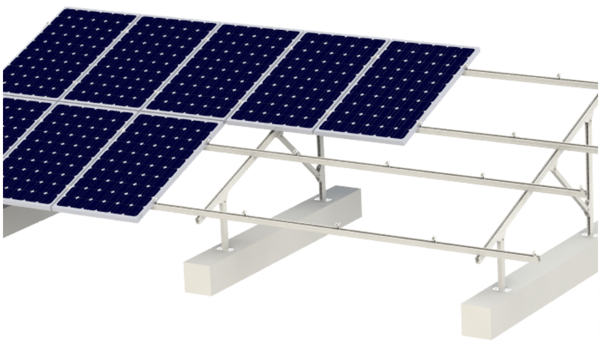


Figure 2.7: Example of an open ground mounting system [71].

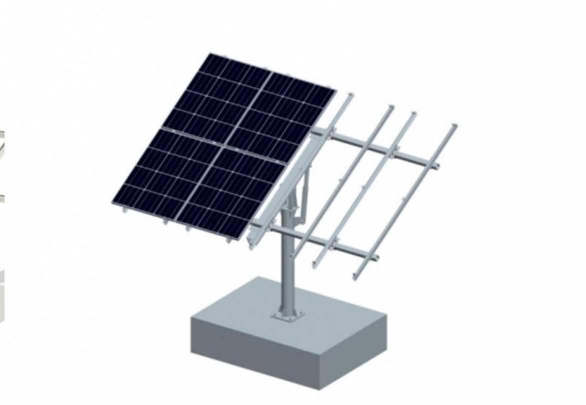


Figure 2.8: Example of an open ground pole mounting [72].

By using a solar tracking device, the generated energy of the PV panels can be increased. A solar tracking device orientates the PV panel to the position in which it has the highest possible solar irradiance throughout the day. In this research this technology is not taken into account because of the following reasons [73]:

1. The cost of the PV-system and mounting increases with approximately 0.9 €/Wp installed. For the modular MeOH system, the cost increases by approximately 800 €.
2. More maintenance is required than a fixed rack
3. The tracking technology leads to a more complex system. This means more site preparation is needed.

2.2.4. Cost of PV Technologies

Table 2.8 gives an overview of the costs for the different PV technologies. These values are obtained through a brief literature review. It is stressed that these values are an estimation and only used as an indication. Due to the lack of data availability, the advice is that ZEF contacts PV panels suppliers for a detailed price overview. For poly-Si and mono-Si, there is data available, which is obtained from a database that is updated monthly. Assumed is that the ribbon-Si is slightly less expensive as is mentioned before. The company First Solar mainly produces CdTe PV modules. This company has cost indication for large scale module purchases. The price range of the a-Si PV panels is more difficult to determine. Most data is more than 6 years old and includes the installation of the PV panels. An estimation of the price is made by comparing outdated data of amorphous, poly, and monocrystalline. Then determine the percentage a-Si panels are cheaper and extrapolate this data. This gives that a-Si panels are around 20% cheaper than polycrystalline panels [74] [57] [75]. It is stressed that this is a very rough estimate.

Table 2.8: Overview of the cost per Wp and 900 Wp for PV modules in euro for different PV technologies.

	Mono-Si	**Poly-Si**	**Ribbon-Si**	**CdTe**	**a-Si**	**CIGS**
Average cost [€]	0.3 [76]	0.23 [76]	0.22 [76]	0.41 [77]	0.185	0.7 [78] [79]
Cost 900 Wp modules [€/Wp]	270	207	198	414	167	630

PV technologies are still relatively new. A learning curve of a particular technology shows that with more production prices decreases. Figure 2.4 shows that the PV market is still growing rapidly. For crystalline-silicon, this learning rate is 28.5 %. This means that when the cumulative capacity is doubled the average price is reduced by 28.5% [80]. For the thin-film technologies, this rate is 25%[32]. These percentages show that the price of crystalline PV panels decreases more than that of thin-film technologies. This is also due to the larger market size of crystalline technologies, meaning that a double in cumulative capacity is reached sooner.

2.2.5. Lifetime PV Panels & Mounting Structure

This section discusses the lifetime of PV panels and the mounting structure. The data from the literature is used in the sensitivity analyses. PV panel manufacturers give two different types of warranties on their PV panels. The first is the equipment warranty and the second is a performance warranty. The equipment warranty is general between 10-15 years. This warranty means that the PV panel is guaranteed to operate for 10-15 years without failing [81]. The performance warranty guarantees the performance of the PV panel. Most manufacturers guarantee that the efficiency is above 80% of the original efficiency after 20-25 years [82]. The decrease in efficiency is different for different PV technologies. Table 2.9 gives an overview of the average decrease in efficiency per year. It is clear from the table that the thin-film PV panels have a more significant decrease in efficiency than the silicon crystalline PV panels, which leads to a shorter lifetime.

Table 2.9: Overview of the average yearly decrease in efficiency [83].

	Mono-Si	Poly-Si	Ribbon-Si	CdTe	a-Si	CIGS
Decrease in efficiency [%]	0.36	0.64	0.64	0.7 [84]	0.87	0.96

For open ground mounting structure the warranty is around 15 years. The manufacturer guarantees that the mounting structure does not fail the first 15 years. The lifespan, in general, is 25 years [85].

2.2.6. Summary Results Literature Study for PV Panels

In this section, a summary is given of the last sections to put the data in more perspective. In table 2.10 an overview is given of the main advantages and disadvantages of different PV panels. Note that this table only compares the two main techniques. In table 2.11 the different specific techniques are compared to each other. The advantages and disadvantage are in comparison with other techniques from the same main technique, so for example, the lowest costs for the ribbon-Si means it has the lowest cost out of the three crystalline silicon PV panels.

Table 2.10: Overview of the main advantages and disadvantages of the different PV panels.

Technique	Advantages	Disadvantages
Crystalline	Higher efficiency Less area required More mature technology	Larger CO_2 footprint
Thin-film	Less efficiency decrease at higher temperatures Smaller CO_2 footprint Can operate with diffuse light Flexible structure	Need more area to deliver same power Shorter lifetime Less efficient Uses toxic elements Uses rare elements

Figure 2.9 gives an overview of the results of the literature study. In the figure it is seen that CdTe has the lowest amount of CO_2 equivalent emissions. The price is included in the figure, it is stressed that these prices are only an indication. The monocrystalline and polycrystalline module prices are obtained from a database that is updated monthly. The other prices are obtained through data from 2015 or older. Figure 2.10 shows the area of PV panel needed to obtain 900 Wp, assuming the efficiencies from the literature study. The figure shows that the thin-film technologies use more area.

2.3. Literature Results Methanol

This section discusses the two main production methods for methanol. The two primary feed materials for methanol production are natural gas and coal. First, the production of methanol from natural gas is discussed. The second production method discussed is methanol produced from coal. An overview of the environmental impact is provided at the end of each

Table 2.11: Overview of the prices, average efficiencies, main advantages and main disadvantages.

Technique	Price €/Wp	Efficiency	Main advantage	Main Disadvantage
Mono-Si	0.3	18% ± 4%	Highest efficiency Longest life time	High Cost
Poly-Si	0.23	16% ± 2%	Lower CO_2 eq. emissions	Lower efficiency than mono-Si
Ribbon-Si	0.22	15.5% ± 2%	Lowest CO_2 eq. emissions Lowest costs	Sligthly lower efficiency than poly-Si
CdTe	0.41	10% ± 1%	Lowest CO_2 eq. emissions	Uses Cadmium Uses Tellerium
A-Si	0.185	6% ± 1%	Silicon is non toxic and a common element	Low efficiency
CIGS	0.7	11.5% ± 1.5%	Highest efficiency of thin film	Uses Cadmium Expensive Uses Indium

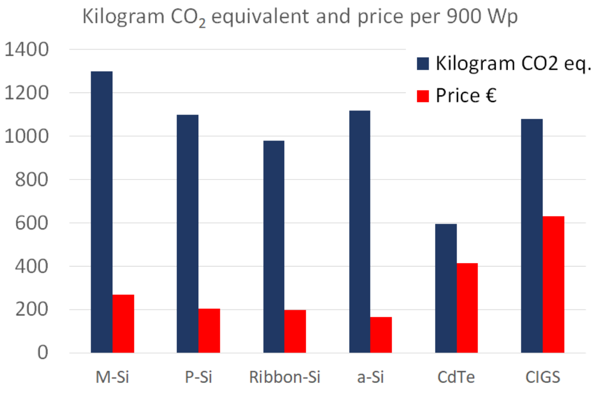


Figure 2.9: Overview of the average kg CO_2 equivalent emissions and costs for producing different PV technologies.

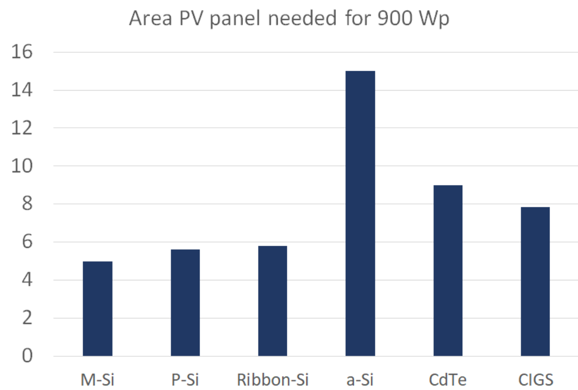


Figure 2.10: The area of the PV panels needed to reach a capacity of 900 Wp based on average efficiencies.

section. The values obtained in this literature study are used for comparing methanol produced from natural gas and coal with methanol produced by ZEF.

2.3.1. Methanol Produced From Natural Gas

Natural gas accounts for around 90% of the methanol production [13]. This methanol is produced from syngas, which is a mixture of CO and H_2 [86]. The most common technique for producing syngas is methane steam reforming from natural gas, depicted in reaction 2.2. The reaction conditions are at high temperatures (800-1000 °C) and high pressures (20-30 bar). The steam can react with CO and produce CO_2. This reaction is called the water gas shift reaction, depicted in reaction 2.3 [87].

$$CH_4 + H_2O \rightleftharpoons CO + 3\,H_2 \tag{2.2}$$
$$CO + H_2O \rightleftharpoons H_2 + CO_2 \tag{2.3}$$

The syngas is first separated from the CO_2 and other impurities. The ratio of H_2 and CO after separation is between 3:1 and 5:1. Next, the syngas is fed into a reaction chamber where the methanol synthesis occurs. In this chamber two reactions take place that produce methanol, these are reaction 2.4 & 2.5. The CO_2 from reaction 2.5 is produced in the water gas shift reaction that occurs in the reaction chamber. The pressure for methanol production is in a range of 50-100 bar, and a temperature range of 200 - 300 °C. This reaction is promoted by the use of catalyst. The most used catalyst is based on the elements Cu/Zn/Al_2O_3 [87].

$$CO + 2\,H_2 \rightleftharpoons CH_3OH \tag{2.4}$$
$$CO_2 + 3\,H_2 \rightleftharpoons CH_3OH + H_2O \tag{2.5}$$

The last step in producing methanol is the separation of H_2O and methanol. The mixture is distilled, which separates the two compounds.

The first impact category discussed is the GWP. The process of producing syngas demands a high temperature, which consumes a large amount of energy. Also, the pressurising of the gasses and the heating for the methanol synthesis demand energy. This energy consumption leads to emissions, that are linked to the energy mix. The process of creating syngas creates CO_2. Table 2.12 gives an overview of the GWP obtained from literature. The values differ mainly due to a difference in energy mixes.

Only the Ecoinvent database has data concerning mineral use and fossil fuel use. The mineral use for the production of methanol from natural gas is low. The minerals that are consumed in the methanol are mainly the catalyst and construction of the plant. The fossil fuel consumption is mainly due to the consumption of natural gas in the production process. The literature values for mineral resource scarcity and fossil resource scarcity are depicted in table 2.12

Table 2.12: Overview of the GWP, mineral resource scarcity and fossil resource scarcity for one ton of methanol produced from natural gas. The last column depicts the average and the standard deviation.

Source	**Ecoinvent [30]**	**Śliwińska et al. [88]**	**Kajaste et al. [89]**	**Li et al.[90]**	**Average**
Kg CO_2 eq.	690	740	880	915	805 ± 11.5%
Kg Cu eq.	1.45 ± 25%	-	-	-	1.45 ± 25%
Kg oil eq.	755 ± 20%	-	-	-	755 ± 20%

2.3.2. Methanol Produced From Coal

This section discusses the general production of methanol from coal. In countries where no natural gas sources are available, coal is used for the production of syngas. An example of a country where coal is used for syngas production is China [87]. The first step in creating the syngas is the gasification of coal. During this process oxygen and steam are blown through the coal at elevated temperatures. Reaction 2.6 depicts the overall gasification reaction of coal. There are different methods of gasification that depend on the type of coal used. Only the most commonly used method is inside the scope of this research.

$$3\,C + O_2 + H_2O \rightleftharpoons H_2 + 3\,CO \tag{2.6}$$

During this reaction also the water gas shift reaction takes place which produces CO_2. The CO_2 can react with the coal, as depicted in reaction 2.7.

$$CO_2 + C \rightleftharpoons 2\,CO \tag{2.7}$$

The syngas created from coal contains more contamination than the syngas produced from natural gas. The main contamination's are CO_2, H_2S and COS (carbon oxysulfide). Through a purification process the impurities are removed. The next steps in the process are the same as the natural gas production route.

For methanol produced from coal no data is available concerning the mineral resource scarcity and fossil resource scarcity. The assumption is made that the mineral resource scarcity is comparable to that of methanol produced by natural gas. The fossil fuel consumption depends on the type of coal used. Table 2.13 shows different values for the GWP obtained from literature .

Table 2.13: Overview of the GWP for one ton of methanol produced from coal. The last column shows the average and the standard deviation.

Source	**Li et al. [91]**	**Kajaste et el. [89]**	**Li et al. [90]**	**Average**
Kg CO_2 eq.	3090	2965	2890	2980 ± 3%

3
Life Cycle Assessment

This chapter discusses the two different LCA's that are conducted. The first LCA is a comparative LCA concerning PV panels. The main goal of this LCA is to advise ZEF on PV panels that have the smallest environmental impact, but still meet their demands. The second LCA is concerning methanol produced by ZEF. This chapter includes the goal & scope and the LCI of the conducted LCA's. The LCIA and interpretation are discussed in chapter 4. This chapter explains all assumptions and the inputs to Simapro.

3.1. Goal & Scope of the Conducted LCA's

This section discusses the goal and scope of the two conducted life cycle assessments. The goal and scope description are in line with the ISO14040 and ISO14044 standards [17] [20].

3.1.1. Goal & Scope Comparative LCA PV Panels

The goal is to determine which PV panel has the least environmental impact by conducting a cradle-to-gate LCA. Monocrystalline, polycrystalline, a-Si, CdTe, and CIGS PV panels are assessed. The results of the LCA will lead to an advice for ZEF. The importance of the research is to minimise the environmental impact of the ZEF solar MeOH farm. This advice helps to make sure that Zero Emission Fuels is zero-emissions.

Scope

Because the modular MeOH system and solar MeOH farm are still in a conceptual phase, the first step is to ”lock” the system. The research is focused on the design of Van Nunen [16]. This means that the plant uses PV panels which have a total capacity of 900 Wp. The amount of ESH is 7 hours. One ESH is equal to an irradiation of 1 kWh/m^2.

The functional unit is PV panels with a capacity of 900 Wp. This capacity is sufficient for ZEF and can be used directly to substantiate the advice. The time horizon that the modular MeOH system operates is 20 years, which is assumed to be the time the PV panels operate [16].

The next step is to determine the product system. This product system describes all the different functions of the system. It includes the boundaries of the system assessed. This system boundary is depicted in figure 3.1. Note this is a very simplified system. The system boundary stops after the PV panel and the mounting is constructed, meaning that it does not include installation or transport from the production facility.

The (LCIA) method used is the ReCiPe endpoint model, which is discussed in chapter 2.1.4. The reason for selecting the endpoint method is that it leads to only three endpoint impact categories that are compared. However, the comparison takes the 18 midpoint categories into account that are weighted to the three endpoints categories. Using the 3 midpoint impact categories does not give clear benefits of one PV panel over the other. The results of the three midpoint impact categories are discussed in appendix C. Using the endpoint model leads to clearer environmental benefits for certain PV panels over the other.

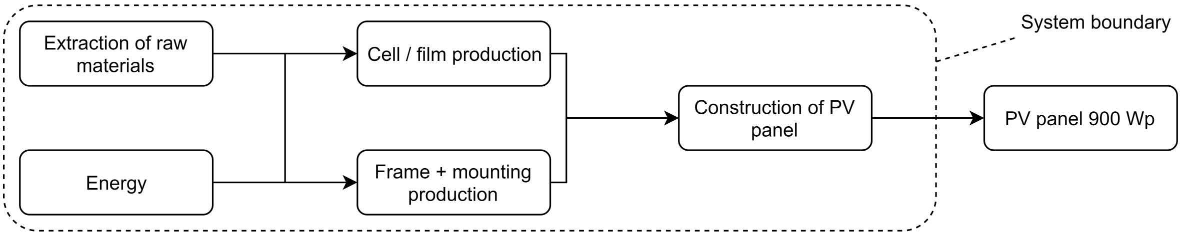


Figure 3.1: Simplified overview of the product system for the manufacturing of PV panels. The dotted line depicts the boundary of the system.

Assumptions

The following assumptions are made in this LCA:

- The average efficiencies of the different PV panels are based on the literature study and are depicted in table 2.11. Appendix B shows the calculations of the efficiency of a PV panel to m^2 of PV panel.
- The efficiency of PV panels decreases with time, as mentioned in chapter 2.2.5. Different PV technologies have different efficiency losses. This difference is not taken into account. The assumption is made that the decrease in efficiency is equal for all PV panels.
- The mounting system used is dependent on the area of the PV panel. For the different PV technologies, it is assumed that the mounting material used per square meter is the same. However, the area of the PV panels is different. The mounting system used is an open ground mounting.
- The lifetime of the PV panels is 20 years. After 20 years the panels are decommissioned. The recycling of the PV panels is not included because currently almost all PV panels are disposed of [92].
- The decrease in PV panel efficiency due to temperature is not included in the comparisons.

3.1.2. Goal & Scope LCA for Solar MeOH Farm

The goal is to determine the environmental impact of the methanol produced by the solar MeOH farm, by conducting a cradle-to-gate LCA of the solar MeOH farm. The impact is assessed using the midpoint impact categories GWP, mineral use, and fossil fuel use. The interest of realisation to inform ZEF about their environmental impact. The LCA leads to an advise to decrease the total environmental impact of the methanol produced by the ZEF solar MeOH farm. The details of the plant will not be accessible to the public.

Scope

The research focuses on the modular MeOH system as designed by Van Nunen [16]. Some slightly more up to date changes have been adopted concerning the DAC and the compressor.

Determining the functional unit of the LCA is less straightforward in comparison to the PV panel LCA. One could use the functional unit one modular MeOH system, or one solar MeOH farm. However, these functional units are more difficult to compare with other forms of methanol production. Solar energy is stored meaning the functional unit can also be MJ of stored solar energy. This can be compared to other forms of renewable energy storage. The difference between methanol storage and for example batteries, is that batteries self-discharge over time. The functional unit that is used is a ton of methanol produced. This is for ZEF the most interesting as they want to compete with the main methods of methanol production. Showing that ZEF has a smaller environmental impact per ton of methanol than other production methods can be a strategic advantage in the methanol market. The functional unit ton of methanol can be recalculated to both other suggested functional units. Because a solar MeOH farm, or modular MeOH system, produces a certain amount of methanol over its lifetime, and methanol can be recalculated to energy stored by using the energy content.

A cradle-to-gate LCA is conducted, because ZEF does not have enough data for the end-of-life of the solar MeOH farm. Figure 3.2 depicts the system boundaries. The first phase of producing methanol is the manufacturing of the modular MeOH system. The construction of the solar MeOH farm is shown as the second phase in the figure. The extraction of resources is outside of the system boundaries. Manufacturing of the micro-plant is expected to have the largest environmental impact. In the operation phase, the plant operates and produces methanol. The production of methanol is assumed not to consume minerals or fossil fuels. Also, the GWP is negative in this phase due to CO_2 absorption from the air. The only process that has a negative environmental impact is electricity consumption. The end-of-life phase of the plant is not taken into account for two reasons. The first reason is that ZEF has no data concerning the end-of-life phase. The second reason is that the assumption is made that the end-of-life has a relatively small environmental impact. This assumption is checked in the sensitivity analysis.

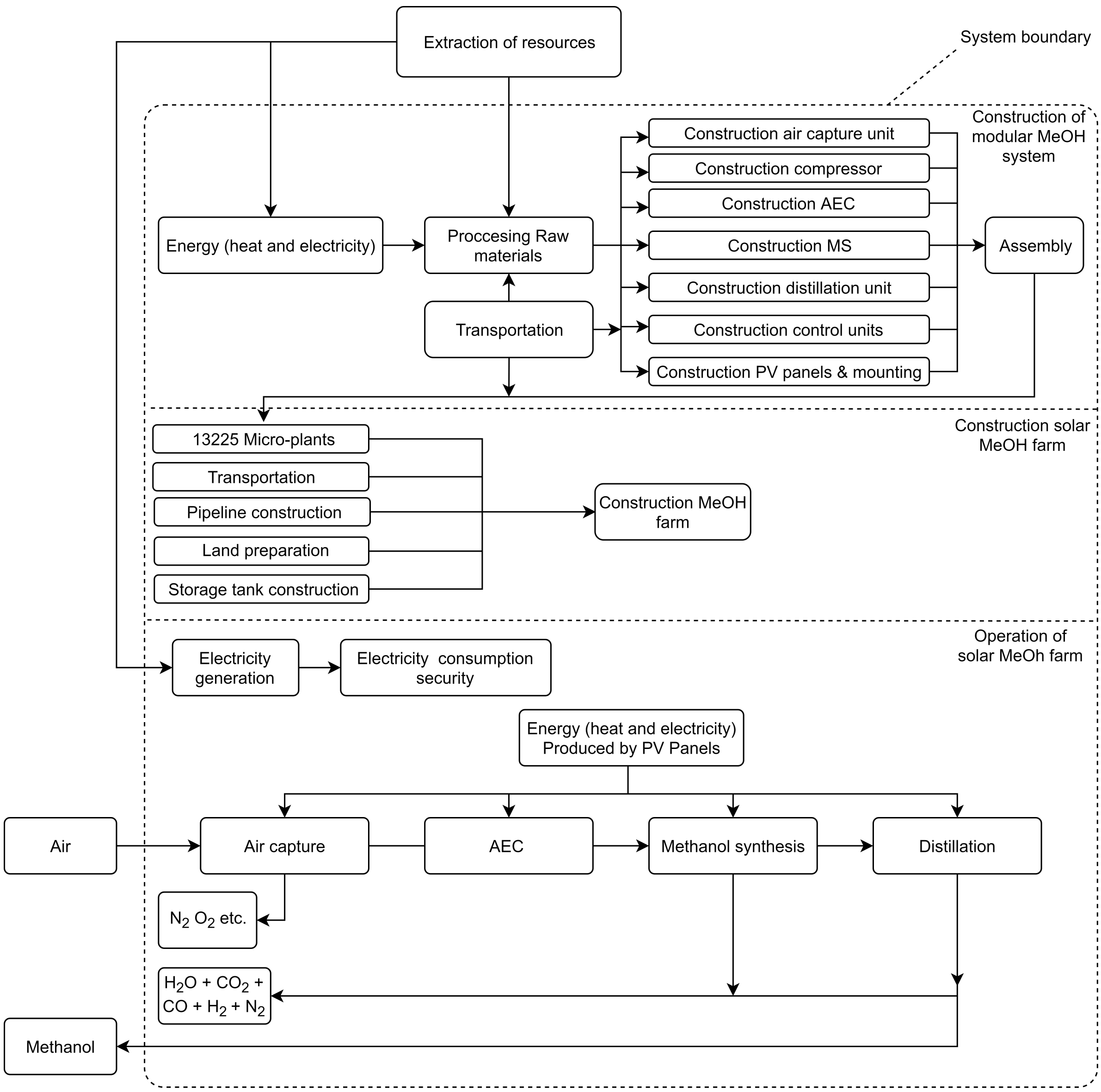


Figure 3.2: The system boundaries of the LCA concerning the methanol produced by the solar MeOH farm of ZEF

In the LCA, an allocation is necessary when multifunctional processes exist. A multifunctional process is a process with more than one product. Every ton of methanol produces 560 kilograms of H_2O, as depicted in figure 1.5. The daily methanol production of the solar

MeOH farm is 7.8 ton per day, meaning 4370 kg H_2O per day. ZEF currently has no plans with the water, meaning the economic value is zero. Besides H_2O also small quantities of N_2, CO_2, CO and H_2 are emitted. The CO_2 emitted is subtracted from the absorbed CO_2. N_2, CO and H_2 are produced in neglectable small quantities during pressure release, or purge, of the methanol reactor. Currently, ZEF has no data on these emissions. ZEF expects a relatively small production of these molecules. The assumption is made that the production is not significant enough to influence the results of this research. The environmental impact is allocated based on the cut-off method, which allocates all environmental impact to the methanol. When an economic value is created for the produced water, the allocation of the environmental impact can be based on economic allocation. Due to this allocation, the environmental impact will always be smaller than the case with no allocation.

The LCIA method used is the ReCiPe midpoint method. This method focuses on 18 different impact categories. For this LCA only three are assessed and discussed in detail, as discussed earlier. These impact categories are the GWP, the resource scarcity, and the fossil fuel scarcity. Using the midpoint impact categories gives a more specific result than using the endpoint method.

For the LCA a base case scenario is assumed. In this scenario, the construction phase takes place in China. This is due to economic reasons, as discussed with ZEF. The modular MeOH systems are transported to Morocco. The optimum location was investigated by a group from the educational master transport, infrastructure and logistics at the TU-Delft [93]. The plant consumes energy based on the energy mix of Morocco. The lifetime of the plant is 20 years, without replacement of parts. The location of Morocco is assumed to have 7 ESH. More assumptions concerning the plant are discussed in the next section.

Assumptions

Different sets of assumptions are made in the LCA. The impact of certain assumption is tested in the sensitivity analyses. This section first lists the general assumption. Secondly, the assumptions related to the modular MeOH system are described, and the last part discusses the assumption made in producing and operating the solar MeOH farm.

- General assumptions.
  - The solar MeOH operates in Morocco where the equivalent sun hours are assumed to be 7, or 7 kWh/(day*m^2).
  - The consumed electricity is equal to the energy mix, which is equal to the data from IEA [94].
  - Transport is depicted in tonne-kilometr. Meaning a certain weight over a certain distance. The modular MeOH system is assumed to be transported in China for 500 kilometers by train. This is the transport from the production facility to the port in Shanghai. From Shanghai, it is shipped to Morocco through the Suez Canal to the port of Agadir, which is approximately 18,000 kilometers. From Agadir, it is transported by road to the solar MeOH farm site, which is a distance of 250 kilometers [93].
  - There is a small amount of methanol dissolved in the water. However, in the current results of the distillation unit, this amount of methanol is not measurable. The assumption is made that the fraction of dissolved methanol in water is small, therefore the water can be discarded without first purifying of the water.
- Assumptions concerning the modular MeOH system.
  - The PV panels used are of the polycrystalline type; this choice follows from the results of the comparative LCA concerning PV panels. The average efficiency over the lifetime of the PV panels is assumed to be 15.5%. The total capacity of the PV panels is 900 Wp (0.9 kWp), and the total area is 5.8 m^2. The average daily energy generation in the 7 ESH environment is 7 * 0.9 = 6.3 kWh, which translates to ≈ 22.7 MJ/day. Details of these calculations are presented in appendix B.

- The plant operates at an efficiency of 51.85%. This efficiency follows from assumptions ZEF made regarding production. This efficiency is defined as the ratio of energy from the PV panel and the energy stored in methanol. The energy content of methanol is 20 MJ/kg. Combining the 51.85% efficiency, the 20 MJ/kg, and the 22.7 MJ daily energy generation leads to a production of (0.5185*22.7)/20 ≈ 0.59 kg methanol per day. Details of these calculations can be found in appendix D.
- The lifetime is 20 years. After this lifetime the entire plant is decommissioned. This means that the production over the lifetime of one modular MeOH system is (0.59 * 365 *20)/1000 ≈ 4.3 tons of methanol.
- No recycling is taken into account for the micro-plant, the assumption is made that recycling has a relatively small environmental impact. For PV panels it is assumed no recycling takes place only decommissioning and then it becomes waste. This is currently the end-of-life of PV panels[92].
- No replacement of different subsystems takes place. No consumption of the catalyst or electrolyte is assumed.
- The production of one kg methanol absorbs 1.37 kg of CO_2. This follows from the fact that one mol of methanol is produced from one mol of CO_2. The CO production is assumed to be neglectable, so it does not influence this ratio. Appendix D shows a detailed overview of the reactions occurring in the micro-plant.
- All components of the modular MeOH system are manufactured in China due to economic reasons.
- Only the production methods of the metals used and injection molding for the plastics is taken into account for the manufacturing of the micro-plant. These materials form a large weight percentage (≈ 82%) of the micro-plant.
- The weight of the micro-plant without follows from the inventory and is 52.8 kg. The PV mounting weight follows from the Ecoinvent data and is equal to 58.1 kg. The weight of the PV panels is calculated by using the average kilogram/m^2 of a polycrystalline PV panel, which is equal to 11.9 kg [95]. The area of the PV panels is 5.8 m^2, meaning the weight is 69.2 kg. Adding these numbers lead to a total weight of 180.1 kg per modular MeOH system. The weight of the modular MeOH system is used in the inventory for transport.

• Assumptions concerning the solar MeOH farm.

  - The daily methanol production of the MeOH farm is ≈ 7.8 tons. This converts to a monthly methanol production of ≈ 237 tons, a yearly methanol production of ≈ 2.84 kilotons, and a lifetime methanol production of ≈ 56.8 kilotons.
  - The plant consists out of 13225 modular MeOH systems. The land use is 24 hectares [93]. The layout of the plant is assumed to be a square, with equal sides with a length of 490 meters. The spacing between the modular MeOH systems is 4.3 meters. This leads to 115 rows existing out of 115 modular MeOH systems.
  - The plant is surrounded by a fence. This fence is present in the Ecoinvent data for PV mounting system. The preparing of the land and land use is also present in the Ecoinvent data for PV mounting system.
  - The modular MeOH systems are connected through pipelines. The length of the pipelines follows from the layout and is 56000 meters. The weight is 0.22 kg/m. This means the total weight of the pipelines is 12.4 tons. The material of the pipelines is polypropylene. This material is chemically resistant against methanol [96]. Because the pressure within the modular MeOH systems is higher than atmospheric pressure, no energy for pumping the methanol to storage is required.
  - The storage capacity is 150% of the monthly production [93]. This capacity is selected because the assumption is made that the methanol is collected monthly. A tolerance factor of 50% is added on top of the monthly production. The density of methanol is 790 kg/m^3 [5]. Combining 150% of the monthly production, ≈ 355 kg methanol, with the density gives a storage capacity of ≈ 450 m^3. The storage tank used in the inventory has a capacity of 4000 m^3. This storage tank is selected because it is specially designed for storing chemicals like methanol, and the process is described in detail in the Ecoinvent database.

– To secure the solar MeOH farm against theft and vandalism different security measures are needed. PV panels and other used materials are known to be sensitive to burglary. To fulfill certain insurance demands, it is assumed that security lights and CCTV are present [97]. This energy consumption is assumed to be 0.1 W/m^2. The lights only operate at night, which is 8.5 hours per day in Morocco, for 20 years and 365 days a year. The construction of the lights and CCTC is not included in the LCA because it is assumed that the environmental impact is relatively small.

– The weight of the 13225 modular MeOH systems that are transported is equal to 13225 * 180 ≈ 2380 * 10^3 kg, or 2380 tons. The weight of the pipelines is 0.5% of this and is not included in the transport. The storage tank has a weight of ≈ 20 ton [30] or 0.85% of the total transported weight. The weight of the storage tank is also not taken into account in the transport.

Uncertainty

The modular MeOH system developed by ZEF is still conceptual. The product is constantly changing, which leads to uncertainty in the results of the LCA. The uncertainties are modeled using standard deviation. The uncertainty analysis starts at a fixed point, which is the mean. The mean is equal to the results from the LCA, for example, the amount of kg CO_2 equivalent. A random value based on a normal standard deviation is added or subtracted. This is done over a thousand times for every subsystem of the modular MeOH system. The results of a thousand iterations lead to a new average with a standard deviation. The outcome of this procedure is an error, or uncertainty, in the results. This method is called a monte-carlo simulation, which is not path-dependent [98]. The standard deviation is determined per subsystem which is done in cooperation with experts on the subsystem and is based on the current results in combination with the goals the subsystem should reach to become operational. Table 3.1 shows the standard deviations in percentages used per subsystem.

Table 3.1: Overview of the standard deviations used in the uncertainty analysis.

Subsystem	**AEC**	**MS**	**DS**	**DAC**	**Compressor**	**Integration**
Standard deviation	30%	20%	50%	50%	20%	30%
Subsystem	**PV**	**Electricity use**	**Transport**	**Pipelines**	**Storage**	
Standard deviation	25%	15%	25%	10%	10%	

3.2. Inventory

LCI PV panels

For the comparison of PV panels, no inventory is shown. The comparison is based on data already available in the Ecoinvent database. The database contains the different type of PV panels that are compared. The functional unit is in m^2 of PV panel. The areas used in Simapro of the different PV panels are given in table 3.2. The area of each PV panel is based on the efficiencies, as mentioned in chapter 2. The open ground mounting system is added to the different PV panels. The functional unit of the mounting system is in m^2 of PV panel. The mounting system is thus dependent on the area of the different PV panels. The inputs for the mounting system are equal to the values presented in table 3.2.

Table 3.2: Overview of the PV panel area that is used as input in Simapro for the different type of PV panels.

PV panel type	**M-Si**	**P-Si**	**Ribbon-Si**	**a-Si**	**CdTe**	**CIGS**
Area [m^2]	5	5.6	5.8	15	8.6	7.8

LCI solar MeOH farm

The inventory implemented in Simapro for the solar MeOH farm is depicted in table 3.3. This table includes the assembly of the modular MeOH systems. A more detailed inventory overview of the different subsystems is presented in table 3.4. The transport of the modular MeOH systems to the solar MeOH farm site is taken into account. The pipelines are present in the Ecoinvent database with functional unit kilogram. The amount of pipelines is listed in the assumptions. A storage tank for liquid chemicals is also present in the Ecoinvent database. This includes four storage tanks of 4000 m^3 while the ZEF plant only uses one. This is the reason only 0.25 unit is used in the inventory. The electricity consumption follows from the assumptions concerning electricity consumption. The energy mix is created using data from IEA [94]. The bottom rows of the table show the output of one solar MeOH farm, which is equal to the lifetime production of 13225 modular MeOH systems.

Table 3.3: The inventory used in Simapro for the solar MeOH farm

Compartment	Amount	Product	Comment
Assembly modular MeOH systems	13225 Units	AEC	Numbers based on design ZEF
	13225 Units	Compressor	
	13225 Units	DAC	-
	13225 Units	Distillation	-
	13225 Units	Integration	-
	13225 Units	MS	-
	13225 Units	PV panels + mounting	From comparative PV LCA
Transport	$4.29 * 10^7$ tkm	Transoceanic freight ship	Shanghai to Agadir
	$5.95 * 10^5$ tkm	Transport lorry	Agadir to farm site
	$1.19 * 10^6$ tkm	Transport freight train	Production site to shanghai
Pipelines	12400 kg	Polypropylene	-
Storage	0.25 Units	Liquid storage tank	From Ecoinvent [30]
Electricity Consumption	$1.49 * 10^6$ kWh	Electricity mix Morocco	Data from IEA [94]
Input	**Amount**	**Output**	**Amount**
Plant	1 plant	Methanol	$5.68 * 10^4$ ton

The inventory that is implemented in Simapro for constructing the micro-plant is depicted in table 3.4. The left column shows which subsystem is described. The amount and material show how much of a certain material is used in each subsystem. Almost all materials are present in the Ecoinvent database. If this is not the case, a comparable replacement is used. This and other comments are mentioned in the most right column. If specific plastics are unavailable in the Ecoinvent database they are replaced by nylon. The plastics that are replaced by nylon have a total weight of 170 grams. This is not significant with respect to the micro-plant, which is 52.8 kg. The plastic of the fans is assumed to be PET, which is a common plastic and available in the Ecoinvent database. The last assumption concerning materials is the sorbent used. The sorbent is assumed to be an Amine. Different Amines are present in the Ecoinvent that are used for absorbing CO_2. Assumed is that monoethanolamine is used as a sorbent. It is the amine with the largest environmental impact compared to other amines used for CO_2 capturing [30] [99]. A more elaborate table of all the different components of the micro-plant can be found in appendix E. In this appendix an overview of all material used is present aswell.

The inventory of the micro-plant also contains production methods. As mentioned in the assumptions, only the production of the largest components by weight are taken into account. The unit of the production method is in a kilogram of manufactured material. These processes are available in the Ecoinvent database.

An overview of the product tree from Simapro for constructing and operating one solar MeOH farm is shown in figure 3.3, which is located at the end of this chapter. This figure illustrates the GWP of the life cycle of the farm, excluding the end-of-life. Not all processes are shown in the figure. The figure only shows the main processes above a cut-off rate of 0.5%. This cut-off rate is based on kg of CO_2 equivalent emissions of the processes. For example, the construction of the pipelines is not depicted because the impact is smaller than 0.5% of the total CO_2 emissions. The green arrows indicate CO_2 equivalent absorbance while the red arrows indicate emissions.

Table 3.4: The inventory used in Simapro for the micro-plant.

Compartment	Amount	Material	Comment
AEC	8020 g	Stainless steel	Mainly casing

Continued on next page

Table 3.4 – *Continued from previous page*

Compartment	**Amount**	**Material**	**Comment**
	4740 g	Polyphenylene sulfide	Cookie-roll [1]
	1650 g	KOH	Electrolyte
	1650 g	Nickel	Electrodes
	200 g	Zirconium oxide	Membrane
	200 g	Polysulfone	Membrane
	150 g	Copper	-
	25 g	Nylon	-
	12 g	Fiberglass	-
	4 g	Rubber	-
	0.24 g	Aluminium	-
	7950 g	Steel pipe drawing	Production method
	4740 g	Injection molding	-
Compressor	5694 g	Stainless steel	-
	1780 g	Aluminium	-
	120 g	Polyoxymethylene	Nylon used
	25 g	Copper	-
	8	Rubber	-
	5500 g	Steel product manufacturing	Production method
	1780 g	Aluminium product manufactering	-
DAC	3000 g	Solvent	Monoethanolamine used
	1400 g	PET	-
	975 g	Stainless steel	-
	670 g	Plastic	From fans, PET Used
	500 g	Aluminium	-
	350 g	Paper	-
	200 g	Glass	-
	100 g	Polyethylene, high density	-
	20 g	Al_2O_3	Peltier element
	11 g	Rubber	-
	0.23 g	Printed wiring board	Vacuum sensor
	1500 g	Injection molding	-
	500 g	Aluminium product manufacturing	Production method
	970 g	Steel product manufacturing	Production method
Distillation	2450 g	Aluminium	-
	450 g	Stainless steel	-
	37 g	Nylon	-
	30 g	Kevlar	Nylon used
	20 g	Al_2O_3	Peltier element
	19 g	Fiber glass	-
	6 g	Rubber	-
	2450 g	Aluminium product manufacturing	Production method
	440 g	Steel product manufacturing	Production method
Integration	6960 g	Stainless steel	Mainly buffers
	4740 g	PET	Mainly casing
	1960 g	Cellulose	Insulation
	540 g	Aluminium	-
	175 g	Printed wiring board	Control system electronics
	46 g	Rubber	-
	4 g	Copper	-
	4740 g	Injection molding	-
	6960 g	Steel product manufacturing	Production method
MS	1490 g	Copper	Heat exchange parts
	1040 g	Aluminium	-
	870 g	Stainless steel	-
	160 g	Al_2O_3	Catalyst

Continued on next page

[1] This is the material that forms the body of the AEC.

Table 3.4 – *Continued from previous page*

Compartment	**Amount**	**Material**	**Comment**
	40 g	ZnO	Catalyst
	23 g	Nylon	-
	20 g	Acrylic	Nylon used
	6.2 g	Fiber glass	-
	2.3 g	Rubber	-
	1490 g	Copper product manufacturing	Production method
	1040 g	Aluminium product manufacturing	Production method
	810	Steel product manufacturing	Production method
PV panels	5.8 m^2	Ribbon-Si PV	From Ecoinvent [30]
	5.8 m^2	Open ground Mounting	From Ecoinvent [30]

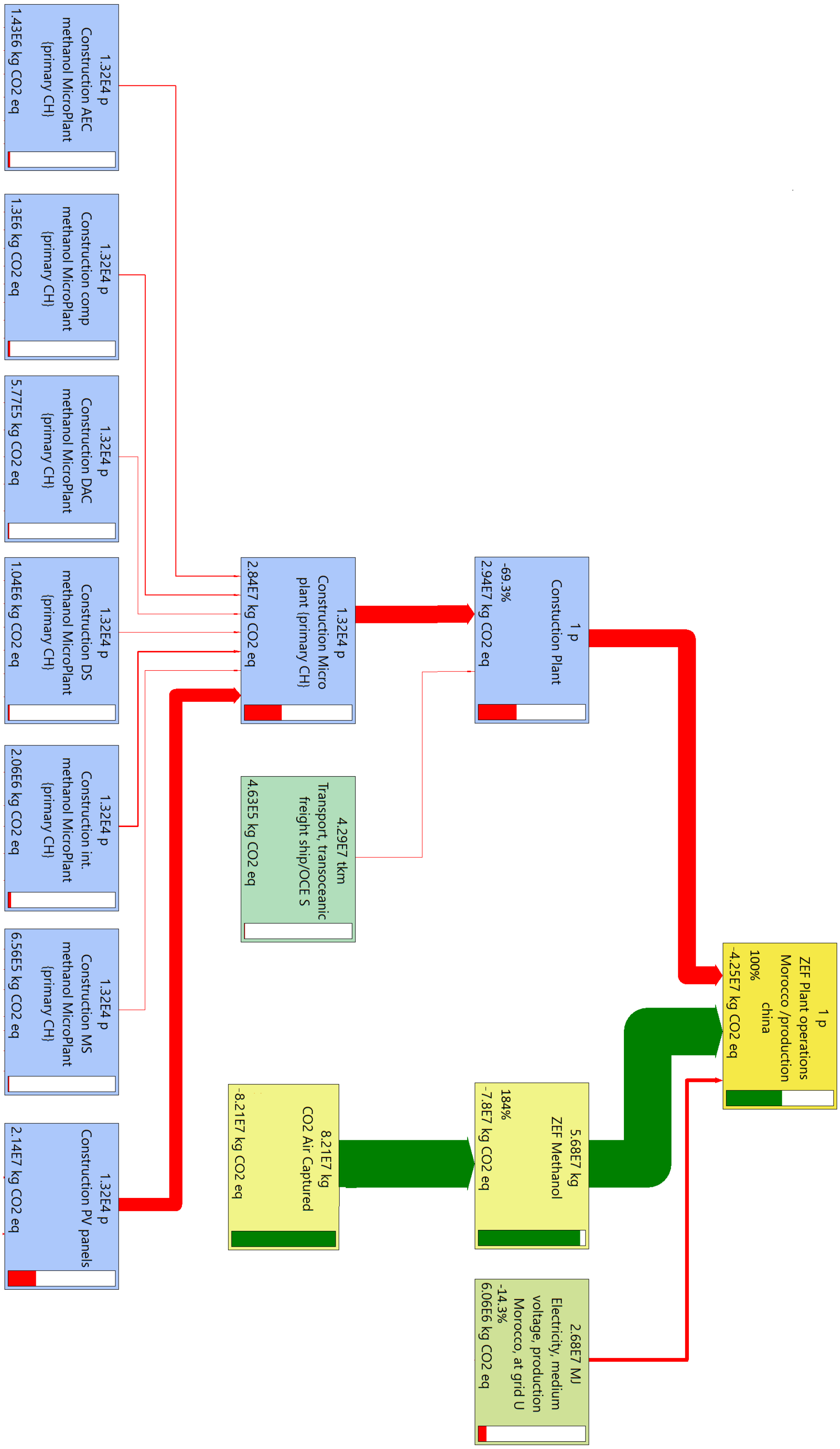


Figure 3.3: The simplified producttree from the Simapro software.

4

Results & Discussion

This chapter discusses the results of the two LCA's. The first section discusses the results from the comparative LCA concerning PV panels. This section discusses the type of PV panel with the smallest environmental impact. The second section discusses the results of the LCA for the methanol produced by the solar MeOH farm. The last section compares the environmental impact of methanol produced by the solar MeOH farm with the main production methods of methanol.

4.1. LCA PV Panels

This section discusses the comparative LCA of different PV panels. The first subsection discusses the results of the LCA. The results are focused on the endpoint impact categories. The second subsection compares the GWP from the LCA with results from the literature study. This comparison is made to check the accuracy of the conducted LCA. The last subsection discusses which PV panel is advised.

4.1.1. Results

The results discussed in this chapter are base on the ReCiPe method that focuses on the endpoint impact category. The results of the midpoint impact categories are discussed in appendix C. As mentioned before, this method did not give clear benefits of one PV panel over the other. For this reason, all 18 midpoint impact categories are included in the assessment. These 18 midpoints are converted to the three endpoint impact categories, damage to human health, damage to the ecosystem, and damage to resource availability. Figure 4.1 depicts the difference in results for the damage to human health and the GWP.

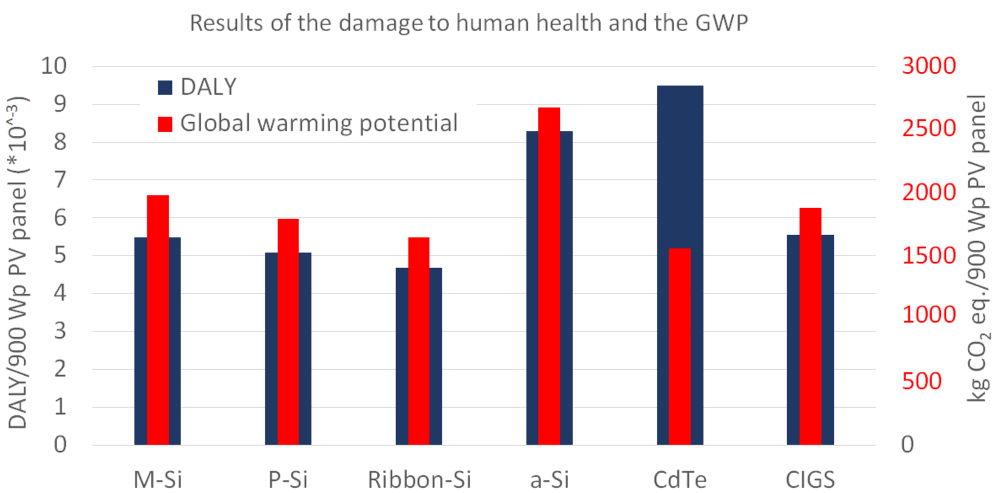


Figure 4.1: The results of the endpoint damage to human health and the midpoint GWP for constructing the different PV panels, including mounting structure.

This figure is used to illustrate why the midpoints do not give clear benefits, but the endpoints do. Figure 4.1 depicts the midpoint impact category GWP in red. CdTe PV panels have the lowest CO_2 equivalent emissions. However, as mentioned in chapter 2, the cadmium used to produce CdTe PV panels is highly toxic. The endpoint damage to human health takes this factor, and others, into account. The trend of the graph when looking at DALY changes and CdTe shows to have the largest environmental impact. For the endpoint impact category damage to human health, the silicon crystalline PV panels have a lower impact than the thin-film technologies. Moreover, the ribbon-Si PV panels have the lowest environmental impact for this endpoint.

Figure 4.2 shows the results for the other two endpoint impact categories, damage to the ecosystem, and damage to resource availability. For the damage to the ecosystem, the silicon crystalline PV panels have a lower impact than the thin-film technologies. The difference between a-Si and CIGS PV panels with the silicon crystalline PV panels is decreased. However, the CdTe PV panel is still the technology with the highest environmental impact. Ribbon-Si PV panels have the lowest environmental impact for both the damage to the ecosystem as the resource availability category endpoints. For damage to resource availability, CdTe and CIGS PV panels are both in the same range as the ribbon-Si, around 80 USD2013.

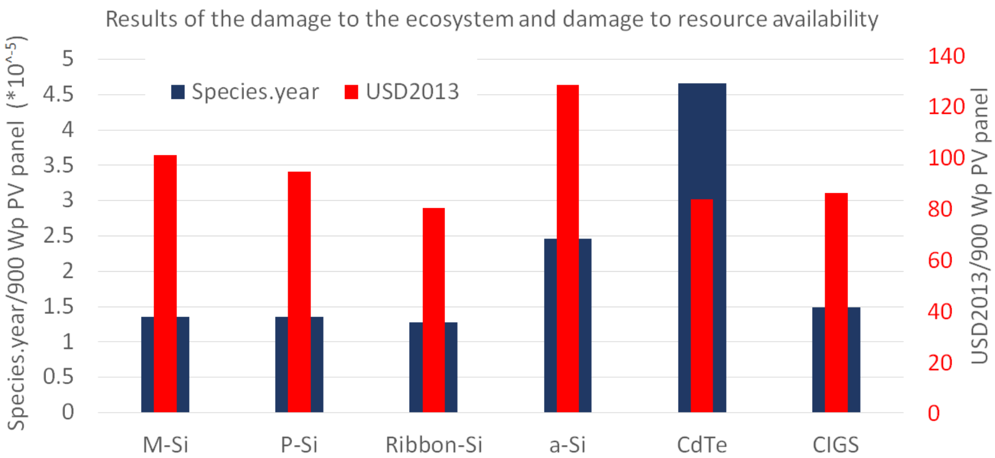


Figure 4.2: The results of the endpoints damage to the ecosystem and damage to resource availability for constructing the different PV panels, including mounting structure.

4.1.2. Comparison Simparo and Literature

To make sure the data from the Ecoinvent is accurate and interpreted correctly, it is compared with values obtained from literature. The GWP of producing PV panels with a capacity of 900 Wp are compared. The literature values used are listed in table 4.1. The uncertainty is equal to the standard deviation between the results from the literature. These values are compared with the results from the LCA conducted in Simapro. The uncertainty in the Simapro data is determined differently than that of the literature, because there is an uncertainty in the efficiencies. From literature, a range of efficiencies per PV panel is obtained, depicted in table 2.11. The uncertainty in the efficiency directly influences the area of PV panel constructed, e.g., a smaller efficiency leads to an increase in PV panel area. The increase in PV panel area constructed leads to an increase in emissions, which leads to an increase in GWP. The uncertainty is determined by using the deviation in efficiency and recalculating this to a standard deviation. Appendix B shows how the efficiency is converted to a standard deviation.

Figure 4.3 compares the results of the assessment with data obtained from literature. The uncertainty from table 4.1 is included in the figure as the error bars. It can be concluded from this figure that the trend is the same. The data obtained from Simapro is concerned to be reliable based on this comparison and is used to substantiate the advice.

Table 4.1: Overview of the GWP obtained from literature and the results from Simapro, including the uncertainty of the results.

	GWP from literature	Uncertainty	GWP from Simapro [30]	Uncertainty
M-Si	1540	± 400	1460	± 325
P-Si	1350	± 290	1210	± 150
Ribbon-Si	1140	± 215	1040	± 135
a-Si	1080	± 230	1120	± 185
CdTe	595	± 175	670	± 65
CIGS	1080	± 125	1065	± 140

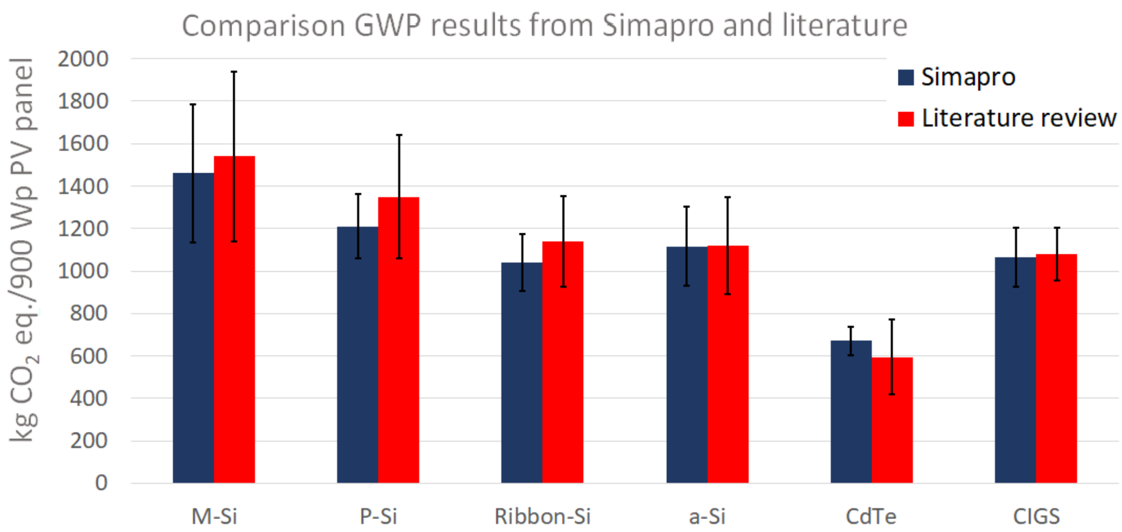


Figure 4.3: Amount of CO_2 equivalent emitted during manufacturing of different PV panels. The red bars show the average emission obtained from literature and the blue bars show the data obtained from the conducted LCA.

4.1.3. Advise PV Panels

The goal of the comparative LCA is to advise which PV panel has the smallest environmental impact. This section gives a discussion, and an advice based on the result from the LCA and information obtained in the literature study. For the endpoint damage to human health, the silicon crystalline PV technologies have a significantly lower impact than the thin-film technologies. The results for the endpoint damage to the ecosystem also show a lower environmental impact for the silicon crystalline PV technologies.

The last endpoint impact category, damage to resource availability, shows that the polycrystalline techniques, the CdTe, and the CIGS have approximately the same environmental impact. The damage to resource availability for these three techniques score within 15% of each other.

Two additional factors are included in the advice. The first factor is the land use of the solar MeOH farm. The PV panels are in size the largest component of the modular MeOH system. More area used means space efficiency of the farm decreases. The silicon crystalline PV technologies have the lowest land used. The second factor is based on costs. From a brief literature review, it followed that the polycrystalline and a-Si PV technologies have the lowest costs.

From these results, there is concluded that the PV panels based on polycrystalline technologies have the lowest environmental impact. Combining the costs with the land use also leads to an advantage for the polycrystalline PV panels. More specific, polycrystalline PV panels produced by the string ribbon technique. The yearly decrease in efficiency for thin-film PV panels is higher than that of the crystalline silicon PV panels. The assumption to not include the lifetime does not influence these results, as including it would lead to a larger benefit of the silicon crystalline PV panels over the thin-film PV panels. The advice for ZEF is to use polycrystalline PV panels produced by the string ribbon technique. In practice, it can be argued that the string ribbon technique is slightly less expensive. This means it is likely that if ZEF purchases the least expensive polycrystalline PV panels, these are produced by the string ribbon technique.

4.2. Results LCA Solar MeOH farm

This LCA is based on the base case scenario, as explained in chapter 3. The first part of this section discusses the results of the base case scenario. First, a general overview is presented; this is followed by a detailed discussion of the different midpoint impact categories. Appendix G discusses the environmental impact of production methods, which do not have a significant environmental impact.

Table 4.2 shows the results of the conducted LCA. It is clear from the table that the manufacturing of the modular MeOH system has the highest environmental impact. The table shows the results for different functional units. The functional unit ton of methanol is used for comparisons. The other two functional units are to show the environmental impact per modular MeOH system and per solar MeOH farm. Table 4.3 shows the energy payback time (EPT) and the CO_2 break-even point in years. How these values are calculated is explained in the following sections, as well as a detailed discussion of the results per impact category.

Table 4.2: Results for the base case scenario after 20 years of production. Showing the standard deviation and the contribution in percentages of different components.

	Global warming potential [kg CO_2 eq.]	**Mineral resource scarcity [kg Cu eq.]**	**Fossil resource scarcity [kg oil eq.]**
Per ton of methanol	-835 ± 50 (6.5%)	10.7 ± 0.7 (6.3%)	127 ± 13 (10%)
Per modular MeOH system	-3570 ± 230 (6.5%)	45 ± 3 (6.3%)	545 ± 50 (10%)
Per solar MeOH farm	$-4.7*10^7 \pm 3.1*10^6$ (6.5%)	$6.1*10^5 \pm 3.8*10^4$ (6.3%)	$7.2*10^6 \pm 7*10^5$ (10%)
Contribution			
Modular MeOH system	**92.8%**	**98%**	**91.7%**
PV panels	69.7%	33.5%	67.7%
Micro-plant	23%	64.5%	24%
Electricity	**3.95%**	**0.12%**	**4.4%**
Transport	**1.94%**	**0.18%**	**2.53%**
Ship	1.51%	0.09%	1.98%
Rail	0.19%	0.05%	0.21%
Road	0.24%	0.04%	0.34%
Plant	**1.34%**	**1.69%**	**1.39%**
Storage	1.3%	1.69%	1.23%
pipelines	0.04%	0%	0.16%

Table 4.3: Overview of the EPT and the CO_2 break-even point in years of methanol production.

	Years of methanol production
EPT	6.9 ± 0.7
CO_2 break-even	7.9 ± 0.8

4.2.1. Global Warming Potential

This section discusses the GWP, in more detail. First, the CO_2 equivalent emissions of constructing and operating the solar MeOH farm are elaborated. This section is followed by an overview of the GWP per material. The last part discusses the CO_2 absorption.

Table 4.2 showed that the manufacturing of the modular MeOH system has the largest environmental impact, with a share of approximately 93%. Figure 4.4 depicts the GWP distribution of constructing and operating the solar MeOH farm. Figure 4.5 depicts the contribution to the GWP for different components of manufacturing the modular MeOH system. From this figure, it can be seen that the manufacturing of the PV panels generates almost 75% of the GWP. Figure 4.6 shows the contribution of manufacturing the PV panel and mounting system on the GWP. The mounting system is a substantial part of the GWP, meaning there is room for improvement possible. On the right side in figure 4.5, the manufacturing of GWP for constructing the different subsystems is depicted. This figure indicates that the DAC and MS relatively have a smaller environmental impact than the other subsystems, which are in the same order of magnitude.

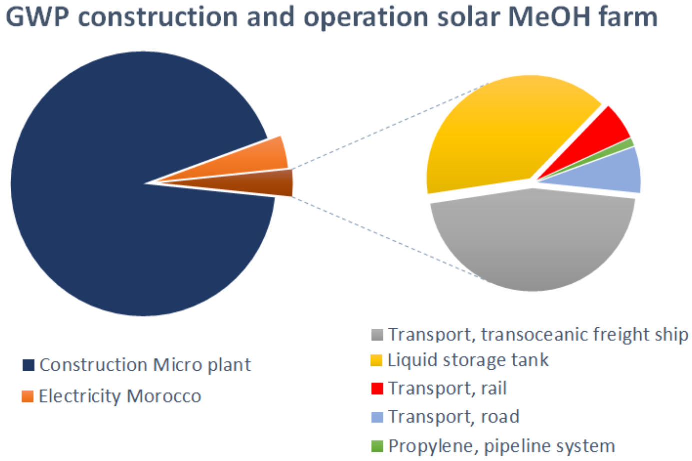


Figure 4.4: Distribution of CO_2 equivalent emitted during construction of the solar MeOH farm.

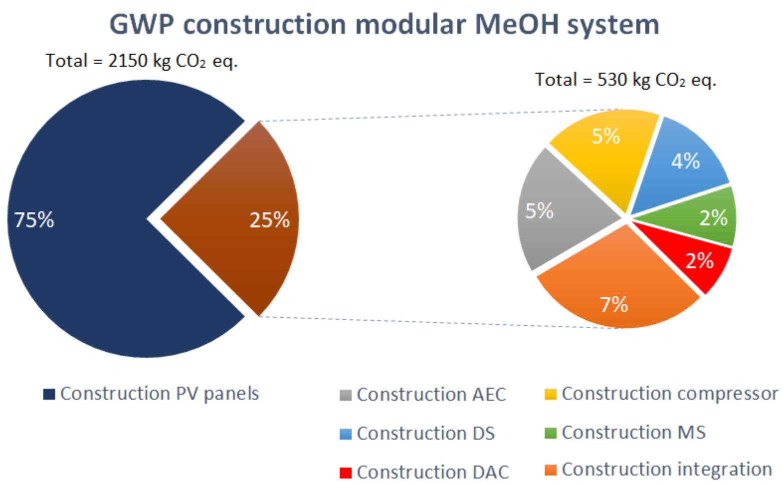


Figure 4.5: Distribution of CO_2 equivalent emitted during manufacturing of the modular MeOH system.

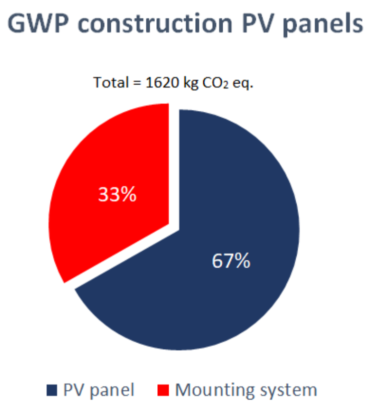


Figure 4.6: GWP percentages of manufacturing the PV panels and mounting structure.

Figure 4.7 visualises the contribution of different materials to the GWP. From this figure, it is clear that the stainless steel and the aluminium have the largest contribution. However looking back at the list of materials in the inventory, stainless steel is the most used material, and for example, printed wiring board only is a small percentage of the weight. To give better insight to which materials have a relatively larger impact the materials are normalised to GWP per kilogram. Figure 4.8 depicts the normalised impact. The printed wiring board has a CO_2 equivalent emissions of 350 kg per kg of material. To not disturb the overview of the graph the printed wiring board is plotted on the left axis, while the other materials are plotted on the right axis.

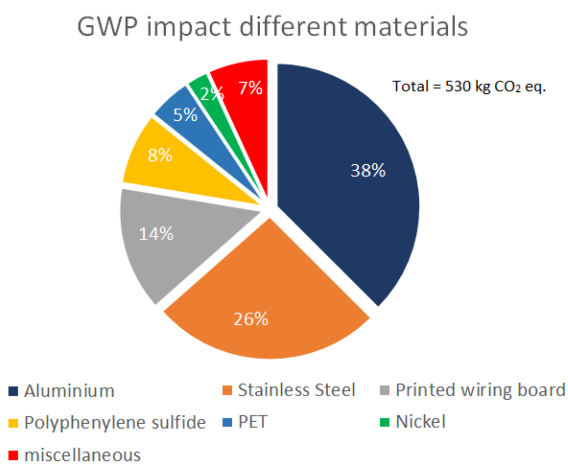


Figure 4.7: Contribution of different materials to the GWP of manufacturing the micro-plant.

Materials with a smaller GWP than zinc oxide are not depicted in the figure.

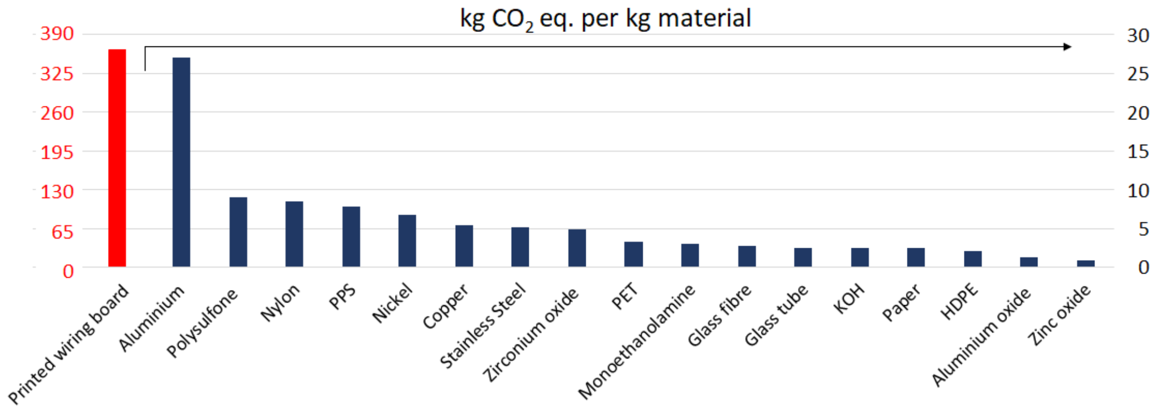


Figure 4.8: Overview of the kg CO_2 equivalent emissions of constructing one kilogram of material for the materials used in constructing the micro-plant.

This graph is used to advise on selecting different types of material. For example, one could argue that the use of printed wired board and aluminium should be minimised. When designing new prototypes, this graph can be used to obtain a material with the smallest GWP.

The process of producing methanol by the solar MeOH farm absorbs CO_2 from the air. This means that the GWP of producing methanol is negative. As mentioned in chapter 3, one solar MeOH farm produces 56.8 kilotons of methanol. 1 kilogram of methanol absorbs 1.37 kilograms of CO_2. In figure 4.9 the CO_2 emissions and absorbance over time are plotted. The darker colour blue line is the average value for the amount of kg CO_2 equivalent. The other two lines are the upper limit and lower limit following from the standard deviation. The results that follow from this graph is that the CO_2 break-even point is after 7.9 ± 0.8 years. The methanol produced before 7.9 years is thus not zero-emission, producing zero-emissions methanol is one of the goals of ZEF. This number can be recalculated to the kg CO_2 equivalent emissions of one modular MeOH systems by dividing by the number of systems.

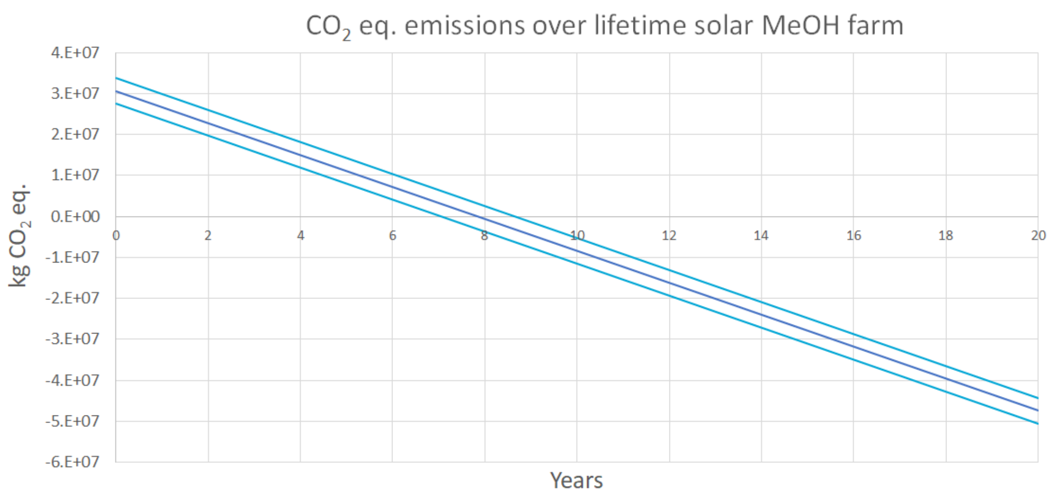


Figure 4.9: Overview of the kg CO_2 equivalent emission over the years of production for the solar MeOH farm. The lighter blue lines indicate the standard deviation.

The GWP per ton of methanol shows a different relationship over time. The CO_2 equivalent emissions of constructing the solar MeOH farm are fixed. This is the starting point of the graph depicted in figure 4.9. Over the lifetime of the farm, methanol is produced, and CO_2 absorbed. The more methanol produced, the more CO_2 is absorbed. More methanol produced also means the GWP of producing the solar MeOH farm is divided by a larger number. This relation is rewritten into equation 4.1.

$$\frac{\text{kg } CO_2 \text{ eq.}}{\text{ton of MeOH}} = \frac{\text{kg } CO_2 \text{eq. from construction phase}}{\text{years} * \text{ yearly production methanol(ton)}} - \text{yearly } CO_2 \text{ absorption(kg)} * \text{years} \quad (4.1)$$

From this equation, it can be concluded that this is not a directly proportional correlation. The equation is visualised in figure 4.10. In the first years of production the kg CO_2 equivalent emitted during the construction phase is the dominant factor. This means the first term of the equation is the largest, which explains the curve of the graph for the first 5 years. This shape is similar to a 1/x function. After that, the curve becomes more linear because the second term of the equation becomes dominant. One ton of methanol can never absorb more than 1370 kg of CO_2. The red line in the graph visualises this maximum absorption or asymptote. This graph is important to make statements about the lifetime. If the lifetime becomes shorter than approximately 6 years the GWP increases exponentially.

The uncertainty only influences the GWP of construction. The methanol production and thus absorption of CO_2 is not influenced by these uncertainties. This explains why the standard deviation lines in figure 4.10 converge.

The potential to decrease the GWP is to lower the starting position of the graph, which is the CO_2 emission of constructing the solar MeOH farm. This would mean the graph shifts down, and the exponential part of the curve would lead to faster CO_2 break-even points. The second conclusion that follows from this figure is that the lifetime of the micro-plants should be long to decrease the GWP.

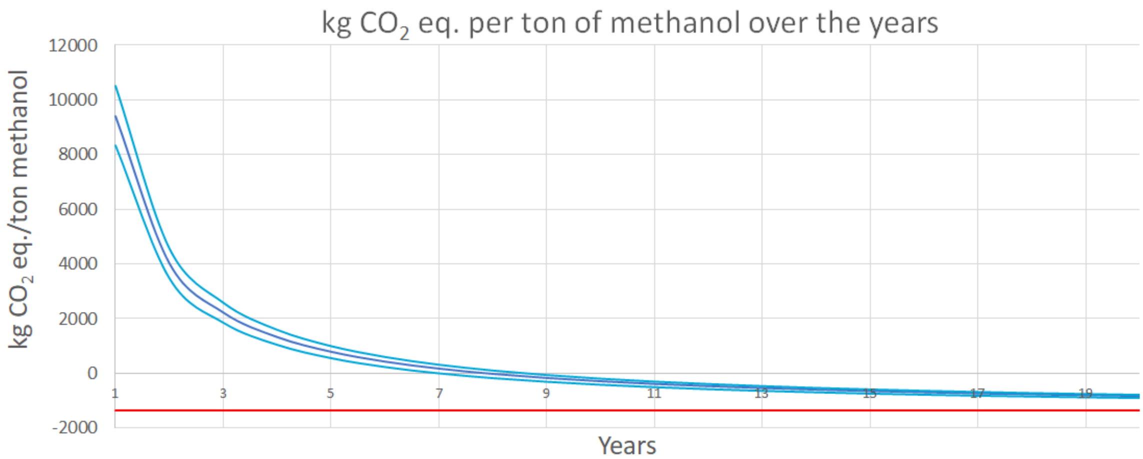


Figure 4.10: This graph illustrates how the kilogram of CO_2 emission per ton of methanol changes over the years of production. The red line indicates the maximum CO_2 absorption/ton of methanol.

As mentioned in chapter 1, a large part of the methanol is used as a fuel. When methanol is burned as fuel the captured CO_2 is rereleased again. For ZEF to have zero-emissions, the methanol produced the first 7.9 ± 0.8 years should be stored in chemicals or plastics. By doing so, the CO_2 absorbed is not emitted again. If the lifetime is equal to 20 years, this means that at least ≈ 40 % ± 4 % of the methanol should be stored in chemicals or plastics to be zero-emission. However, there can be argued that this CO_2 is not taken out of the circle forever, but just for a longer time in comparison with methanol used as a fuel. The GWP can be used to calculate the global temperature increase or decrease, which is explained in appendix F.

4.2.2. Mineral Resource Scarcity

This section discusses the midpoint impact category of mineral resource scarcity. From table 4.2 it can be seen that only 2% of the mineral consumption is due to electricity use, transport, storage, and pipelines of the solar MeOH farm. In figure 4.11 the results for manufacturing the modular MeOH system are depicted with respect to the different subsystems. The PV panel manufacturing has less impact in this category in comparison with the GWP. Figure

4.12 shows the contribution of the PV panels and mounting system. The mounting system uses more minerals than the PV panel. The reason for this is that the frame is built up from around 20 kg aluminium and 38 kg of steel. Silicon is a very common element, so it has a low weighting factor in this impact category. For the manufacturing of the micro-plant, the AEC jumps out because of the use of nickel in the electrodes.

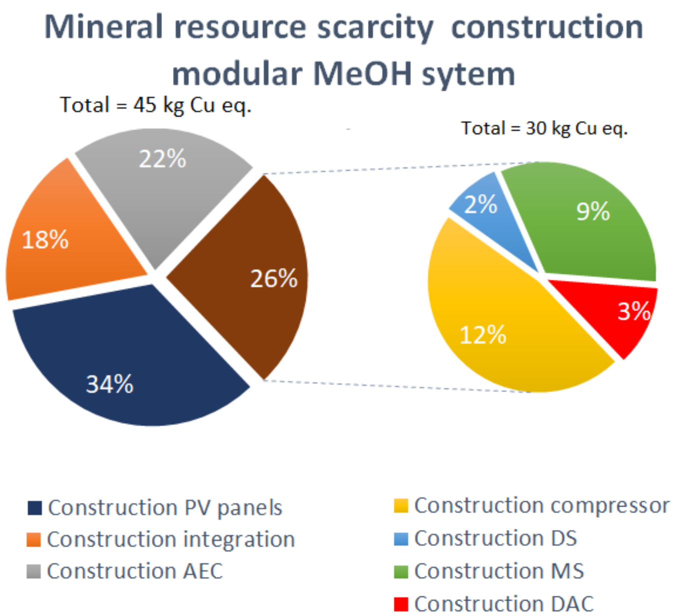


Figure 4.11: Distribution of Cu equivalent consumed for manufacturing the modular MeOH system.

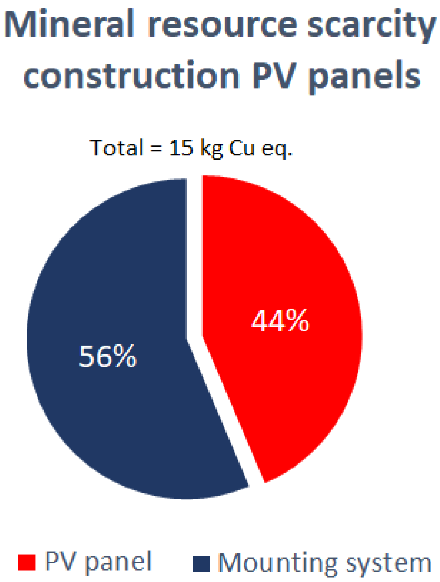


Figure 4.12: Mineral resource scarcity percentages of manufacturing the PV panels and mounting structure.

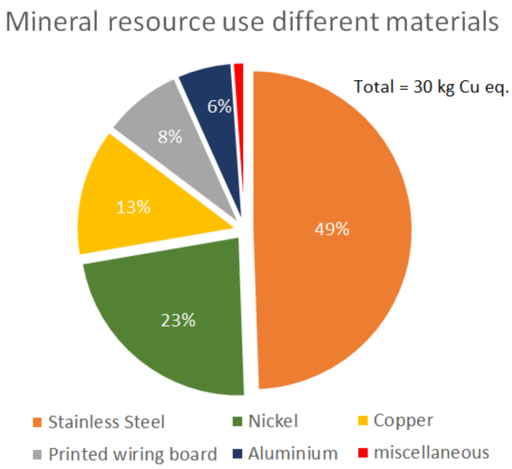


Figure 4.13: Contribution of different materials to the mineral resource use of manufacturing the micro-plant.

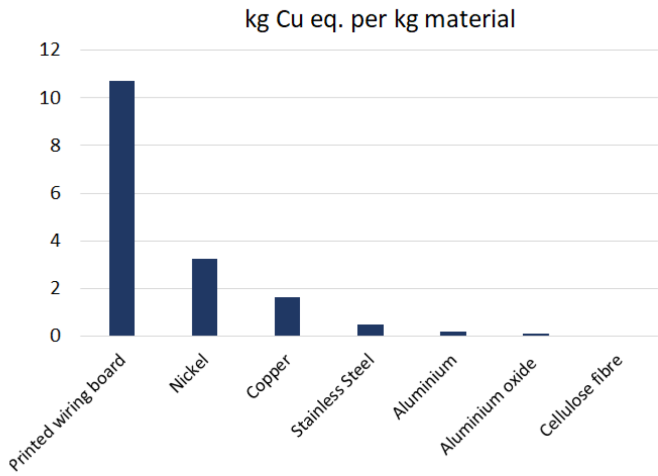


Figure 4.14: Overview of the kilogram of Cu equivalent consumption of producing one kilogram of material.

The mineral resource consumption for different materials can be visualised just as the GWP, which is depicted in figure 4.13. One can now see a different follow-up. The AEC is one of the most significant contributors. Because aluminium is a very common metal, the mineral use is significantly lower than the GWP of aluminium. The materials have been normalised, which is depicted in figure 4.14. Again the printed wiring board shoots out which reconfirms the statement that the use of this should be limited. The figure only shows the top 7 materials because the values drop significantly after aluminium oxide. All plastics consume little minerals. Nickel is hard to replace because other materials that work as an electrode in an alkaline environment are most likely rarer. This impact category can be influenced significantly by changing from metals to plastics.

4.2.3. Fossil Resource Scarcity

This section discusses the midpoint impact category of fossil resource scarcity. The last section elaborates on the EPT. Figure 4.15 depicts the fossil resource use of constructing the solar MeOH farm. The results of the GWP and fossil resource scarcity are comparable. Table 4.2 showed that the contribution percentages are in the same order of magnitude. Once again, the manufacturing of the modular MeOH system has the most significant impact. Figure 4.16 shows that the manufacturing of the PV panel consumes around 74% of the fossil fuels used. Figure 4.17 shows the distribution of oil equivalent of constructing the PV panels and mounting system, and figure 4.18 shows the oil equivalent per kilogram of material. In comparison with the GWP, the aluminium has a relatively smaller impact. The trend in the rest of the graph is similar to that of the GWP. The distribution of the fossil resource scarcity is not discussed in further detail because it follows the same trend as the GWP. The consumption of fossil resources is directly linked to the emission of greenhouse gasses. To extract the energy stored in fossil resource, they are burned, and this emits greenhouse gasses. This explains why these two impact categories follow the same trend.

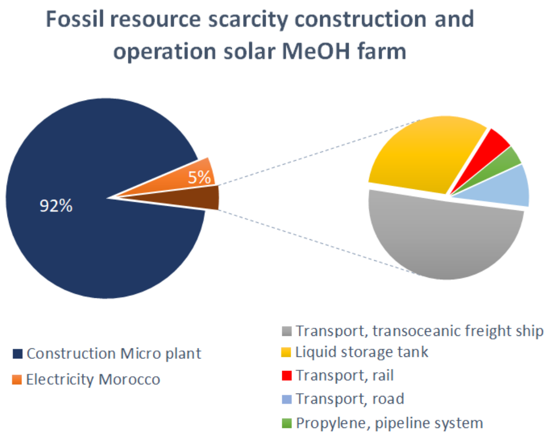


Figure 4.15: Distribution of oil equivalent consumed during construction of the solar MeOH farm.

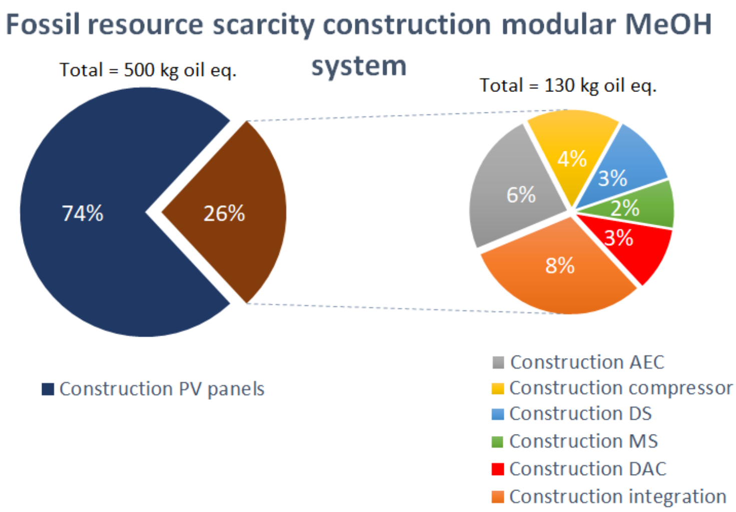


Figure 4.16: Distribution of oil equivalent consumed for manufacturing the modular MeOH system.

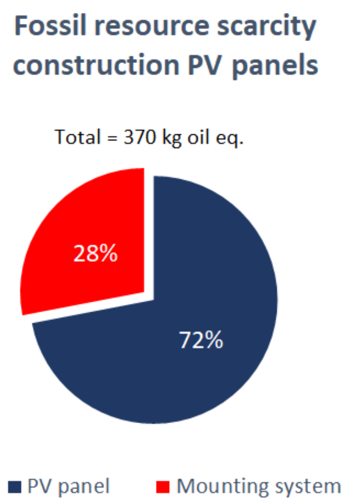


Figure 4.17: Fossil resource scarcity percentages of manufacturing the PV panels and mounting structure.

By using the Ecoinvent model, the energy used to construct a solar MeOH farm can be determined. This energy consumption is approximately $4.85*10^8 \pm 10\%$ MJ. The standard deviation is assumed to be the same as the fossil resource scarcity because this is directly linked to energy use. The energy content of one kilogram of methanol is 20 MJ, which is the lower heating value. By combining the energy content and the methanol production, the EPT is calculated, which is 8.5 ± 0.85 years. This is compared with the EPT of polycrystalline PV panels, which is around 3.5 years [100]. This number only takes the manufacturing of the PV panel into account. Transportation and farm construction are not taken into account. To make a fair comparison, the energy use for constructing only the modular MeOH system is used. The manufacturing of one modular MeOH system requires approximately $2.96*10^4$ $\pm 10\%$ MJ. By using the production of one modular MeOH system, the energy payback can

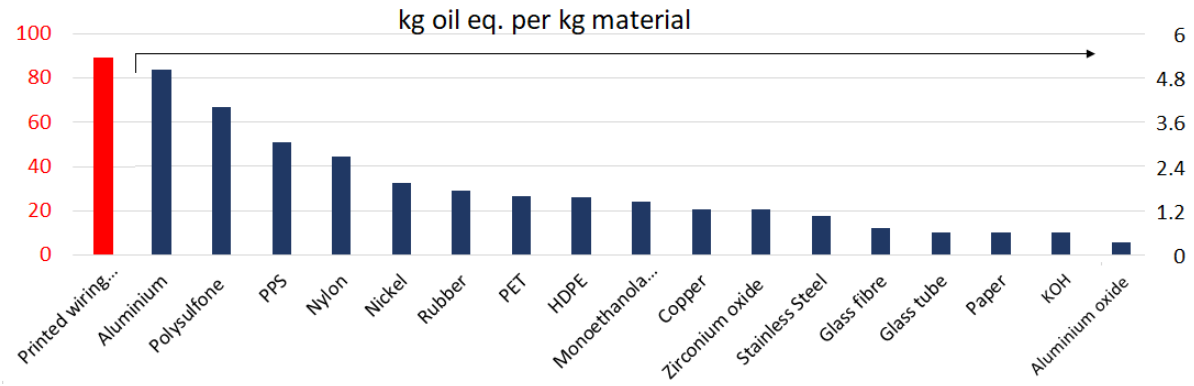


Figure 4.18: Overview of the kilogram of oil equivalent consumed for producing one kilogram of material.

once again be calculated. This number is 6.9 ± 0.7 years. This is almost double that of the polycrystalline panel, which can be explained because the efficiency of the micro-plant is around 50%. This is one year earlier than the CO_2 break-even point. From now on, when the EPT is discussed in this research, only the energy to produce one modular MeOH system is taken into account.

4.3. Comparison Main Production Methods of Methanol

Chapter 2.3 described the environmental impact of the main production routes for producing methanol. In this section the environmental impact per ton of methanol is compared with the methanol produced by the solar MeOH farm. Due to lack of data for the impact categories mineral resource scarcity and fossil resource scarcity the main focus is on the GWP. In this comparison the production rate of the main production routes is equal to that of the solar MeOH farm.

4.3.1. GWP Comparison

The results for the production of the methanol produced by ZEF includes the construction of the solar MeOH farm. This means that the CO_2 emissions start at a positive value. It is assumed that one ton methanol absorbs 1370 kilogram of CO_2. After 20 years this leads to the same GWP as when starting at zero, but using the emission value of ≈ -835 CO_2 per ton methanol. Figure 4.19 depicts these different ways of interpretation. One can see that after 20 years the results are equal. After this, a new farm is constructed which the red line includes. The black line includes this impact of construction in the average CO_2 absorption. The red line is used in the comparisons because it shows break-even points. When the line of CO_2 emissions of ZEF methanol crosses another line than at that point in time the methanol produced by ZEF has less CO_2 emissions.

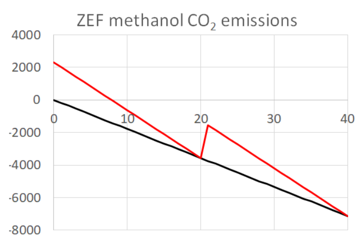


Figure 4.19: CO_2 eq. emissions for methanol produced by ZEF with different ways of interpretation.

Figure 4.20 depicts the comparison in GWP between the two main production methods and methanol produced by the ZEF solar MeOH farm. The methanol produced by ZEF emits less CO_2 than natural gas after approximately 5 years. As mentioned before, 90% of the methanol is produced by the natural gas route. Producing methanol from coal produces more CO_2 equivalent. After approximately 2.5 years the ZEF methanol has fewer CO_2 equivalent emissions than methanol produced from coal. The error is included in the figure as the lighter red lines. The methanol produced by ZEF includes the construction of the plant. However, natural gas and coal routes do not include the construction of capital goods. In the Ecoinvent database, data is available for the construction of a natural gas to methanol plant. The impact of this construction contributes 0.17% to the GWP, which is not significant. Assuming that constructing the capital goods for the coal to methanol plant is approximately the same, this would contribute 0.05% to the GWP. Concluding that including the construction does not change the results. Table 4.4 shows the GWP per ton of methanol for the different production methods.

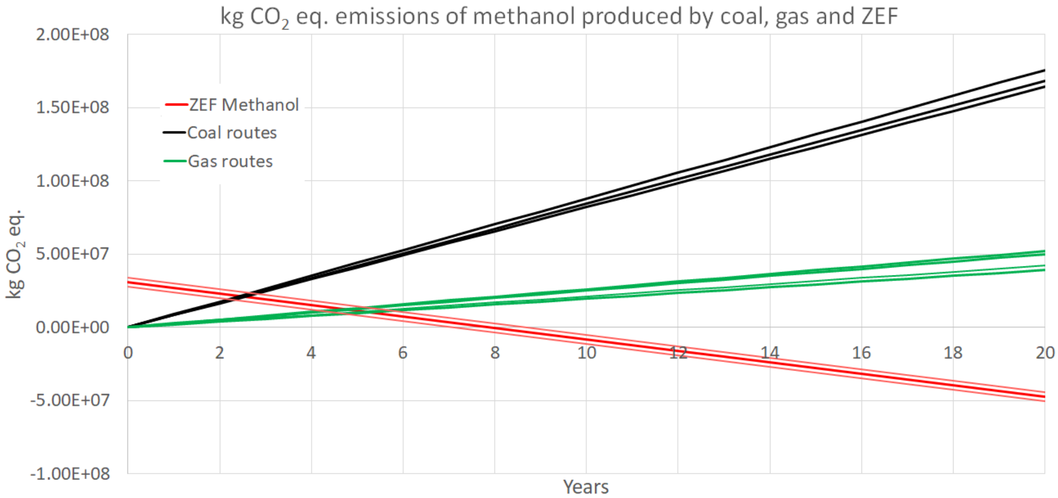


Figure 4.20: Comparison of the CO_2 equivalent emissions for methanol produced from coal, natural gas, and the ZEF solar MeOH farm.

4.3.2. Mineral Resource Scarcity & Fossil Resource Scarcity

The data available for the last two impact categories are scarce. However, the Ecoinvent database does contain information for these impact categories. Table 4.4 depicts the results for producing one ton of methanol. The data is only available for the natural gas route, which is the most used feedstock for methanol.

Methanol produced by ZEF consumes significantly more minerals. This follows from the fact that the modular MeOH system is smaller than conventional methanol production plants. The relative lifetime and production are also less than that of a conventional methanol plant. ZEF consumes more materials but compensate that by lower GWP and fossil resource use. ZEF methanol consumes fewer fossil resources than the natural gas route. In this process, natural gas, which is a fossil resource, is consumed. The ZEF plant only consumes fossil resources during the construction of the solar MeOH farm. During operation, it does not consume fossil or mineral resources.

The assumption is made that the mineral resource use of the coal production route is approximately equal to that of the natural gas route. No other statements can be made concerning the coal production route because no data is available. A comparative LCA should be conducted between the coal route and the ZEF methanol route to obtain this data.

Table 4.4: Overview of the average environmental impact per ton of methanol produced by ZEF, from naturals, and from coal.

Production method	GWP	Mineral resource scarcity [kg Cu eq.]	Fossil resource scarcity [kg oil eq.]
ZEF	-835 ± 6.5%	11 ± 6.3%	125 ± 10%
natural Gas	805 ± 11.5%	1.45 ± 25% [30]	755 ± 20% [30]
Coal [30]	2980 ± 3%	-	-

5
Sensitivity Analysis

In this chapter, a sensitivity analysis is conducted. In chapter 3 the assumption made in the LCA have been discussed. The goal of this chapter is to quantify the effect of the assumptions on the environmental impact. This chapter only discusses the sensitivity analysis of the LCA concerning the solar MeOH farm. Different scenarios are presented which change specific assumptions. The results of the sensitivity analysis indicate on which factors ZEF should focus to keep their environmental impact as small as possible. The results also indicate which assumptions need to be further researched or experimented. The PV panels and mounting system contribute to a large share of the environmental impact. For this reason, the first two scenarios focus on these components. In the third scenario the lifetime of the PV panels and mounting system is discussed. The fourth scenario focuses on the efficiency and lifetime of the micro-plant. In the fifth scenario, the effect of the location of operation for the Solar MeOH farm is discussed. The micro-plant is assumed to have no malfunctioning. Scenario six discusses the influence of malfunctioning. The last scenario explains the effects of recycling. The end of the chapter shows an overview of the results from the sensitivity analysis.

In this chapter, a relative increase in environmental impact with the base case scenario is depicted as a positive number or percentage. When the environmental impact decrease, this is depicted with a negative number or percentage. When percentages are presented in tables, and the environmental impact increases in comparison with the base case scenario, that is indicated by a red colour. The green colour is used when the environmental impact decreases. So, for example, when the total amount of absorbed CO_2 equivalent decreases, this is depicted by a positive red percentage. For this chapter the standard deviation is expressed in absolute terms, not percentages.

5.1. Scenario 1: PV Panels Efficiency

The PV panels contribute approximately two thirds to the GWP and fossil fuel use, and one third to the mineral use. This means that a change in the assumptions can have a significant change in environmental impact. Two main assumptions that influence the environmental impact are the efficiency and the lifetime of the PV panels. The impact of the efficiency is analysed in this section. The section is concluded by a short discussion concerning PV panels.

The trend in PV panels is that the efficiency is increasing over time. This trend has been discussed in chapter 2.2. The assumed average efficiency of 15.5% can be an underestimate in future scenarios. The current record efficiency for polycrystalline PV panels on a lab-scale is 22.3%, the highest efficiency for a polycrystalline module currently is 19.9% [32]. Assumed is that in the coming years the efficiency increases further while the cost decreases. Based on these assumptions, two new efficiencies for the PV panels are selected for this scenario. These new efficiencies represent the possible efficiency of PV panels in the coming years. The new efficiencies are 19% and 21%. These scenarios indicate how much the environmental impact changes with increasing efficiency of PV panels. While the efficiency increases the capacity remains 900 Wp, meaning that the production of the solar MeOH farm does not increase. However, the area of PV panels needed to obtain the same capacity decreases. The materials used per square meter of PV panel is assumed to remain the same.

The change in environmental impact for the described scenarios is depicted in figure 5.1. Due to the efficiency increase of the PV panels, the area needed to produce 900 Wp becomes smaller. This directly influences the materials used in manufacturing the PV panels, and thus the environmental impact of producing the modular MeOH system. Besides this, the mounting system needed decreases. As mentioned before, the mounting system has a functional unit m^2 of PV panel. The change is most significant for fossil fuel use and GWP. The change in numbers is shown in table 5.1. These results show the importance of more efficient PV panels.

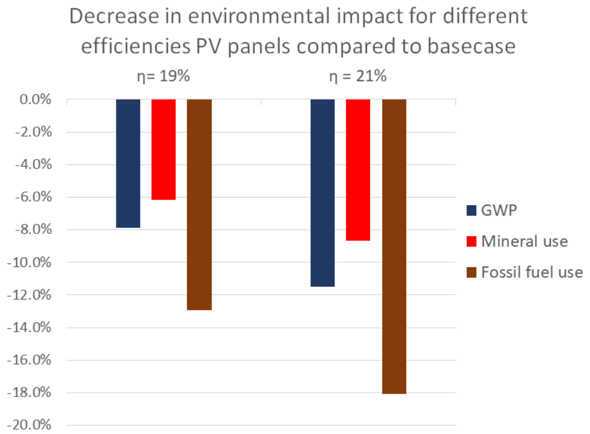


Figure 5.1: The relative decrease in environmental impact by increasing the efficiency of the PV panels.

Table 5.1 depicts the midpoint impact categories fossil resource scarcity and mineral resource scarcity as mineral use and fossil fuel use, respectively. The difference between the scenario and the base case shows the difference between the average values.

Table 5.1: Results of the environmental impact when the efficiency of the PV panels is increased. Using the functional unit ton of methanol.

	GWP	Mineral use	Fossil fuel use	CO_2 break-even [y]	EPT [y]
19%	-900 ± 45	10 ± 0.6	110 ± 11	6.9 ± 0.7	6 ± 0.6
Difference base case	-7.8%	-6.5%	-13.4%	-1 year	-0.9 year
21%	-930 ± 40	9.8 ± 0.6	105 ± 10	6.5 ± 0.6	5.6 ± 0.56
Difference base case	-11.5%	-8.5%	-17.3%	-1.4 year	-1.3 year

From this scenario, it is concluded that an increase in PV panel efficiency decreases the environmental impact significantly. More research should be conducted on the PV panels. Currently, ribbon-Si PV panels have the lowest environmental impact. This can change in the future to other PV technologies. To decrease the uncertainty for PV panels, further research should be conducted on PV panels. A factor that influences the efficiency is the use of so-called bifacial PV panels. These PV panels absorb not only direct sunlight but also diffused sunlight. The assumption is made that this does not significantly influence efficiency. This assumption should be researched further. Also, the assumption that when efficiency increases the area of the PV panels decreases but the materials used per square meter remain the same needs to be further researched.

5.2. Scenario 2: Mounting System

In chapter 2.2.3, the mounting System is described. From a report of the IEA concerning PV systems inventory and life cycle assessments, other mounting systems are found [69]. The first mounting design uses more stainless steel and less concrete than the base case mounting system. The second mounting design uses more concrete and slightly more aluminium. The last design is a concept and uses the second design but replaces the aluminium with wood. Constructing PV mounting systems with wood is a new trend in PV mounting construction. It can possibly decrease the environmental impact of the mounting system [70]. Table 5.2 gives an overview of the materials for the different mounting systems. The materials depicted in the table are the materials that change with respect to the base case. Important is to note that the land use and fencing of the farm are kept the same. The only factor that changes is the main materials used.

The results of using different mounting systems are presented in figure 5.2 and table 5.3. Design 1 increases the environmental impact of all three impact categories significantly. The uncertainty increases in this scenario because the uncertainty in the PV panels becomes more dominant. With the second design, the GWP and fossil resource use decrease with approximately 5% and 6.5% respectively. The last design especially decreases the use of

Table 5.2: Materials used in kilogram for different designs of the mounting system based on a PV panel area of 5.8 m^2. Note that the unit of wood is m^3.

	Stainless steel	Aluminium	Concrete	Wood
Design 1	66.7	7.3	0	0
Design 2	23.3	0	46.6	0
Design 3	0	1	46.6	0.3 m^3

minerals, due to the replacement of steel and aluminium with wood. However, the EPT increases significantly. This is because the sawing of wood consumes much energy. Wood can be used, but the lifetime of the wood is uncertain. Fire safety can be an issue but is not included in this research. The costs of the wood structures also tend to be higher [70].

From these results, there is concluded that the mounting system can significantly influence the environmental impact. Not only in positively but also negatively. For ZEF, it is essential to design a PV mounting system that is durable. The advice is to design a mounting system and conduct an LCA for this mounting system. The lifetime of an aluminium or stainless steel frame is longer than 20 years. This means that in reality, more than one micro-plant can be attached to the frame. The next scenario includes this longer lifetime.

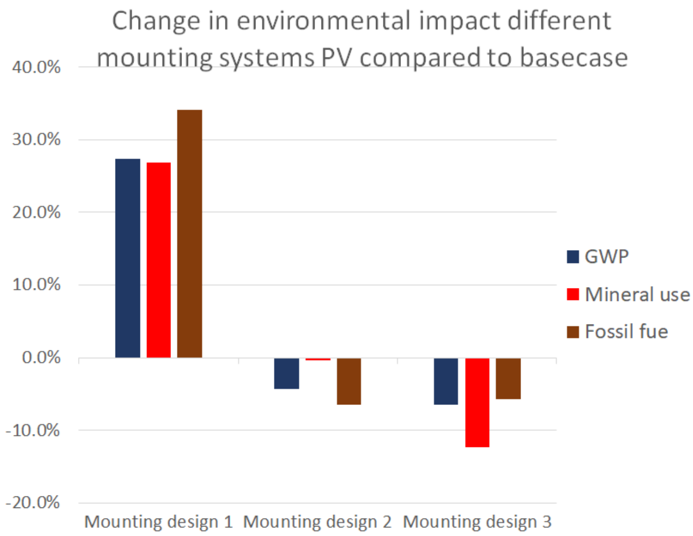


Figure 5.2: Change in the environmental impact of the different mounting designs with respect to the base case scenario.

Table 5.3: Results of the environmental impact for changing the mounting system of the PV panels. Using the functional unit ton of methanol.

	GWP	Mineral use	Fossil fuel use	CO_2 break-even [y]	EPT [y]
Design 1	-600 ± 85	13.5 ± 0.9	170 ± 18	11.3 ± 1.3	9.3 ± 1
Difference base case	28%	26%	34%	3.4 year	2.4 year
Design 2	-870 ± 50	10.6 ± 0.7	120 ± 11.5	7.3 ± 0.7	6.5 ± 0.63
Difference base case	-4.2%	-1%	-5.5%	-0.6 year	-0.4 year
Design 3	-885 ± 46	9.4 ± 0.6	120 ± 11.5	7.1 ± 0.9	12 ± 1.2
Difference base case	-6%	-12%	-5.5%	-0.8 year	4.1 year

5.3. Scenario 3: Lifetime PV & mounting system

The lifetime of the PV panels has been discussed in chapter 2.2. Over the lifetime of the PV panels, the efficiency decreases. The lifetime of PV panels is often said to be 20-25 years. However, after 20-25 years the efficiency is often guaranteed to be 80% of the original efficiency. This means the lifetime of the PV panels can be longer than 20-25 years. Currently, it is not exactly known how long PV panels can still generate energy. Most PV panels are decommissioned after 20-25 years. For this scenario, it is estimated that PV panels can still generate energy after 40 years [83].

The decrease in efficiency for the PV panels in the solar MeOH farm is 0.64% per year, in the first year, an efficiency decrease of 3% is assumed [83]. The start and end efficiency are derived using these assumptions combined with the average efficiency, and the lifetime of the PV panel of 20 years. The starting efficiency of the PV panel is 16.8%, and the efficiency after 20 years is 14.2%. A detailed overview of these calculations is presented in appendix B. In the model, the average efficiency is used over 20 years to calculate the methanol production, which is 15.5%. This also means the average capacity of the PV panels is 900 Wp. When a longer lifetime is assumed, the average efficiency and capacity decline due to the efficiency degradation.

Lifetime 25 years

The lifetime in the base case scenario is assumed to be 20 years. This lifetime is based on the lifetime of the micro-plant and the guaranteed lifetime of PV panels. However, as mentioned in chapter 2, this guaranteed lifetime can also be 25 years. The same holds for the mounting system. The lifetime of the mounting system is often around 25 years. This scenario assumes that the lifetime of the PV panels and the mounting system is 25 years. The lifetime of the micro-plant itself remains 20 years.

When the lifetime increase to 25 years, the average efficiency and capacity of the PV panels decreases. For the first 20 years, the same methanol production and environmental impact is assumed as the base case. In the years of operation 20-25, the average PV panel efficiency decreases to 13.9% and the average capacity to 805 Wp. The decrease in average efficiency and capacity lead to less methanol production than in the first 20 years. After 20 years the micro-plant is decommissioned, but the PV panels and mounting remain. After 5 years these are decommissioned as well. For this scenario, the manufacturing of one time the PV panels and mounting system is taken into account, and 1.25 times the manufacturing of the micro-plant. The construction of one time the pipelines, storage, and fence is assumed.

Figure 5.3 shows the CO_2 emissions for this scenario. The first 20 years are the same as the base case. However, the last five years show a less steep slope. There is an increase in CO_2 equivalent emission after 20 years. This is due to the impact of constructing 0.25 micro-plant. The other 0.75 of the micro-plant is not included because in this scenario the micro-plant operates over the lifetime 25-40 years with new PV panels. An overview of the change in environmental impact is shown in table 5.4.

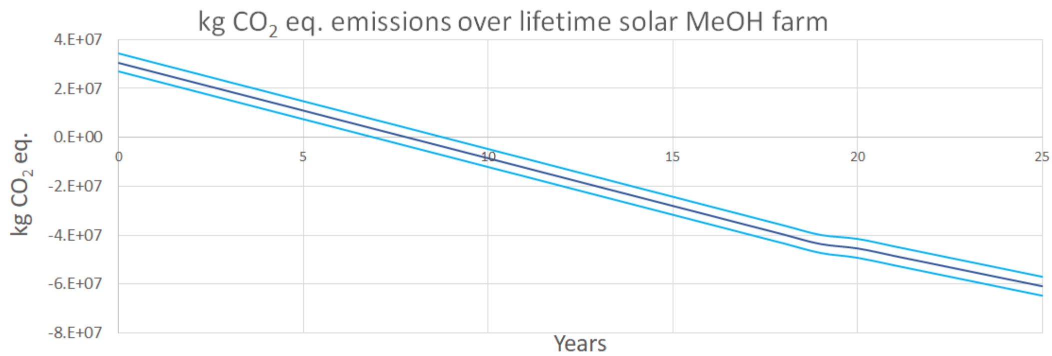


Figure 5.3: Overview of the CO_2 equivalent emissions of the solar MeOH farm for 25 years of methanol production.

Lifetime 40 years

The first 20 years of production have the same methanol production and environmental impact as the base case. In the years of operation 20-40 years, the average PV panel efficiency decreases to 13.1% and the average capacity to 760 Wp. After 20 years the micro-plant is decommissioned, but the PV panels and mounting remain. After another 20 years, these are decommissioned as well. For this scenario, the manufacturing of one time the PV panels and mounting system is taken into account, and two times the manufacturing of the micro-plant. The construction of one time, the pipelines, storage, and fence is assumed.

Figure 5.4 shows the CO_2 emissions for this scenario. The first 20 years are the same as the base case. The last 20 years show a less steep slope. This decrease in slope is due to the decrease in efficiency of the PV panels. Less efficiency leads to less production of methanol. Less methanol production leads to less CO_2 absorbance. There is an increase in CO_2 equivalent emission after 20 years. This is due to the impact of constructing one micro-plant. An overview of the change in environmental impact is shown in table 5.4.

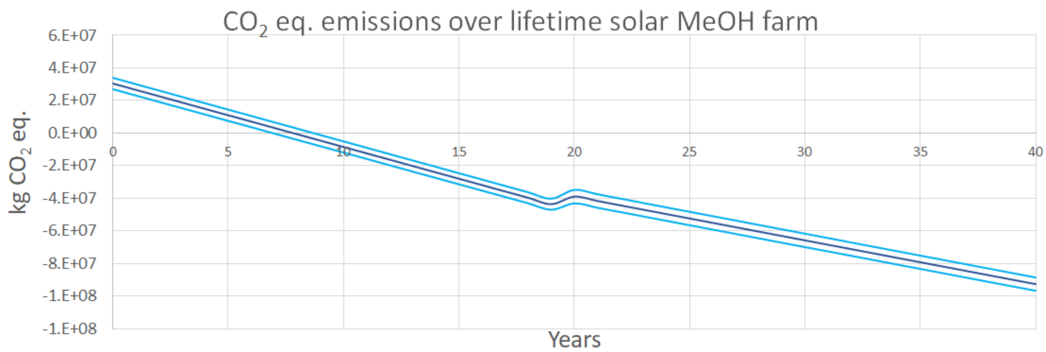


Figure 5.4: Overview of the CO_2 equivalent emissions of the solar MeOH farm for 40 years of methanol production.

Overview results

Table 5.4 shows the results of the two different lifetimes of the PV panels and mounting system lifetime. The EPT and CO_2 break-even are not shown in the table because these remain the same as the base case. The scenario that the PV panels and mounting system can operate for 25 years is a realistic scenario. ZEF should make sure the PV panels and mounting system can operate for 25 years to decrease their environmental impact.

Table 5.4: Results of the environmental impact for longer lifetime of the PV panels and mounting system.

Lifetime	GWP	Mineral use	Fossil fuel use
25 year lifetime	-895 ± 55	10.4 ± 0.9	115 ± 14
Difference base case	-7.2%	-2.8%	-9.5%
40 year lifetime	-970 ± 45	10.4 ± 0.85	97 ± 11
Difference base case	-16.2%	-2.5%	-23.5%

5.4. Scenario 4: Efficiency & Lifetime Micro-Plant

This scenario first discusses the efficiency of the micro-plant, the second part discusses the lifetime of the micro-plant and the subsystems. The focus of this scenario is the micro-plant itself.

Efficiency

The efficiency of the micro-plant is assumed to be 51.85%. However, this efficiency is based on assumptions and calculations. There are no experimental results to confirm this efficiency. Higher losses than expected in the process can decrease efficiency. This scenario assumes efficiencies of 40% and 30%. The decrease in efficiency directly affects the methanol production of the micro-plant, and thus of the entire solar MeOH farm. The environmental impact of constructing the solar MeOH farm, however, remains the same. Less methanol production always leads to a higher environmental impact, which also means the EPT and CO_2 break-even time increase.

Table 5.5 shows the effect of the efficiency decrease on the environmental impact. The increase in environmental impact shows a direct relation for mineral use and fossil use. The mineral use and fossil fuel use do not depend on the production of methanol, meaning that less production of methanol leads to a linear increase of environmental impact. For the GWP, as discussed in chapter 4, this relation is not linear. This relation is described in equation

4.1. Figure 5.5 shows the CO_2 equivalent emissions over the lifetime. From the results, it is concluded that the efficiency of the micro-plant has a significant influence on the environmental impact.

Table 5.5: Results of the environmental impact for lower efficiencies of the micro-plant. Using the functional unit ton of methanol.

	GWP	Mineral use	Fossil fuel use	CO_2 break-even [y]	EPT [y]
Efficiency 40%	-695± 68	13.4 ± 0.85	160 ± 16	9.8 ± 1	8.6 ± 0.9
Difference base case	16.8%	25%	26%	1.9 year	1.7 year
Efficiency 30%	-470 ± 90	17.8 ± 1.2	210 ± 21.5	13.2 ± 1.4	11.5 ± 1.2
Difference base case	43%	67%	65%	5.2 year	4.6 year

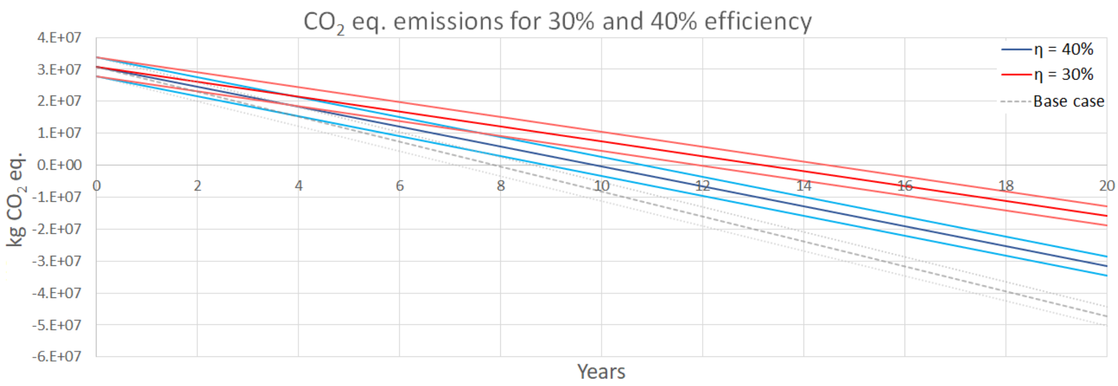


Figure 5.5: The CO_2 equivalent emissions of the solar MeOH farm with in blue the case of 40% efficiency and in red 30% efficiency, including standard deviation.

Lifetime of micro-plant

Another assumption regarding the micro-plant is the lifetime. The lifetime is assumed to be 20 years. The minimum lifetime to be zero-emission is equal to the CO_2 break-even point. This scenario discusses the lifetime of different subsystems.

Some components are known to have a lifetime of 20 years, for example, the casing. However, other parts have a debatable lifetime. The DAC, the AEC, and the compressor are doubted to have a 20 year lifetime. For the DAC, it is unknown how long the sorbent stays stable or how materials react to the sorbent. The AEC operates with a pressure of at least 51 bar and with pure oxygen in alkaline environments. The electrolyte is also known to degrade over time. Because of these factors, the lifetime of the AEC is assumed to be shorter than 20 years. The compressor uses a gearbox which has moving parts, which leads to wear of cylinders and gears. After discussing with experts from ZEF, certain lifetimes are estimated for the discussed subsystems. These lifetimes are depicted in table 5.6. All other subsystems are assumed to have a lifetime of 20 years in this scenario.

Table 5.6: Overview of the estimated lifetimes used in this scenario for the different subsystems.

	Compressor	DAC	AEC
Lifetime in years	5	10	5

The lifetime in table 5.6 means that after operating a certain amount of years, the entire subsystem is replaced. Figure 5.6 shows how the replacing of subsystems influences the GWP. It seems as if the slope of all replacements is the same. This is not the case, the slope at 10 years is less steep. However, as seen in figure 4.5, the DAC only contributes around 2% to the GWP. The results are summarised in table 5.7. From this table, it can be concluded that the influence on the environmental impact of replacing components is significant, especially the mineral resource scarcity, which is doubled. The AEC and compressor account for 34% of the mineral resource consumption. Both need to be produced 4 times in this scenario.

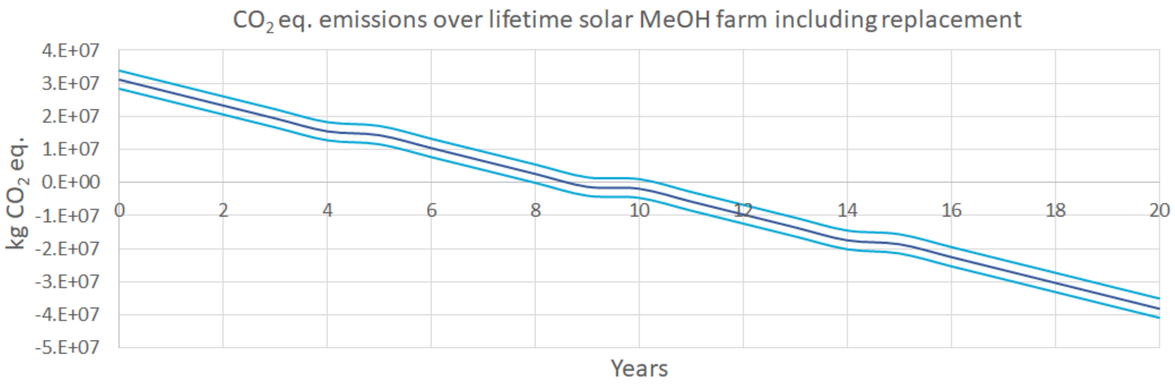


Figure 5.6: Results of the CO_2 equivalent emissions over lifetime with replacing certain subsystems.

Table 5.7: Overview of the change in environmental impact when replacement of subsystems is assumed. Using the functional unit ton of methanol.

	GWP	Mineral use	Fossil fuel use	CO_2 break-even [y]	EPT [y]
Replacement of subsystems	-670 ± 50	21.5 ± 1.6	170 ± 15	9 ± 1.1	9.1 ± 0.8
Difference base case	19.8%	100%	34%	1.1 year	2.2 year

5.5. Scenario 5: Location of Operation Solar MeOH Farm

A group from the educational TU-Delft master of Transport Infrastructure and Logistics (TIL) [93] made a report that discusses the best location to operate the plant. The advice from this report is based on economics. The advice is three locations, namely Morocco, Peru, and Oman. The base case scenario assumed that the operation is in Morocco. There are three assumptions that change with location, the first one is the transport of the modular MeOH system. Table 4.2 shows that transport has a small contribution to the environmental impact. The change in transport is not included in this chapter due to this small contribution. However, appendix H discusses different transportation scenario's. The second assumption that changes with location are the amount of ESH, and the last assumption that changes is the electricity mix. This section discusses the ESH and the electricity mix.

Change in ESH

The base case scenario assumed 7 ESH. Two different scenarios are assessed, namely, 5 and 3 ESH. 3 ESH is the number of sun hours present in a country like the Belgium or parts of the Netherlands. 5 ESH is the number of sun hours that occur in southern Spain [101]. Appendix B shows how irradiance data is recalculated to ESH. The results for the CO_2 emissions over time are shown in figure 5.7. It can be seen that with 3 ESH, the GWP of the solar MeOH farm is almost positive after 20 years of operation. An overview of the results is shown in table 5.8. It follows from the table that the difference between 5 and 3 ESH is significant. The change in ESH directly affects the production of the plant, just like the efficiency of the micro-plant does.

The change in ESH has the same trend in environmental impact as the efficiency change. It is possible to calculate the efficiency decrease that has the same increase in environmental impact as a certain decrease in ESH and vice versa. For example, 3 ESH is equal to a decrease in the power of ≈ 43%. The same drop in energy would be 43% of 50%, which means an efficiency of 21.5%. The reason the efficiency and ESH are discussed and changed separately is that ESH is location depended and efficiency is dependent on the performance of the micro-plant. So even though they are correlated, they are treated differently. One can see that a drop of 20% in efficiency does not influence the environmental impact as bad as 3 ESH. Concluding that the location, which is linked to the ESH, is the more important factor to take into account.

The assumption that 7 ESH occur in Morocco is an overestimation. The amount of ESH can significantly reduce the production of the solar MeOH farm. Less production of methanol leads to a higher environmental impact per ton of methanol. The advise following from this scenario is to operate the solar MeOH farm on a location with the highest amount of ESH. When looking at the advice from TIL concerning locations, the location with the highest ESH would be Peru [101].

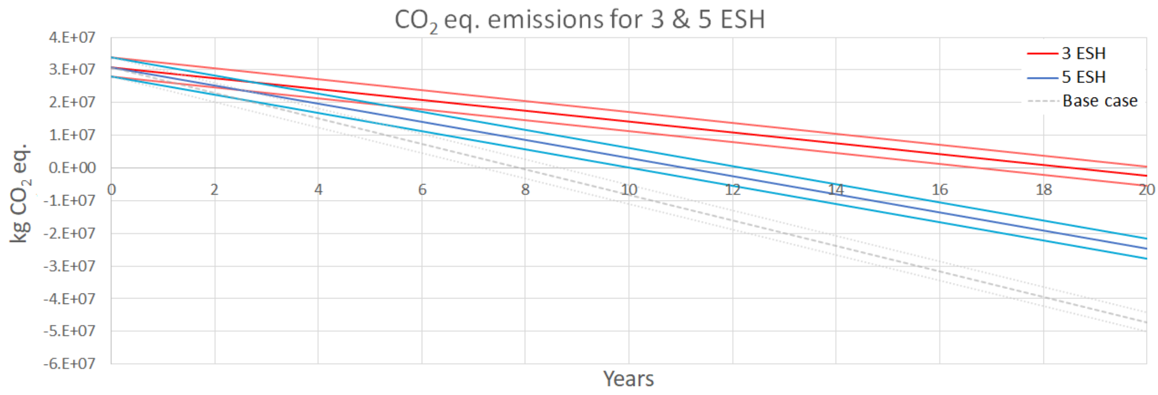


Figure 5.7: The CO_2 equivalent emissions of the farm. The blue line depicts 5 ESH and the red line 3 ESH, including standard deviation.

Table 5.8: Results of the environmental impact for different ESH for operation of the solar MeOH farm. Using the functional unit ton of methanol.

	GWP	Mineral use	Fossil fuel use	CO_2 break-even [y]	EPT [y]
5 ESH	-615 ± 75	15 ± 1	180 ± 18	11 ± 1.1	9.7 ± 1
Difference base case	26.5%	40%	40%	2.1 year	2.8 year
3 ESH	-110 ± 120	25 ± 1.7	300 ± 30	18.4 ± 1.8	16.1 ± 1.6
Difference base case	85%	133%	135%	10.5 year	9.2 year

Change in electricity mix

The second parameter that changes with location is the electricity mix. The current assumptions include electricity use. The energy mixes of the different countries are found in a database of the IEA [94]. In table 5.9 the energy mixes of different scenarios are presented. Three different locations are used Peru, Oman, and Norway. Norway has been selected because it has a very high share of renewable energy. This indicates how the environmental impact changes in a renewable world. During the comparison, the transport is kept according to the base case.

Table 5.9: Overview of the energy mix for different countries.

	Morocco	Peru	Oman	Norway
Coal	55.8%	1.6%	0%	0.1%
Oil	9.5%	2.3%	2.7%	0%
Gas	19.4%	45.8%	97.3%	1.7%
Hydro power	5.5%	46.5%	0%	96.7%
Solar power	0%	0.5%	0%	0%
Wind power	9.9%	2%	0%	1.4%
Biofuels	0%	1.2%	0%	0%

The results are depicted in table 5.10. The impact category mineral resource use has no significant change. The amount of energy consumed during the operation of the solar MeOH farm stays the same as in the base case. The methanol production also remains the same, meaning that the EPT does not change. The change in CO_2 break-even point is not depicted in table 5.10 because it does not decrease significantly. This scenario shows that environmental impact can be decreased by using more environmentally friendly energy mixes. Electricity is consumed 8.5 hours a day for 365 days a year for 20 years. It should be noted that electricity use is a large uncertainty. For example, It could be that only the edges of the field need lighting or that the farm generates the electricity that is consumed. Because the change in environmental impact can be significant, the assumption concerning electricity consumption should be further researched.

Table 5.10: Overview of the change in environmental impact for different electricity mixes. Using the functional unit ton of methanol.

Electricity mix	GWP	Mineral use	Fossil fuel use
Peru	-843 ± 50	10.7 ± 0.7	125 ± 12.5
Difference base case	-1%	-.04%	-2.4%
Oman	-837 ± 50	10.7 ± 0.7	126 ± 12.7
Difference base case	-0.2%	-.05%	-0.8%
Norway	-850 ± 45	10.7 ± 0.7	122 ± 12
Difference base case	-1.8%	-.04%	-3.9%

5.6. Scenario 6: Malfunctioning of Micro-Plant

The assumption is made that every micro-plant operates for 20 without malfunctioning, which is not a realistic scenario. Within the micro-plant, many different components have a change of malfunctioning. This scenario discusses what the effect is of including malfunctioning on the environmental impact. After a discussion with experts from ZEF, a failure rate of 3% is assumed. This failure rate means that every year 3% of the solar MeOH malfunctions and does not produce methanol anymore. The malfunctioned micro-plants are not replaced in this scenario. The malfunctioning directly affects the methanol production.

The malfunctioning decreases methanol production, and consequently the CO_2 absorption. The CO_2 equivalent emissions are depicted in figure 5.8. The curve of the graph follows that of an exponential decline. The effect on the GWP for the first years is not significant. However, the effect increases over the years. Table 5.11 shows the change in environmental impact. This scenario gives a more realistic overview of the environmental impact than the base case. The change in environmental impact is significant. When ZEF has more precise data concerning malfunctioning, this data should be included in the LCA.

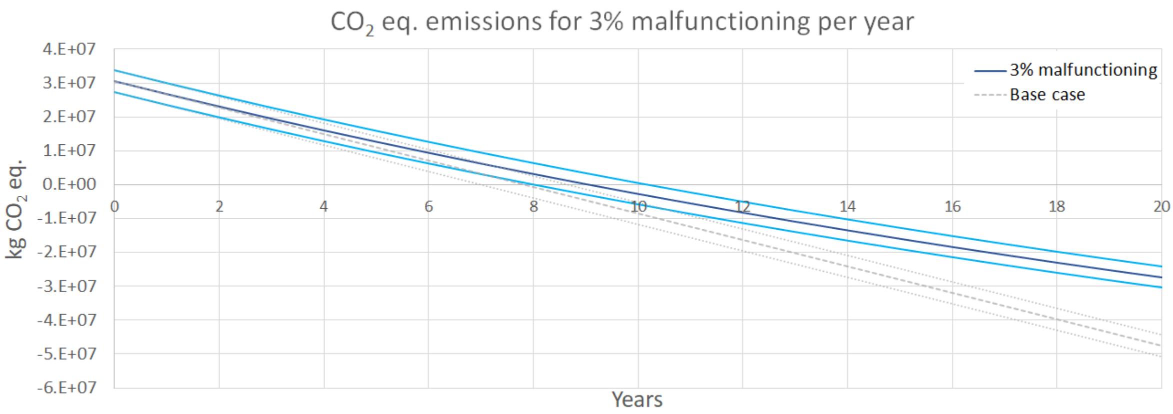


Figure 5.8: The CO_2 equivalent emissions over lifetime when 3% of the solar MeOH farm malfunctions every year.

Table 5.11: Overview of the change in environmental impact when including a yearly malfunction of 3%. Using the functional unit ton of methanol.

	GWP	Mineral use	Fossil fuel use	CO_2 break-even [y]	EPT [y]
3% malfunctioning	-650 ± 75	14.4 ± 1	170 ± 17	9.4 ± 1	8.3 ± 0.8
Difference base case	22.5%	35%	35%	1.5 year	1.4 year

5.7. Scenario 7: Recycling of Solar MeOH Farm

This scenario discusses the environmental impact of recycling. The recycling is not taken into account in the LCA of the solar MeOH farm. For PV, this assumption holds because currently, almost all PV panels are disposed of [92]. This disposal does not lead to a significant increase in GWP or fossil resource use. During disposal, no minerals are consumed, leading to no consumption of minerals. For the recycling of the micro-plant however, the environmental impact of recycling can be more significant. To estimate the environmental impact, the four materials that contribute most to the micro-plant, in weight, are taken into account. These four materials are stainless steel, aluminium, Polyethylene terephthalate (PET) and Polyphenylene sulfide (PPS). These materials account for 74% of the weight. An overview of these materials is given in table 5.12. The values for PPS are assumed to be comparable with that of PET. From literature, the amount of GWP for recycling the different materials is found. These values are significantly lower than that of primary materials. Especially the secondary metals have a lower GWP. When including recycling in the LCA, the GWP of the solar MeOH farm increases by 2.5%, meaning the CO_2 absorption decreases by 2.5%. This partly substantiates the assumption of not including recycling. However, an allocation problem arises when including recycling.

The allocation of the environmental impact for recycling is not straight forward. One could allocate the extra environmental burden of recycling to the first solar MeOH farm constructed. This means that in this case, the extra environmental impact is added to the construction of the farm. This leads to a 2.5% increase in GWP. Assuming that the materials are recycled and used for another solar MeOH, this would lead to no environmental impact for the production of the recycled materials. This is not a reasonable comparison. The other way to allocate the environmental impact is to allocate it entirely to the recycled product. There are more ways of allocating the environmental impact, for example, seeing the difference in GWP as avoided emissions or allocating the GWP based on economic values. Meaning the GWP increase is smaller than the 2.5% mentioned before because the environmental impact should be allocated.

Concluding that for GWP, the impact is not significantly influenced when including recycling. The assumption to not include the end of life in the LCA is justified.

Table 5.12: Values for recycling of the four most used materials.

	Stainless steel	Aluminium	PET	PPS
Kilogram in micro-plant	23	6.3	6.1	4.7
CO_2 per kg material	5.15	27	3.26	7.8
CO_2 per kg recycled material	1.5 [102]	2.9 [103]	2.1 [104]	5.1 [104]
Difference [%]	-70%	-89%	--35%	-35%

For fossil resource scarcity and mineral resource scarcity, data availability is limited. Fossil resource scarcity decrease is assumed to be equal to GWP, which is the general trend observed in this research. Mineral resource use, however, is a different story. This can significantly reduce due to recycling. This is due to the fact that the minerals, for example, aluminium, are reused. ZEF should further research how much impact recycling has on the mineral resource scarcity when the end-of-life phase is known.

5.8. Overview Results Sensitivity Analysis

This section provides an overview of all the results of the sensitivity analysis. Table 5.13 shows the results for the different impact categories. Table 5.14 presents the results of the CO_2 break-even point and the EPT. From these tables, the following conclusions can be derived:

- ZEF should focus on the lifetime of the micro-plants. The malfunctioning scenario and the replacement scenario both show a significant increase in environmental impact. To minimise the environmental impact, the different subsystems should be durable.

- A 1% decrease in the micro-plant efficiency increases the environmental impact with more than 1% for all impact categories. Further research should focus on reaching high efficiencies or minimising efficiency decrease.
- The advice regarding location is to operate the solar MeOH farm in Peru. Peru shows a lower environmental impact on electricity use, and 7 ESH are more likely to occur in Peru. The more ESH, the more methanol production, and thus lower environmental impact. The amount of ESH important to keep the environmental impact small.
- The higher the PV panel efficiency, the lower the environmental impact, meaning that in the next decade, it is likely the environmental impact of the PV panels decreases. The PV panels contribute the most to the environmental impact. When the PV panels operate for a longer time than 20 years, the environmental impact decreases. A longer lifetime is a realistic scenario, and ZEF should research which PV panels have long lifetimes.

Table 5.13: Overview of the environmental impact and the difference with the base case for the different scenario's discussed in this chapter. Using functional unit ton of methanol

Functional unit 1 ton of methanol		GWP [kg CO_2 eq.]		Mineral use [kg Cu eq.]		Fossil fuel use [kg oil eq.]	
		Result	Difference base case	Result	Difference base case	Result	Difference base case
Base case		**-835 ± 50**		**10.7 ± 0.7**		**127 ± 13**	
PV	**η = 19%**	-900 ± 45	-7.8%	10 ± 0.6	-6.5%	110 ± 11	-13.4%
	η = 21%	-930 ± 40	-11.5%	9.8 ± 0.6	-8.5%	105 ± 10	-17.3%
	Mounting design 1	-600 ± 85	28%	13.5 ± 0.9	26%	170 ± 18	34%
	Mounting design 2	-870 ± 50	-4.2%	10.6 ± 0.7	-1%	120 ± 11.5	-5.5%
	Mounting design 3	-885 ± 46	-6%	9.4 ± 0.6	-12%	120 ± 11.5	-5.5%
	Lifetime 25 years	-895 ± 55	-7.2%	10.4 ± 0.9	-2.8%	115 ± 14	-9.5%
	Lifetime 40 years	-970 ± 45	-16.2%	10.4 ± 0.85	-2.5%	97 ± 11	-23.5%
Micro-plant	**η = 40%**	-695± 68	16.8%	13.4 ± 0.85	25%	160 ± 16	26%
	η = 30%	-470 ± 90	43%	17.8 ± 1.2	67%	210 ± 21.5	65%
	Replacement	-670 ± 50	19.8%	21.5 ± 1.6	100%	170 ± 15	34%
MeOH farm	**5 ESH**	-615 ± 75	26.5%	15 ± 1	40%	180 ± 18	40%
	3 ESH	-110 ± 120	85%	25 ± 1.7	133%	300 ± 30	135%
	Electricity Peru	-843 ± 50	-1%	10.7 ± 0.7	-.04%	125 ± 12.5	-2.4%
	Electricity Oman	-837 ± 50	-0.2%	10.7 ± 0.7	-.05%	126 ± 12.7	-0.8%
	Electricity Norway	-850 ± 45	-1.8%	10.7 ± 0.7	-.04%	122 ± 12	-3.9%
	3% malfun-tioning	-650 ± 75	22.5%	14.4 ± 1	35%	170 ± 17	35%

Table 5.14: Overview of the CO_2 break-even point and the EPT, including the difference with the base case, for the different scenario's discussed in this chapter.

Functional unit 1 ton of methanol		CO2 break-even [y]		EPT [y]	
		Result	Difference base case	Result	Difference base case
Base case		**6.9 ± 0.7**		**7.9 ± 0.8**	
PV	**η = 19%**	6.9 ± 0.7	-1 year	6 ± 0.6	-0.9 year
	η = 21%	6.5 ± 0.6	-1.4 year	5.6 ± 0.56	-1.3 year
	Mounting design 1	11.3 ± 1.3	3.4 year	9.3 ± 1	2.4 year
	Mounting design 2	7.3 ± 0.7	-0.6 year	6.5 ± 0.63	-0.4 year
	Mounting design 3	7.1 ± 0.9	-0.8 year	12 ± 1.2	4.1 year
	Lifetime 25 years	6.9 ± 0.7	-	7.9 ± 0.9	-
	Lifetime 40 years	6.9 ± 0.7	-	7.9 ± 0.9	-
Micro-plant	**η = 40%**	9.8 ± 1	1.9 year	8.6 ± 0.9	1.7 year
	η = 30%	13.2 ± 1.4	5.2 year	11.5 ± 1.2	4.6 year
	Replacement	9 ± 1.1	1.1 year	9.1 ± 0.8	2.2 year
MeOH farm	**5 ESH**	11 ± 1.1	2.1 year	9.7 ± 1	2.8 year
	3 ESH	18.4 ± 1.8	10.5 year	16.1 ± 1.6	9.2 year
	Electricity Peru	6.9 ± 0.7	-	7.9 ± 0.9	-
	Electricity Oman	6.9 ± 0.7	-	7.9 ± 0.9	-
	Electricity Norway	6.9 ± 0.7	-	7.9 ± 0.9	-
	3% malfuntioning	9.4 ± 1	1.5 year	8.3 ± 0.8	1.4 year

6

Conclusion & Recommendations

6.1. Conclusion

What type of PV panels have the lowest environmental impact?

The environmental impact of the following PV panels have been compared in this research: monocrystalline silicon, polycrystalline silicon, amorphous silicon, CdTe, and CIGS. The polycrystalline silicon type PV panels have the smallest environmental impact, based on the ReCiPe endpoint method. On all three endpoint impact categories, the polycrystalline silicon PV panels have the lowest environmental impact. Within this technique, the PV panels produced by the string ribbon method have a slightly lower impact category than the cast and sawing technique.

What are the main contributors to the environmental impact?

- **Global warming potential:** The main contributor to the GWP is the manufacturing of the modular MeOH system, which contributes 92.8% to the GWP. This is mainly due to the construction of the PV panels and the mounting system, which together contribute to 69.7% of the whole. The other 7.2% of the GWP is due construction of the solar MeOH farm, transportation, and electricity use.
- **Mineral resource scarcity:** The main contributor to the mineral resource scarcity is the modular MeOH system, which contributes 98% to the mineral resource scarcity, of which 64.5% is the construction of the micro-plant. The impact is mainly due to the use of stainless steel, nickel, and copper in the micro-plant. The mineral resource scarcity can be significantly decreased by replacing metals by plastics where possible.
- **Fossil resource scarcity:** The main contributor to the fossil resource scarcity is the construction of the modular MeOH system, which contributes 91.7% to the fossil resource scarcity. This is mainly due to the construction of the PV panels and the mounting, which together contribute to 67.7%. The fossil resource scarcity and the GWP follow the same trend.

How does the environmental impact of ZEF methanol production compare with the main production routes of methanol?

The main production routes emit CO_2 while methanol produced by ZEF absorbs CO_2. The methanol produced by ZEF has a lower GWP compared to the methanol produced from natural gas after approximately 5 years of producing methanol, while for methanol produced by coal, this is approximately 2.5 years. Per ton of methanol, the impact of ZEF methanol is about 1600 and 3800 kg of CO_2 equivalent lower than that of natural gas and coal respectively. The mineral resource scarcity per ton of methanol is around 8 times higher, and the fossils resource scarcity is around 6 times lower for methanol produced by ZEF compared to methanol produced from natural gas. No data concerning the last two impact categories is available for methanol produced from coal. To obtain data in these impact categories, an LCA for the coal route should be conducted.

How do different locations of operation influence the environmental impact?

The location of operation can significantly increase the environmental impact of the methanol produced by ZEF. The location-dependent factor that influences the environmental impact most significantly is the amount of ESH, while transport has a much smaller environmental impact. It is therefore vital to operate the solar MeOH farm on a location with a high amount of ESH to decrease the environmental impact.

How do uncertainties influence the final result?

There are two types of uncertainties. The first is due to that the micro-plant is still conceptual, and the second is due to uncertainties in assumptions.

- The standard deviation in the results of the base case is 6.5% for the GWP, 6.3% For the mineral resource scarcity, and 10% for the fossil resource scarcity. These standard deviations are based on the uncertainty in the different components of the solar MeOH farm.
- The uncertainties in the assumptions that can significantly increase the environmental impact are the efficiency and the lifetime of the micro-plant. A 1% decrease in micro-plant efficiency increases the environmental impact with more than 1% for the three impact categories discussed in this research. Replacement and malfunctioning of the micro-plant are linked to the lifetime and increase the environmental impact significantly.

What is the environmental impact based on global warming potential, mineral use, and fossil fuel use, for methanol produced by the ZEF solar MeOH farm?

- **Global warming potential:** The GWP is -835 ± 50 (6.5%) kg CO_2 equivalent per ton of methanol, indicating that the methanol produced by ZEF absorbs CO_2. When the end-use of methanol is included, approximately 40% of the methanol produced by ZEF should be used for plastic and chemicals to produce zero-emission methanol. After 7.9 ± 0.8 years of production the solar MeOH farm has reached the CO_2 break-even point, this break-even point is the moment when the CO_2 equivalent emissions from construction the solar MeOH farm are equal to the CO_2 equivalent absorbed.
- **Mineral resource scarcity:** The mineral resource scarcity is 10.7 ± 0.7 (6.3%) kg Cu equivalent per ton of methanol, mainly due to the manufacturing of the micro-plants. When replacing components of the micro-plants is included, this impact category shows the most significant increase. This is the only impact category that has a higher environmental impact compared to the current commonly used production methods of methanol. The mineral resource scarcity can be significantly decreased by replacing metals by plastics where possible.
- **Fossil resource scarcity:** The fossil resource scarcity is 127 ± 13 (10%) kg oil equivalent per ton of methanol. The energy consumption is directly linked to the fossil resource scarcity, with an EPT of the modular MeOH system of 6.9 ± 0.7 years of methanol production.

6.2. Recommendations

A set of recommendations is provided based on this research:

- The environmental impact of transport is low. The main focus when selecting a location for operation should be on the amount of ESH, as more ESH directly decreases the environmental impact. More production of methanol always decreases the environmental impact.
- The efficiency of the micro-plant should be as high as possible. When the efficiency is less than the assumed 51.85%, the environmental impact increases significantly.
- The manufacturing of the PV panels contributes most to the GWP and the fossil resource scarcity. Therefore, it is advised to use polycrystalline PV panels. However, PV technologies are new and constantly changing. The efficiencies of the PV panels are increasing over time, and the costs of PV panels are decreasing over time. Also, the production methods are becoming more efficient. Hence ZEF should update the LCA

concerning the PV panels when close to the realisation of the solar MeOH farm, ensuring that polycrystalline is still the PV technology with the smallest environmental impact.

- Manufacturing of the mounting system has a significant environmental impact. ZEF should design, or choose, a mounting system that has a small environmental impact which still holds up to the demands.
- The lifetime of the PV panels and mounting system are longer than 20 years. By consulting PV manufactures ZEF can make sure they have a guaranteed lifetime of at least 25 years, which leads to a decrease in environmental impact.
- The electricity consumption contributes to around 4% of the GWP and fossil resource scarcity. ZEF should contact security companies to see what kind of security they are obligated to have. When this is known, ZEF can think of methods to produce their own electricity.
- A long lifetime of the modular MeOH system and the different subsystems is vital to reduce the environmental impact. The assumption concerning the lifetime and replacement should be tested. The focus for designing new subsystems should be on lifetime. Lifetime is a more important factor than the materials used. When the lifetime is shorter than 6 years the GWP increases exponentially.
- Currently, the micro-plant is still conceptual. When data from experiments are known, these should be implemented in the Simapro model. This data could be, for example, the lifetime of the micro-plant and efficiency. By implementing the data, the environmental impact can be assessed in every stage of the design.
- This research showed that the recycling materials does not decrease the GWP significantly. The fossil resource scarcity is assumed to have approximately the same decrease as the GWP. The decrease in environmental impact for the mineral resource scarcity can be significant, because minerals are reused. When the end-of-life of the solar MeOH is known it should be included in the LCA. The mineral resource scarcity is the only impact category that has a larger environmental impact than the main production methods of methanol. Including the recycling could decrease the environmental impact of this impact category.

A

Appendix A: Explanation of Midpoint and Endpoint Impact Categories

The next example [21] shows how the impact category can be used. The example also shows the category indicators and the characterisation model. In this example the category indicator is used for the LCA concerning the methanol produced by the solar MeOH farm. The endpoints are used for the comparison of the PV panels. Notice that the endpoint could also be ecosystem damage in this example.

- Impact category: global warming
- Inventory results: the amount of various greenhouse gasses emitted per functional unit
- Characterisation model: baseline model of 100 years of the international panel of climate change
- Category indicator: infrared radiative forcing (W/m^2)
- Characterisation factor: conversion of each greenhouse gas (kg CO_2-equivalents/kg gas) to GWP.
- Category indicator result: kilograms of CO2- equivalents per functional unit
- Category endpoints: damage to human health

The different midpoints are converted to the endpoints by using weighing factors, or characterisation factors. Figure A.1 shows how the 18 different midpoint impact categories are converted to the three endpoint impact categories. An example is the conversion of kg of copper equivalent to USD2013 the ReCiPe model uses a value of 0.23 i.e., one kilogram of copper equivalent is equal to 0.23 USD2013. However, for the fossil resource scarcity the characterisation factors are different depending on the different fossil fuels. To find a detailed overview of all characterisation factors one should consult the ReCiPe 2016 report of the RIVM [18].

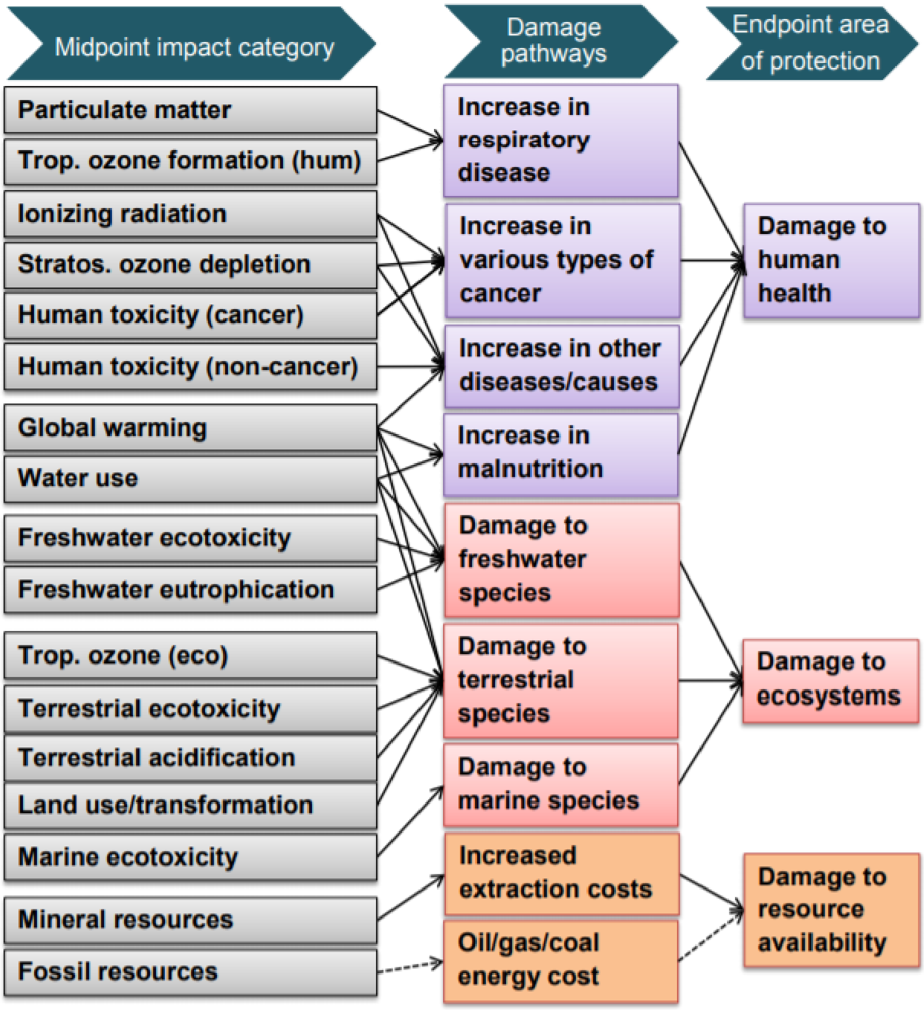


Figure A.1: Overview of how the 18 midpoint impact categories are converted to the three endpoint impact categories [18].

B

Appendix B: Calculations Concerning PV Panels

This appendix discusses calculations that concern the PV panels.

CO_2 equivalent per kWh to Co_2 equivalent per m^2

From literature different data is available for PV panels concerning CO_2 emissions. However, this is mostly expressed in CO_2/kWh. The first step in finding the CO_2 equivalent per 900 Wp is to recalculate kWh to m^2 of PV panel. Equation B.1 shows how the CO_2 equivalent/kWh is calculated. The denominator of the fraction calculates the amount of kWh the PV panels generates over its lifetime. The efficiency is depicted as η.

$$\frac{\text{kg CO}_2\text{ equivalent of manufacturing}}{\text{Capacity PV panel(kWp)} * \text{ESH(h/day)} * 365\text{(days/year)} * \text{lifetime(years)}} = \frac{\text{kg CO}_2\text{ equivalent}}{\text{kWh}} \tag{B.1}$$

The capacity of the PV panel is calculated as depicted in equation B.2. The energy in is based on the irradiation under standard test conditions. One hour of this standard irradiation is equal to one ESH (1kWh/m^2). The performance ratio is included in the efficiency.

$$\text{Energy in } (1000\text{ W/m}^2) * \text{m}^2\text{ of PV panel} * \eta(\%) = \text{Capacity(Wp)} \tag{B.2}$$

Combining equation B.1 and B.2 and rewriting this leads to equation B.3. This equation shows how to recalculate CO_2 equivalent per kWh to Co_2 equivalent per m^2.

$$\frac{\text{kg CO}_2\text{ equivalent}}{\text{m}^2} = \frac{\text{kg CO}_2\text{ equivalent}}{\text{kWh}} * \text{ESH} * 365 * \text{lifetime} * \eta(\%) \tag{B.3}$$

CO_2 equivalent per m^2 to CO_2 equivalent per Wp

Some of the results of the data is in CO_2 equivalent per m^2, but most are per kWh. The first step to calculate CO_2 equivalent per m^2 to CO_2 per Wp is to calculate the Wp per square meter. This is shown in equation B.4.

$$\eta(\%) * 1000(\text{W/m}^2) = \text{Wp/m}^2 \tag{B.4}$$

This is combined with equation B.3 to obtain equation B.5. To obtain the kg CO_2 per 900 Wp for example one multiplies the outcome of this equation by 900.

$$\frac{\text{m}^2}{\text{Wp}} * \frac{\text{kg CO}_2\text{ equivalent}}{\text{m}^2} = \frac{\text{kg CO}_2\text{ equivalent}}{\text{Wp}} \tag{B.5}$$

Using efficiency to obtain standard deviation

The standard deviation in the results of Simapro are determined by uncertainty in effiency. Equation B.4 showed how the efficiency influences the Wp/m^2. For the standard deviation the range of uncertainty, for example, 1% is used. This 1% leads to a maximum and minimum m^2 to reach the desired capacity. This range of m^2 is used in Simapro to determine a range of, for example, GWP.

ESH to daily energy generation

The amount of ESH can be used to calculate to the amount of kWh/m^2 per day. Combining this with the overall efficiency of the PV panel and are lead to a energy generation. This is depicted in equation B.6.

$$\text{Daily energy generation} = \text{ESH} * \text{m}^2 * \eta(\%) \text{ PV panel} = \text{Wp} * \text{ESH} \tag{B.6}$$

Irradiation data to ESH

From the solar atlas [101], the irradiation data of locations can be determined. The unit of this irradiance is kWh/m^2 per year. By dividing this number by 365, the kWh/m^2 per day is obtained. This is equal to the amount of ESH because one ESH is equal to one kWh/m^2.

Effieciency decrease over time

The efficiency of a PV panel decreases over time. From the start and end efficiency and the lifetime the average efficiency is calculated. In this research the average efficiency is used to determine the energy generation of the PV panels. In the first year of operation the efficiency drops more than in the other years. How the efficiency over the years is calculated is depicted in equation B.7.

$$\eta(\text{year}) = \eta_{\text{start}}(\%) * (1 - ((\frac{\text{first year efficiency decrease}}{100}) + ((\frac{\text{yearly efficiency decrease}}{100} * \text{years})) \tag{B.7}$$

From the start efficiency, the end efficiency, and the lifetime the average efficiency can be calculated. This is depicted in equation B.8.

$$\text{average efficiency} = \frac{\text{start efficiency} - \text{end efficiency}}{\text{years}} \tag{B.8}$$

C

Appendix C: Midpoint Impact Categories for the Comparative LCA Concerning PV Panels

This appendix explains why the midpoint impact categories are not used to compare the different PV technologies. In the first stages of the research, only the midpoint impact categories had been analysed. The midpoints did not lead to clear benefits between the different PV panels. Especially the difference between the CdTe and the polycrystalline silicon PV panels was small. These two technologies are the two types of panels that score the lowest on the GWP. CdTe panels do score significantly higher on mineral resource use. The other two impact categories are similar. To better substantiate the advice, the endpoints impact categories are used in the report.

Figure C.1 shows the GWP for manufacturing PV panels with a capacity of 900 Wp, including the mounting system. From this figure, it can be seen that CdTe has fewer emissions than the other types of PV panels. The second-lowest emitter is polycrystalline that is produced using the string ribbon technique (Ribbon-Si).

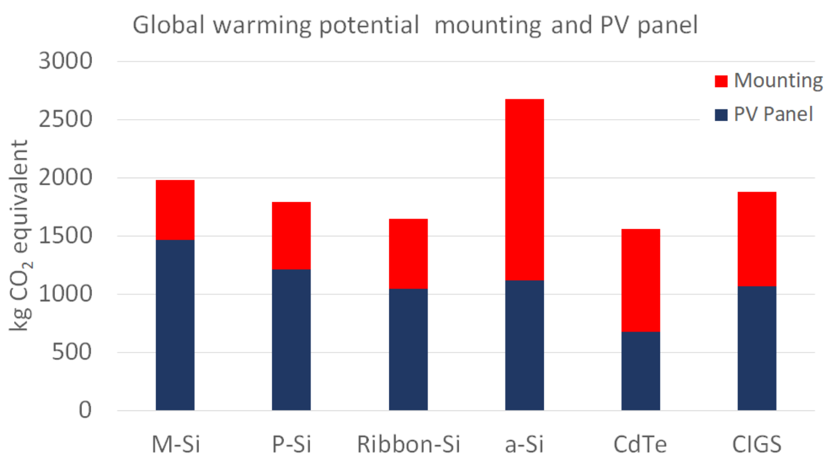


Figure C.1: Results of the midpoint impact category GWP for different PV panels.

Figure C.2 shows the fossil resource scarcity of producing PV panels with a capacity of 900 Wp, including mounting system. Ribbon-Si and CdTe consume the least amount of fossil resources. The a-Si shows the highest fossil resource use. A strong correlation between GWP and fossil resource scarcity is present.

The last category assessed is the mineral resource scarcity. Figure C.3 shows the results of the assessment. As mentioned in chapter 2, Indium is a very rare element, which is the reason that CIGS scores the highest in this impact category. CdTe PV panels consume the rare element Tellurium. One square meter of thin-film CdTe only consumes 25.2 grams of CdTe and 0.2 grams of Tellurium. This midpoint impact category shows an advantage for the crystalline silicon technologies.

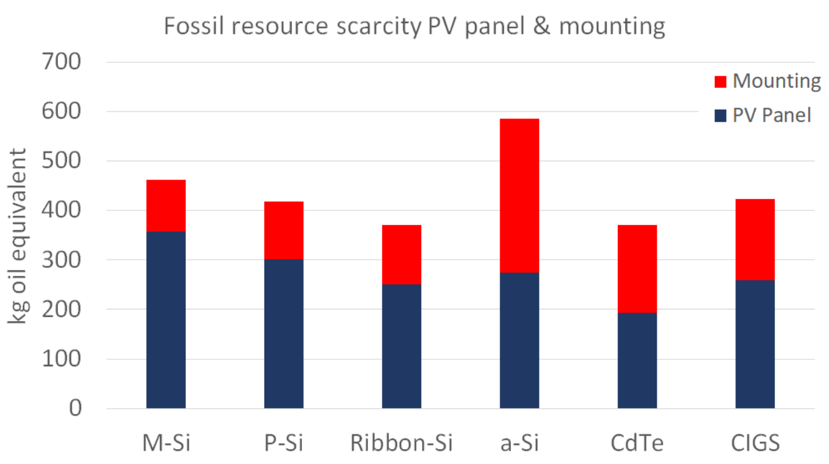


Figure C.2: Results of the midpoint impact category fossil resource scarcity for different PV panels.

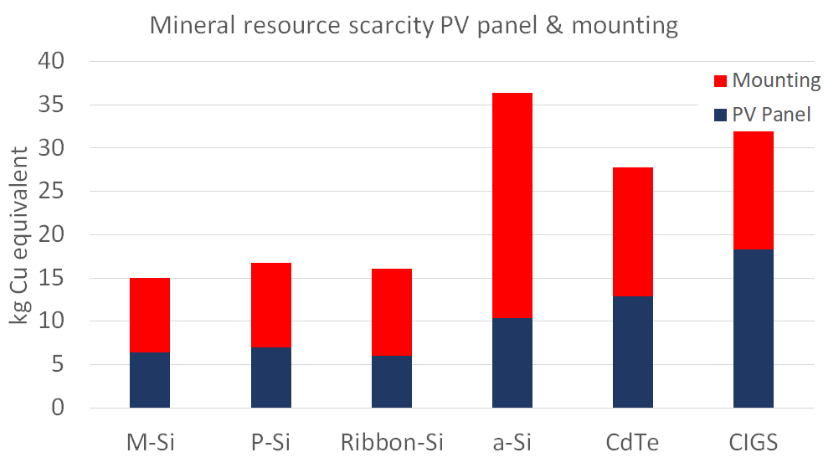


Figure C.3: Results of the midpoint impact category resource scarcity for different PV panels.

These graphs show that the difference between the CdTe and the polycrystalline PV panels is not significant. Only the mineral resource scarcity shows a significant difference. To better substantiate the advise the endpoints have been used in this research.

D

Appendix D: Details Energy Use & Reactions in the Micro-Plant

This section provides a detailed overview of the energy use and the reactions occurring in the micro-plant. Table D.1 shows an overview of these reaction and energy use. The mole fractions are based on assumptions concerning the different subsystems. The energy used per subsystem is depicted as kWh per 0.947 mole MeOH output. This is the methanol output for 1 mole of CO_2. The total energy use is approximately 0.31 kWh/0.947 mole MeOh. This can be recalculated to ≈10.7 kWh/kg MeOH, or 38.6 MJ/kg. Combining this with the energy density of 20 MJ/kg gives an efficiency of the micro-plant of 51.85%.

Table D.1: Overview of the reactions and energy consumption of the micro-plant.

Input	Value	Unit	Output	Value	Unit
DAC					
Air	-	mole	H_2O	9	mole
Electricity	0.048	kWh/0.947 mole MeOH output	CO_2	1	mole
			Left over air mass		
Compressor					
H_2O	9	mole	H_2O (to environment)	6	mole
CO_2	1	mole	CO_2	1	mole
Electricity	0.018	kWh/0.947 mole MeOH output	H_2O (in system)	3	
Degasser					
CO_2 (dissolved)	0.052	mole	H_2O	3	mole
O_2	1.5	mole	CO_2 (to environment)	0.052	mole
H_2O	3	mole			
AEC					
H_2O	3	mole	H_2	3	mole
Electricity	0.246	kWh/0.947 mole MeOH output	O_2	1.5	mole
MS					
H_2	2.842	mole	MeOH	0.947	mole
CO_2	0.947	mole	H_2O	0.947	mole
Electricity	0.004	kWh/0.947 mole MeOH output			
DS					
MeOH	0.947	mole	MeOH	0.947	mole
H_2O	0.947	mole	H_2O (in MeOH)	0.004	mole
Electricity	0.005	kWh/0.947 mole MeOH output	H_2O (to environment)	0.944	mole

E

Appendix E: Detailed Overview LCI of Micro-Plant

This appendix focuses on the LCI of the micro-plant. Table E.1 shows a summary of all materials used for constructing one micro-plant. The bottom part of the table shows the production method. When a material is not available in the Ecoinvent database, a comparable material is selected. If this is the case, it is shown in the last column.

Table E.1: List of the materials used for constructing a micro-plant. The last column depicts materials used when no data is available of that specific material. Manufacturing of the materials is shown in the bottom rows.

Material	Weight [g]	Material used
Stainless steel	22965	
Aluminium	6310	
PET gf 45	6140	
Polyphenylene sulfide	4739	
PEI/Tepa	3000	Monoethanolamine
Cellulose	1960	
Copper	1872	
KOH	1650	
Nickel	1650	
Plastic	670	
Paper	350	
Glass	200	
Zirconium oxide	200	
polysulfone	200	
Al2O3	200	
Printing board	175	
polyoxymethylene	120	Nylon
HDPE	100	
Nylon	85	
Rubber	76	
ZnO	40	
Fiber glass	37	
kevlar (Aramiden)	30	Nylon
Acrylic	20	Nylon
Stainless steel product manufactering	22965	
Injection molding	11904	
Aluminium product manufactering	6310	
Copper product manufactering	1872	

The following tables depict the materials used per sub-system. The tables are more detailed than the one presented in chapter 3. When all the materials described in these tables are added up one obtains table E.1.

Table E.2: Overview of the materials and components of the alkaline electrolytic cell.

Part description	Gram [g]	Material
Cookie roll	4739	Polyphenylene sulfide
Casing	7945	Stainless steel
Electricity wires	151	Copper
KOH (electrolyte)	1650	KOH
Electrodes	1650	Nickel
Membrame part 1	200	Zirconium oxide
Membrame part 2	200	Polysulfone
Level sensor	4	Stainless steel
Heat sensor	0,24	Aluminium
Pressure sensor	16	Stainless steel
Solonoid valves	55	Stainless steel
	25	Nylon
	12	Fiber glass
	4	Rubber

Table E.3: Overview of the materials and components of the methanol synthesis.

Part description	Gram [g]	Material
Pipes reactor	810	Stainless steel
Cold tube	40	Aluminium
Valve block	1000	Aluminium
Heat exchange part	1451	Copper
Catalyst	160	Al2O3
Catalyst	40	ZnO
Catalyst	40	Copper
Heaters	10,8	Nylon
	15,5	Stainless steel
O-ringen	0,32	Rubber
Level Sensor	1,17	Stainless steel
Heat sensor	0,12	Aluminium
Pressure sensor	16	Stainless steel
Frequency sensor	20	Acrylic
Solonoid valves	27	Stainless steel
	12	Nylon
	6	Fiber glass
	2	Rubber

Table E.4: Overview of the materials and components of the distillation unit.

Part description	Gram [g]	Material
Aluminium parts	2450	Aluminium
Pipes	363	Stainless Steel
Capillary material	30	Kevlar (Aramiden)
Heat Sensor	0,2	Aluminium
Level Sensor	2	Stainless steel
Peltier elements	20	Al2O3
Solonoid valves	82	Stainless steel
	37,0	Nylon
	18,5	Fiber glass
	6	Rubber

Table E.5: Overview of the materials and components of the direct air capture.

Part description	Gram [g]	Material
Glass desorption chamber	200	Glass
Aluminium parts	500	Aluminium
Steel parts	970	Stainless Steel
Copper parts	200	Copper
Rubber	10	Rubber
Plastic casing	1400	PET gf 45
Absorber racks	350	paper
PEI/TEPA	3000	PEI/TEPA
Fans	670	plastic
HDPE parts	100	HDPE
Level Sensor	4	Stainless steel
Vacuum Sensor	0,23	Printing board
Heat Sensor	0,12	Aluminium
O rings	0,45	Rubber
Peltier elements	20	Al2O3

Table E.6: Overview of the materials and components of the compressor.

Part description	Gram [g]	Material
Big gears	120	polyoxymethylene
Small gears	20	Stainless steel
Gearbox steel	584	Stainless steel
Gearbox aluminium	1779	Aluminium
Pistons	5051	Stainless steel
Pressure sensor	16,02	Stainless steel
Heat sensor	0,06	Aluminium
O rings	7,8	Rubber
Drone motor	25	Copper
	23	Stainless Steel

Table E.7: Overview of the materials and components of the integration.

Part description	Gram [g]	Material
Casing	4740	PET gf 45
Isolation	1960	Cellulose
Buffers	6240	Stainless steel
Closing buffer	540	Aluminium
Printing boards	174,72	Printing board
Cables copper	4	Copper
Cables rubbers	46	Rubber
Tubing	720	Stainless steel

F

Appendix F: GWP to Temperature Change

This appendix briefly discusses how the GWP can be used to calculate the global temperature increase or decrease. In an equilibrium situation, the amount of radiation energy going into a system is equal to the radiation that goes out. Radiative forcing is the amount of deviation from this equilibrium. If the forcing is positive the system heats up, and if it is negative it cools down [105]. In this case, the system is the earth and the radiative forcing, in watt per square meter, is due to the amount of greenhouse gasses in the atmosphere. With a script made by Greg Schivley obtained from [106], one can make an estimate of the radiative forcing with the obtained absorption. The results of this script are depicted in figure F.1. After 100 years the radiative forcing due to the produced methanol is equal to ≈$4.6*10^{-8}$ W/m^2. This translates to a cooling of $2*10^{-8}$ ±40 % Kelvin [107].

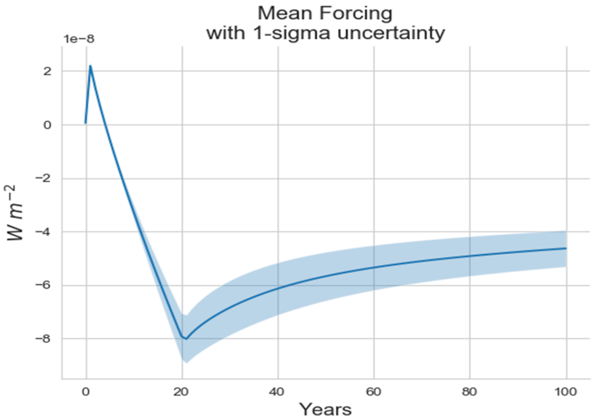


Figure F.1: Results of the radiative forcing, including one standard deviation uncertainty plotted as the light blue shade. Note that the scale of the vertical axis is to the power -8.

One can see that the graph first increases due to the construction of the solar MeOH farm. Then the production of MeOH starts, and thus the absorption of CO_2. After 20 years the mean forcing increases again. The hypothesis for this is that due to the extra CO_2 absorbed equilibriums in the atmosphere shift to producing CO_2 until a new equilibrium is found. The graph seems to stabilise over the years.

G
Appendix G: The Environmental Impact of Manufacturing and Production Methods

In the LCA not only the manufacturing of materials but also the production methods of the micro-plant are taken into account. The share of the environmental impact of the methods and manufacturing is shown in figure G.1. It can be seen that again most of the environmental impact is due to the manufacturing of the different materials. This small impact is the reason not to discuss it in detail in this report.

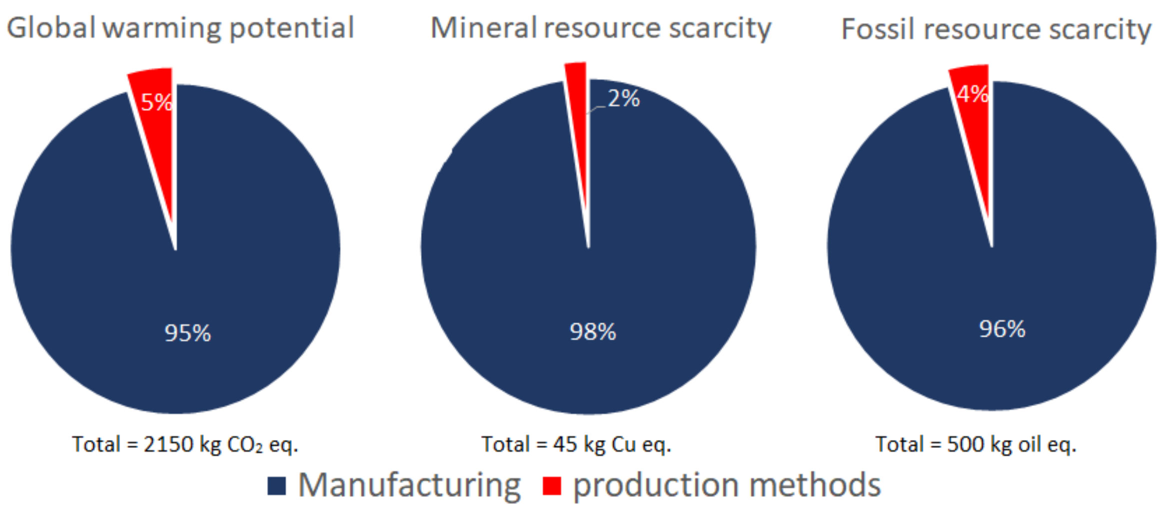


Figure G.1: The environmental impact per impact category for production and manufacturing relative to constructing one modular MeOH system

H

Appendix H: Extra Location Scenarios

This appendix discusses two scenarios that are not included in the report. The first concerns the manufacturing of the modular MeOH system in Europe. The second scenario focuses on the effect of transportation to different locations. They have not been included in the report because it was clear from the results they would not have a large impact.

Scenario H1: Location Production

The materials in the base case scenario are produced in China. The main reason for this assumption has been explained in chapter 3. This scenario investigates what happens to the environmental impact when the manufacturing takes place in Europe. The production methods, in general, are expected to be more efficient in Europe. This could lead to a decrease in environmental impact.

Figure H.1 depicts the effect of producing materials in Europe. The effect on the GWP and Mineral use is slightly lower, around 0.3 %. Fossil fuel use, however, can be reduced by approximately 2%. This decrease is due to the higher energy efficiency and the different energy mix in Europe. The price is generally higher in Europe for materials than in China. Because the change in environmental impact is small, it is found not to be feasible to produce in Europe.

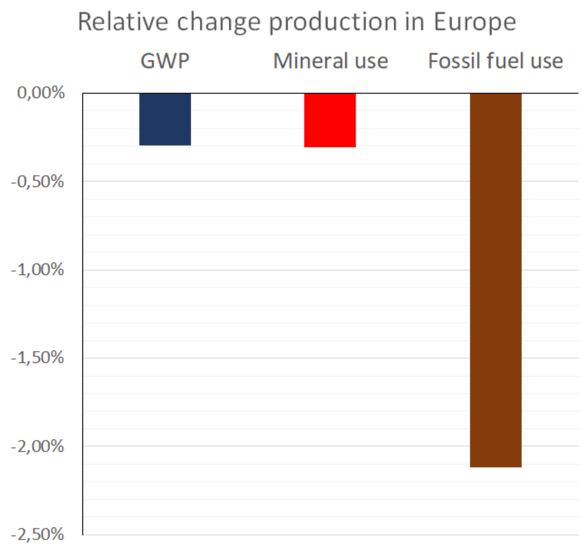


Figure H.1: Relative change for different impact categories when producing in Europe.

Scenario H2: Location Operation

A group from the TU-Delft master of Transport Infrastructure and Logistics (TIL) [93] made a report that discusses the best location to operate the plant. The advice from this report is based on economics. The advice is three locations namely Morocco, Peru, and Oman. The base case scenario assumed that the operation is in Morocco. In this section, the results of operating in Peru and Oman are discussed.

To look at the influence of transport three different scenarios are discussed. One is transporting to Peru, one transporting to Oman and the last one has double the transport. The reason this last scenario is discussed is that it can give an idea of the maximum change in the environmental impact of transport. In table H.1 the assumptions for the four different scenarios are depicted. Keeping in mind from chapter 3 that the weight of one micro plant is around 180 kg, and the weight of the entire plant is estimated on 2380 ton. Rail transport takes place in china and is assumed to be constant for different locations.

Figure H.2 depicts the impact the different location has on the three different impact categories. The impact on GWP and mineral resource use are small. Even in the extreme case, the increase in GWP is smaller than 1%. For fossil resource use the change in impact is

Table H.1: Overview of the different transport values for different scenarios.

	Ship [km]	Ship [tkm]	Rail [km]	Rail [tkm]	Road [km]	Road [tkm]
Base case	18,000	4.3E+07	500	1.19E+06	250	5.95E+05
Peru	19,000	4.5E+07	500	1.19E+06	300	7.1E+05
Oman	10,000	2.4E+07	500	1.19E+06	50	1.9E+05
Extreme case	25,000	5.95E+07	1000	2.4E+06	800	1.9E+06

slightly larger. This is logical because more transport means more use of fossil fuels. The main conclusion that is drawn is that the location has a small impact on the environmental impact, and therefore not included in the report. It should not be the main focus for reducing the environmental impact.

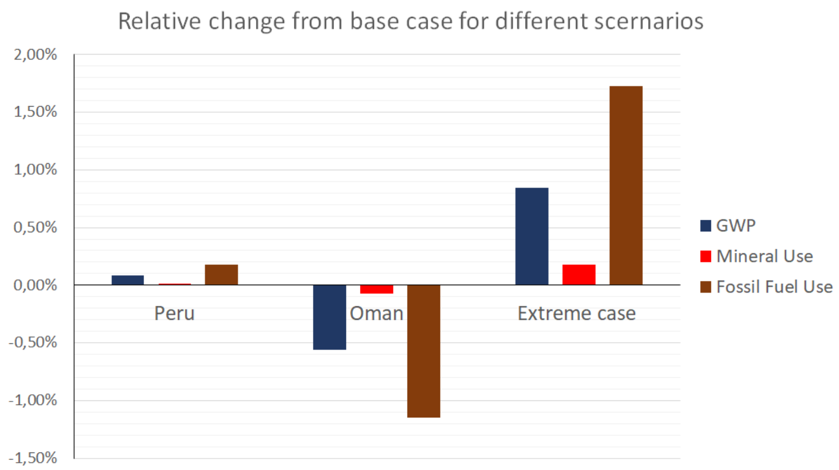


Figure H.2: The change in environmental impact for transporting to different locations.

Bibliography

[1] United nations. 175 states sign paris agreement, 2016. https://unfccc.int/news/175-states-sign-paris-agreement.

[2] United nations. The paris agreement, 2016. https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement.

[3] Jos GJ Olivier, KM Schure, and JAHW Peters. Trends in global co2 and total greenhouse gas emissions. *PBL Netherlands Environmental Assessment Agency*, page 5, 2017.

[4] Statistics data browser. https://www.iea.org/statistics. Accessed: 22-03-2019.

[5] Methanol. https://pubchem.ncbi.nlm.nih.gov/compound/methanol#section=Odor. Accessed: 26-03-2019.

[6] Energy density of methanol. https://hypertextbook.com/facts/2005/JennyHua.shtml. Accessed: 26-03-2019.

[7] Methanol. https://biologydictionary.net/methanol/. Accessed: 26-03-2019.

[8] International Energy Agency. The future of petrochemicals. Report, 2018.

[9] The methanol industry. https://www.methanol.org/the-methanol-industry/. Accessed: 26-03-2019.

[10] Methanex posts regional contract methanol prices for north america, europe and asia. https://www.methanex.com/our-business/pricing. Accessed: 26-03-2019.

[11] The changing face of the global methanol industry. http://www.methanol.org/wp-content/uploads/2016/07/IHS-ChemicalBulletin-Issue3-Alvarado-Jun16.pdf. Accessed: 26-03-2019.

[12] Engineering conversion factors. https://web.archive.org/web/20100825042309/http://www.ior.com.au/ecflist.html. Accessed: 31-07-2019.

[13] Matthias Blug, Jens Leker, Ludolf Plass, and Armin Günther. Methanol generation economics. In *Methanol: The Basic Chemical and Energy Feedstock of the Future*, pages 603–618. Springer, 2014.

[14] Eu ends target for food-based biofuels but will only halt palm-oil support in 2030. https://www.transportenvironment.org/news/eu-ends-target-food-based-biofuels-will-only-halt-palm-oil-support-2030. Accessed: 31-07-2019.

[15] Methanol from biomass. http://www.etipbioenergy.eu/images/methanol-fact-sheet.pdf. Accessed: 27-03-2019.

[16] David van Nunen. System integration for solar powered methanol synthesis. Master's thesis, TU-Delft, 2019.

[17] International Organization for Standardization. ISO 14040, 2006.

[18] Rijksinstituut voor Volksgezondheid en Milieu. Lcia: the recipe model, 2011.

[19] Recipe. https://www.pre-sustainability.com/recipe. Accessed: 01-08-2019.

[20] International Organization for Standardization. ISO 14044, 2006.

[21] Walter Klöpffer and Birgit Grahl. *Life cycle assessment (LCA): a guide to best practice.* Wiley-VCH, 2014.

[22] Ralph Horne, Tim Grant, and Karli Verghese. *Life cycle assessment: principles, practice and prospects*. Csiro Publishing, 2009.

[23] Ann-Christin Pålsson. Central concepts in lca, 2011. https://tosca-life.info/getting-started-guides/life-cycle-assessment/how-to-perform-an-lca/central-concepts-in-lca/.

[24] Anne-Marie Tillman, Tomas Ekvall, Henrikke Baumann, and Tomas Rydberg. Choice of system boundaries in life cycle assessment. *Journal of Cleaner Production*, 2(1):21–29, 1994.

[25] Michael Z Hauschild and Mark AJ Huijbregts. *Introducing life cycle impact assessment*. Springer, 2015.

[26] Interpretation of metrics: Dalys and damage to human health. https://www.pre-sustainability.com/news/metrics-interpretation-daly-and-damage-to-human-health. Accessed: 06-08-2019.

[27] species-years. https://www.learner.org/courses/envsci/glossary/definition.php?invariant=species_years. Accessed: 06-08-2019.

[28] MAJ Huijbregts, ZJN Steinmann, PMF Elshout, G Stam, F Verones, MDM Vieira, A Hollander, M Zijp, and R Van Zelm. Recipe 2016: A harmonized life cycle impact assessment method at midpoint and endpoint level report i: Characterization. 2016.

[29] The big 6 environmental impact categories. https://www.slideshare.net/sustenergy/the-big-6-environmental-impact-categories. Accessed: 27-03-2019.

[30] Ecoinvent 3.4. https://www.ecoinvent.org/database/older-versions/ecoinvent-34/ecoinvent-34.html. Accessed: 15-03-2019.

[31] Standard test conditions. https://wiki.openmod-initiative.org/wiki/Standard_test_conditions. Accessed: 08-07-2019.

[32] ISE Fraunhofer. Photovoltaics report. www.ise.fraunhofer.de, 2018.

[33] Solar cell efficiency. https://www.pveducation.org/pvcdrom/solar-cell-operation/solar-cell-efficiency. Accessed: 08-07-2019.

[34] RL Wallace, JI Hanoka, S Narasimha, S Kamra, and A Rohatgi. Thin silicon string ribbon for high efficiency polycrystalline solar cells. In *Conference Record of the Twenty Sixth IEEE Photovoltaic Specialists Conference-1997*, pages 99–102. IEEE, 1997.

[35] The production of polycrystalline silicon. https://medium.com/@solar.dao/the-production-of-polycrystalline-silicon-20fb990790c9. Accessed: 07-03-2019.

[36] What are the most efficient solar panels of 2019? https://ecotality.com/most-efficient-solar-panels/. Accessed: 07-03-2019.

[37] Dajun Yue, Fengqi You, and Seth B Darling. Domestic and overseas manufacturing scenarios of silicon-based photovoltaics: Life cycle energy and environmental comparative analysis. *Solar Energy*, 105:669–678, 2014.

[38] Vasilis M Fthenakis, Hyung Chul Kim, and Erik Alsema. Emissions from photovoltaic life cycles. *Environmental science & technology*, 42(6):2168–2174, 2008.

[39] Pankaj Kumar. *Organic solar cells: device physics, processing, degradation, and prevention*. CRC Press, 2016.

[40] Lingotto di silicio monocristallino drogato di antimonio. http://it.yixinwafer.com/monocrystalline-silicon-ingot/n-type-monocrystalline-silicon-ingot/antimony-doped-monocrystalline-silicon-ingot.html. Accessed: 04-05-2019.

[41] Pros and cons of monocrystalline vs polycrystalline solar panels. https://www.solarreviews.com/blog/pros-and-cons-of-monocrystalline-vs-polycrystalline-solar-panels. Accessed: 06-03-2019.

[42] Askari Mohammad Bagher, Mirzaei Mahmoud Abadi Vahid, and Mirhabibi Mohsen. Types of solar cells and application. *American Journal of optics and Photonics*, 3(5):94–113, 2015.

[43] Royal Society of Chemistry. Silicon, 2019.

[44] Wafer production - wafer material. http://www.renewable-energy-concepts.com/solarenergy/solar-technology/wafer-production.html. Accessed: 07-03-2019.

[45] Vasilis Fthenakis, Rick Betita, Mark Shields, Rob Vinje, and Julie Blunden. Life cycle analysis of high-performance monocrystalline silicon photovoltaic systems: energy payback times and net energy production value. In *27th European Photovoltaic Solar Energy Conference and Exhibition*, pages 4667–4672, 2012.

[46] Thin film vs. crystalline silicon pv modules. https://www.civicsolar.com/support/installer/articles/thin-film-vs-crystalline-silicon-pv-modules. Accessed: 13-03-2019.

[47] Cadmium-cd. https://www.lenntech.nl/periodiek/elementen/cd.htm. Accessed: 12-03-2019.

[48] Te/telluur. https://periodieksysteem.com/element/telluur. Accessed: 12-03-2019.

[49] Shruti Sharma, Kamlesh Kumar Jain, and Ashutosh Sharma. Solar cells: in research and applications—a review. *Materials Sciences and Applications*, 6(12):1145, 2015.

[50] Jinqing Peng, Lin Lu, and Hongxing Yang. Review on life cycle assessment of energy payback and greenhouse gas emission of solar photovoltaic systems. *Renewable and sustainable energy reviews*, 19:255–274, 2013.

[51] Hyoungseok Kim, Kyounghoon Cha, Vasilis M Fthenakis, Parikhit Sinha, and Tak Hur. Life cycle assessment of cadmium telluride photovoltaic (cdte pv) systems. *Solar Energy*, 103:78–88, 2014.

[52] Enrica Leccisi, Marco Raugei, and Vasilis Fthenakis. The energy and environmental performance of ground-mounted photovoltaic systems—a timely update. *Energies*, 9(8):622, 2016.

[53] Michael Stuckelberger, Rémi Biron, Nicolas Wyrsch, Franz-Josef Haug, and Christophe Ballif. Progress in solar cells from hydrogenated amorphous silicon. *Renewable and Sustainable Energy Reviews*, 76:1497–1523, 2017.

[54] Pecvd. http://www.plasma-therm.com/pecvd.html. Accessed: 11-03-2019.

[55] Thin film vs. mono/polycrystalline panels. https://www.energymatters.com.au/panels-modules/thin-film-monocrystalline/. Accessed: 11-03-2019.

[56] Silicon-si. https://www.lenntech.com/periodic/elements/si.html. Accessed: 11-03-2019.

[57] Solar cell comparison chart – mono-, polycrystalline and thin film. https://energyinformative.org/solar-cell-comparison-chart-mono-polycrystalline-thin-fil
Accessed: 12-03-2019.

[58] Sharp solar panel 90w (thin-film amorphous). https://www.energymatters.com.au/sharp-solar-panel-90w-thinfilm-amorphous-p-6.html. Accessed: 12-03-2019.

[59] Antonio Dominguez-Ramos, Michael Held, Ruben Aldaco, Matthias Fischer, and Angel Irabien. Prospective co2 emissions from energy supplying systems: photovoltaic systems and conventional grid within spanish frame conditions. *The International Journal of Life Cycle Assessment*, 15(6):557–566, 2010.

[60] Sense. *LCA analysis: Sustainability evaluation of solar energy systems, revised version.* University of Stuttgart., 2008.

[61] Sergio Pacca, Deepak Sivaraman, and Gregory A Keoleian. Parameters affecting the life cycle performance of pv technologies and systems. *Energy Policy*, 35(6):3316–3326, 2007.

[62] P Frankl, A Corrado, and S Lombardelli. Photovoltaic (pv) systems. final report. *ECLIPSE (Environmental and Ecological Life Cycle Inventories for present and future Power Systems in Europe)*, 2004.

[63] Cigs zonnepanelen, voor- en nadelen. https://www.zonnepanelen.net/cigs-zonnepanelen/. Accessed: 13-03-2019.

[64] Types of thin film solar panels. https://www.energysage.com/solar/101/about-solar-panels/thin-film-solar-panels-amorphous-cadmium-telluride-and-cigs/. Accessed: 13-03-2019.

[65] Olindo Isabella, Arno Smets, Klaus Jäger, Miro Zeman, and René van Swaaij. Solar energy: The physics and engineering of photovoltaic conversion, technologies and systems. *UIT Cambridge Limited*, 2016.

[66] Federica Cucchiella and Idiano D'Adamo. Estimation of the energetic and environmental impacts of a roof-mounted building-integrated photovoltaic systems. *Renewable and Sustainable Energy Reviews*, 16(7):5245–5259, 2012.

[67] Kristine Bekkelund. A comparative life cycle assessment of pv solar systems. Master's thesis, Institutt for energi-og prosessteknikk, 2013.

[68] MJ Mariska de Wild-Scholten. Energy payback time and carbon footprint of commercial photovoltaic systems. *Solar Energy Materials and Solar Cells*, 119:296–305, 2013.

[69] Vasilis Fthenakis, HyungChul Kim, Rolf Frischknecht, Marco Raugei, Parikhit Sinha, Matthias Stucki, et al. Life cycle inventories and life cycle assessment of photovoltaic systems. *International Energy Agency (IEA) PVPS Task*, 12, 2011.

[70] Japanese pv installers choosing wooden racking for solar panel ground-mounting. https://www.solarchoice.net.au/blog/news/japanese-firms-choose-wooden-racking-for-solar-panel-ground-mounting-081014. Accessed: 06-07-2019.

[71] Aluminium portrait ground mounting system. http://www.landpowersolar.com/Solar-Ground-Mount.html?Solar-Mounting=1&Solar-Frame=72. Accessed: 09-07-2019.

[72] Pole ground mounting system. https://www.antaisolar.com/pole-ground-mounting-system_p23.html. Accessed: 09-07-2019.

[73] Advantages and disadvantages of a solar tracker system. https://www.solarpowerworldonline.com/2016/05/advantages-disadvantages-solar-tracker-system/. Accessed: 06-08-2019.

[74] IRENA. Renewable energy technologies: Cost analysis series. Technical report, International renewable energy agency, 2012.

[75] Solar panels cost. https://www.solarenergyforus.com/solar-panels-cost/. Accessed: 12-03-2019.

[76] Pv spot price. https://m.energytrend.com/pricequotes.html. Accessed: 06-03-2019.

[77] A Rix, JDT Steyl, J Rudman, U Terblanche, and JL van Niekerk. First solar's cdte module technology-performance life cycle health and safety impact assessment. *Centre for Renewable and Sustainable Energy Studies*, 2015.

[78] Kelsey AW Horowitz, Ran Fu, Tim Silverman, Mike Woodhouse, Xingshu Sun, and Mohammed A Alam. An analysis of the cost and performance of photovoltaic systems as a function of module area. Technical report, National Renewable Energy Lab.(NREL), Golden, CO (United States), 2017.

[79] 150 watt zonnepaneel flexibele cigs dunne film pv zonnepaneel voor boten flexibele zonnepaneel 12 volt. https://dutch.alibaba.com/product-detail/150-watt-solar-panel-flexible-cigs-60628623856.html?spm=a2700.7724838.2017115.226.8cbf52b47wwCs7. Accessed: 13-03-2019.

[80] Xiaoting Wang and Allen Barnett. The evolving value of photovoltaic module efficiency. *Applied Sciences*, 9(6):1227, 2019.

[81] What is the lifespan of a solar panel? https://news.energysage.com/shopping-solar-panels-pay-attention-to-solar-panels-warranty/. Accessed: 06-08-2019.

[82] Solar efficiency losses over time. http://sroeco.com/solar/solar-efficiency-losses-over-time/. Accessed: 06-08-2019.

[83] Dirk C Jordan and Sarah R Kurtz. Photovoltaic degradation rates—an analytical review. *Progress in photovoltaics: Research and Applications*, 21(1):12–29, 2013.

[84] Nicholas Strevel, Lou Trippel, Chad Kotarba, and Imran Khan. Improvements in cdte module reliability and long-term degradation through advances in construction and device innovation. *Photovoltaics International*, 22:66–74, 2013.

[85] Pole ground mounting system. https://www.foenpv.com/pole-ground-mounting-system_p86.html. Accessed: 06-08-2019.

[86] Jens R Rostrup-Nielsen. Syngas in perspective. *Catalysis today*, 71(3-4):243–247, 2002.

[87] Giulia Bozzano and Flavio Manenti. Efficient methanol synthesis: perspectives, technologies and optimization strategies. *Progress in Energy and Combustion Science*, 56:71–105, 2016.

[88] Anna Śliwińska, Dorota Burchart-Korol, and Adam Smoliński. Environmental life cycle assessment of methanol and electricity co-production system based on coal gasification technology. *Science of the Total Environment*, 574:1571–1579, 2017.

[89] Raili Kajaste, Markku Hurme, and Pekka Oinas. Methanol-managing greenhouse gas emissions in the production chain by optimizing the resource base. *AIMS ENERGY*, 6(6):1074–1102, 2018.

[90] Jingying Li, Xiaoxun Ma, Heng Liu, and Xiyu Zhang. Life cycle assessment and economic analysis of methanol production from coke oven gas compared with coal and natural gas routes. *Journal of Cleaner Production*, 185:299–308, 2018.

[91] Zheng Li, Dan Gao, Le Chang, Pei Liu, and Efstratios N Pistikopoulos. Coal-derived methanol for hydrogen vehicles in china: energy, environment, and economic analysis for distributed reforming. *Chemical Engineering Research and Design*, 88(1):73–80, 2010.

[92] Solar panel waste: A disposal problem. https://wattsupwiththat.com/2018/12/23/solar-panel-waste-a-disposal-problem/. Accessed: 09-07-2019.

[93] I. Vendrik K. Verhoeven L. Volberda A. Buitenweg, D. van Rooij. Analytically determining the optimal location for a solar methanol farm, 2019.

[94] Statistics, global energy data at your fingertips. https://www.iea.org/statistics/?country=WORLD&year=2016&category=Energy%20supply&indicator=TPESbySource&mode=chart&dataTable=BALANCES. Accessed: 04-07-2019.

[95] Size and weight of solar panels. https://news.energysage.com/average-solar-panel-size-weight/. Accessed: 09-07-2019.

[96] Pp - polypropylene - chemical resistance. https://www.engineeringtoolbox.com/polypropylene-pp-chemical-resistance-d_435.html. Accessed: 09-07-2019.

[97] Solar farm security guide. https://www.safesitefacilities.co.uk/knowledge-base/solar-farm-security-guide. Accessed: 09-07-2019.

[98] Monte carlo simulation definition. https://www.investopedia.com/terms/m/montecarlosimulation.asp. Accessed: 03-05-2019.

[99] Andreas Brekke, Cecilia Askham, Ingunn Saur Modahl, Bjørn Ivar Vold, and FM Johnsen. Environmental assessment of amine-based carbon capture. *Scenario modelling with life cycle assessment (LCA). Report no. OR*, 17, 2012.

[100] Khagendra P Bhandari, Jennifer M Collier, Randy J Ellingson, and Defne S Apul. Energy payback time (epbt) and energy return on energy invested (eroi) of solar photovoltaic systems: A systematic review and meta-analysis. *Renewable and Sustainable Energy Reviews*, 47:133–141, 2015.

[101] Global solar atlas. https://globalsolaratlas.info/?c=2.04524,15.096703,3. Accessed: 01-07-2019.

[102] Jeremiah Johnson, BK Reck, T Wang, and TE Graedel. The energy benefit of stainless steel recycling. *Energy policy*, 36(1):181–192, 2008.

[103] R Zare, J Nouri, MA Abdoli, and F Atabi. Life cycle assessment of secondary extruded aluminum production process in industrial city of arak. *Applied Ecology and Environmental Research*, 14(2):125–135, 2016.

[104] Li Shen, Evert Nieuwlaar, Ernst Worrell, and Martin K Patel. Life cycle energy and ghg emissions of pet recycling: change-oriented effects. *The International Journal of Life Cycle Assessment*, 16(6):522–536, 2011.

[105] Explained: Radiative forcing. http://news.mit.edu/2010/explained-radforce-0309. Accessed: 01-07-2019.

[106] Ghg forcing calculations in excel using ghgforcing package. https://github.com/gschivley/easyghg. Accessed: 04-05-2019.

[107] Piers Mde F Forster and Jonathan M Gregory. The climate sensitivity and its components diagnosed from earth radiation budget data. *Journal of Climate*, 19(1):39–52, 2006.