ASSESSMENT OF THE QUANTITY OF SOLAR POWER PLANT'S CLIMATE IMPACTS DURING ITS LIFE CYCLE IN DIFFERENT APPLICATIONS

Lappeenranta–Lahti University of Technology LUT

Master's programme in Sustainability Science and Solutions, Master's thesis

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Examiners: Professor Risto Soukka, Dc.S. (Tech.)

Post-doctoral researcher Jani Sillman, Dr.S. (Tech.)

ABSTRACT

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Assessment of the quantity of solar power plant's climate impacts during its life cycle in different applications

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Keywords: Solar electricity, electrolysis, synthesis, carbon capture, P2X, methanol, methane, life cycle assessment, RED III

By 2050 the whole energy sector should reach carbon neutrality. The oil dependence and entrenchment of fossil fuel use are the greatest challenges in the transport sector. Synthetic fuels from renewable energy sources could enable a transition in a sector where transformation is desperately needed.

The calculations are based on life cycle assessment regulations and the review is conducted in accordance with RED III. Methanol and methane were selected as end-products, which were produced using green hydrogen from solar electricity and carbon dioxide captured from a biogenic source. The results were assessed also from a total efficiency point of view, hence the energy transferring to end-product is weaker in more processed fuels. Finally, the study focused on what requirements the ELY Centre should set for operators.

The results showed that methanol production compared to methane produces more end-product related to land area but causes more emissions per end-product. The biggest emission source was detected to be hydrogen production, and the material selection and heat utilisation were detected to affect significantly to the emissions. Additionally, it was detected that threshold values of RED III were met when producing methanol form solar electricity.

TIIVISTELMÄ

Lappeenrannan–Lahden teknillinen yliopisto LUT

LUT Energiajärjestelmät

Ympäristötekniikka

Tuuli Sievä

Aurinkovoimapuiston elinkaaristen ilmastovaikutusten suuruusluokan arviointia erilaisissa sovellustapauksissa

Diplomityö

2024

99 sivua, 29 kuvaa, 3 taulukkoa ja 2 liitettä

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Vuoteen 2050 mennessä koko energiasektorin tulisi saavuttaa hiilineutraalisuus. Haasteena liikennesektorilla on tällä hetkellä vahva öljyriippuvuus ja fossiilisten polttoaineiden vakiintunut käyttö. Uusiutuvaa energiaa hyödyntävät synteettiset polttoaineet voivat mahdollistaa muutoksen sektorilla, jossa murros on erittäin tarpeellista.

Laskennat perustuivat elinkaarimallinnuksen säädöksiin ja RED III:n mukaiseen tarkasteluun. Lopputuotteiksi valikoitui metanoli ja metaani, joiden valmistamiseen käytettiin vihreää vetyä aurinkosähköstä ja biogeenisestä lähteestä talteen otettua hiilidioksidia. Tuloksia tarkasteltiin myös kokonaishyötysuhteen näkökulmasta, sillä prosessoiduissa polttoaineissa energian siirtyminen lopputuotteeseen on heikompaa. Lopuksi pohdittiin, mitä vaatimuksia ELY-keskuksen tulisi asettaa toiminnanharjoittajille.

Tulokset osoittivat, että metanolin tuotannolla metaaniin verrattuna saavutetaan enemmän lopputuotetta suhteessa pinta-alaan, mutta aiheutetaan lopputuotetta kohden enemmän päästöjä. Elinkaarisesti merkittävin päästönlähde todettiin olevan vedyntuotanto, ja materiaalivalinnoilla ja lämmön hyödyntämisellä oli huomattavia vaikutuksia päästöihin. Lisäksi tuloksista oli havaittavissa, että RED III:n mukaiset raja-arvot on mahdollista saavuttaa, kun metanolia tuotetaan aurinkosähköstä.

ACKNOWLEDGEMENTS

After many tears, moments of hyperfocus, energy drinks, playlists repeated and nicotine pouches later, here we are.

I appreciate the help from my examiners Risto Soukka and Jani Sillman from LUT University. I sincerely thank you for your time and knowledge you were willing to share. I am also thankful for the feedback I was given. Furthermore, I would like to thank Timo Ålander, Mika Toikka and Antti Puhalainen from ELY for your time and interest regarding the project.

Originally, I didn't want to go to study in an unfamiliar city, but without it I would have missed many important characters in my life, my wife, the friends I made through my studies, and my best friend Viivi, with whom I was able spend three years together. I hope you had the best retirement days a cat could get. Even though the university years were not the easiest for me, and at some points giving up felt a much more feasible option than pushing forward, I am grateful for all the good memories and laughs that I was able to experience.

I also appreciate the help from my family, especially from Meri. I also would like to give special acknowledgement to my wife, who supported me during my studies and went through the hardest and the happiest moments with me. I am very grateful that you believed in me whenever I doubted myself. Suki and Toph, thank you for all the cuddles I received. I love you both the most.

Overall, I feel like I am not done with learning and self-development, and finishing my thesis is just the beginning of my journey. I am excited to see what opportunities the future holds.

SYMBOLS AND ABBREVIATIONS

Abbreviations

AC	Alternating current
AEC	Alkaline water electrolysis
A-LCA	Attributional life cycle assessment
CC	Carbon capture
CCS	Carbon capture and storage
CCU	Carbon capture and utilisation
C-LCA	Consequential life cycle assessment
C-Si	Crystalline silicon
CSP	Concentrated solar power
DC	Direct current
DH	District heating
DME	Dimethyl ether
DMFC	Direct methanol fuel cell
EIA	Environmental impact assessment
ELY	The Centre for Economic Development, Transport, and the Environment
EU	European Union
FU	Functional unit
GHG	Greenhouse gas

HHV	High heating value
HTE	High-temperature electrolysis
ICE	Internal combustion engine
LCI	Life cycle inventory analysis
LCA	Life cycle assessment
LCIA	Life cycle impact assessment
LHV	Lower heating value
LNG	Liquefied natural gas
LPG	Liquefied petroleum gas
LTE	Low-temperature electrolysis
MEA	Monoethanolamine
MTBE	Methyl tert-butyl ether
P2X	Power-to-X
PEM	Polymer electrolyte membrane
PV	Photovoltaic
RES	Renewable energy source
RFNBO	Renewable liquid and gaseous fuels of non-biological origin
RWGS	Reverse Water Gas Shift Reaction
SOEC	Solid oxide electrolyser

Chemical Compounds

Al_2O_3	Aluminium oxide
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
CO_3OH	Methanol
CuO	Copper (II) oxide
H_2	Hydrogen
H_2O	Water
Ni	Nickel
O_2	Oxygen
Pd	Palladium
Rd	Rhodiums
ZnO	Zinc oxide

Greek characters

α	Solar radiation angle	[°]
β	Solar module tilt angle	[°]

Units

Area	[cm^2, m^2]

Carbon dioxide equivalent	[CO_2e]
Electric current	[A]
Electric potential	[V, kV]
Energy	[kWh, MJ, GJ]
Length	[mm, m]
Mass	[kg, t]
Power	[kW_p, MW_p, W, kW, MW, GW]
Pressure	[MPa]
Temperature	[°C]

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1. Introduction

The current demand for sustainable and affordable energy solutions has increased urgently due to the fossil fuel supplies continuously shrinking. Within the last decades solar energy has been acknowledged more as one of the most promising renewable energy sources (RES) because of its cost efficiency and accessibility globally. With RES technologies it is possible to mitigate the impacts that are intensifying climate change as they offer alternative solutions compared to primary energy. (Moukhtar et al. 2021) The transition towards sustainable energy sources takes time because the conventional fuels and energy solutions have established a role in our society, and therefore it is important to heavily increase systems like solar power to advance the transition. (LUT University 2019.) However, in Finland, it has been estimated that the carbon negativity can be achieved in the production of electricity and district heat by 2030. By 2050 the whole energy sector would nearly be emission free. (Energiateollisuus 2024; Työ- ja elinkeinoministeriö 2014.)

It is estimated that solar energy may become the main energy production solution in the future, due to its economic feasibility and the storage potential. Also, solar power, apart from wind power, is the only scalable form of energy production. In addition to environmental drivers, there are also geopolitical reasons for the transition towards the solar power. For example, in Europe, gas dependence, the price of electricity, uncertainty regarding energy availability caused by the Russian war of aggression in Ukraine and a general interest in renewable forms of energy production are the main causes why solar power is becoming more common. (LUT University 2019.)

Globally the annual average of solar irradiation per square meter arriving to Earth’s atmosphere is 1360 W (Coddington et al. 2016). In the sunniest regions of the world, this allows the production of solar energy up to 2500 kWh/m^2 annually. In Finland the solar radiation is approximately 900 kWh/m^2 depending on the geographical location. According to Finnish Energy Agency the production of solar energy in 2022 was total of 635 MW, which considers also the electricity produced by households. The amount of solar power from Finland's electricity production currently is close to 1% and it is estimated to be

increasing over time. There are plans of constructing multiple solar power plants of several hundred megawatts annual production rate. Additionally, Fingrid, which is the Finnish grid company, has received inquiries regarding offshore wind and solar power projects for a total of more than 100 GW. According to the estimations by Fingrid, there could be solar power plants with a total capacity of 7 GW total operating in Finland by 2030. (LUT University 2019.) The Figure 1 presents all the solar power plants in the region of southeast Finland by this day (7.4.2024), all of which are in the pre-examination or approval phase. There are a total of 13 of these planned plants and if all are approved as such, the total power generated would be up to 1,6 GW annually. (Motiva & Finnish Energy Authority 2023.)

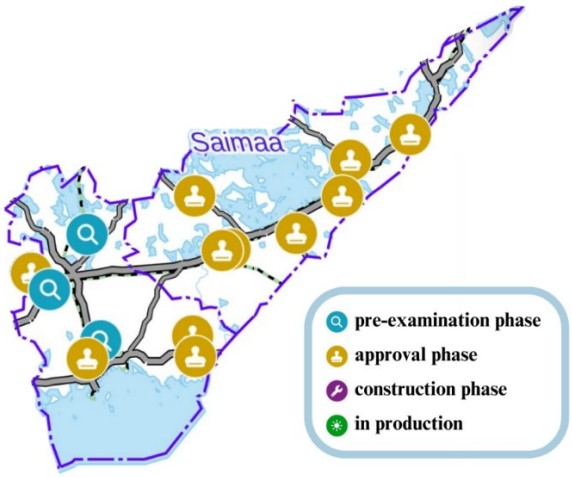

Figure 1. The current (7.4.2024) amount and state of all southeast Finland's solar power plants that are larger than 1 MW (Adapted from Motiva & Finnish Energy Authority 2023).

Shifting towards carbon-neutrality and reducing greenhouse gas emissions (GHGs) in the transportation sector has proven to be challenging due to the global demand for mobility, cultural mobility patterns and transport sector being the least diversified energy end-use sector. Also, replacing oil-based fuels has its limitations regarding the technical aspect. (Blas et al. 2020.) All the existing alternative fuel types are not compatible with all the existing transportation methods. These alternatives would be electrification, biofuels, synthetic fuels, methane, and Liquefied Petroleum Gas (LPG). Additionally, the compatibility affects the

requirements for the fuel, for example the desired travelling distance. (European Commission 2011.) The fuel option availability is presented in the Figure 2.

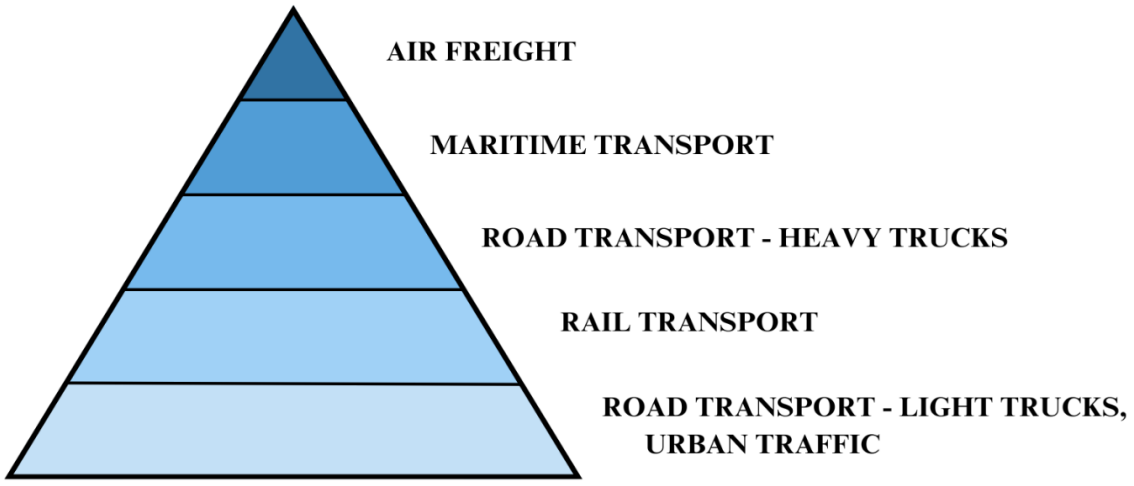

Figure 2. Fuel option availability in transportation sector (Adapted from Soukka 2021).

As the Figure 2 presents, the most options are available for road transport, such as light trucks and urban traffic. In these, all of the existing alternatives can be utilised as fuel. As an exception, electrification and methane-based fuels can only be used for shorter distances. In rail transportation, electrification, biofuels, synthetic fuels and methane-based liquefied natural gas (LNG) can be used. Watercrafts, such as maritime, short-sea shipping and inland vessels, can operate with biofuels, synthetic fuels and LNG. Additionally, shorter distances with inland ships and sea shipping can be run with LPG. The only alternatives currently for conventional oil-based fuels in air transportation are biofuels and synthetic fuels. (European Commission 2011.)

Hydrogen economy and especially green hydrogen, which is hydrogen produced using renewable energy in electrolysis technology, provides an approach for decarbonisation in industrial sectors that are generally really energy intensive. Such sectors are for example transport and chemical. (Hermesmann & Müller 2022.) Conventionally, hydrogen is produced by steam reforming natural gas and the process results in quite extensive

greenhouse gas emissions (Uusitalo et al. 2017). Approximately 80 % of all produced hydrogen in 2022 was originated from unsustainable sources, which reinforces the assumption that there would be a need for more sustainable solutions for the hydrogen-based products (Jonsson & Miljanovic 2022). Especially power-to-X (P2X) technologies provide a solution when the carbon-neutral future and independence from the fossil energy sources are wanted to be reached. (Matinmikko et al. 2022.) During P2X process synthetic fuels are produced from carbon dioxide, hydrogen from water and electricity from a sustainable and renewable source referred as green electricity (Matinmikko et al. 2022; European Environment Agency). These fuels are also known as E-fuels (European Technology and Innovation Platform). In the Figure 3 the P2X process is presented in a simplified form and the pathways to the end-product are shown.

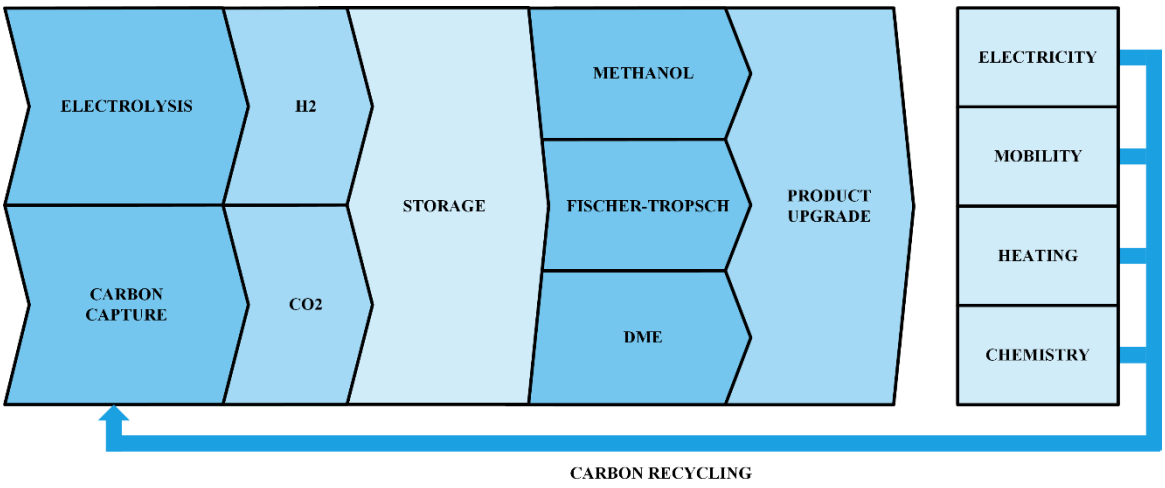

Figure 3. P2X process and its pathways (Adapted from Dieterich et al. 2020).

The synthetic liquids can be for example methanol, methane, dimethyl ether and ammonia, and these can be further processed into gasoline, diesel, or kerosene (LUT University 2018; Dieterich et al. 2020). These synthetic fuels can be used for example in the engines of ships, trucks, and cars instead of the conventional fuels without any additional investments in the vehicle itself, which helps the transition towards carbon neutrality (LUT University 2018).

The main objective of the thesis is to develop the assessment of climate impacts in solar power plant projects and to analyse various product chains and evaluate their entities to produce metadata. Also, the aim is to concentrate on the value chains of the P2X process, to enhance the decision-making process. As the renewable energy production and consumption has increased recently and synthetic fuels could provide a solution in transportation sector transitioning to carbon neutrality, this study assesses the life cycle climate impacts of synthetic fuels produced from solar electricity. Due to a common misconception that solar power can be produced limitlessly without generating any climate impacts, there is a need to clarify and justify the produced metadata and calculation methods for further applications. The motivator for the thesis study is that the southeast Finland's Centre for Economic Development, Transport, and the Environment (ELY) has received reservations for solar panel power plants and the climate impacts of those are wanted to be determined. Additionally, the thesis aims to produce results in which the total efficiency of the process can be assessed.

The research in this thesis is carried out quantitatively and it is divided into a theoretical study and a calculation part. The theoretical part is based on literature and scientific data acquired by research. The theoretical part focuses on solar power plants, P2X phases such as carbon capture, electrolysis, synthesis of methanol and methane. Additionally, the storage options and the fuels that are processed from methanol and methane are studied. The theory part studies the literature behind the life cycle assessment regulations and the RED III directive, and the calculation is executed in accordance with the findings. After the calculation part, results are presented, analysed, and interpreted.

The research questions that are studied in this thesis are:

- What are the climate impacts when solar electricity is transformed into synthetic fuels and how does methanol compare to methane?
- Is it possible to stay within the threshold values from RED III with methanol production?
- How much energy from solar electricity is transferred into the end-product?
- What key issues must ELY-centre address to ensure that the operators achieve climate benefits in solar power projects?

The study is limited to assess only methanol and methane fuels. It is observed how synthetic fuels compete with each other regards to climate impacts. The hydrogen is produced via electrolysis by utilising the electricity from solar power plant. In other process phases the required electricity is taken from the grid. Regarding the P2X process, the carbon for the synthesis process is captured from bio-based source. The study is conducted with a factor in mind that the whole process happens in a unified area from the solar energy production to the methane or methanol production, and thus there is no need to consider any transportation requirements. The calculation is conducted in two parts, one which focuses on the system level climate impacts and other that is done utilising the RED III directive. The system level calculation is based on typical life cycle assessment (LCA) process and provides comparability of climate impacts of different end products, in this case methanol and methane. The calculation results of this method aim to bring more knowledge to the necessary questions needed to be asked from the operators. The RED III based calculation method focuses on if it is possible to stay within the directive set legislative threshold values regarding the climate impacts. The legislative calculation method only considers the methanol production. Since the study is carried out for ELY Centre, specifically located in the southeast of Finland, it is limited to focus on the possibilities that are available in that region. The study concentrates only on the magnitude of climate impacts and therefore the environmental impacts are only discussed in the theory part. The social and economic impacts are left out of the scope of this study.

2. Solar power plants

Solar power plants that have production capacity over 1 MW, are classified as industrial scale plants (Wattson 2023). Currently, there are 24 active industrial scale solar power plants in Finland and the largest solar power plant has a production capacity of 34 MW. (Motiva & Finnish Energy Authority 2023.) Great strides are being made in the size of power plants, as most of the planned solar power parks are within the 50-100 MW range, but there are also several plants over 500 MW capacity. (Motiva 2023.) It is estimated that by 2030, the number of plants will increase to 120 and the production capacity will reach over 9 500 MW (Wattson 2023).

Solar electricity is produced with panels that are formed from solar cells. The cell is an electronic semiconductor, and solar radiation creates a voltage between its lower and upper surface. (Rauhala et al. 2024.) Solar power plants can be designed to be either off-grid or grid-tied. The produced electricity from off-grid plants is directly stored and it can be used whenever needed. With properly optimised storage systems, power reliability can be maintained even in periods of low production rates. This system is great, especially for locations that are more remote. The grid-tied system is connected to the local utility grid. The electricity can be sold back to the grid if it has been produced excessively and on lower production rate periods the electricity can be withdrawn from the grid. Both systems have their own advantages compared to each other. (PVCase 2023.)

The desired level of voltage can be achieved when required number of cells are connected in series and the solar power area consists of series of connected solar panels. Solar power plant that reaches 10 MW production or more, needs additionally a transformer station, in which the medium voltage is converted to high voltage. This enables connection to the high voltage grid. (Rauhala et al. 2024.)

The key parts of ground mounted solar power plant are the panels, inverters, transformer, electrical grid connection and power station. The panels are installed to racks and are generally surrounded by metal frames that are mounted to ground, either with weights or with poles sunk into the ground. The racks can be fixed or equipped with sun tracking devices. The panels are mounted in rows, and typically the row of solar panel is on a 24–45-degree angle towards south and the panels height varies from 0.5 meters to 5 meters. Solar panels generally reflect less than 5 % from the solar radiation coming to the surface of the panel. The rows are connected to the inverters, in which the direct current (DC) is converted to alternating current (AC). This can be done either centrally or in smaller chains, which are is also known as string inverters. As an advantage of string inverters is that the whole system manages better with degradation of singular panels such as shading or damage, since the effects are limited to that chain only. On centrally connected systems, the degradation of singular panel can weaken the production of the entire system. The electric power produced by the solar power plant can be transformed with the transformer into different voltage levels, higher or lower, depending on the need, before feeding the electricity to the electricity grid. The solar power plant is connected to the electricity grid usually with power station, so that the electricity can be utilised in consumption. The power station handles the conversion, transmission and management of the electricity produced by the solar power plant. The industrial-sized plants generally are connected to the national or regional electricity grid. (Rauhala et al. 2024.) These key parts are presented in the Figure 4.

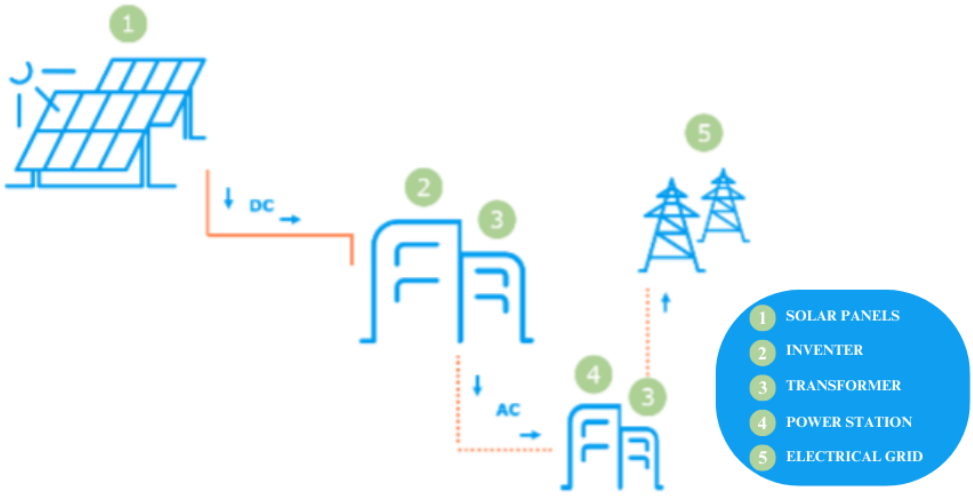

Figure 4. The ground mounted solar power plant principal functions (Adapted from Rauhala et al. 2024).

The technical lifespan of the solar power plant is approximately 30–40 years. The inverters service from 15 to 20 years approximately (Rauhala et al. 2024). For example, in the Huuhansuo-Suurisuo solar plant project, the plant is estimated to endure at least 30 years, and the lease agreements for the area are drawn up for 40 years. The service life of the foundations is planned to be longer than 40 years, and possible future updates are going to be executed on top of these foundations. (Envineering 2023.) In the Figure 5 the key activities of ground-mounted solar power plant through the plant's life cycle phases are presented.

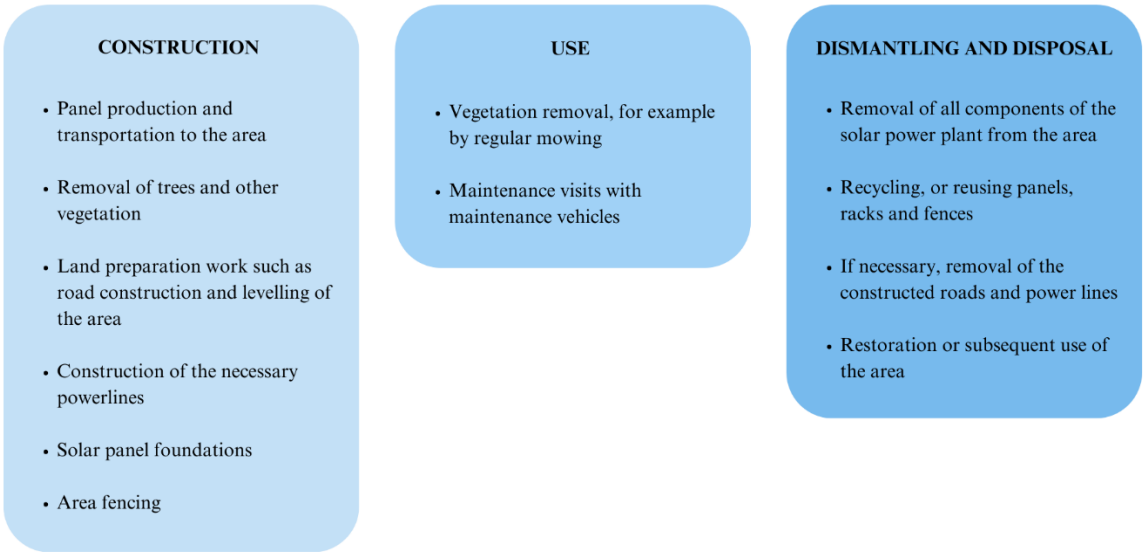

Figure 5. The central functions of ground-mounted solar power plant from cradle-to-grave (Adapted from Rauhala et al. 2024).

From the Figure 5 can be seen that most of the activities required to achieve a functional solar power plant are concentrated in the construction and dismantling phase. The construction phase consists of panels being produced and transported to the area and the preparation of the area for the solar panels and foundations. Additionally, the required electric work and roads need to be constructed. The use phase is mainly maintaining the functionality of the panels and clearing excessive vegetation from the area. After the plant has reached the end of its life, all the components are dismantled and recycled or reused accordingly. Usually, the roads and power lines are left as they are, but, if necessary, those

are removed as well. The area is then restored, and it could be used for a further need. (Rauhala et al. 2024.)

2.1. Planning

When planning and executing the construction of solar power plant, it is required to comply with the official regulations. (Tampereen Tilapalvelut 2023.) The construction of solar energy projects is governed by the Land Use and Construction Act. (Rauhala et al. 2024.) Additionally, in accordance with the Electricity Market Act, it is required that the electricity producer will inform the Finnish Energy Agency of the construction plan and commissioning of the plant, if the plant is over 1 MW (Wattson 2023). The construction practices of a solar plant are decided on a municipality-by-municipality basis and are conducted within the boundaries set by the legislation (Rauhala et al. 2024). It is necessary that the solar power plant carries out the requirements set by municipalities, for example the demands regarding building control, electricity and rescue services. (Tampereen Tilapalvelut 2023.)

Municipalities use steering tools to facilitate land use. For example, master plan, site plan, building order and solution for design requirements, building and operation permits are used as adequate methods to determine further land use. Generally, the area zoning process begins with the initiative of real estate business and stems from a need. (Rauhala et al. 2023.) Additionally, Environmental impact assessment (EIA) is an ancillary process to the zoning, and it is applied whenever the project is considered to have significant impacts on the environment (Finland's environmental administration 2023). It is an administrative procedure done by either Regional State Administrative Agency or the municipal environmental protection authority (Regional State Administrative Agency). With the assessment, it is aimed to reduce or prevent environmental impacts that are caused by the project, and therefore it is done while the project is still in the preparation stage to influence the decision-making process if necessary. (Finland's environmental administration 2023.) EIA process is based on the Act on the Environmental Impact Assessment Procedure (Elinkeino-, liikenne- ja ympäristökeskus 2024). The procedure is not automatically applied to the industrial-scale solar power plant, but a solar power plant can be subjected to an EIA

based on a case-by-case decision, if the environmental impacts are assumed to be significant by their quality and scope. This also considers the combined effects of different projects. (Elinkeino-, liikenne- ja ympäristökeskus 2023.)

The permitting and construction phases of a solar power plant of tens of megawatts can take up to two to three years at the minimum. Whenever the plant size increases to hundreds of megawatts, the permitting naturally takes a much longer period. The fluency of the project phases, such as land acquisition and permitting, as well as the number of personnel used for construction affects substantially the speed of project implementation. (Wattson 2023.)

The planning phase additionally includes plans for the layout of the plant. This includes for example the planning of placements of the panel row arrangements and maintenance roads. (Rauhala et al. 2024.) Typically, a panel system that has a nominal power of 1 peak kilowatt (kW_p) is considered to require approximately 5 m^2 area. The nominal power of a panel is tested in a laboratory in Standard Test Conditions, in which the panel is predisposed to 1000 W/m^2 of solar radiation and the cell temperature is set at 25 °C. A system with 1 kW_p nominal power generally produces 800–1000 kWh in southern Finland and 700–900 kWh in northern Finland annually. The yield of solar system is mainly influenced by the efficiency of the solar panels and the amount of radiation. Also, the temperature of the panels, mounting angle and cleanliness are factors that contribute to the electricity production. Additionally, the yield is affected by the efficiency of other parts of the system, such as the inverter and possible battery, as well as the possible shading that falls on the panels. (Motiva a.) The recommended size of a unified panel field is 20 m by 20 m, and a 1.6 m wide maintenance road is required to be constructed between the panel fields (Tampereen Tilapalvelut 2023). The spacing between the panel rows is needed to avoid excessive shadow. The gap between the rows also influences how many panels can be placed in the area. The spacing depends on the size and the angle of the panels as well as the angle of the sun. (GSE Integration.) The spacing is visualised in the Figure 6. By leaving just enough room between the panel rows enables the land area to be utilised as efficiently as possible (GSE Integration).

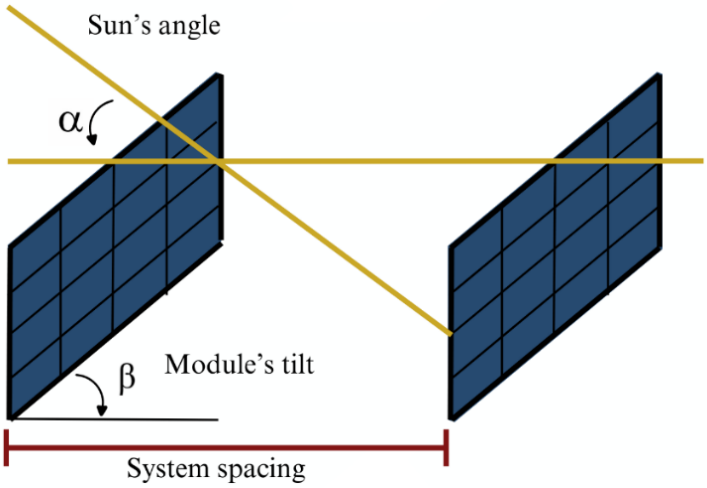

Figure 6. Spacing of solar panel rows (Adapted from GSE Integration).

Based on the GSE Integration, the spacing can be determined by the following equation:

$$D = L * (\sin(\beta) * \tan(90 - \alpha) + cos(\beta))$$

where D is spacing [mm], L is length of the long side of the associated module [mm], α is the angle of solar radiation [°] and β is the tilt angle of the modules [°].

2.2. Construction

The most used options of solar energy systems used in both small and large power plants are photovoltaic (PV) and concentrated solar power (CSP), and these both can be utilised commercially (Moukhtar et al. 2021). The operating principle of PV systems are that the cell component is made from a light absorbing material and when exposed to sunlight, enough energy is generated to release electrons in the cell structure. A built-in-potential barrier can produce a voltage from the released electrons, which is then used when current is directed through the circuit. (Parida et al. 2011.) Photovoltaics are panels that can be either mounted on the ground on top of foundations or on a roof, and the most used technology is

currently wafer based crystalline silicon (c-Si) which dominates the market with 95.4 % (Carrara et al. 2020). CSP systems, on the other hand, capture large amounts of solar energy with either lenses or mirrors and focus the energy down to a receiver. (Breyer 2023.) This energy heats a high temperature fluid in the receiver. The heat is also known as thermal energy, which can be generated into electricity with a turbine or a power engine. (U.S. Department of Energy a.) This thesis focuses merely on the PV systems since the they produce solar electricity directly, unlike CSP.

Generally, the construction of solar power plants is focused on central areas. More remote areas, for example areas that were previously used in peat production and are now freed, fields and forests, are not that commonly utilised due to the impacts on the environment. The construction of solar plants is begun by laying foundations. Generally, the panels are mounted on metal racks and the frame is measured to endure the loads from wind and snow. The panels are installed on the ground on top of the pillars, poles and stands. The racks are typically installed on the ground either with screw or hammer poles depending on the soil characteristics of the area. The most commonly used option is hammer poles, made out of steel due to cost effectiveness. The disadvantage of hammer poles is that they don’t penetrate any obstacles on the ground. They can still be installed by drilling holes in the ground and the hole is then filled with concrete and the pole. The screw poles are used in cases where the ground has a lot of impediments. Due to the spiral shape, they can be left closer to the surface of the ground. Before installing the screw poles, a hole needs to be drilled. When utilising cement weights, the racks are attached to heavy concrete slabs, which are left on top of the ground. The cement weights are used for example in cases where it is not possible or viable to drill poles into the soil. Sometimes, a ground mounted solar panel row can be installed into the existing or shaped slope. (Rauhala et al. 2024.) The different foundation options are presented in the Figure 7.

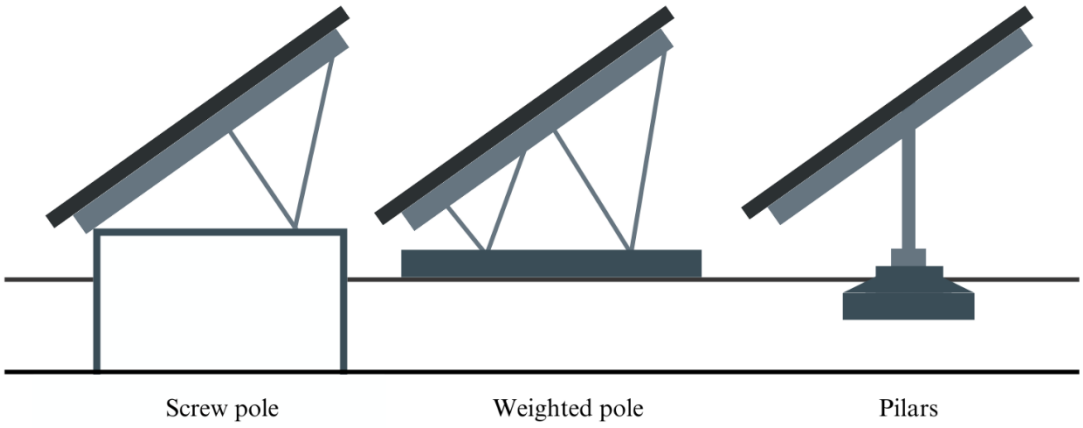

Figure 7. Different solutions for the solar panels' foundations (Rauhala et al. 2024).

The construction of a solar power plant doesn't fundamentally require land mass exchange aside from the road construction. However, there could be a need for some levelling work. Additionally, in the construction phase it is important to consider what kind of undergrowth is desired for the area. The area of solar panels needs to include maintenance roads, which are used during the construction period and for maintenance during use. The maintenance roads need to be designed in a way that also heavy vehicles can move around the field of panels. (Rauhala et al. 2024.)

The maintenance roads are built on top of the subsoil. A filter cloth is placed in between preventing the subsoil and built layers from mixing. At the same time, the filter cloth limits the rise of water from the subsoil. The layers of the road are formed by a dividing layer, a load-bearing layer and two separate wear layers. The dividing layer increases the bearing capacity of the structure and limits the rise of water from the subsoil. The purpose of the load-bearing layer is to increase the capacity to withstand load effects. The lower wear layer helps to keep the structures dry and the uppermost layer, which is usually asphalt or crushed stone, forms an even layer for traffic. (Väylävirasto 2020.) The area of solar panels can be fenced and pathways for animals can be left between the fences (Rauhala et al. 2024).

2.3. Use

Solar electricity systems do not require much maintenance. Annual maintenance activities include only the maintenance of transformers and if the system includes a battery, it is worth to inspect visually on an annual basis. Additionally, all electrical parts that are exposed to the weather conditions, such as wires and connectors, should be visually inspected annually. If there are any noticeable defects, wears, changes in shape or colour, or anything abnormal, electrical contractor should be approached. Whenever it is necessary, the panels should be cleaned, the excessive vegetation from the area should be removed and the snow accumulated on the panels should be removed. These maintenance efforts are done to allow the panels to function optimally. Since the lifecycle of a solar power plant is much longer than for example the parts used, the inverters and batteries need to be change at least once during the plant's lifecycle. (Rauhala et al. 2024; Motiva b.)

Solar power plants are still inspected a lot on foot, where faults are searched for with a hand-held thermal camera. Yet, the utilisation of new technologies in the maintenance of solar power plants has increased its popularity nowadays. For example, drones can be used to capture any failures within the plant and the inspection image data can be saved for further use. The panel failure observations can also be comprehensively compared with each other when all description data is visible at once. In addition, the quality of defects can be classified from the footage, and the most critical items can be detected. (Evision.) Also, different kinds of measurements can be done by a smart system that utilises the inverters operating system. The current optimisers connected to the panels collect the necessary data on the operation of the system and the condition of the individual solar panels. Typically, the failure of a solar power plant occurs in one component. The smart system ensures that the failure of one solar panel does not affect other panels. The smart system is also able to indicate which component has failed, so it is easy for maintenance to make an exact or even predictive replacement. This accurate data reduces maintenance time and costs. One of the worst failures of a solar power plant is arcing. It can be caused, for example, by a damaged cable or a weakened connector. At worst, the arc can set the surrounding materials on fire. The smart system detects the arcs and lowers the voltage so that the arcing stops. In traditional system, the arc is only extinguished when the panels are covered. (Solnet 2020.) The competitiveness of

newer technologies compared to on foot inspections are due to the speed and safety of the process (Evision). Additionally, the cost and the time required to spend for a maintenance is decreased (Solnet 2020).

2.4. End of life

The materials used in the PV systems can vary depending on the technology used. The general materials in the PV systems are concrete, steel, plastic, glass, aluminium and copper. (Carrara et al. 2020.) The general material intensities are listed in the Table 1 below.

Table 1. Solar panel material intensities (Carrara et al. 2020.)

Intensities	**Amount [t/MW]**
Concrete	60.7
Steel	67.9
Plastic	8.6
Glass	46.4
Aluminium	7.5
Copper	4.6

Concrete is used in the system support structures as well as steel. Plastic is commonly used for protecting the panels from environmental effects. Glass on the other hand can be found in substrates and module encapsulations. The module frames, racks and supports are made from aluminium. Copper is used for the wiring, cabling and earthing. Also, copper can be found in inverters, transformers and PV cell ribbons. Other materials that can be found in the PV systems include silicon, silver, germanium, cadmium, tellurium, indium, gallium and selenium. These latter materials are technology dependent. (Carrara et al. 2020.)

The methods and work steps used to dismantle the solar power plant are the same as in the construction phase. (Rauhala et al. 2024). The end of life of PV system follows the general approaches used in waste management, in which the materials are tried to reuse, recycle or recover as thoroughly as possible. If the panel can’t be reused as it is, the aluminium frame

is removed either for reuse or material recovery. (IRENA 2016.) The module is shredded, and the different materials are separated (Fthenakis 2000). Most material fractions can be recovered and recycled for further processing (IRENA 2016). For example, almost all glass and external metal parts of a solar PV system can be recycled or reused as is. Also, the silicon used in the panels can be further processed and used in the production of new panels. (Rauhala et al. 2024.) Silver and smaller portions of tin and lead can present some recycling difficulties. The potential environmentally hazardous materials are copper and zinc and semiconductor or hazardous materials such as indium, gallium, selenium, cadmium tellurium and lead require specific waste treatment that is in accordance with the native legislation. Additionally, the non-recoverable, non-recyclable material fractions are required to be disposed of accordingly. (IRENA 2016.) The potential opportunities of reduction, reuse or recycling of a PV system is presented in the Figure 8.

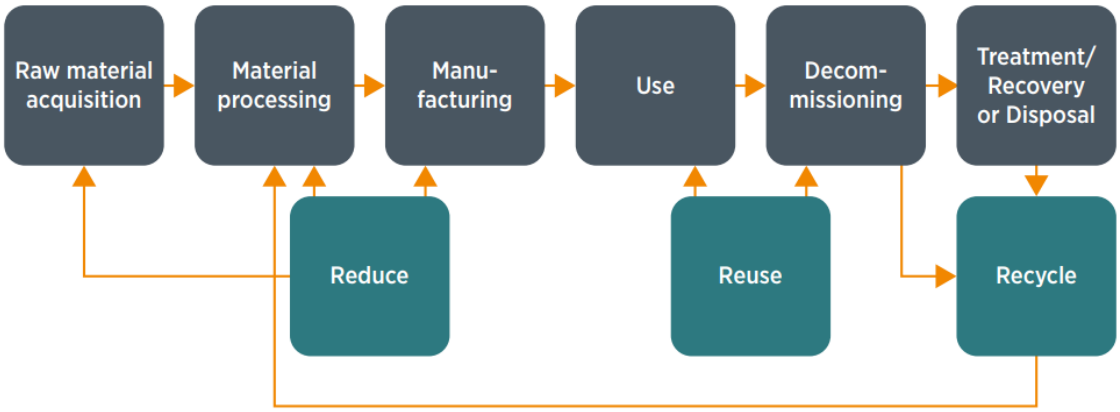

Figure 8. Potential opportunities for reduction, reuse, or recycling during the life cycle of a PV panel (from IRENA 2016).

2.5. Impacts on the climate and environment

With solar electricity implementations reduction of GHG emissions can be achieved. Also, with solar electricity, the potential to mitigate climate change effects occurs. For example, solar electricity has positive impacts on quality of air and water use reduction in energy production. Also, solar systems can provide ecosystem services via carbon sequestration, pollination, and ground and stormwater management to local species. Since the interest in

solar projects has increased, the understanding of how the projects impact the ecosystems and climate should be widened in order to limit these impacts and increase the received benefits. (U.S. Department of Energy b.) Hence the challenges related to the climate and environment occurring due to solar systems and solar electricity are further discussed in this chapter.

2.5.1. Climate impacts

The direct climate impacts of solar power plants can be divided into three categories:

- the carbon footprint of the project
- changes due to land use
- renewable and emission-free electricity produced by the production area

In addition to direct climate impacts, the indirect impacts include impact on community structure, traffic impacts, competing land use options and their effects on the climate (Rauhala et al. 2024.)

The carbon footprint considers all the emissions regarding the material acquisition, construction work and demolition. (Rauhala et al. 2024.) The cells of solar panels to this day use rare materials, which will be scarce in future if alternative materials are not discovered. Also, the manufacturing of panels causes emissions. (Wattson 2023.) These impacts are quite short term if compared to the life cycle of the plant. The climate effects of solar electricity originate mainly from the construction and commissioning phase, and the emissions are typically from the modifications required to produce solar electricity in the facility area and vegetation removal. During normal operation, there aren’t emissions occurring to the air, water or soil. (Rauhala et al. 2024.) Emissions during construction don’t have significant effects on the air quality of nearby areas. During operation, solar power plant doesn’t cause emissions that impairs the quality of air. (Rauhala et al. 2024.)

However, the most significant emission source is from land use. Industrial scale solar power plants require a lot of land area, even if the area would be as optimised as possible. In addition, the actual panel field, at least road and electricity infrastructures, transformer stations and a possible underground cable network are required to be constructed in order to establish a well-functioning plant. (Wattson 2023) The changes regarding land use consist of effects on carbon sinks and storages. Depending on the soil type, the impacts could differ. Also, the impacts differ whether only soil emissions are spectated compared to the land use. For example, if the area has trees that need to be removed, the emissions from vegetation removal should be added to the soil emissions. (Rauhala et al. 2024.) In terms of soil emissions, the worst option to locate solar power plants would be an area that was at some point utilised in peat production. Thus, the area in former peat production has the highest emission potential. (Puhalainen, e-mail 20 June 2024). However, if the peatland's water level is risen, the area functions merely as a methane emission source and provides a carbon sink. (Luke 2024.) Also, the peatlands could offer a basis for solar power plants, since those already have existing roads. Additionally, if vegetation would grow on top of the peat surface, the greenhouse gas emissions from decomposition of peat residues and erosion would be reduced. (Rauhala et al. 2024.) Mineral soil on the other hand has the lowest soil emission factor. Land use change caused by solar power plant construction will increase soil GHG emissions unless the peat production area is wetted. The most significant emissions occur when solar power plants are constructed on a forest soil. (Luke 2024.) The development of solar panel and cell technologies can improve the reduction of emissions in the future, as production efficiency increases, and less land area is required to produce the same amount of electricity. Also, various properties such as double-sided panels and racks that turn in accordance with the sun's movements, could improve the land area requirements. (Wattson 2023.)

2.5.2. Environmental impacts

Although, the solar energy projects are aimed to achieve emission-free domestic energy production, environmental impacts occur during the projects. The potential of solar energy is great, but there is very little experience of its wider implementation, and unity in guidance and procedure is still deficient in Finland. Since the construction of large solar power plants is growing strongly, the environmental impacts must be acknowledged especially in the planning phase of the project, before any actual measures have been taken. The impacts and their significance are highly dependent on the characteristics and the environment of the location. Furthermore, the occurred impacts could be scattered in the surrounding environment and ecosystems, rather than happen necessarily in the source. Despite the size of the project would change, the type of project impacts would stay similar yet the weighting of the significance of the effects may change (Rauhala et al. 2024).

In the EIA process mentioned in the 2.1 chapter, the environmental impacts considering solar power plants that could affect the environment are for example the effects on the

- natural environment of construction sites
- birds that are breeding or migrating
- local animals such as species of game, squirrels, bats and frogs
- nearby Natura areas and other nature conservation areas
- landscape and significant landscape areas
- land use
- surface and groundwater

All environmental impacts noted in the EIA, are not necessarily significant in each existing and upcoming solar power plant project, and it is noted that the impacts could occur as positive rather than negative. In each EIA cases each plant is evaluated individually and only the relevant impacts are considered further. (Rauhala et al. 2024.)

Restrictions regarding the placement of the solar power plant are related to avoiding areas that are in their natural state and are valuable by their natural values. Also, areas that are inhabited by protected species or are included in the distribution areas of those species should be avoided. Exceptions related to Finnish legislation, such as exceptions related to Nature Conservation Act and Water Act, might in some cases be relevant to take into consideration. (Elinkeino-, liikenne- ja ympäristökeskus 2023.) Natura 2000 is a project that is implemented throughout Europe, across all EU member states and by which it is aimed to protect the most valuable and threatened species and habitats (European Environment Agency 2023). When operating near area that is included in the Natura 2000 network, it may be necessary to notify about the measures that might influence on the Natura area. Furthermore, a Natura assessment could be executed. (Elinkeino-, liikenne- ja ympäristökeskus 2023.) Within South Karelia, there are 53 Natura 2000 locations (Finland's environmental administration).

2.6. Advantages and disadvantages of solar energy

The sun naturally produces energy. In 14.5 seconds, as much energy as humanity uses in a day reaches the earth from the sun. (LUT University 2019.) The most acknowledged advantage of solar power is the sufficiency, since it will be available for next 6.5 billion years (Vattenfall). As an energy source, solar power is sustainable, clean, cost-free and abundant, and is described as one of the promising energy sources there is (Moukhtar et al. 2021). It can be used without the energy source shrinking, and by using it is possible to transition from fossil fuels and energy sources. Additionally, the availability of solar power is nothing like other energy sources. The resources can be accessed worldwide, albeit some countries have access to more radiation annually than others. (Vattenfall.) Even though the radiation is not equal across the globe, the panels used to collect the power from the sun can be used modularly. With correct installation angles, the production is more efficient. Despite the radiation being higher in hotter climates, the process can be done more efficiently in colder climates, as voltage output reduction could be caused by extreme heat. (Ahmed et al. 2023.) Compairing solar panels to wind turbines, the production of solar energy doesn't require any moving parts that are causing noise, and the solar panels do not require active maintenance. Furthermore, the solar energy sector constantly develops the used

technologies, for example it has been discovered by nanotechnology and quantum physics studies that the electricity production of solar panels could be tripled. (Vattenfall.)

Even though solar power doesn't generate emissions as such, in directs and environmental impacts occur. These are originated from the panel production such as the materials and energy needed, transportation, and installation. Solar cell production phase requires materials, for example some minerals that are expensive and rare, and therefore the production means consumption of limited resources. One of the most limiting factors with solar power is that it can only be produced during the daylight hours. (Vattenfall.) Although the production time is limited, the timeline of the peaks goes relatively hand-in-hand with the demand hours of several power systems (Moukhtar et al. 2021). The solar power plant requires a relatively large land area, which is away from other purposes. Roughly, 1 MW_p plant needs a land area of one hectare. (Solarigo Systems 2020.) There are cases of agrivoltaics globally, which are a combination of solar energy production and agriculture, but its applicability to Finnish conditions is still under research (Trommsdorff 2020; Energiequelle 2024). Most of Finland's land area is forest and they act as a carbon sink. From environmental aspect it is not rational to cut down the whole forest in order to construct a solar power plant. The electricity from the solar power plant should also be able to be fed to the consumption site, and less often there is wasteland in the immediate vicinity of large consumption sites for which no other use can be found. When constructing the plant further from the consumption site, electricity grid is needed. Currently the total price of solar electricity can't compete that well with other electricity prices from renewable energy sources. (Solarigo Systems 2020.)

3. P2X process and phases

In accordance with Climate Change Conference held by United Nations in Paris in 2015, the whole energy sector should reach nearly to zero regarding the net emissions. This is aimed to prevent the global temperature to rise more than 1.5 ◦C above the preindustrial level and to slow the climate change and its effects on the globe. This change would need a great amount of power generation that doesn't emit CO_2 into the atmosphere and energy sector primary based on renewable energy sources, such as wind and solar. As a solution for energy storages and carbon-neutral fuels, Power-to-X has gained more interest especially in recent years due to the climate goals that need to be met. (Vázquez et al. 2018.)

Power-to-X is a concept that contains producing consumables by utilising renewable energy, and it facilitates the energy system revolution that is required to achieve more sustainable future (European Energy; LUT University 2018). The end-products from P2X chains can be for instance in transportation, agriculture or chemical sector. Additionally, P2X can be applied into heating and cooling, or industries such as steel, cement or food. (Siemens Energy.) It can be applied into synthetic fuel production by capturing carbon dioxide or nitrogen from air, hydrogen from water. The synthetic fuels, methane, methanol, dimethyl ether and ammonia can then be used in motors of various transportation vehicles. (LUT University 2018.)

The four main phases of producing synthetic fuels are energy collection, H_2O and CO_2 collection, oxide dissociation and fuel synthesis. The general objectives of the whole process are to capture carbon dioxide and collect water, which are dissolved into hydrogen and/or carbon monoxide in energy conversion process that is powered by selected energy source. The dissolved hydrogen and carbon monoxide can be then further processed into alcohols and hydrocarbons, which in this case refers to a range of carbonaceous fuels such as gasoline, diesel and dimethyl ether. In the Figure 9 different pathways to create synthetic fuels are presented. (Graves et al. 2011.)

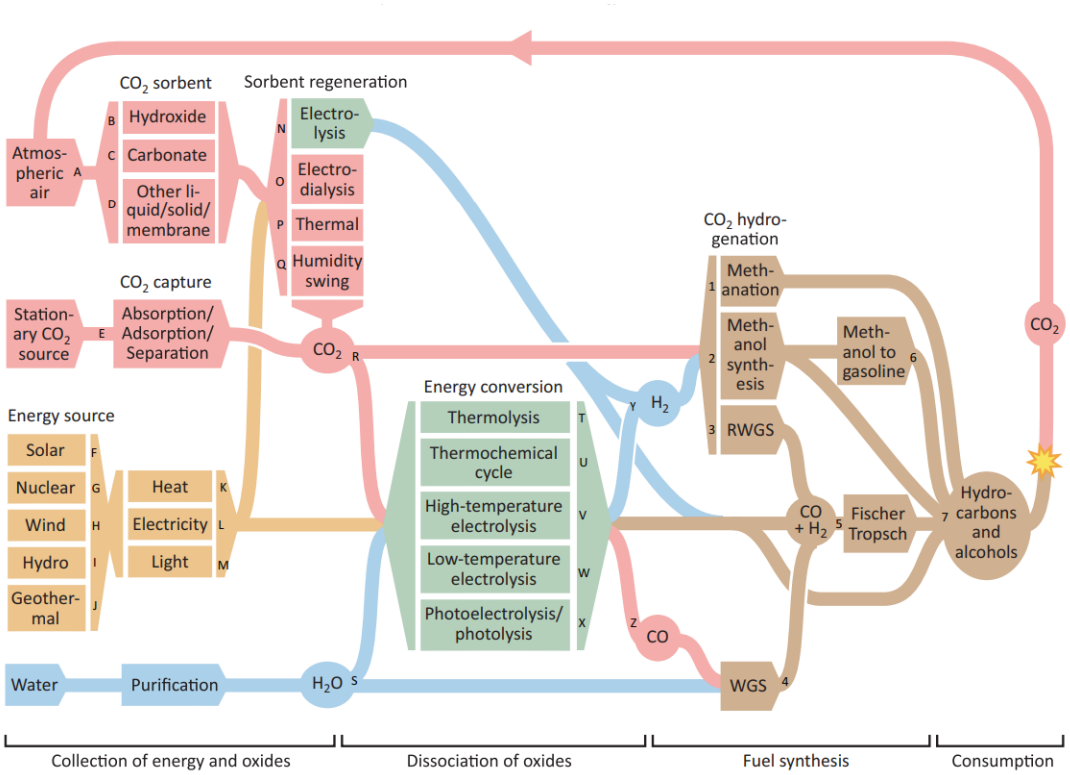

Figure 9. Different pathways of creating hydrocarbon fuels from H_2O and CO_2 (Graves et al. 2011).

Each of these phases presented in the Figure 9 can be conducted with several different technologies. For example, CO_2 can be captured directly from the air or from a stationary source. However, the most common way is to capture CO_2 from large-scale industrial plants. Alternative non-atmospheric source of carbon are geothermal power plants. Options for CO_2 capture technologies are further discussed in this chapter. As an energy source for hydrocarbon production, either solar, nuclear, wind, hydro or geothermal power can be utilised. Therefore, the production chain is not bound to individual energy resources. Both captured CO_2 and H_2O can be dissociated via energy conversion processes, which are thermolysis, thermochemical cycle, high-temperature electrolysis (HTE), low-temperature electrolysis (LTE) and photolysis, which produce H_2 and CO. These can be further processed individually or simultaneously to obtain the end-product of synthetic fuels, which then are consumed in transportation sector. Overall, if this synthetic fuel production is wanted to achieve on a larger scale, it would consume a great amount of water. The only way to achieve more sustainable solution would require utilisation of sea water or some other type of non-potable water (Graves et al. 2011). Since the thesis is limited to study only synthetic fuels

produced from solar electricity and CO_2 from a bio-based source with electrolysis process, the Figure 10 presents the pathways of the studied process based on the Figure 9. According to the scope of this study, the rest of this chapter considers the P2X process in accordance with the Figure 10.

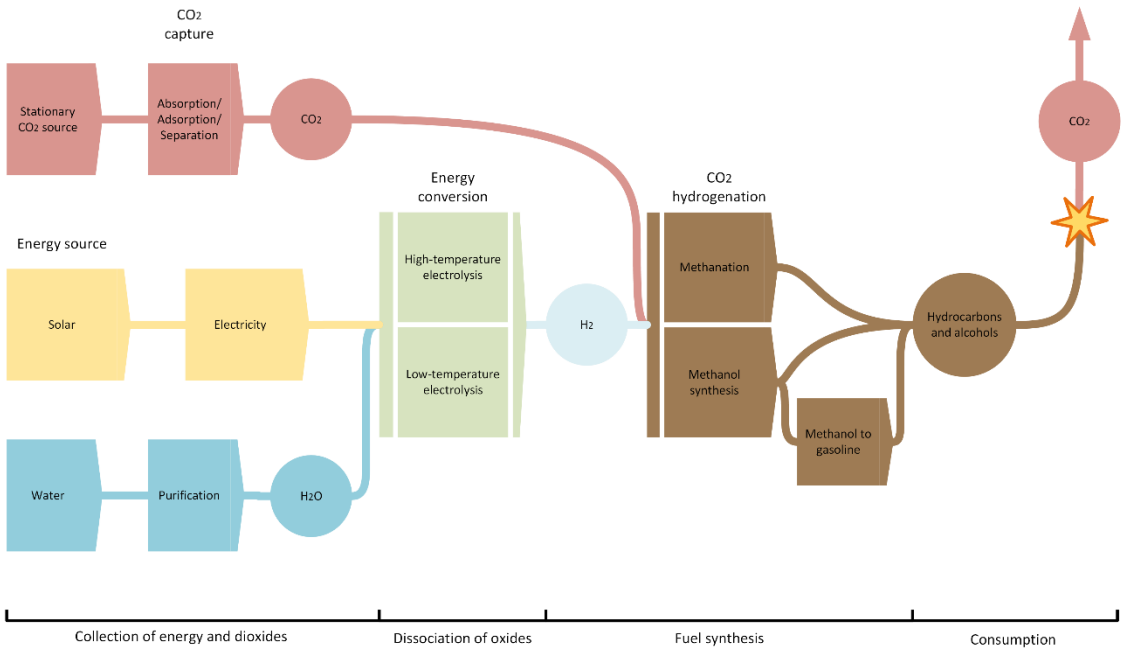

Figure 10. The review model of this thesis for produce hydrocarbon fuels from H_2O and CO_2 (Adapted from Graves et al. 2011).

3.1. CO_2 Capture

Transitioning towards more sustainable energy systems necessitates technologies, which enable lower GHG emissions and carbon capture (CC) provides feasible solution to decrease the emission by capturing CO_2 from the source of emission, or directly from the air. The captured CO_2 can further be stored or employed into other uses. The latter is also known as carbon capture and utilization (CCU). With CCU the conventional product chains such as fuel production can be substituted with more sustainable option. (Maksimov 2022.)

The carbon capture technologies are categorised to post-combustion, pre-combustion and air separation followed by oxyfuel combustion technologies (Rackley 2017). CO_2 stream can be separated from the exhaust flue gas stream or natural gas stream in various ways (Khalid 2022). In post-combustion systems liquid solvents are used in capturing CO_2 from flue gas stream. The flue gas is primarily composed of nitrogen from the air. (IPCC 2005.) In pre-combustion technology, the CO_2 is removed with syngas mixture and the syngas is either received from the flow before combustion by gasification or steam reforming. The gasification is concluded to a carbonaceous fuel for example coal, waste or biomass. In the steam reforming process methane is further processed into syngas or natural gas that is partial oxidised. (Cousins et al. 2019.) In oxyfuel combustion on the other hand, oxygen is used instead of air in the production of flue gas from combustion of primary fuel. Due to this, high CO_2 concentration flue gas can be attained. (IPCC 2005.) The CO_2 capture technologies and technologies' systems are presented in the Figure 11.

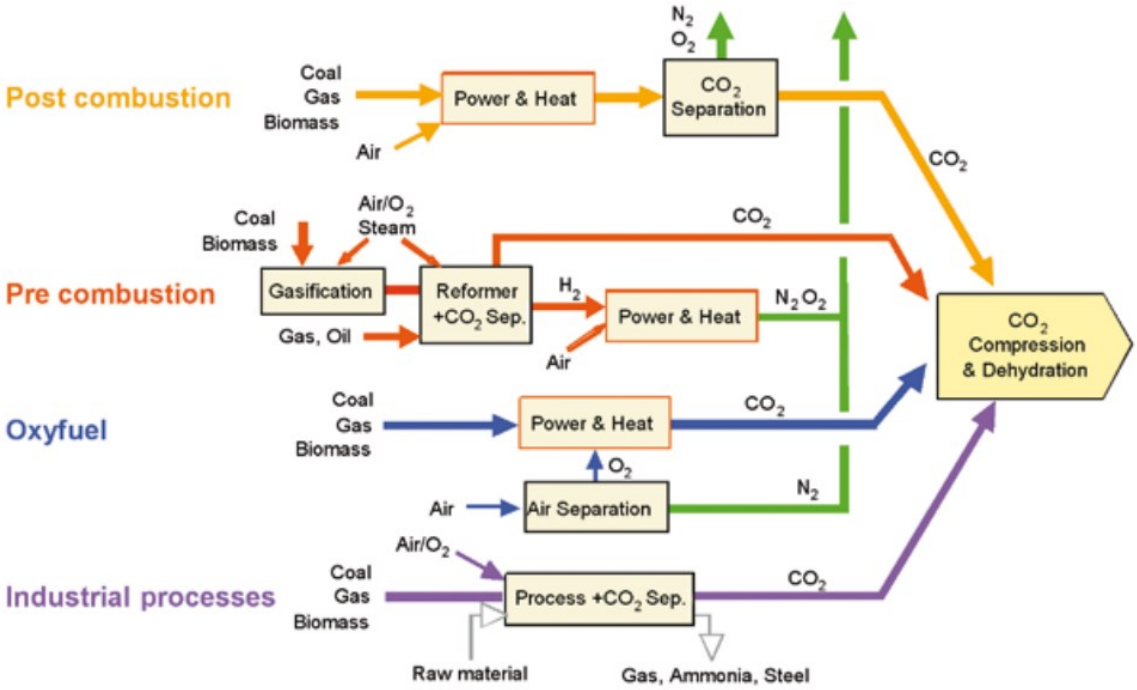

Figure 11. CO_2 capture technologies. (From IPCC 2005).

The selection of the capture method is highly depending on the industry and the industrial process it is applied to (Maksimov 2022). The methods that could be used for capturing CO_2

are absorption, adsorption, cryogenic distillation, membranes, gas hydrates and chemical looping (Khalid 2022). These CC technologies and methods are presented in the Figure 12.

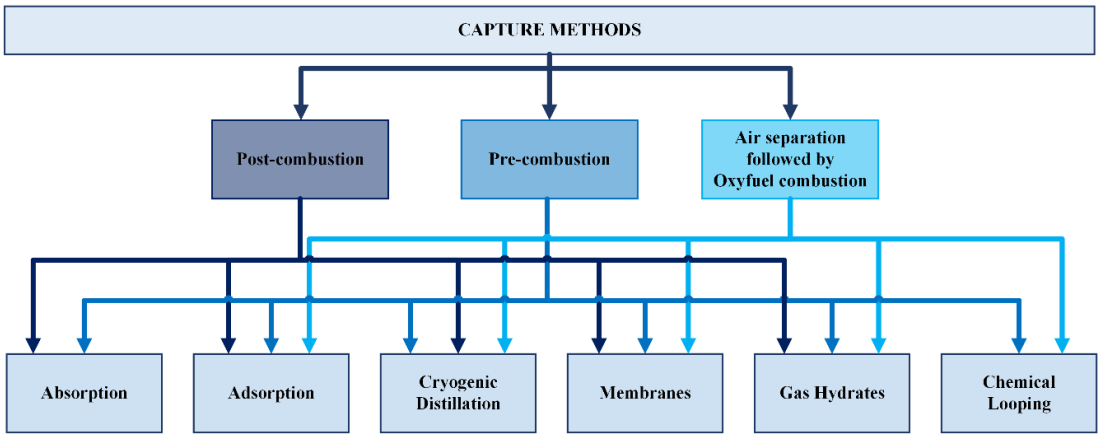

Figure 12. CO_2 capture methods (Adapted from Aker Carbon Capture 2022).

This thesis focuses only on the post-combustion carbon capture technology and the absorption method is further studied. Absorption is the most used gas separation method, and it can occur both physically and chemically. In physical absorption a substance also known as absorbate is attached to another substance known as absorbent. However, in chemical absorption either a molecule, an atom or an ion enters the interior of an absorbent. The absorbents are most commonly solvents in a CO_2 capture process. (Khalid 2022.)

Specifically, the focus in this thesis is in the monoethanolamine (MEA) separation hence it is the most prominently available and commonly utilised method in the market. It has been regarded as one of the most sensible post-combustion technologies, because even with low CO_2 concentrated flue gas high reactivity can be reached. (Jung et al. 2013.) In MEA separation, CO_2 is separated from gas flow with chemical reaction by utilizing an organic solvent (Reiter & Lindorfer 2015). The process flow of is presented in the Figure 13.

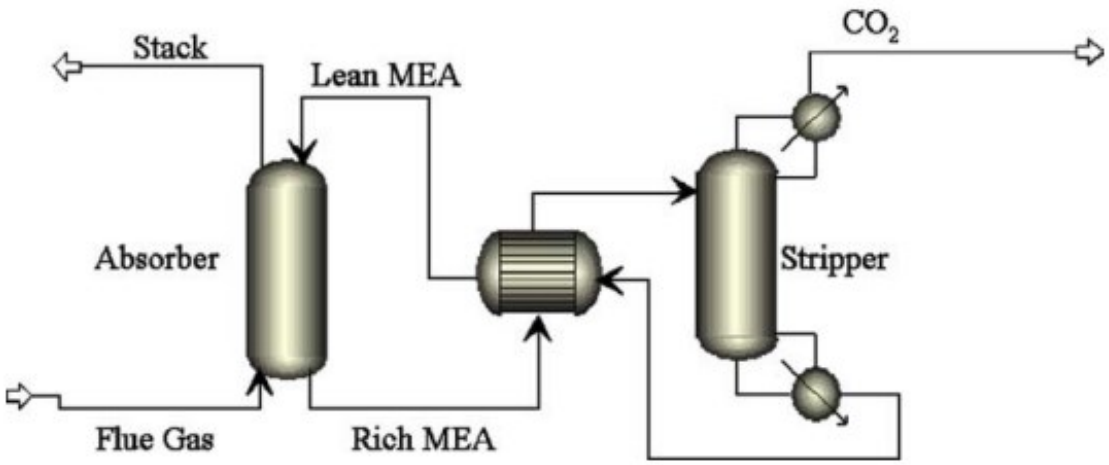

Figure 13. MEA absorption process flow (From Alie et al. 2005).

MEA process chain forms out of an absorber, heat exchanger and stripper (Jung et al. 2013). In the process, 30 weight-% MEA solution is utilised in CO_2 absorption generally at 1 bar and 25–50 °C (Christensen & Bisinilla 2021). The capture rate of CO_2 is generally assumed to be 90 % in the literature (Volkart et al. 2013). The flue gas that has the CO_2 is fed through the bottom of the absorber and the MEA solvent is fed through the top of the absorber. The CO_2 is selectively absorbed by the solvent and the CO_2 infused solvent is drained through the bottom of the absorber to the heat exchanger. In the heat exchanger, the CO_2 infused solvent is preheated. After preheating, the solvent is fed to the stripper in which the CO_2 is desorbed with high temperature. (Jung et al. 2013.) The temperature can vary from 100–140 °C. CO_2 is collected at the top of the stripper and compressed for transportation and storing purposes. (Christensen & Bisinilla 2021.) CO_2 is generally transported via pipelines and ships and before hydrocarbon production, CO_2 must be compressed for storage (Bui et al. 2018; Uusitalo et al. 2017). The excessive MEA is recovered and used again in the absorption. (Christensen & Bisinilla 2021.) A small fraction of MEA exits the process due to the MEA degradation and must be replaced (Uusitalo et al. 2017). The MEA degradation is mainly due to oxygen and impurities in the flue gas (Korneef et al. 2008).

3.2. Electrolysis

Electrolysis is one of major water-splitting methods to create hydrogen. There are three main technologies available, Alkaline (AEC), Polymer Electrolyte Membrane (PEM) and Solid Oxide Electrolyser Cell (SOEC), and only Alkaline and PEM are in commercial use. (Cavaliere 2023.) Therefore, SOEC is not further studied in this thesis. Electrolysis requires both water and electricity. To produce 1 kilogram of hydrogen, approximately 9 litres of water is needed. Electrolysis also generates heat and 8 kilograms of oxygen as a by-product. (IEA 2019.) Electrolysis can be done either as a high-temperature electrolysis or low-temperature electrolysis (Graves et al. 2011). In the HTE the water is turned into steam by using thermal energy and then the steam is dissociated into H_2 and O_2 at temperatures ranging from 600 °C and 1200 °C. This process consumes less electricity than LTE which occur temperatures between 20 °C and 120 °C. (Badrul et al. 2022; Chandrasekar et al. 2021.) Other water-splitting methods are thermochemical cycles and thermolysis, yet these are not discussed further in this thesis. (Graves et al. 2011). The operational temperatures are presented in the Figure 14.

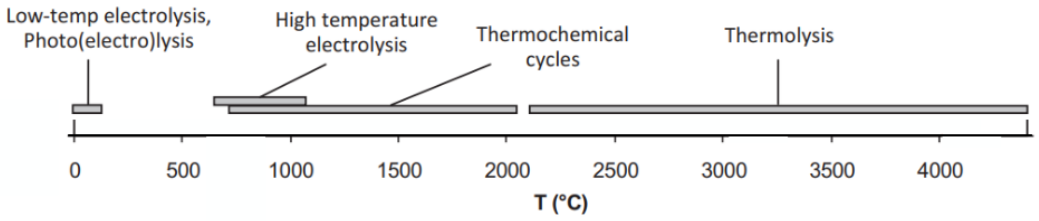

Figure 14. Operational temperatures of water-splitting methods to produce hydrogen. (Adapted from Graves et al. 2011)

The main purpose of electrolysis is to split the water molecules into oxygen and hydrogen while applying enough electric current through the system. The electrolytic cell, in which the process happens, consists of an external power supply, the anode, the cathode and an electrolyte which separates anode and cathode while conducting ions. (Cavaliere 2023; Jonsson & Miljanovic 2022.) Anode has an anodic catalytic layer to oxidise the water and similarly, cathode has a cathodic catalytic layer for the water reduction. When a voltage is

applied, a direct current passes the electrodes, and the water molecules are divided into hydrogen and oxygen. (Cavaliere 2023.)

In situations where solar power is utilised in production of hydrogen via electrolysis process, the PV cell could be attached to an electrolysis cell, which enables the system to function without the need of any moving parts. Thus, PV cells are an optimised solution if considering large-scale production and automated maintenance. Additionally, electrolysis cells, such as photovoltaic cells, possess a property that it is possible to define the operational efficiency of the electrolysis. (Graves et al. 2011).

3.2.1. PEM electrolyser

The PEM electrolyser consists of an anode and a cathode surrounding a membrane. Anode is in the inlet side of the cell and functions as decomposition place for water molecules. The water molecules divide into ions and oxygen. The oxygen and some of the inlet water exit the cell through the membrane and travel to the cathode side of the cell in which hydrogen is generated through ions being reduced. The transition from anode to cathode side occurs due to an active electric field. The half reactions of the PEM electrolyser go in accordance with Jonsson & Miljanovic as follows:

$$anode: H_2O \rightarrow \frac{1}{2}O_2 + 2H^+ + 2e^-$$

$$cathode: 2H^+ + 2e^- \rightarrow H_2$$

$$Overall: H_2O \rightarrow H_2 + \frac{1}{2}O_2$$

The chemical reaction happens in the membrane and there is a layer of porous catalyst layer placed in each side of it. Together, the membrane and the catalyst layer from Membrane

Electrode Assembly which is connected to a current collector to a distribution plates. The distribution plates, also known as bipolar plates, provide an ability to stack cells and give structural coherence to the cell and channels for the products and reactants. (Jonsson & Miljanovic 2022.) The Figure 15 presents the cell structure of PEM electrolyser.

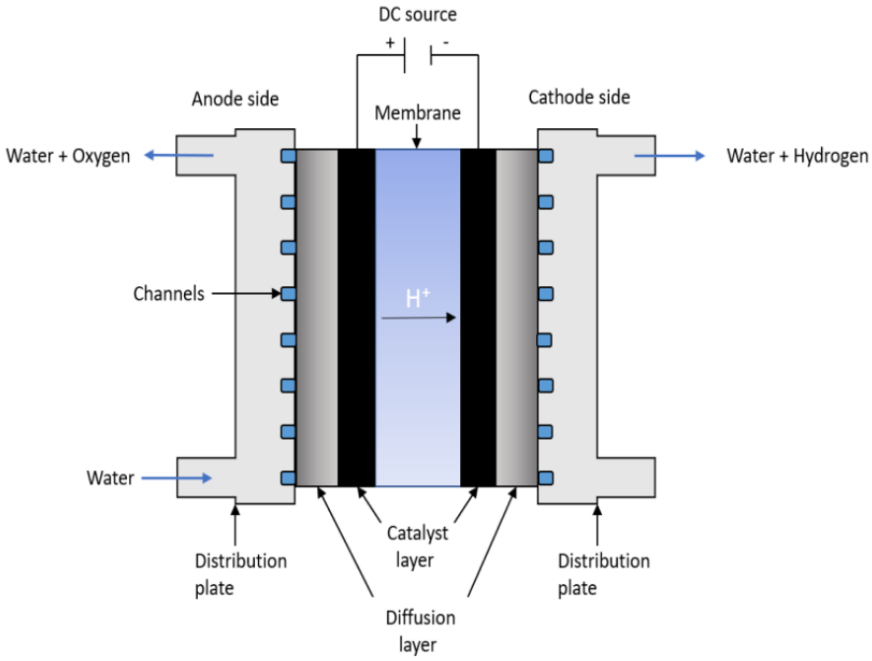

Figure 15. PEM electrolyser schematic (Jonsson & Miljanovic 2022).

The PEM electrolyser is a compact unit with fast response time and high current density (> 2 A cm^2). It has the ability to produce very pure hydrogen (99.9 %) while having high energy efficiency of 70–80 %. Generally, the voltage used in a PEM electrolyser is between 1.6 V to 2.0 V. A downside of PEM is that in the modern electrolysers, the anode and the cathode are manufactured from rare noble metals, which increases the price of PEM and affects the production cost. The operational lifetime of PEM is between 30 000 and 90 000 hours. (Jonsson & Miljanovic 2022; Palys & Daoutidis 2022; IEA 2019.)

3.2.2. Alkaline water electrolysis

In alkaline electrolysis a liquid solution is used as the electrolyte solution (Ajeeb et al. 2024). This liquid is surrounded by an anode and a cathode. Anode and cathode are separated by a membrane layer, which prevents product gas fluctuation at one electrode. When an electric current is applied, reactions take place. (Jonsson & Miljanovic 2022.) Based on Jonsson & Miljanovic, the half reactions go followingly:

$$anode\colon\ 2OH^- \rightarrow \frac{1}{2}O_2 + H_2O + 2e^-$$

$$cathode\colon\ 2H_2O + 2e^- \rightarrow H_2 + 2OH^-$$

$$Overall\colon H_2O \rightarrow H_2 + \frac{1}{2}O_2$$

The negative terminal from the DC is connected to the cathode, and the hydrogen ions consume the electrons to produce hydrogen. The cell voltage used is generally a bit higher than in PEM, between 1.8–2.4 V. Hydroxide ions are released due to this, and without them migrating to the anode side through the separator, an electrical imbalance would occur. In the anode side oxygen is released and the produced hydrogen is collected at the cathode. (Jonsson & Miljanovic 2022.) The cell structure of AEC is presented in the Figure 16. The most common electrolyte solution consists of potassium hydroxide and sodium hydroxide (Chatenet et al. 2022). This solution is used to prevent any occurring corrosion. Nickel is used as an electrode material due to its low cost. The efficiency of alkaline water electrolysis is between 60 % to 80 % and the operational temperature is approximately 30–80 ◦C. (Jonsson & Miljanovic 2022.) The operational lifetime of AEC can reach up to 90 000 hours (Palys & Daoutidis 2022).

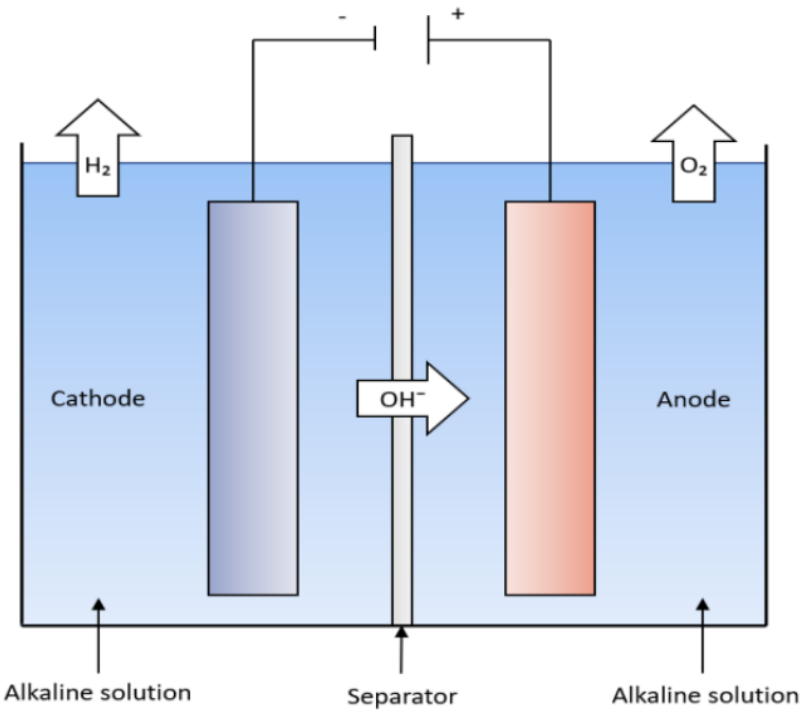

Figure 16. Alkaline electrolyser schematic (Jonsson & Miljanovic 2022).

The electrolysis with the alkaline technology is considered a well-established method and it can be scaled up to MW production range. Compared to PEM, alkaline water electrolysis is more cost effective. The components used in alkaline are more durable than in PEM and therefore offer a longer operational lifespan for the unit. On the other hand, alkaline technology has low partial range of load, the density of the current is limited, and the operating pressure is low. The separator in the system doesn't completely prevent the access of gases diffusing to the opposite sides. This causes losses in the produced hydrogen, since the hydrogen catalyses back to water in the anode side. If mixed in terms of hydrogen diffusing back to the wrong side, efficiency of the system and the safety decreases, since the mixing increases explosion risk especially at a low load level. This is a problem when the alkaline electrolyser is receiving electricity from solar or wind power. Also, the current density of alkaline electrolysis is only 0.1–0.4 A cm^2 due to the systems ohmic losses. Additionally, the electrolyser can't operate in high pressure and therefore requires a design which is bulky and doesn't stack compactly. (Jonsson & Miljanovic 2022.)

3.2.3. Waste heat and hydrogen storage

The production of green hydrogen emits only oxygen and heat, and it can be achieved by powering the electrolyser with renewable energy (Jonsson & Miljanovic 2022). The efficiency of the electrolysis process is approximately only 60–70 % which means that almost a third of used electricity is wasted as heat (Vartiainen 2020). However, the efficiency can be reported in higher heating value (HHV) or lower heating value (LHV), which are not comparable to each other. Furthermore, the announcement method of efficiency is not standardised whether to use HHV or LHV. The energy content of a fuel is measured by its higher heating value (HHV). For hydrogen, the HHV is 39.4 kWh/kg or 141.8 MJ/kg. There's also a lower heating value (LHV), which is 33.3 kWh/kg or 120 MJ/kg, but this is only relevant when the substance is burned without recovering heat from the flue gases. When the latent heat from the flue gases is recovered, there is no combustion, or if hydrogen is used as a feedstock, using the LHV can be misleading as it may overestimate the potential for waste heat. By using HHV in the calculations, the consistent energy balance in electrolyser of fuel cell can be achieved. Additionally, it offers a clearer understanding of hydrogen's total energy content and gives a more accurate estimate of the amount of waste heat that can be recovered. (Van der Roest et al. 2023) However, it is possible to change the LHV based efficiency to the HHV based efficiency and roughly estimate the efficiencies in different heating values. For example, if the LHV based efficiency of an electrolyser is 60 % and the LHV of hydrogen is previously mentioned 33.3 kWh/kg, the energy consumption would be 55.5 kWh/kg. Then to receive the HHV based efficiency, the HHV value of hydrogen, which is 39.4 kWh/kg is divided with the LHV based energy consumption. By this, the HHV based efficiency would be approximately 71 %. (Sillman, e-mail 7 October 2024.)

The waste heat generated from the electrolysis can reduce the CO_2 emissions if utilised properly and is used to replace heat from fossil energy sources. The heat utilisation facilitates the change to free from fossil sources and lowers the production cost of hydrogen. (Van der Roest et al. 2023.) The excessive heat can be utilised for example in recuperators, waste heat recovery boilers, regenerators, heat exchangers and heat pumps. The suitable use of utilisation depends much on the fluid type and heat sources' temperature. Additionally, the

intended application acts as a factor for the suitability. Waste heat recovery boilers are used typically to convert low to medium exhaust gases into steam. Recuperators are used as a heat exchanger and are applicable to increase temperatures of exhaust gases. Both heat recovering methods are not ideal for district heating (DH) applications. Better options for DH applications would be heat exchangers, in which heat is transferred between two fluids, and heat pumps, which can transfer heat from air and liquid sources to a heat sink with low electricity consumption. Heat pumps are essentially carbon-free option for waste heat recovery unit, if there would not occur any refrigerant leakages and fossil-free electricity is utilised. (Jonsson & Miljanovic 2022).

Hydrogen has many storage options. For example, it can be stored as gas, liquid or as a part of a metal or polymer. Long term and large-scale storing of hydrogen with gaseous hydrogen underground in aquifers, depleted petroleum or natural gas reservoirs, or man-made caverns from mining operations has been found to be rational. Hydrogen could also be stored in hydrides, either solid or liquid, in low temperature cryogenic liquids or in a combination of these. Petrochemical industry, industry that produces chemical products from petroleum with the refining process, is almost the only one in which the hydrogen doesn't need to be stored prior to its eventual endpoint usage. This is because after it's being produced from a hydrocarbon feedstock, the hydrogen is being utilised almost immediately. (Cavaliere 2023; Matar & Hatch 2001.)

3.3. Synthesis

Production of renewable energy does not always meet demand, and occasionally the production can exceed the market need. However, battery technology is not yet at the level where large-scale electricity storage and energy system balancing would be possible. An alternative for energy systems would be the production of liquid or gaseous fuels in electrolysis from hydrogen and carbon dioxide. The fuels have significant energy storage potential, especially since the fuels could use existing fuel infrastructure and storages with only minor adjustments. Also, the energy transfer from the electricity sector to other sectors would be possible. (Uusitalo et al. 2017.)

3.3.1. Methanol conversion

Methanol is used across many industries and the demand annually is more than 110 Mt. It is required for instance in production of formaldehyde, acetic acid, dimethyl ether (DME) and methyl tert-butyl ether (MTBE) and gasoline. Also, methanol has great properties, such as its high-octane rating, to substitute or function as an additive for fuel and modified diesel engines. Since it is conventionally produced from natural gas via the syngas route, the significant CO_2 reductions can be established by utilising green hydrogen and carbon capture. The process itself has its challenges but offers a promising pathway towards sustainable methanol production. (Azhari et al. 2022.)

The production of methanol from sustainable sources involves either CO or CO_2 as the reactant (Azhari et al. 2022). In methanol synthesis CO_2 and H_2 react with each other and produce a mixture of gases. This mixture is cooled down to condense the formed end products, methanol and water. The process requires a catalyst. (Uusitalo et al. 2017.) For example, copper (II) oxide (CuO), zinc oxide (ZnO), or aluminium oxide (Al_2O_3) are commonly used as a catalyst. The methanol conversion is set to occur typically at 250–300 ◦C and 5–10 MPa. (Azhari et al. 2022.) Some CO_2 and H_2 do not react during the process and therefore are cycled back into the methanol conversion process. The water and methanol are separated from each other and purified for further use. (Uusitalo et al. 2017.) Based on Azhari et al. 2022. the reactions of methanol produced from CO and CO_2 are following.

$$CO + 2H_2 \leftrightarrow CH_3OH \quad \Delta H^\circ = -90.5\ kJ/mol$$

$$CO_2 + 3H_2 \leftrightarrow CH_3OH + H_2O \quad \Delta H^\circ = -49.5\ kJ/mol$$

CO_2 is much more stable than CO, and therefore the process varies from the thermodynamic point of view depending on which is used as a reactant. The heat formation of CO_2 molecule compared to CO is higher. Also, the bonds in CO_2 are much stronger. This means that to

activate the CO_2 molecules, much higher energy input is required. CO_2 can be converted into CO by endothermic Reverse Water Gas Shift Reaction (RWGS). The use of CO_2 as a reactant, can cause challenges during the synthesis. The water formed as a by-product from CO_2 and H_2 can act as a deactivator of the catalyst, especially when copper-based catalyst is used. Hence, the development of design of catalyst and reactor, together with the study of reaction kinetics, is essential for enabling the production of methanol from CO_2. (Azhari et al. 2022.) Methanol yield in typical industrial conditions is limited to stay within 18–58 % for CO_2-based syngas, when the CO-based syngas can reach up to 89 % under the same conditions (Maksimov 2022).

3.3.2. Methanation

Methane production in 2019 was nearly 100 Mt, of which only less than a percent was originated either from biomass or renewable sources (Kang 2021). Natural gas has an established role in the production of methane, due to its availability (Helmeth). Also, 35 % of the produced methane was coal-based. Methane has wide application in various markets, for example in marine, automotive or construction industries. Methane is mostly used in the production of formaldehyde, acetic acid, methyl methacrylate, ethylene and propylene. (Kang 2021.) The production of methane from hydrogenated CO_2 has not yet achieved a solid position on the industrial scale, but few demonstration plants are in operation (Helmeth). However, it is a promising application of captured carbon since the pipelines built for natural gas purposes could be directly used for CO_2-based methane (Zhang et al. 2024).

Methanation, also known as Sabatier reaction, is a chemical reaction in which CO_2 or CO is converted into methane (Helmeth). It is the most developed conversion process for hydrogen at the moment (Stenberg & Bardow 2015). The reaction takes place at high temperature and low temperature conditions (Helmeth). Methanation is a highly exothermic reaction, which results in high conversion losses if the heat is not used fully. The operating demonstration plants have reported achieving 95 % methanol conversion rate from CO_2. (Stenberg &

Bardow 2015) The following equation presents the CO2 methanation reaction in accordance with Uusitalo et al. 2017.

$$CO_2 + 4H_2 \leftrightarrow CH_4 + 2H_2O \quad \Delta H^\circ = -165.0\ kJ/mol$$

The methanation reaction also requires a catalyst due to the molecule structure of CO_2, especially when operating in lower temperatures. Most catalysts used in CO_2 methanation are either noble metals or non-noble metal-based catalysts. Noble metals, such as Rhodium (Rd) and Palladium (Pd) have demonstrated good activity which leads to high selectivity of methane production even at higher temperatures. From the non-noble metal-based catalysts, Nickel (Ni) is the most studied metal to be used in methanation. (Zhang 2024.)

3.4. Fuels as end-products

Nearly 91 % of the fuels in the transportation sector are relied on oil production (IEA). The synthetic fuel production from RES would diversify the current energy solutions and offer carbon reductions in the transportation sector (Kim et al. 2011). Yet, a challenge in the production of synthetic fuels is the relation between the energy used in production and the energy remaining for consumption. This is due to the phases during which the whole production chain consumes vast amounts of electricity. (Efuel-today 2023.)

Methanol as a fuel is very versatile and has been a possible alternative to traditional fuels derived from crude oil. It can be used in road, maritime and aviation transportation. The biodegradability of methanol makes it more environmentally friendly fuel than a traditional marine fuel. It can be used as a fuel as such, or it can be mixed with gasoline. Also, it can be used to produce biodiesel, MTBE and DME. Combined, these fuels represent approximately 31% from the total methanol consumption. In this century, the direct use of an additive or substitute for gasoline inside internal combustion engines (ICEs) has increased. Also, modified diesel engines and advanced hybrid and fuel cell vehicles can use methanol as fuel.

However, the volumetric energy density of methanol is approximately half of what gasoline or diesel has. Hence the tank sizes of the vehicle would have to be changed, if similar ranges are wanted to achieve. The direct conversion of methanol's chemical energy into electrical power in ambient temperature is possible with direct methanol fuel cells (DMFCs). The MTBE is most used in Asia and Mexico, yet the use is prohibited in some countries such as the United States of America due to issues with contaminated groundwater. Biodiesel is a product from a reaction, in which methanol reacts with fats and oils. DME, on the other hand, is produced by dehydrating methanol and the produced gas can be liquefied. DME functions as a diesel fuel substitute. (Kang 2021.) E-SAF, which is an aviation fuel, could also be produced through CO_2-based methanol synthesis (Etasca).

Methane can be used directly in gas engines that run with natural gas, biogas, LNG or bio-based LNG. Also, methane could be blended with these fuels in any ratio. Especially the opportunities of methane from green hydrogen lies in the maritime and heavy truck industries, where the direct electrification of the transportation is not viable option to reduce carbon emissions. The use of methane as a fuel would not require new investments related to the logistics, infrastructure or equipment and thus could be applicable option to the transportation sector. (Ren-Gas 2024.) Additionally, the use of LNG has been studied to be used as rail transportation fuel and has gained interest (Barta et al. 2016). Thus, the use of CO_2 hydrogenated methane could have a place in railway sector.

Both methanol and methane function as an energy storage as it is, since it provides energy on sectors that can't utilise direct electricity. Also, whenever the electricity production exceeds the electricity demand, the electricity could be utilised in other sectors. (Uusitalo et al. 2017; Ren-Gas 2024.) The storage and distribution network of methanol is already extremely comprehensive. It can be transported via ships, barges, railways and trucks. Similarly to oil and oil-derived products, methanol can also be transported inside of pipelines. The demand for refuelling stations of methanol from RES is fundamentally similar to the filling stations of conventional systems and for example the same tanks can be used as such. Refuelling lines and gaskets on the other hand may need some minor changes. The pumps for methanol can be accommodated next to the already existing gasoline or diesel

pumps. In maritime transportation sector, methanol could be stored similarly to bunker fuel due to being liquid at atmospheric pressure. (Kang 2021.) Storing methane can also utilise the existing gas infrastructure. Methane can be either liquid or gas when stored and transported. In 2016, European Union (EU) launched STOREandGO -project to prove the readiness of e-methane storages in the conventional systems. Methane in the liquefied form can be transported and stored similarly to liquefied natural gas. As gas, methane can be injected into prevailing gas grid systems, which consist of pipelines and storage tanks placed underground. (European Comission a.)

4. Assessing the climate impacts by using LCA

Life Cycle Assessment is used as a management tool used to quantify environmental and health impacts and consumed and depleted resources that occur during the cradle-to-grave stages of a process or a product (Muthu 2021; Raadal & Modahl 2022). LCA can also be utilised as a tool to aid decision-making by assessing a process and predicting both its positive and negative outcomes. Based on the overall impact, the determination whether the process should be proceeded with can be carried much more easily. (Muthu 2021.) The main standards regarding LCA are international standards ISO 14040 and ISO 14044. The principles and frameworks of life cycle assessment are described in the ISO 14040, and the ISO 14044 provides the requirements and guidelines regarding LCA. (Pallas 2021.)

LCA is an iterative process, and it comprises of four phases which all are necessary to carry out. The phases are:

1) Goal and scope definition
2) Inventory analysis
3) Impact assessment
4) Interpretation

The goal and scope definition phase defines the basis of the assessment such as upcoming steps, system boundaries and details. (Raadal & Modahl 2022.) Additionally, the functional unit (FU) is defined during this phase. Functional unit is a way to quantify various functions that occur within the system and act as a reference. The functional unit enables subsequent comparison of the LCA results since all the input and output flows are linked to it. (Soukka et al. 2020.) This phase affects significantly to the depth of the study and the results can differ depending on the boundaries set and the goal of the study (SFS-EN ISO 14040:2006). In the life cycle inventory analysis phase (LCI), data is gathered for the system, and a life cycle inventory is created (Raadal & Modahl 2022). The required information regarding the inputs and outputs are gathered in order to conduct the study and reach the goals set in the

previous phase. The aim of life cycle impact assessment phase (LCIA) is to help the assessing of the LCI results with additional information and to deepen the understanding of the results' environmental importance. (SFS-EN ISO 14040:2006.) This phase includes categorising and characterising the output of the analysis in accordance with the potential impact of different environmental impact categories (Raadal & Modahl 2022). Impact categories commonly considered in this phase are climate change, ozone depletion, acidification, eutrophication, ionising radiation, human toxicity, respiratory inorganics, land use, resource depletion, ecotoxicity and photochemical ozone formation. (European Commission 2010.) The interpretation phase compiles the results of LCI, LCIA or both, and the conclusions, recommendations and decision-making are presented based on the results and in conformity with the goal and scope definition (SFS-EN ISO 14040:2006). The principles of LCA are presented in the Figure 17.

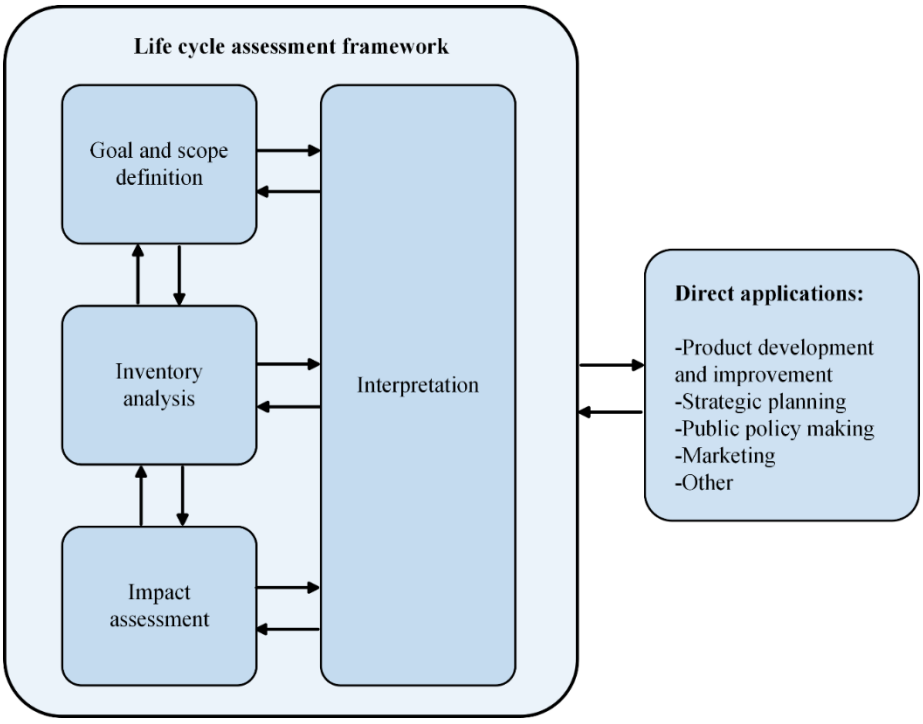

Figure 17. Principles of LCA (Adapted from SFS-EN ISO 14040:2006).

One of the main central points of LCA is to consider the whole technical system, including the production, usage, and disposal of the product and to consider all indirect processes that

are relevant to the technical system. Also, it is essential to take into account the complete energy and material flows through the product's value chain instead of only focusing on the isolated process or activity. Additionally, rather than spectating the results only from singular environmental indicator, several essential environmental impact categories should be used for the whole system. (Raadal & Modahl 2022).

There are two principal approaches when conducting LCA, attributional (A-LCA) and consequential (C-LCA) (Raadal & Modahl 2022). A-LCA is the more conventional perspective, and it regards the stable internal flows of a specific production system. C-LCA on the other hand focuses on the indirect environmental effects of a decision, typically a change in the demand of a product. (Silva & Sanjuán 2019.) In each Life Cycle Assessment case, the approach to complete the assessment should be identified (Muthu 2021). Allocation, by which input, and output flows of a process or a product system are divided, should be avoided if possible (SFS-EN ISO 14044: 2006).

5. Climate impact assessment in accordance with RED III

RED III (2023/2413) is a directive that was actuated at the end of 2023 by the European Parliament and Council (Työ- ja elinkeinoministeriö 2023). It is based on the implementation of the European Green Deal program presented in 2019 and on the regulation published in 2021, where the EU's goal in 2050 is to be climate neutral. Currently, over 75 % of all GHG emissions from the EU are actuated from energy sector. Therefore, the transition towards sustainable energy solutions is required, in order to achieve the targets. (Directive (EU) 2023/2413 of the European Parliament and of the Council.) The directive aims to put in the actions outlined in the REPowerEU plan in 2022, by which clean energy production, energy supply diversification and energy savings are tried to achieve. Additionally, the energy dependence from Russia's energy supplies has been tried to be avoided. (European Commission b). The central aim of the directive is to increase the general target for renewable energy for the entire EU from the current 32 % to 42.5 % by 2030. The directive also contains more detailed regulation on several different topics, of which the most important themes for Finland are bioenergy, transport and licensing procedures for renewable energy production facilities. (Työ- ja elinkeinoministeriö 2023.) The implementation of the directive means for the EU member countries that they are obligated to fulfil more ambitious targets considering the transportation sector, district heating and cooling, buildings and industries. Also, the sub-targets set in the directive aim to expedite the incorporation of renewable energy in sectors where the progress has been slower. (European Council 2023.) In this thesis the research focuses only on the targets of the transportation sector.

Regarding the transportation sector, the member countries can choose to either reduce 14.5 % of greenhouse gas intensity of the renewables by 2030 or increase the share of renewables to 29 % of the final consumption of energy by 2030. Additionally, the share of advanced biofuels and renewable fuels of non-biological origin (RFNBOs) should achieve the 5.5 % target from renewable energies in the transport sector by 2030. Advanced biofuels are typically extracted from non-food-derived feedstocks and RFNBOs generally refers to hydrogen and hydrogen derived synthetic fuels. (European Council 2023.)

To achieve climate neutrality by 2050, certain calculation methods have been created. By these it is aimed to increase the amount of renewable electricity consumption and therefore the production as well. Also, the calculation methods include a factor to the emission savings in transportation sectors that are hard to electrify to expedite the transition. (Directive (EU) 2023/2413 of the European Parliament and of the Council.)

The calculations of emissions derived from RFNBO's considers emissions from the supply of inputs, processing, savings from carbon capture and storage (CCS), transport and distribution, and fuel combustion. Whenever emissions only from the production are considered, a well-to-gate method is used. This considers only the three first categories of emissions. (Muron et al. 2024.) The boundaries of GHG emission analysis methods are presented in the Figure 18.

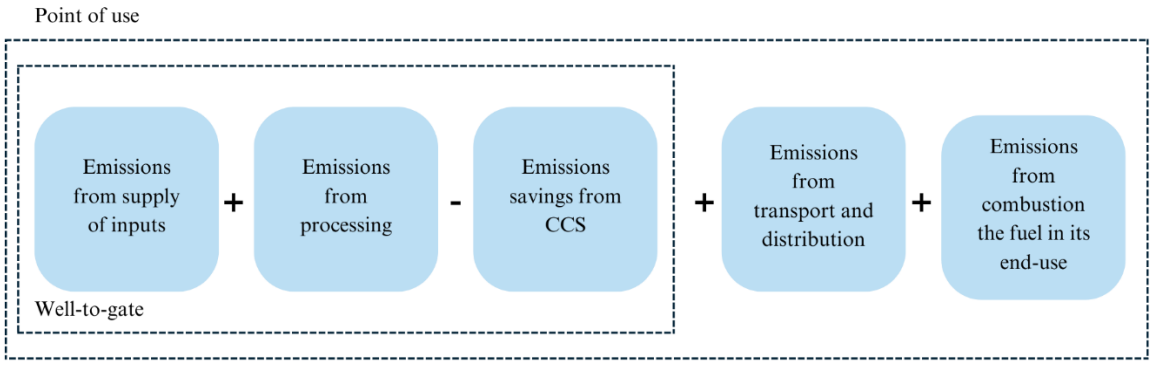

Figure 18. GHG emission analysis boundaries in accordance with RED III (adapted from Muron et al. 2024).

The emissions reduction compared to conventional fuel should be 70 %. For all RFNBOs and recycled carbon fuels, the total emissions of the fossil fuel comparator are determined to be 94 gCO_2e/MJ. (Muron et al. 2024.) The emissions of renewable energy utilised in the production of methanol is considered as zero (Directive (EU) 2023/2413 of the European Parliament and of the Council). If electricity is taken from the grid, the national grid mix emissions should be added to the calculations. Also, if the carbon is captured from a climate

neutral source, such as biomass, flue gas or directly from the air, the end-of life emissions are considered zero as well. (Methanol Institute.)

The savings compared to the fossil fuel comparator shall be calculated with following equation in accordance with Commission Delegated Regulation (EU) 2023/1185:

$$\text{Savings} = \frac{E_F - E}{E_F}$$

where E is total emissions from the use of renewable liquid and gaseous transport fuel of non-biological origin or recycled carbon fuel and E_F is total emissions from the fossil fuel comparator.

6. System under review

In this chapter the goal and scope of the study is determined. The system boundary is presented and the material flows described in detail. Additionally, the functional unit is determined. The calculation part of the study consists of system level study and RED III directive-based study. The key differences of the calculations are expressed in goal and scope chapter. The inventory analysis presents the material and energy flows from quantitative point of view and certain assumptions for the calculations are concluded. The impact assessment is divided into two chapters, one focuses on the system level calculations impacts and the other compiles the results from RED III based calculations.

6.1. Goal and Scope definition

The goal of this study is to determine the climate impacts of a product chain, in which the electricity from solar power plant is further processed into synthetic fuels. The study is conducted by utilizing two methods, system level study and a study that is based on the RED III directive. The system level study is aimed to bring more knowledge of end-product comparability, in this case the comparison between methanol and methane, and solve how the climate impacts change if another product is chosen to be produced instead of another. The directive-based study research, if it is possible to stay within the threshold values regulated related to the emissions and climate impacts, when producing methanol from solar electricity. In both cases the calculations regard only carbon dioxide emissions.

The FU defined earlier in the text was determined to be m^2 of required land area for solar panels in the system level review, and 1MJ produced end-product in the RED III review, to make the results comparative with the directive. The FU is different in these review models, because with the system level review it is aimed to present how much each end-product can be achieved from the same land area, and how much the whole process emits carbon dioxide depending on the end-product. Overall, the competitiveness of the products is assessed in order to enhance the decision-making process especially in cases in which the end-product is not decided yet. The RED III review on the other hand considers only methanol and if it

would stay within the threshold values set in the RED III directive. By this, the legislative constraints regarding the emission calculation of RFNBOs are described. Also, the study method aims to assess how the production of synthetic fuels derived from renewable energy compares to the conventionally produced ones.

The system boundary for system level review is presented in the Figure 19. It includes stages from panel production to synthetic fuel production. The process considers the inputs needed for the electrolysis to produce hydrogen, which are solar electricity and water. The carbon capture requires thermal energy, electricity, carbon dioxide and some chemicals as feedstock to produce utilisable CO_2. Both syntheses need electricity, hydrogen and carbon dioxide to produce the end-product, however the by-products vary. From methanol synthesis in addition to the end-product, only water and heat are generated. The methane synthesis can't utilise all the input carbon dioxide and hydrogen, so additionally to the water and heat, these are produced from the methanation. The system boundary is the same for the directive-based calculation, however the methane production is not considered.

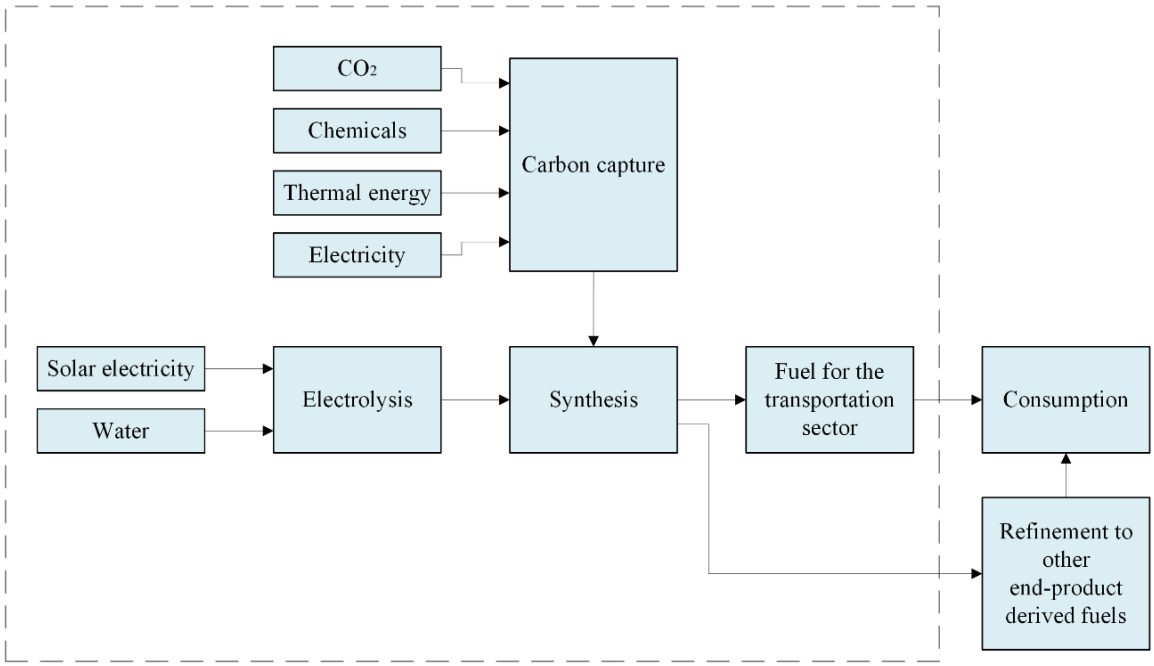

Figure 19. System boundary of the study.

The data used in this thesis for the calculations is merely secondary. Therefore, it is a compilation of data based on previous studies found. The LCA calculations are in accordance with ISO 14040 and ISO 14044. The data is summarised in the following chapter. The data for inputs and outputs are the same for both study methods, system level and RED III, yet the factors that will be under consideration in the results vary.

6.2. Inventory analysis

In this chapter the materials flows are defined quantitively. The inventory data of the calculations is combined in the Appendix I. The data and assumptions were selected to be applicable to the aims and scope of the study and therefore cannot necessarily be applied for other purposes. The reliability of the data and results are assessed in the uncertainty and data evaluation chapter.

Assumptions that were made during the thesis were:

- The plant is off-grid plant
- The whole area is covered with solar panels and does not include maintenance roads
- Solar power plant has a lifecycle of 30 years
- AEC electrolysis is used to produce hydrogen
- Carbon capture is done with MEA absorption
- Thermal energy for CC is bio-based

Additionally, both calculation methods include assumptions that heat emissions from syntheses are zero, because the energy sector is estimated to reach carbon neutrality by 2030 in Finland (Energiateollisuus 2024). Larger solar power plants are still in the permitting phase or on drawing boards, and the energy palette could have drastic changes in a few years. The calculation of this study will only assess the land use emissions for unvegetated peatland, not land use and change. Based on the Carrara et al. 2020., the material fractions required to construct a solar power plant is combined in the Figure 20.

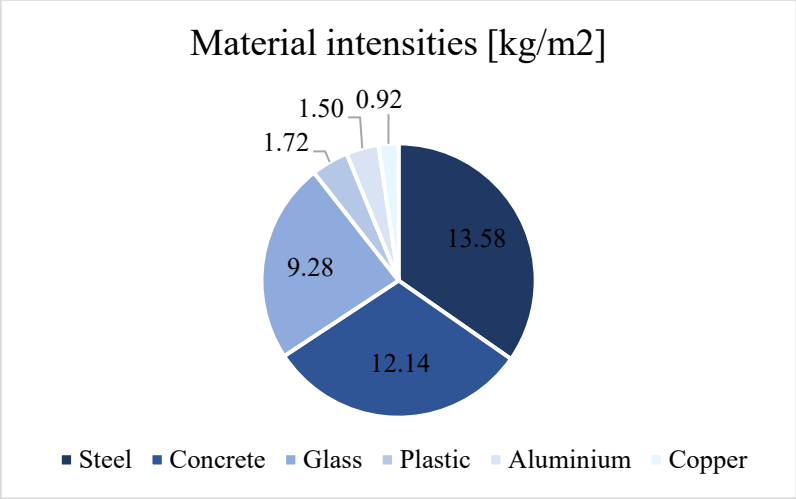

Figure 20. Material intensities of solar power plant in comparison to 1 m^2 required land area of solar panels

Electrolysis consumes solar electricity and water and the main outputs in addition to hydrogen are heat and oxygen. The hydrogen is then further synthesised with carbon dioxide and electricity into methane or methanol. The by-products from methanation are water, carbon dioxide, hydrogen and heat. From methanol conversion only heat and water are produced as a by-product. Carbon dioxide requires to be captured before the synthesis and main inputs are MEA, carbon dioxide, electricity and heat. The efficiency of this process is 90 % (Volkart et al. 2013). In inventory analysis, it was determined that the solar electricity production would be annually 648 MJ/m^2, and therefore the total energy during the lifecycle would be 19.44 GJ that is fed to the electrolysis. Depending on the efficiencies and the produced end-product, the input and output values of material and energy flows alter. In the following figures the material and energy flows of the system are presented and since the electrolyser efficiency plays crucial role in the end-product production, the process has been studied with two different efficiencies. Figure 21 presents the case, when the LHV efficiency of electrolysis is 63 % and Figure 22 presents the same scenario, yet the LHV efficiency is 70 %. The values of both figures are scaled to what 1 m^2 of solar panels produce electricity annually.

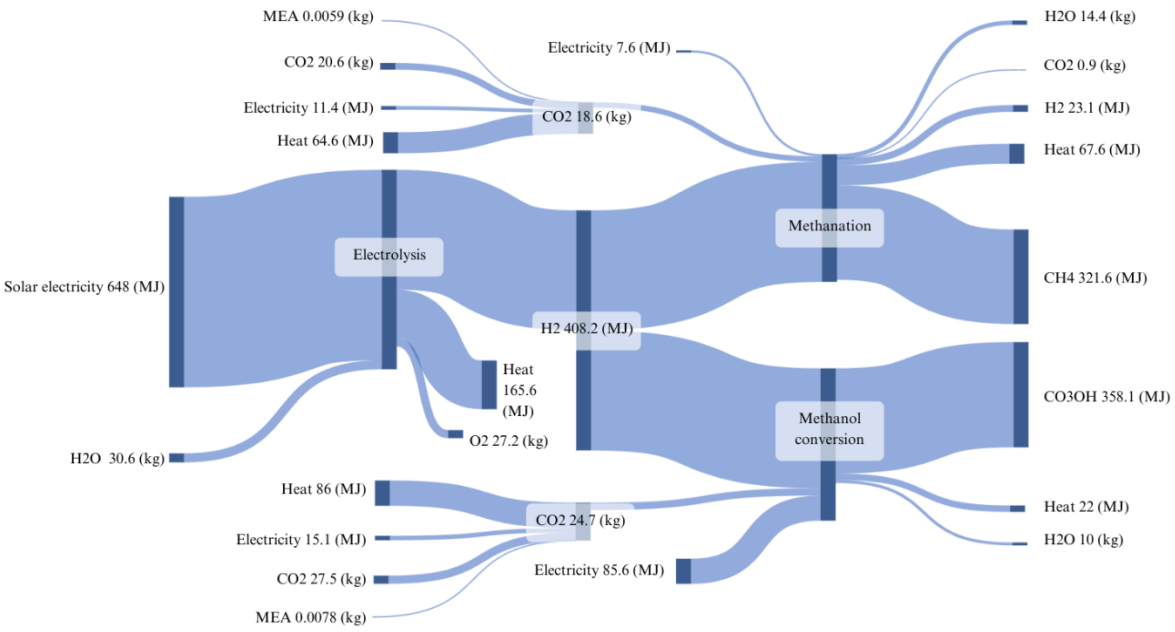

Figure 21. Annual material and energy flows when electrolysis occurs on 63 % LHV efficiency per m^2.

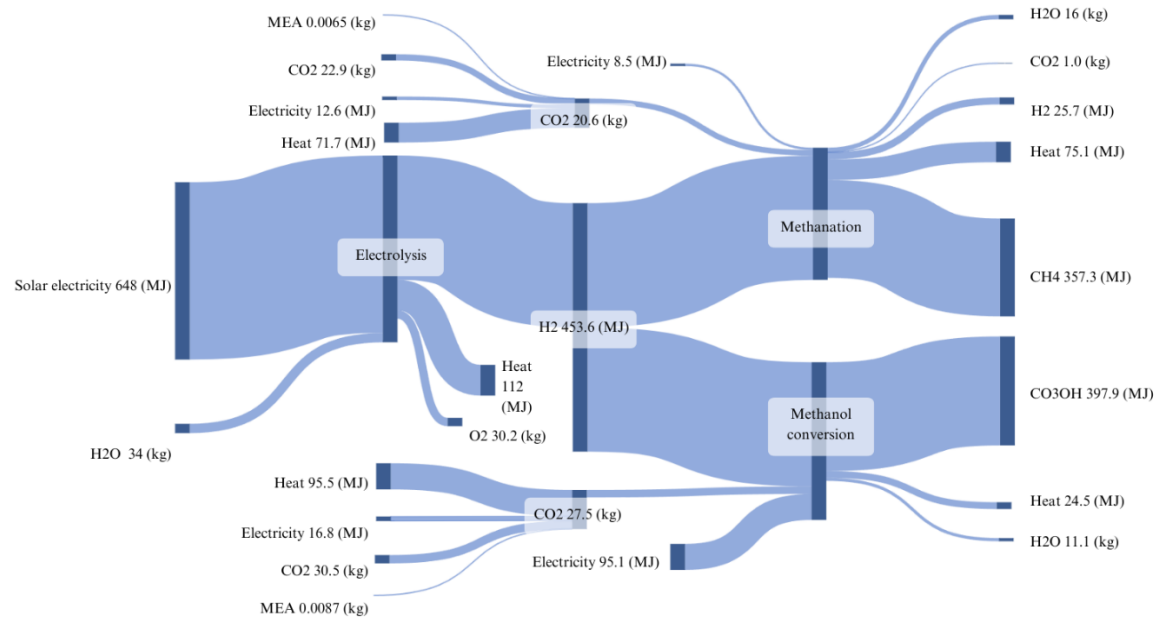

Figure 22. Annual material and energy flows when electrolysis occurs on 70 % LHV efficiency per m^2.

In the Figure 21, in which the process with 63 % electrolysis efficiency is presented, 30.6 kg of water is required annually to produce 408.2 MJ hydrogen. From this, 165.5 MJ of heat and 27.2 kg oxygen is generated. Whether the hydrogen is further processed into methanol

or methane, additional electricity and CO_2 is required. For methanol production the needed electricity is 95.1 MJ and for methane it is only 8.5 MJ. The MEA input is 0.000284 kg per kg of captured CO_2 according to Volkart et al. 2013. Based on this it was calculated that when lower electrolyser efficiency is used, the MEA consumption is annually 0.0059 kg or 0.0078 kg depending on which end-product is produced. The amount of captured carbon when producing methanol is 30.5 kg and when producing methane, it is 27.5 kg. The methane production needs 11.4 MJ electricity and 64.4 MJ thermal energy, and methanol 15.1 MJ electricity and 86 MJ thermal energy. Overall, the methanol production reaches to 358.1 MJ, yet 22 MJ of heat and 10 kg of water is also generated. Methane production with lower electrolyser efficiency is 321.6 MJ. From this, 14.4 kg of H_2O, 0.9 kg of CO_2, 23.1 MJ of H_2 and 67.6 MJ of heat is generated as a by-product.

From the Figure 22 can be seen that the water need for hydrogen production is 34 kg. This results in 453.6 MJ of H_2, 112 MJ heat and 30.2 kg O_2. The material and energy requirements of methanation are 20.6 kg CO_2 and 8.5 MJ electricity, and the CC inputs are 0.0065 kg MEA, 22.9 kg CO_2, 12.6 MJ electricity and 71.7 MJ heat. With higher electrolyser efficiency 357.3 MJ of CH4 can be produced annually, and this results in 16 kg H_20, 1 kg CO_2, 25.7 MJ H_2 and 75.1 MJ heat as by-products. The methanol conversion needs 27.5 kg CO_2, which production consumes 95.5 MJ heat, 16.8 MJ electricity, 30.5 kg CO_2 and 0.0087 kg MEA, and 95.1 MJ electricity. Overall, 397.9 MJ methanol can be produced, from which 24.5 MJ of heat and 11.1 kg H_2O is generated.

The overall efficiency of the process varies depending on the efficiency of the electrolyser and the end-product produced. To achieve the most energy to stay in the end-product, the production of methanol with higher electrolyser efficiency would be the best option. This reaches to 64.1 % overall efficiency. The production of methanol with lower efficiency has the second highest overall efficiency, 55.3 %, and thus assumption that the methanol production could be energy-wise the most feasible option for solar electricity. With methane production, 55.1 % could be reached with higher efficiency and 49.6 % with lower. In both Figures 21 and 22, the heat from electrolysis shows all the heat that leaves the process. Assumed, that the heat exchanger efficiency would be 80 %, in lower efficiency electrolysis,

the utilisable heat in DH would be 132.5 MJ/m^2 annually. Utilisable heat would be 89.2 MJ/m^2, when higher efficiency is used. The use of heat utilisation in DH is further discussed in Chapter 7.3.

The following Figures 23 and 24 present the same material flow values that were previously defined, however these are scaled to 1 MJ of produced end-product. The Figure 23 considers methanol and Figure 24 defines the material flows of methane production. This helps to clarify the comparison between products and efficiencies, for the further discussion. The Figure 23 functions also as a basis for the RED III calculation.

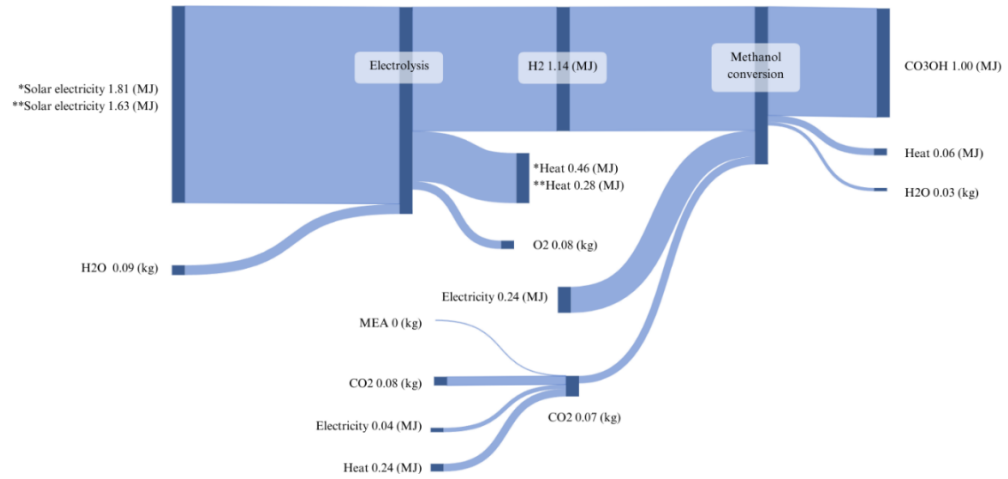

Figure 23. Flows of methanol production per 1 MJ end-product

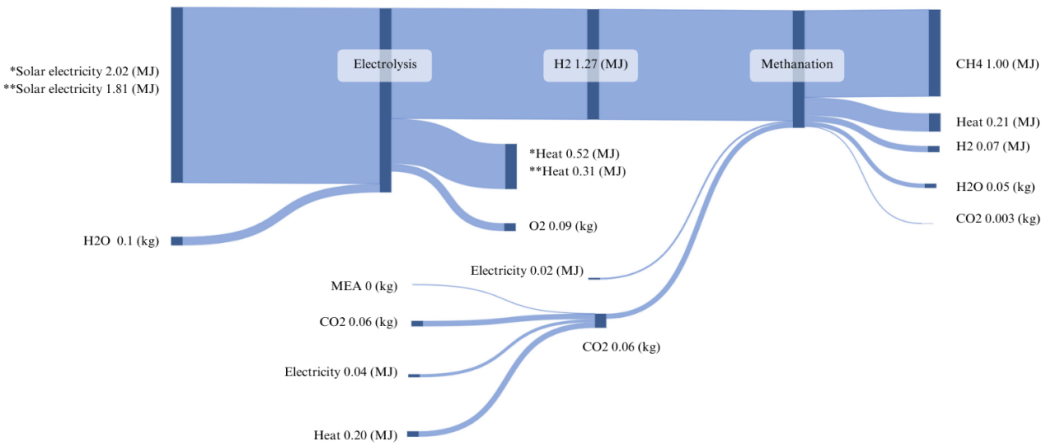

Figure 24. Flows of methane production per 1 MJ end-product.

Based on the Figures 23 and 24 only variable values in the processes are concerning the electrolysis heat production and energy demand when considering the differences between efficiencies. The lower LHV efficiency of electrolysis is presented in both Figures with *, and the higher LHV efficiency is described with **. The lower efficiency in both methanol and methane production needs more electricity input and produces more heat. As presented in the Figure 23, in order to produce 1 MJ methanol, 1.63 MJ to 1.81 MJ electricity is needed in addition to 0.09 kg water. From these 1.14 MJ hydrogen can be produced. If the lower efficiency is used, 0.46 MJ of heat is generated, and the higher efficiency results in 0.28 MJ heat. Additionally, 0.08 kg water is needed. The synthesis needs 0.24 MJ electricity and 0.07 kg CO_2 in order to produce 1 MJ methanol. The CC approximately consumes 0.08 kg CO_2, 0.04 MJ electricity and 0.24 MJ thermal energy. The MEA consumption is small when scaled to the production of 1 MJ methanol. In accordance with the Figure 24, the electricity consumption with lower efficiency is 2.02 MJ and higher efficiency 1.81 MJ in order to produce 1 MJ methane. With these, 0.1 kg water is used to produce 1.27 MJ hydrogen, 0.09 oxygen and depending on the efficiency 0.31 MJ to 0.52 MJ heat. Similarly to the methanol production, the MEA consumption is existent but minor. In order to produce the 0.06 kg CO_2 for the synthesis, approximately the same amount of CO_2 is fed into CC system with 0.06 MJ of electricity and 0.20 MJ thermal energy. In addition to 1 MJ of CH_4, 0.21 MJ heat, 0.07 MJ hydrogen, 0.05 kg water and 0.003 kg CO_2 is generated.

6.3. Impact assessment – System level

In this chapter the results of the system level study are presented. The results are in the form of emitted carbon dioxide per the FU. The results are scaled to the lifetime of a solar power plant, 30 years. The heat from electrolyser is not utilised. In inventory analysis, it was determined that the solar electricity production would be annually 648 MJ/m^2, and therefore the total energy that is fed to the electrolysis during the lifecycle would be 19.44 GJ.

The Table 2 presents the emissions from material acquisition and demolition of panels in accordance with the material fractions defined in Chapter 2.4. The values for emission factors were retrieved from the CO2data database. Aluminium was chosen to be fully virgin

material for the acquisition and the plastic was incinerated after the panel dismantling. The material emission impacts are further studied in the sensitivity analysis section.

Table 2. Emissions from panel manufacturing and demolition.

Materials	**Material acquisition [kgCO_2e/m^2]**	**Panel demolition [kgCO_2e/m^2]**
Concrete	0.98	0.07
Steel	40.74	0.03
Plastic	4.43	5.16
Glass	12.99	0.19
Aluminium	10.80	0.003
Copper	4.60	0.002
Total	**74.54**	**5.45**

In addition to the materials used in the panels, the LCA emissions of solar power plant is comprised from land use emissions and emissions from other demolition. The emission factor of land use is approximately 1.179 kgCO_2e/m^2 annually for unvegetated peatland, and the emission factor of other demolition is 10 kgCO_2e/m^2. As the electrolyser is powered with solar electricity, it is assumed that other emissions from hydrogen production is not generated. The syntheses and carbon capture utilise grid electricity, which emission factor is taken into consideration in the calculations, additionally to MEA emission factor. The climate impacts of the whole P2X process are presented in the Figures 25 and 26. The Figure 25 presents the lifecycle emissions, when the lower electrolysis efficiency is used and the Figure 26 presents the same, yet with higher efficiency. Both Figures present the results in a way, from which the impacts of certain lifecycle phase can be indicated separately.

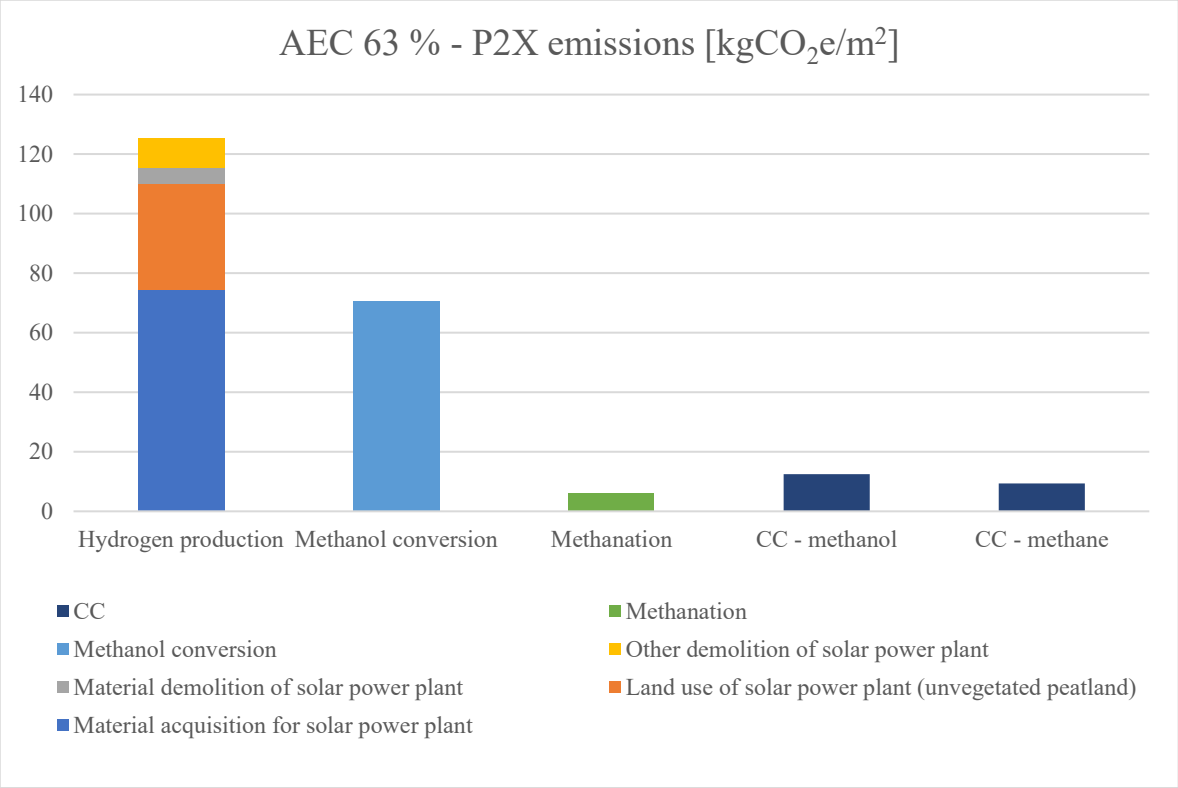

Figure 25. Lifetime emissions of P2X process based on the area when electrolysis efficiency LHV 63 %.

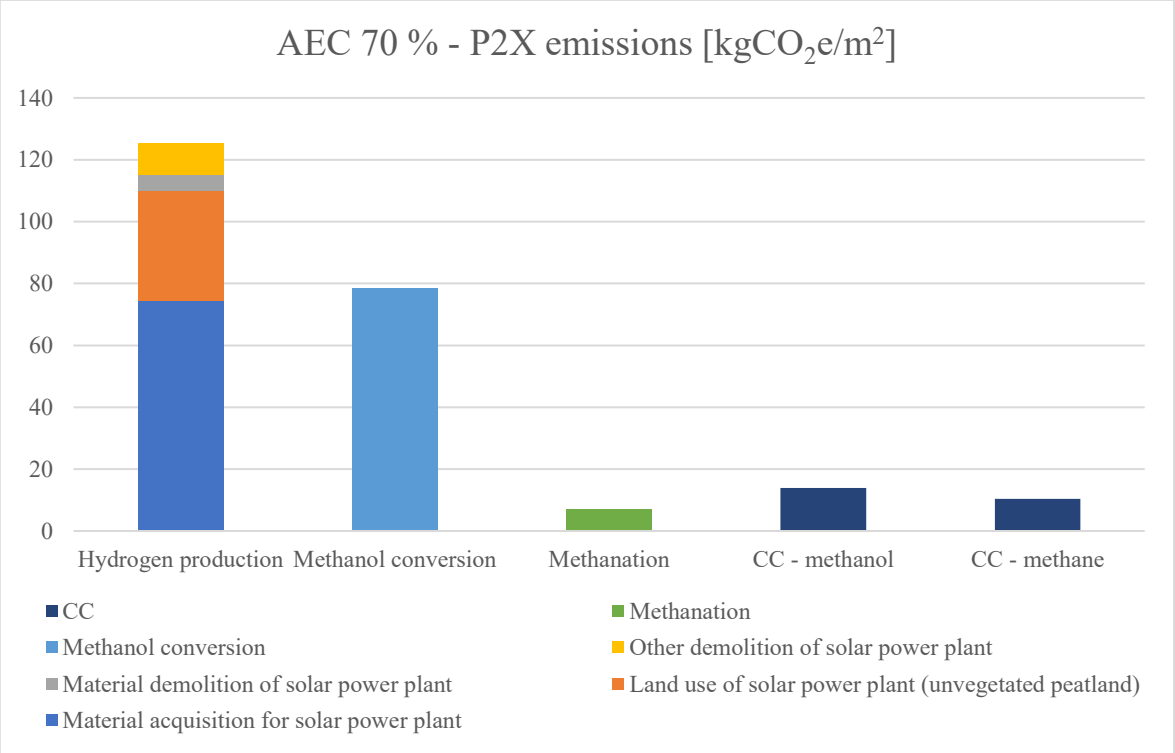

Figure 26. Lifetime emissions of P2X process based on the area when electrolysis efficiency LHV 70 %.

The total emissions of the methanol produced with lower efficiency is 208.4 $kgCO_2e/m^2$, and with higher efficiency 217.7 $kgCO_2e/m^2$. For methane the lower efficiency value would be 141.0 $kgCO_2e/m^2$ and higher 142.8 $kgCO_2e/m^2$. Overall, the Figures 25 and 26 illustrate that the hydrogen production is the most emitting phase of the process as it is accounted for 57.6 % to 60.1 % of the methanol production emissions and 87.8 % to 88.9 % of the methane production. Material acquisition of the solar panels has the most impact, 59.5 %, on the hydrogen production. From the hydrogen production emissions, land use is 28.2 %, material demolition is 4.3 % and other demolition is 8 %. Methanol conversion generates 33.9–36.0 % and the carbon capture for methanol conversion generates 6.0–6.4 % of the overall emissions. From the overall emissions, the share of methanation varies from 4.5 % to 4.9 %, and the carbon capture is accounted of 6.6–7.3 %. The percentage of emissions from each life cycle phase decreases, when higher electrolyser efficiency is used. Based on the Figures 25 and 26 a significant difference can be seen depending on whether methanol or methane is produced, and by which efficiency. The values implicate that it would be better to produce methane and favour lower efficiency. However, with the same number of solar panels, much more methanol can be produced compared to methane, especially when production is in large scale. The same applies to the higher efficiency. To have more detailed assessment of the emissions, the Figure 27 presents the same results but scaled to 1 MJ of the end-product.

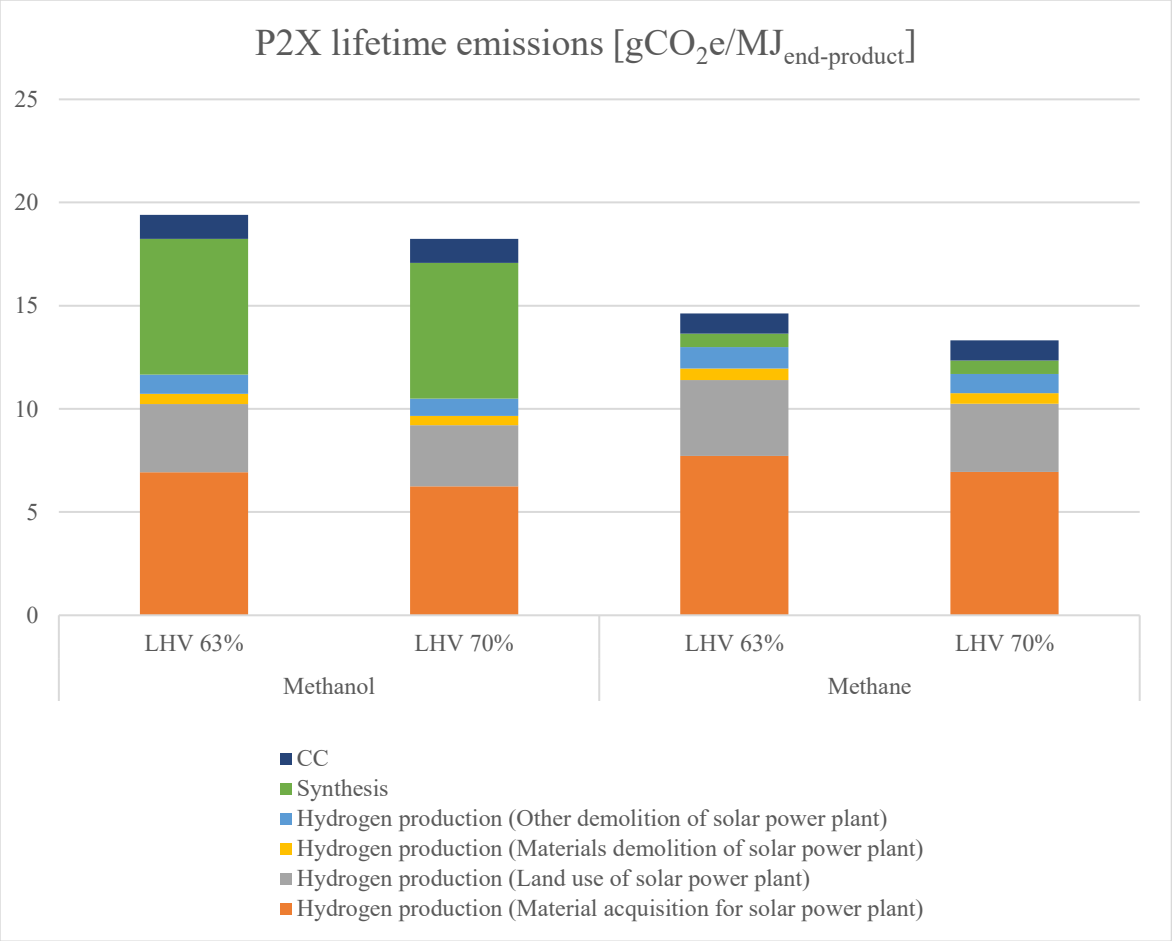

Figure 27. Lifetime emissions of P2X process based on the MJ produced end-product.

The results presented in the Figure 27 verify that more end-product can be achieve from a same land area when methanol is produced. Due to this, the hydrogen production emissions are much higher when producing 1 MJ of methane compared to 1 MJ of methanol. However, due to the high electricity consumption of methanol conversion and the use of grid mix in the synthesis, methanol reaches higher overall emissions. The life cycle emissions for methanol are 19.4 gCO_2e/MJ_{CO3OH} and 18.2 gCO_2e/MJ_{CO3OH}. For methane the emissions are 14.6 gCO_2e/MJ_{CH4} and 13.2 gCO_2e/MJ_{CH4}. The higher the efficiency, the lower the emissions as more end-product can be obtained. On a scale of 1 MJ of produced end-product the differences of the emissions are not that significant, however when put to a larger production scale, the contrast increases substantially. As the hydrogen production has great impact on the overall emissions, the heat utilisation in DH is further studied in the Chapter 7.3.

6.4. Impact assessment – RED III

In this chapter the directive-based impact sources are defined. The input data and assumptions considering this study method was determined in the Chapter 6.2. RED III directive considers renewable electricity emission-free. Therefore, the hydrogen production is considered carbon neutral. Also, the thermal energy used in carbon capture is bio-based and assumed emission-free in the inventory analysis. In accordance with RED III, the threshold value that should be subceeded by 70 % is 94 gCO_2e/MJ_{CO3OH}. The results of the RED III study are compiled in the Table 3.

Table 3. Methanol emissions based on the RED III directive

Methanol conversion	**Amount [gCO_2e/MJ_{CO3OH}]**
Hydrogen production	0.00
Synthesis Grid mix FI	6.57
CC Grid mix FI	1.16
CC Heat	0.00
CC MEA	0.00
Total emissions	**7.73**

Based on the Table 3, the only contributing factor to the emissions is the electricity from the grid which is consumed in the methanol conversion and carbon capture. There also occurs emissions from the consumption of MEA, however when compared to the 1 MJ of produced methanol, the scale of emissions is insignificant. The results shown in the Table 3 considers both electrolyser efficiencies, since the Figure 23 presented that only altering parameters depending on the used efficiency are amount of solar electricity and heat generated. Based on the precept set in the directive, the parameters are not regarded in the calculations, as both are solar electricity derivatives. In accordance with the Table 3 When solar electricity is used to produce green hydrogen, which is further utilised in the production of methanol, the emissions stay under the threshold value, and the savings reach to 91.8 %.

7. Results interpretation and discussion

The aim of this chapter is to interpret the results of the study and create discussion based on the received information. The interpretation is conducted by assessing the sensitivity of the of the results, and analysing any uncertainties noticed along the way. Additionally, in the comparison section, the results are compared to a situation in which the heat is utilised in district heating. Additionally, this chapter considers the rest of the research questions that were not considered yet.

7.1. Sensitivity analysis

The calculation left some variables open for interpretation and thus certain assumptions were made during the assessment. Factors affecting the sensitivity are for example the limitations set for the data collection, the quality of used data and the functional unit. Hence the sensitivity analysis is required to define how sensitive the results are if the values would be altered.

It was presented in the Chapter 6.3. that the hydrogen production, specifically the material acquisition affects significantly to the emissions of the whole P2X process in the system level study. Therefore, the sensitivity analysis is done by changing the materials from acquisition and demolition and see if material selection would be a significant factor to the overall emissions. The baseline in Figure 28 presents the same input data regarding what was used in the LCA earlier. The alternative scenario presents a situation where instead of using virgin aluminium, fully recycled aluminium was used for the panel production. Also, instead of the panel's plastic being incinerated at the end-of-life phase, in the alternative scenario it would be recycled.

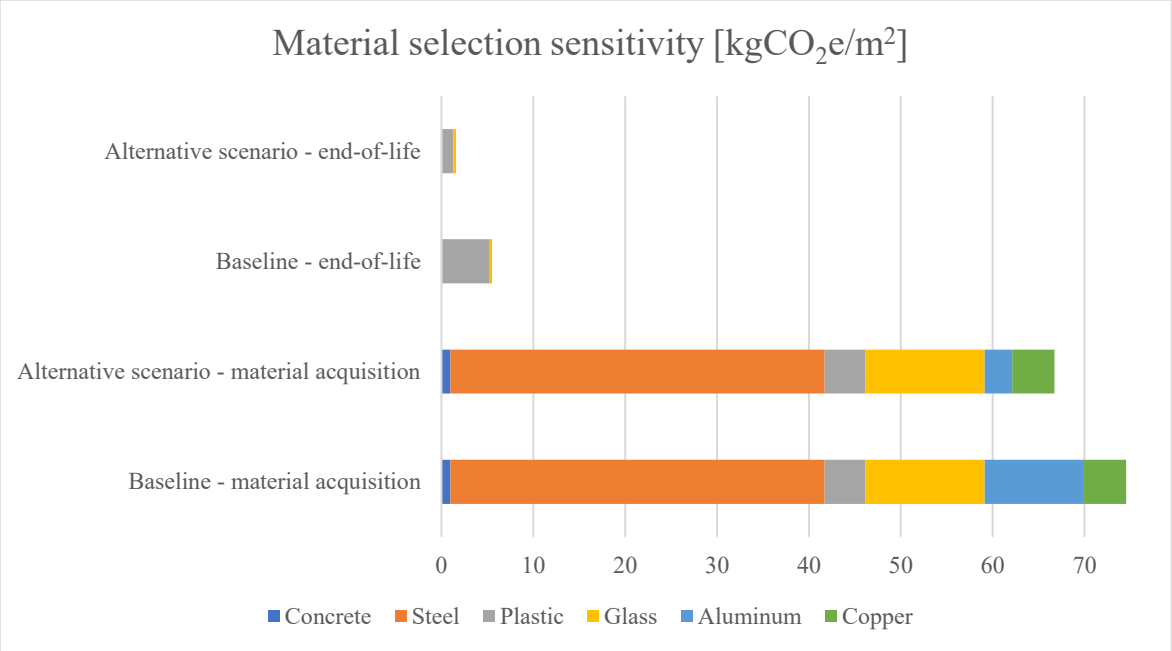

Figure 28. Material selection sensitivity.

The overall emission of the baseline is 79.99 $kgCO_2e/m^2$, from which the material acquisition is 74.54 $kgCO_2e/m^2$ and the panel demolition is 5.45 $kgCO_2e/m^2$. The overall emission from the alternative scenario is 68.24 $kgCO_2e/m^2$. From this the material acquisition is 68.24 $kgCO_2e/m^2$and panel demolition 1.49 $kgCO_2e/m^2$. The emissions from material acquisition and demolition could be reduced by 14.7 % by selecting more sustainable materials regarding panel production and choosing recycling instead of energy recovery. Although the emissions occur only once in the solar panel plant's lifecycle, if new panels are not required to be manufactured, the material and disposal method selection offers a good emission reduction possibility. The potential is the highest with methane. With alternative scenario, the overall emissions reduce by 8.3 % when the lower efficiency is used and 8.2 % when the higher efficiency is used. The overall emissions of methanol would reduce by 5.6 % with lower efficiency, and 5.4 % with higher efficiency.

In this study, the emission factor of hydrogen production was decided to be the sum of material acquisition, land use, material demolition and other demolition emissions. The life cycle emissions, 125.4 $kgCO_2e/m^2$, was received. However, two different emission factors were found from the literature. Based on the Schlömer et al. 2014. the emission factor for

solar utility PV systems is 48 $kgCO_2e/MWh$. In accordance with this, the life cycle emission of hydrogen production would be 259.2 $kgCO_2e/m^2$. Based on Ajeeb et al. 2024., the emission factor for solar based electrolysis is 3.08 $kgCO_2e/kg_{producedH2}$. Calculations based on this value would lead to 314.3 $kgCO_2e/m^2$ for the lower electrolyser efficiency and 349.3 $kgCO_2e/m^2$ for the higher electrolyser efficiency. The variation between these values would lead to assumption that the emissions from hydrogen production used in this study might be lower than they actually would be. However, there variation between the literature values and the values used in this thesis could differ due to the scope of the emission factor, for example this thesis did not take transportation into account, or for example geographical reasons.

7.2. Uncertainty and data evaluation

This chapter aims to assess the reliability of the results of the study and to identify factors that have influenced the outcome. Some uncertainties were already discussed in the sensitivity analysis, but in this chapter, the aim is to detect comprehensively the remaining significant ones. Additionally, the data is being evaluated for its consistency and completeness.

The most significant uncertainty is because no primary data was available. Therefore, the used data was secondary and was retrieved from literature. Additionally, what adds to the uncertainty, is the factor that the data was collected from various sources. Although efforts were made to monitor the quality of the data, and it was to retrieve values that would co-operate with each other, it is possible that some of the values are inconsistent. Therefore, a corresponding study should be conducted to reproduce the results of the calculations.

The factor that the area is assumed to be fully covered with solar panels brings uncertainty to the study. Generally, the whole area cannot be utilised a unified panel field due to factors that affect the land use, for example the Natura 2000 areas. Also, the area typically consists of maintenance roads and other factors requiring construction. In Appendix II there are three

different scenarios on how the maintenance roads could be implemented in accordance with the recommendations discussed in Chapter 2.1. Compared to the annual energy content of solar electricity of 648 MJ/m^2 used in this study, the electricity production could vary between 529–600 MJ/m^2 if maintenance roads would be considered. This would have a great effect on the volume of the end-products produced. Therefore, it is safe to assume that the emissions of the whole process in terms of studied scope were slightly higher than they would be in practice.

However, the emissions could compensate the factor that some parameters were left outside of the study. If a more comprehensive study is wanted, the transportation should be also considered. Yet, if calculations would be done to existing solar power plant, the data specifics such as the area, annual energy production, panel amount and arrangements, the panels' efficiency and how the maintenance roads are accommodated would be obtainable. Hence, this study should be used more as a guideline if applied to a specific case.

Other factors that could have resulted in uncertainties are land use, the energy palette assumption and electricity transmission losses. The soil of the area was determined to be unvegetated peatland. As peatlands are considered in the literature as the worst option regarding the emissions to construct a solar power plant, the results would demonstrate the highest possible emissions from land use. However, it was stated that if the peatlands' water level is increased, the peatland generates merely methane emission and functions as a carbon sink. Therefore, the received results would not necessarily implicate the worst possible emissions, and in practice the land use, and land use change could contribute to carbon handprint. If the plant would be constructed to some other soil type, which would require vegetation removal, those emissions should be taken into account as well. The energy palette, and the factor that synthesis heat would be carbon neutral, is a valid assumption in terms of future prediction, though the results may not fully reflect the current situation. Additionally, the electricity transmission losses were not regarded in the calculations and therefore the results could vary from the proper situation. The transmission losses are approximately 4 % for the grid-tied systems, and the more electricity is needed to be transmitted, the more transmission losses occur (Caruna 2021).

7.3. Comparison

In this chapter the results from system level study are compared to situation in which the heat side stream of electrolysis is utilised in district heating. The heat exchanger efficiency was assumed to be 80 %. In accordance with Chapter 6.3, the annual heat generation with lower electrolyser efficiency is 165.6 MJ/m^2 from which 132.5 MJ/m^2 is utilisable. Similarly, for the higher electrolyser efficiency, the generated heat is 112.0 MJ/m^2 from which 89.2 MJ/m^2 can be utilised. Scaled to 1 MJ of CO_3OH, the generated heat is 0.46 MJ, and utilisable heat is 0.37 MJ with AEC LHV 63 %. The generated heat for methanol with higher efficiency is 0.28 MJ/MJ_{CO3OH} from which 0.23 MJ/MJ_{CO3OH} is utilisable. For CH_4, the AEC LHV 63 % generated heat is 0.52 MJ, and utilisable heat is 0.41 MJ. The AEC LHV 70 % generated heat on the other hand is 0.31 MJ/MJ_{CH4} from which 0.25 MJ/MJ_{CH4} is utilisable.

Compared to the situation presented in the Chapter 6.3, which is presented in this comparison as a baseline, all emissions do not transfer into the end-product if heat is utilised. Thus, allocation is needed to assess the impacts. If all heat is utilised from the hydrogen production, only the share of hydrogen is considered in the end-product's emissions. Based on the input data the hydrogen production generates heat, hydrogen and oxygen, but oxygen is not considered in the end-products in this comparison. The share of the hydrogen as an end-product in AEC LHV 63 % is 71.1 %, and in AEC LHV 70 % it is 80.2 %. The hydrogen shares are same whether methane or methanol is produced. As more hydrogen is produced, it can be assumed that less reductions regarding the CO_2 emissions can be achieved with higher efficiency. The Figure 29 presents the baseline, in which all emissions through the process are considered to transfer to the end-product. Also, the Figure 29 presents the alternative in which the heat is utilised in DH.

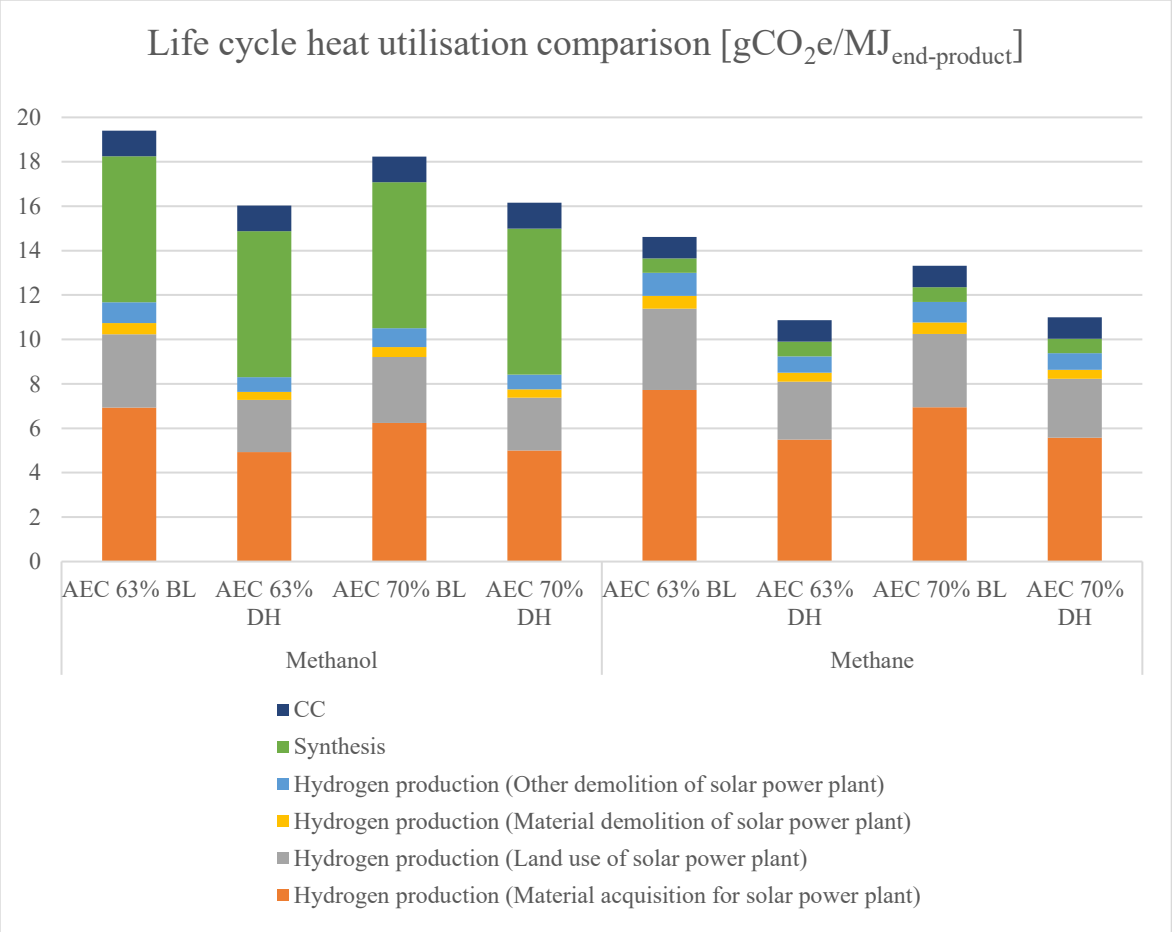

Figure 29. Life cycle heat utilisation comparison for methanol and methane.

The Figure 29 shows that the emission reductions from heat utilisation varies depending on which efficiency is used, and which end-product is produced from the solar electricity. The best reductions, 25.7 %, compared to baseline can be achieved with methane production with lower efficiency. The methanol production with lower efficiency and methane production with higher efficiency reaches the next best reduction with 17.4 % compared to the originally studied situation. The least reductions occur with methanol production with higher efficiency. Overall, it can be stated that higher efficiency enables less reductions and since the methanol production consumes great amount of electricity the reductions are less in that production chain. The comparison shows that methane production is better option in terms of carbon dioxide emission whether the heat is utilised or not. Since methanol production is far more efficient compared to methane, it can be assumed that renewable electricity usage in synthesis would make methanol more competitive alternative.

7.4. Final discussion of the study

In this chapter, the results are discussed more in detail and the comparison of methanol and methane is made. Additionally, the focus of this chapter is on the factors and issues that are needed to be regarded when setting requirements for solar power project operators.

As reviewed in the Chapter 3. there are plenty of P2X paths that can be taken to receive the same outcome. Different technologies and methods can be proceeded with in terms of production of synthetic fuels. The selection of the end-product should be the basis when determining what path choices are proper to use. As, the synthetic fuel production industry itself is a relatively new field, the best available technologies should be considered based on the literature findings. With a scientific theory backing the planning process, the actual use phase would end up with great results in terms of production and sustainability.

It was stated in the theory part, that both methanol and methane have versatile options in terms of utilisation. Both function as energy storages in sectors where the use of direct electricity is not possible. Methanol and methane can be used as a fuel as such, and it can be mixed with other fuels like gasoline. Also, there are plenty of methanol and methane derivative fuels that can be produced into different purposes, from which different industries could select the best alternatives for their own consumption needs. The possibilities lie in the road, maritime and aviation sectors. The storing of the produced fuels could utilise the existing fuel storages with minor modifications. However, solar electricity production requires a large land area, and therefore might not be feasible for all industries that consult ELY regarding the possibility of emission reductions. Additionally, the production of synthetic fuels is not necessarily the most feasible option for industries that focus merely on the solar electricity production. From the perspective of ELY, the best target group of synthetic fuel production from solar electricity would be industries that consume a significant amount of fuel, and that have available land or roof area that could be covered by solar panels. Also, for industries where electrification is challenging, there are opportunities to reduce emissions by utilising synthetic fuels. Additionally, companies that travel for

business a lot could profit from the use of these fuels. The self-sufficiency possibilities for operators could function as a motivator to proceed with these kinds of projects. Such projects could also indicate to stakeholders that the company strives to reduce their emissions, and that the company functions more sustainably compared to competitors. Overall, the possible routes to decrease the operators' carbon footprint with synthetic fuel production should be detected in the planning phase already. The operators' need for certain synthetic fuel should be as part of the conversations and whether the RFNBOs should be regarded as an option. Additionally, the restrictions regarding the land area that is determined to be utilised in the production should be assessed in detail.

Overall, the methanol conversion presented better results in terms of production per land area compared to methanation. Also, methanol conversion presents less side streams, the same land area could be utilised in more end-products, which would assumably be a contributing factor to an operator when considering synthetic fuel production. In the methane production all CO_2 and H_2 put into the system cannot be utilised. However, due to the ten times higher electricity consumption in synthesis, the methanol emissions are higher as well. The methanol production could benefit from renewable electricity consumption in the synthesis, especially if the production was industrially scaled. The use of renewable energy utilisation in synthesis might result in favour to methanol compared to methane, as more methanol can be produced from the same solar panel area. As the selected end-product determines restrictions regarding the land area requirements, the more alterations between different soil types and soils effect on the overall results should be further studied. Additionally, it was noticed that material selection and the alternative material disposal methods impact greatly in the overall emissions. However, it can be assumed that when solar panel technologies advance, the higher fuel production can be reached. If the operators want to achieve the most amount of end-product, which would be assumable from economic point of view, higher efficiencies of the process phases should be regarded as an option. Heat utilisation was detected to impact the emissions as well. Therefore, ELY Centre should focus regard these issues when discussions with solar power project operator emerges.

8. Conclusions

The aim of this study was to receive results, that would develop the climate impact assessment of solar power projects, and to analyse the impact of synthetic fuel production from a solar source. It was important to identify all the process phases and their material and energy inputs to receive results from the overall impacts of the process. The process phases were discussed in detail in order to produce metadata for educational purposes. The goals of the study were met by conducting a comparison between end-product and directive-based assessment. The two different approaches considering the calculations aimed to show the results in more comprehensive manner. The motivation behind the LCA approach was to help the decision making as the requirements regarding for example the materials, land use and electricity consumption were discussed further. Also, the results of this thesis could be used as a guideline for ELY in cases which the operators are interested in solar electricity derived synthetic fuel process but haven't proceeded with the project planning and selected the end-product yet. The RED III approach aimed to detect whether it is possible to stay within the threshold values and provide more end-product approach. These results could be utilised in cases in which the RFNBO end-product is already determined to be produced. Additionally, studying the overall efficiencies and discussing what factors should be considered, when requirements are imposed on solar project operators, provided more profound results that would help the decision making of ELY-centre.

Based on the literature, there is multiple paths that end up in the same outcome. There is a variety of different technologies and methods that can be utilised in P2X processes. However, it can be assumed that other technologies could perform better than others. Furthermore, the production of synthetic fuels from renewable energy sources is a relatively new industry, as conventional fuels have dominance in the transportation sector. Therefore, it was quite challenging to find practical or other studies that would address the same input data that this thesis did. Thus, it was not possible to compare the results of this study to other studies.

It was noticed that methanol compared to methane production would result in more end-product when the same land area of solar panels is used. Hence methanol results in greater overall efficiency. The higher the electrolyser efficiency, the more end-product it is possible to obtain. However, the higher efficiency leads to less emission reductions, as less heat is generated. Even with heat utilisation, the hydrogen production was detected to have most effect on the overall emissions. Based on the results, the most significant factors contributing to the hydrogen production emissions were materials and land use. Also, the methanol generates more emissions as the methanol conversion consumes much more electricity than methanation. On the other hand, the RED III threshold values were able to be met with methanol production. However, the RED III study defines the whole hydrogen production emission-free.

The utilisation possibilities of both methanol and methane are versatile, as they can be used in the road, maritime and aviation sectors, and they would not require many changes in the existing fossil fuel infrastructure. Even if all industries could not utilise the synthetic fuel production, possibilities for production were detected in sectors that consume a lot of fuels on a daily basis and/or have challenges in electrification. If a company or an industry has a need for emissions reductions, and spare surface area is available, self-sufficient synthetic fuel production could impact the company image towards the stakeholders. Additionally, it could be possible to increase the company's competitiveness compared to competitors. Through the results it was possible to detect the most important factors for ELY Centre to address when discussing requirements of the solar power projects with operators. For example, the need of the operators defines the process phases and end-products. It was detected that the synthetic fuel production might not be applicable for all solar electricity projects but could provide a solution when decreasing the carbon footprint. Additionally, as a disadvantage of more produced fuels it the factor the energy losses throughout the process chain. Due to this the end-product maintains only a fraction of the input energy amount.

Overall, it should be acknowledged that this study is a thesis work and hence uncertainties may occur. For example, data collected for the study was secondary. Although efforts were made to select data that is compatible with each other, some inconsistencies may be found

as data had to be combined from several different sources. For instance, it was detected that depending on whether the hydrogen emissions are based on the solar electricity production or on hydrogen production, the overall emissions alter at some level. The sensitivity analysis was conducted to determine how emissions would change depending on the emission factor. As this thesis was conducted with Excel rather than a software that is specifically meant for the LCA calculations, the reliability decreases at some level since some calculation errors might have been harder to detect. Additionally, certain assumptions were to be made and thus some uncertainties could have occurred. Also, all factors that could have affected the results may have not been considered or were left outside research parameters to ensure that the scope of the master's thesis was not exceeded. For example, as this study focused only on the land use rather than land use and change, the results might vary from more specific assessment. Based on the literature findings it was noticed that depending on the soil type the effects on the environment might differ greatly. The land area that was at one point utilised in peat production and is wetted, could function as a carbon sink in the use phase and therefore enhance the carbon handprint of the project. To produce more comprehensive results from land used and how it affects the overall emissions, further research should be conducted. Despite this, all uncertainties were tried to be detected and discussed. Also, comprehensive results were received and the conclusions, as well as the comparison between the different application scenarios, were made. Therefore, it can be summarised that this study offers a good foundation for further research of methanol and methane production from solar electricity.

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Appendix I, 1. Inventory data – Annual inputs and outputs

Solar electricity				
Electricity	**Amount**		**Unit**	**From**
Nominal power	0.2		kW_p/m^2	Motiva a.
Electricity production	0.18		kWh/m^2	Motiva a.
	648		MJ/m^2	Motiva a.
Electrolysis				
Inputs	**Amount**		**Unit**	**From**
	LHV 63 %	**LHV 70 %**		IEA. 2019.
H2O	30.6	34.0	kg/m^2	IEA. 2019.
Electricity	648		MJ/m^2	Motiva a.
Outputs	**Amount**		**Unit**	**From**
	LHV 63 %	**LHV 70 %**		
H_2	408.2	453.6	MJ/m^2	Calculation based on efficiencies
Heat/steam	165.6	112.0	MJ/m^2	Calculation based on efficiencies
Heat that could be utilised in DH	132.5	89.6	MJ/m^2	80 % heat exchanger efficiency assumption
O_2	27.2	30.2	kg/m^2	IEA. 2019.
Methanation				
Inputs	**Amount**		**Unit**	**From**
	LHV 63 %	**LHV 70 %**		
CO_2	18.6	20.6	kg/m^2	Uusitalo et al. 2017.
H_2	3.4	3.8	kg/m^2	Uusitalo et al. 2017.
Electricity	7.6	8.5	MJ/m^2	Uusitalo et al. 2017.
Outputs	**Amount**		**Unit**	**From**
	LHV 63 %	**LHV 70 %**		
CO_2	0.9	1.0	kg/m^2	Uusitalo et al. 2017.
H_2	0.2	0.2	kg/m^2	Uusitalo et al. 2017.
CH_4	321.6	357.3	MJ/m^2	Uusitalo et al. 2017.
H_2O	14.4	16.0	kg/m^2	Uusitalo et al. 2017.
Heat	67.6	75.1	MJ/m^2	Uusitalo et al. 2017.
Methanol conversion				
Inputs	**Amount**		**Unit**	**From**
	LHV 63 %	**LHV 70 %**		
CO_2	24.7	27.5	kg/m^2	Uusitalo et al. 2017.
H_2	3.4	3.8	kg/m^2	Uusitalo et al. 2017.
Electricity	85.6	95.1	MJ/m^2	Uusitalo et al. 2017.
Outputs	**Amount**		**Unit**	**From**
	LHV 63 %	**LHV 70 %**		
CO_3OH	358.1	397.9	MJ/m^2	Uusitalo et al. 2017.
H_2O	10.0	11.1	kg/m^2	Uusitalo et al. 2017.

Appendix I, 2. Inventory data – Annual inputs and outputs

Heat	22.0	24.5	MJ/m^2	Uusitalo et al. 2017.
MEA absorption - for methanation				
Inputs	**Amount**		**Unit**	**From**
	LHV 63 %	**LHV 70 %**		
MEA	0.0059	0.0065	kg/m^2	Volkart et al. 2013.
Heat	64.6	71.7	MJ/m^2	Volkart et al. 2013.
Electricity	11.4	12.6	MJ/m^2	Volkart et al. 2013.
CO_2	20.6	22.9	kg/m^2	Volkart et al. 2013.
Outputs	**Amount**		**Unit**	**From**
	LHV 63 %	**LHV 70 %**		
CO_2	18.6	20.6	kg/m^2	Volkart et al. 2013.
MEA absorption - for methanol conversion				
Inputs	**Amount**		**Unit**	**From**
	LHV 63 %	**LHV 70 %**		
MEA	0.0078	0.0087	kg/m^2	Volkart et al. 2013.
Heat	86.0	95.5	MJ/m^2	Volkart et al. 2013.
Electricity	15.1	16.8	MJ/m^2	Volkart et al. 2013.
CO_2	27.5	30.5	kg/m^2	Volkart et al. 2013.
Outputs	**Amount**		**Unit**	**From**
	LHV 63 %	**LHV 70 %**		
CO_2	24.7	27.5	kg/m^2	Volkart et al. 2013.

Appendix II. Solar power plant gridding options