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# Life Cycle Assessment of synthetic hydrocarbons for use as jet fuel: "Power-to-Liquid" and "Sun-to-Liquid" processes

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# Contents

# Abbreviations /Glossary/Definitions

| | |
|---|---|
| BG | Biogas |
| BM | Biomethane. Upgraded biogas, i.e. with a higher methane content than in biogas. |
| BtL | Biomass-to-Liquid (for production of biofuels) |
| CCU / CCS | Carbon Capture and Utilization / Carbon Capture and Storage |
| CH | Switzerland |
| $CH_4$ | Methane. May contain fossil or biogenic Carbon. |
| CO | Carbon Monoxide |
| $CO_2$ | Carbon Dioxide |
| CORSIA | Carbon Offsetting and Reduction Scheme for International Aviation |
| CSP | Concentrated Solar Power |
| DAC | Direct Air Capture |
| DNI | Direct Normal (solar) Irradiation |
| ENTSO-E | European association for the cooperation of transmission system operators (TSOs) for electricity |
| ES | Spain |
| FT | Fischer-Tropsch synthesis: Process which converts syngas with a specific $H_2$:CO ratio (usually 2:1 molar reached through water gas-shift) on a catalyst bed (mostly Iron or Cobalt, with Nickel or Ruthenium as alternatives) into hydrocarbon mixture ("syncrude") which is then split into various fuel products. The exothermic process generally runs at temperatures between 150°C and 300°C and needs cooling. |
| FT PtL | Fischer Tropsch Power-to-Liquid pathway |
| GHG | Greenhouse Gas Emissions. Indicator for the Life Cycle Impact Assessment method "Climate Change" |
| GWP | Global Warming Potential |
| $H_2$ | Hydrogen |
| $H_2O$ | Water molecule |
| HTHP | High-temperature Heat Pump |
| ICAO | International Civil Aviation Organisation |
| IPCC | Intergovernmental Panel on Climate Change |
| Jet Fuel | Jet Fuel A-1 is abundantly used for powering aircraft. It is a carefully refined, light petroleum. |
| kerosene | kerosene is a fuel type used in turbine engines of aircraft. Usually, the fuel used is Jet A-1. This report uses the generic term "kerosene", and does imply one specific type of kerosene. Variations within the kerosene class are not supposed to have substantial influence on the LCA results. |
| LCA | Life Cycle Assessment |
| LCI | Life Cycle Inventory |
| LCIA | Life Cycle Impact Assessment |
| LHV | Lower Heating Value |
| LPG | Liquefied Petroleum Gas – a potential co-product from kerosene production |
| LY | Libya |
| MeOH | Methanol |
| MeOH PtL | Methanol Power-to-Liquid pathway |
| NL | Netherlands |
| NG | Natural gas |
| PEM | Polymer Electrolyte Membrane, used in water electrolysis for $H_2$ production |
| PtL | Power-to-Liquid |
| PV | Photovoltaics |
| RWGS | Reverse Water Gas Shift. Reaction needed during syngas synthesis. |
| SAF | Sustainable Alternative Fuel |
| StL | Sun-to-Liquid |
| Syncrude | Mixture of hydrocarbons. Equivalent to the conventional crude oil. Is split into various fuel products such as gasoline, kerosene, diesel, naphtha, lubricating oil in the Fischer-Tropsch process. |
| Syngas | Mixture of $H_2$ and CO which has the advantage to not include inert $CO_2$ |
| US | United States |

# Summary

Low carbon synthetic kerosene will be part of the decarbonisation portfolio in the aviation sector. This project evaluates the environmental impacts of the production of synthetic kerosene. The report presents the results of a Life Cycle Assessment of synthetic kerosene produced via a Fischer-Tropsch Power-to-Liquid (FT PtL) pathway, a methanol PtL (MeOH) pathway, and three designs of a Sun-to-Liquid (StL) production. The geographical scope is Switzerland and Europe, and the assessment represents current or near-future conditions.

The results show that the **synthetic kerosene in general allows for a reduction in greenhouse gas (GHG) emissions** – and thus impacts on climate change - compared to its conventional, fossil-based counterparts. The use of low-carbon or waste energy sources for obtaining hydrogen ($H_2$) and carbon dioxide ($CO_2$) combined with optimised process design leads to reductions in GHG emissions of over 70% and going up to nearly 95% compared to the fossil benchmark value of 89 g $CO_2$-eq/MJ (3.9 kg $CO_2$-eq/kg) as defined by (CORSIA 2019). Carbon neutrality can just about be reached via the use of biogas from biowaste as carbon source in the StL reforming of methane pathways. But also the two PtL and a pure thermochemical StL pathway can reach very low climate change impacts with only ca. 5 to 10 g $CO_2$-eq/MJ kerosene (>90% reduction potential). Most decisive are the electricity source for the water electrolysis process for $H_2$ production as well as the greenhouse gas intensity of the capture process of the required $CO_2$. This latter depends on the $CO_2$ source – industrial or Direct Air Capture (DAC) – and which electricity and heat sources are used for the capture process. Furthermore, the use of $CO_2$ captured from industrial processes demands a common understanding on which of the involved partners gets the credit of decreasing $CO_2$ emissions via the use of such "recycled" $CO_2$, as no double counting of such credits must occur.

**Data availability** for specific process designs is scarce, and detailed data on the refining of synthetic hydrocarbons ("syncrude") to synthetic fuels could not be found or approximated in depth because of the complexity of the refining processes and the physical properties of the involved oils and waxes. Existing refineries will have to be involved in refining of increasing volumes of syncrude. Likewise, reliable data on processing the methanol to synthetic kerosene could hardly be found. The Fischer-Tropsch based PtL pathway has been modelled based on one study. The Methanol PtL pathway only covers the synthetic methanol production in detail.

For **both types of PtL designs**, obviously the choice of the power source for the electrolysis is most important. The greenhouse gas (GHG) intensity of input electricity is heavily reflected in the results for the PtL pathways, while it plays a minor role in StL which nearly exclusively uses in-house low-carbon solar energy as energy supply. It is an important finding of this work that it is not sufficient to switch to renewable electricity sources in general - such as wind, PV, or reservoir hydropower. All these may only allow for minor reduction potential, starting from only 16% reduction in case only the electrolysis process is driven by these sources, and all other processes still rely on medium- to high carbon electricity sources such as the general European grid mix. This can however be optimised when all processes which can be controlled by the producer of the synthetic fuel ($CO_2$ capture, electrolysis, synthesis of the fuel) are driven by very low-carbon energy sources for both heat and power input. These are namely run-of-river hydropower, concentrated solar power without backup firing of natural gas, or wind and solar plants at sites with very favourable conditions.

Detailed data for the **various StL pathways** were provided by Synhelion, a company aiming for large-scale production of synthetic kerosene via the use of solar energy. Promising reductions of up to 90% compared to climate change impacts of conventional kerosene can be reached with their pure solar thermochemical process design. The two pathways relying on reforming of methane approach carbon neutrality when the carbon source is from biogas produced from biowaste. The use of high-temperature solar heat allows for process optimisation, and also coupling of the production plant with industries such as the cement industry, so that decarbonisation is reached for both the industrial process as well as for the production and use of synthetic kerosene.

The economic implications of the findings of this work have not been part of the study. **The prices for $CO_2$ emissions, $CO_2$ from DAC or industry, renewable electricity sources, and waste or renewable heat** sources will be decisive for the resulting total cost of the synthetic kerosene. But not only this, also the (local) availability of $CO_2$ point sources, renewable energy, biomass, or transportation and storage possibilities for $CO_2$, $H_2$ and kerosene will steer the actual design of the production process.

This work shows that **synthetic kerosene can contribute to decarbonisation of the aviation sector.** Work building on top of this report should showcase the **transition pathway** to reach that goal, starting from today and reaching out to the near future. Optimal production sites (with regards to e.g. location, availability of renewable energy, its storage, and availability of $CO_2$) have to be designated, transport and storage of the synthetic kerosene need to be organized, and the refineries have to start including syncrude in their processes as soon as significant volumes can be produced.

# 1 Introduction

Direct $CO_2$ emissions from air traffic were responsible for around 2.4% of the total global $CO_2$ emissions from fossil fuel use in 2018 (Graver et al. 2019). This makes the total of all airlines stand on the same rank as the countries in the lower world’s top 10 greenhouse gas emitter countries[1]. In addition, a variety of effects on climate from air traffic contribute on top of these direct emissions, such as reflection of solar radiation, $NO_x$ emissions leading to changes in stratospheric ozone production or sulfate aerosols increasing reflectivity of low altitude clouds. Depending on the research question, flight activity, fuel type, or temporal scope, such effects may contribute with one tenth or a multiple of the direct $CO_2$ emissions to the combined climate effects of air traffic (Lee et al. 2021). In Switzerland, 12.5% of the total Greenhouse Gas emissions in 2019 stem from direct $CO_2$ emissions from national and international flights, with a rising tendency (BAFU 2015).

The so-called “Carbon Offsetting and Reduction Scheme for International Aviation” (CORSIA) is a global market-based instrument that aims to stabilize the $CO_2$ emissions caused by the aviation sector on the level of the year 2020 via offsetting international aviation $CO_2$ emissions. The CORSIA scheme has been agreed on in 2016 by the International Civil Aviation Organization (ICAO). It “obligates airlines to monitor and report their emissions and to purchase emission reduction units generated by projects in other sectors, to cover any growth in $CO_2$ emissions above 2020 levels from 2021.”[2] As per beginning of 2021, 88 states participated in that scheme, including Switzerland[3,4]. A total of 107 states have confirmed mandatory or voluntary participation by the beginning of the year 2022. This is important as only routes flown between participating states must be offset. In its first phase (2021-2026), CORISA will cover around a third of all aviation emissions[4]. The second phase (2027-2035) will make participation in CORISA mandatory for most states[2], and thus increase the incentives to reduce $CO_2$ emissions.

However, it is expected that the total amount of flight person kilometers will continue to increase in the coming decades, so that offsetting and increased efficiency will only have a limited effect. Further, alternative drives will not be suitable for long haul flights for the time being, so that sustainable alternative fuels (SAFs) with rather high energy density will become major players for a reduction of flight greenhouse gas emissions (Schmidt et al. 2018; Pavlenko and Searle 2021). Such alternative fuels include hydrocarbons from biogenic feedstocks (“***biofuels***” or ***“Biomass-to-Liquid (BtL)***) on the one hand and ***synthetic fuels*** on the other hand. The latter are in the focus of this analysis, namely produced via ***“Sun-to-Liquid” (StL)*** and “***Power-to-Liquid” (PtL)*** fuels. SAFs still don’t play a role in the aviation sector as per today: Less than 0.01% of the needed amount of aviation fuels were provided from alternative sources in 2018 (Pavlenko and Searle 2021). Seven fuels have so far been certified for use in aviation by the ASTM International standards organization (Pavlenko and Searle 2021), and regulations for blending SAFs with conventional jet fuels apply. Due to rigid safety standards, the use of synthetic kerosene in aircraft is regulated in detail with regards to chemical and physical specifications and blending into conventional kerosene.

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[1] https://www.wri.org/insights/interactive-chart-shows-changes-worlds-top-10-emitters

[2] https://www.southpole.com/what-is-corsia-and-how-does-it-affect-your-airline

[3] https://www.icao.int/environmental-protection/CORSIA

[4] https://github.com/dw-data/corsia. This GitHub page visualises country participation and emissions (forecasts) of the CORSIA initiative.

**This work is on synthetic kerosene, i.e. biofuels are not part of the content of this report.** An overview on the PtL and StL production pathways is provided in Figure 1.

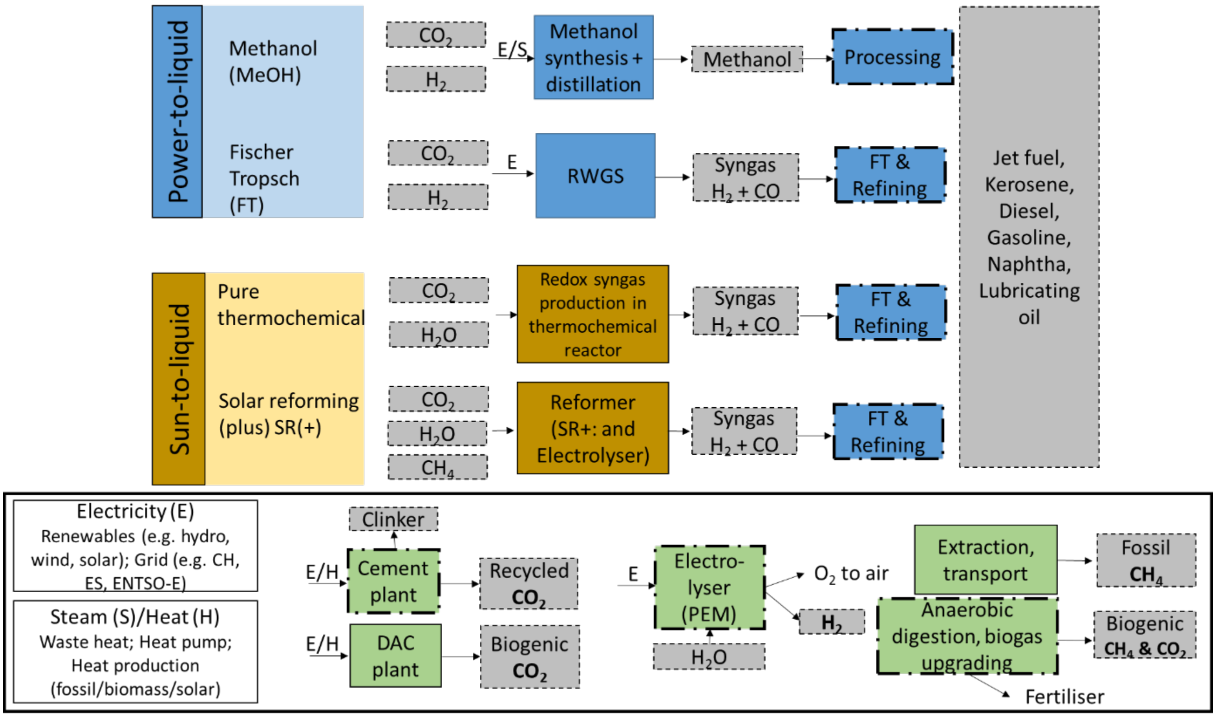

*Figure 1: Simplified PtL and StL pathways, with underlying inputs shown in the box at the bottom. The slash-dotted boxes indicate multi-output processes where choices have to be made on how to attribute environmental burdens of the process to the individual co-products. Grey boxes with dotted line indicate a molecule, gas or fuel. RWGS = reverse water gas shift; DAC = direct air capture; FT = Fischer Tropsch. Within FT, the syngas is converted into liquid hydrocarbons, which are then refined to the desired fuels.*

In ***methanol-based PtL (MeOH PtL)*** pathways, methanol is turned into liquid fuel. In conventional production, methanol is produced by using fossil feedstocks, running them through a reformer to produce syngas. The latter is sent to a reactor and distillation. Several renewable production pathways for methanol are under development or exist based on biomass, municipal waste, or power. In the methanol PtL pathway, hydrogen is again produced via electrolysis and then combined with $CO_2$. Other than in the Fischer-Tropsch PtL pathway and in the conventional methanol production, $H_2$ and $CO_2$ are directly turned into methanol in a reactor with subsequent distillation to e-methanol. Processing of the e-methanol is then needed to turn it into jet fuel.

***Fischer-Tropsch based PtL*** (FT PtL) pathways convert electrical power into liquid fuel with hydrogen and $CO_2$ as inputs. In a first step, hydrogen is produced via electrolysis and then combined with $CO_2$. As the latter is an inert gas, it is turned into CO via reverse water gas shift in a second step. The mixture of $H_2$ and CO with a ratio of ~2:1 is the syngas. ***StL pathways*** make use of the high temperatures available from solar energy, so that the production of $H_2$ and CO usually happens in one single step. The syngas from both pathways is then processed to liquid fuel in two steps: First, the syngas is fed into the Fischer-Tropsch reactor and leaves it as hydrocarbon liquid. This mixture of hydrocarbon waxes may also be called "syncrude" and is somewhat comparable to petroleum/crude oil. Complex refining processes then result in several liquid fuels, while maximizing the volume of the target fuel – in our case kerosene - is the goal.

A short note. The Fischer-Tropsch process is the conversion of syngas into hydrocarbons only, while often one of the complete potential PtL pathways is called “Fischer-Tropsch”. This naming of the Power-to-Liquid pathway “Fischer-Tropsch” may be slightly misleading to believe that the full process chain is “Fischer-Tropsch”, which is not the case. The actual “Fischer-Tropsch” process is also used within the Sun-to-Liquid pathway as one processing element. In this report, we try to differentiate clearly between the “FT process” itself, and the “FT PtL pathway”. Further, the FT process is in literature not always clearly separated from other processes happening to supply the FT process itself with inputs (e.g. syngas), or separated from the refining process, so that comparison of energy balances and information in literature needs to be done with care, and data for the individual steps in the full chain cannot always be found due to aggregation.

Synthetic kerosene may be produced at various locations within Europe and on the World, and combinations of locally available renewable energy and $CO_2$ resources can optimise not only the environmental performance of synthetic kerosene, but also the economic and social costs of production, transport and use. **This study focuses on Switzerland and Europe.**

PtL pathways have already reached high **levels of technology readiness (**TRL >7), and some have successfully been demonstrated in practice[5]. StL pathways have successfully been demonstrated at pilot scale (TRL >6). TRL of the processes supplying $CO_2$ (DAC, industrial $CO_2$ capture) and $H_2$ (e.g. high-temperature electrolysis) are partly still lower (TRL >5).

The individual pathways are shortly explained on a technical level in the following subchapters, while details on the modelling choices for the PtL and StL processes are given in chapter 3. Before, chapter 2 explains the methodology for performing the Life Cycle Assessment. Chapter 5 presents the results of the LCA, and chapter 6 concludes this study with a summary of the major findings and an outlook.

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[5] The worlds’ first production plant for $CO_2$ neutral synthetic kerosene from wind power and $CO_2$ from biowaste has started production in October 2021 in Werlte, Germany. https://www.solarify.eu/2021/10/04/173-werlte-produktions-anlage-fuer-co2-neutrales-synthetisches-kerosin-eroeffnet/

## 1.1 Power-to-Liquid (PtL)

The production of synthetic fuels with PtL can be performed via three pathways:

A) Fischer-Tropsch (FT) synthesis

B) Methanol (MeOH) synthesis

C) others, such as Dimethylether (DME) or Oxymethylenether (OME)

The first two are well-known when based on fossil raw materials, being used for large-scale and continuous full-load production of fossil-based liquid fuels in gas-to-liquid plants. However, the combination with electricity from renewables and $CO_2$ from industrial processes may require a shift to more flexible, part-load and small-scale concepts, and/or these new production pathways will need to be scaled up (Dieterich et al. 2020). Further, electrolysis efficiency and carbon capture methods need to be improved. In addition, only the products from Fischer-Tropsch and subsequent refining can readily be used in aircraft, while methanol, DME and OME require further processing for this use. Only FT and Methanol pathways are part of this report.

***Fischer-Tropsch (FT) PtL synthesis:*** Within the FT PtL chain, hydrogen ($H_2$) and $CO_2$ are combined to react to syngas – a mixture of $H_2$ and CO in order to get rid of the inert $CO_2$. The preferred process to get rid of $CO_2$ is a reverse water-gas shift (RWGS) reaction. The *hydrogen* is produced via *water electrolysis* ($H_2O$) using electricity (power), while the *$CO_2$* has to be *captured* either in industrial processes or from the atmosphere. The *syngas* with a specified $H_2$:CO ratio (ca. 2:1) is further converted within the Fischer-Tropsch process to *syncrude (a mixture of hydrocarbons)* at temperatures of around 200-350°C and pressures between 10-50 bar (Evans and Smith 2012)[6]. The presence of an iron or cobalt catalyst is required. The syncrude is composed of hydrocarbons with various lengths. It is then split into various fuel products via distillation based on varying boiling points. The complete process includes hydrocracking, isomerization, and distillation, as already well-known from conventional refineries for crude oil. The resulting fuel is cleaned according to the needs of the final intended use. This step is steered such that the educts are optimised for the desired fuel, such as gasoline, kerosene, or diesel. The energy requirements can be decreased significantly with smart energy integration designs of the FT process, and the plant overall efficiency can further be improved by recirculating off-gases (Marchese et al. 2020). Compared to the storage of the electricity from renewables in batteries or use in Power-to-Gas (PtG) processes, the PtL products show advantageous energy densities and may thus serve for efficient coupling of the power and the mobility sector, potentially embracing the industry using fossil raw material via carbon capture and utilization (Dieterich et al. 2020). And overview on current pilot and demo FT PtL plants is presented in (Dieterich et al. 2020).

The FT process modelled in this work is based on a publication modelling the production of hypothetical fuels from $CO_2$ using proven technologies and relying on the performance of data of a gas-to-liquid plant of Shell in Qatar converting natural gas into syngas with subsequent converstion into liquid fuel (Van Der Giesen et al. 2014). Details are given in chapter 3.1.

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[6] Both high-temperature (>300°C) and low-temperature (ca. 180°C-250°C) processes exist.

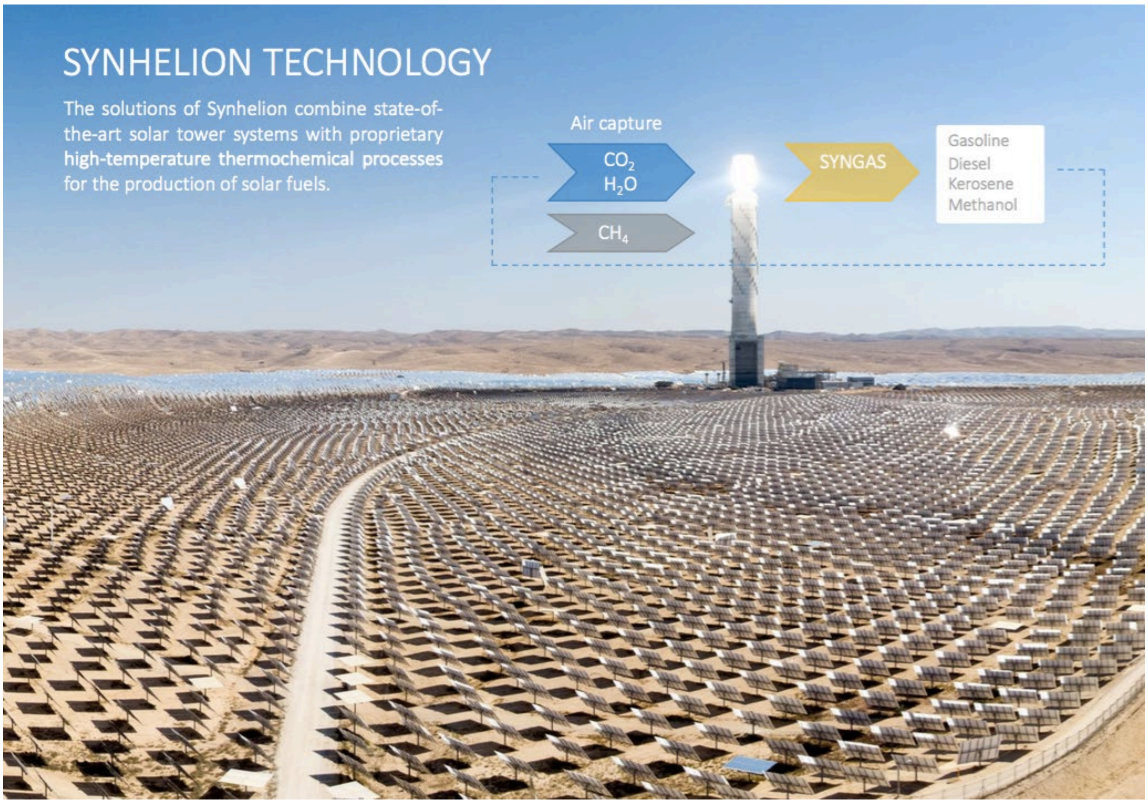
***Methanol synthesis and processing to liquid fuel:*** In this production pathway, *syngas* is combined with catalysts which are mixtures of copper, zinc oxide, alumina or magnesia in a highly exothermic reaction most commonly performed in a fixed-bed reactor at a pressure of around 20 to 60 bar (Dieterich et al. 2020). Production of the methanol is done either in a one-step process from $CO_2$ and $H_2$ directly not requiring a reverse water gas shift reaction. Alternatively, a two-step process to produce first syngas and then methanol can be done. The methanol is *synthesized* and *distilled*. Then, it may be upgraded and used directly in gasoline-methanol blends, or can serve as raw material for the production of fuels such as gasoline, diesel, or kerosene. Processes for the latter are in development and not well described in literature. Currently, most methanol production uses steam methane reforming of natural gas. One commercial plant for $CO_2$ to methanol conversion exists in Iceland, using $CO_2$ from geothermal flue gas (Dieterich et al. 2020).

The methanol synthesis process modelled in this work is based a publication modelling of a specific methanol production pathway integrated into a cement plant on the one hand (Meunier et al. 2020); and a second publication modelling of methanol synthesis for production of Poly(oxymethylene) dimethyl ethers (OME) for use in vehicles on the other hand (Hank et al. 2019). Turning the methanol into kerosene is a largely unknown process as per today. An approximation is made based on data presented in (Albrecht et al. 2013). Details are given in chapter 3.1.3.

## 1.2 Sun-to-Liquid (StL)

In contrast to the PtL pathway, the energy from sun does not make a detour via electricity and separated electrolysis, but the high temperatures enabled by concentrating solar energy are directly used to drive the reaction to produce syngas. This implies less conversion losses and thus higher efficiency of the process. The only inputs needed are therefore solar energy, $H_2O$ and $CO_2$.

For the modelling of the StL pathway, collaboration with *Synhelion* was established. Synhelion is a spin-off from ETH Zürich which develops a fully integrated StL pathway for production of synthetic kerosene, aiming to supply half of the Swiss kerosene use by 2030 and even covering half of all European flights by 2040. Within this time horizon, Synhelion wants to develop and commercialize the coupling of direct capture of $CO_2$ and $H_2O$ from air with large heliostat fields, solar towers and receivers, and conventional Fischer-Tropsch, thus using solar heat to turn $CO_2$ and $H_2O$ into synthetic fuels (Figure 2).


SYNHELION TECHNOLOGY

The solutions of Synhelion combine state-of-the-art solar tower systems with proprietary **high-temperature thermochemical processes** for the production of solar fuels.

*Figure 2: How the Synhelion StL pathway for production of synthetic fuels looks like. Taken from https://www.solarpaces.org/at-Synhelion-solar-jet-fuels-get-ready-for-take-off/*

Synhelion has already produced syncrude at demonstration plants, and is currently scaling up and optimising at sites in Madrid, Spain (1000 m$^2$ solar field) and Germany (20’000 m$^2$)[7].

At the current development stage, additional input of methane ($CH_4$) is needed to run a solar reforming pathway (see chapter 3.2). However, a pure thermochemical pathway was demonstrated at pilot scale (Schäppi et al. 2022) and is now scaled-up and also shown in this work. Synhelion has established collaboration with cement plants to secure the $CO_2$ needs. The aim is to switch the energy

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[7] https://Synhelion.com/about/news/the-road-to-market-for-solar-fuels

supply to the cement plants to be full solar[8]. Synhelion further envisages direct air capture on site as a $CO_2$ source.

## 1.3 Existing literature

Literature exists on synthetic kerosene from biomass (Cox et al. 2014; Neuling and Kaltschmitt 2018; Doliente et al. 2020; Liebich et al. 2021a; Pavlenko and Searle 2021), but recent and robust publications on life cycle assessment of synthetic kerosene via PtL or StL are scarce (Liebich et al. 2021a; Zang et al. 2021c).

Default GHG emission values including combustion as defined by CORSIA for **biofuels** range between **5 g $CO_2$-eq/MJ and 60 g $CO_2$-eq/MJ –** compared to the fossil benchmark fuel with 89 g $CO_2$-eq/MJ**.** When indirect land use changes are included in the calculation, the results increase by ca. one third in most cases, and decrease in some specific cases (ICAO 2021a; Pavlenko and Searle 2021). Several other studies summarized in (Pavlenko and Searle 2021) agree with this range, presenting values from **15 up to 62 g $CO_2$-eq/MJ**. Biofuels from various sources are discussed in (Doliente et al. 2020), who collected GHG emission values from various publications. They are within the huge range of **-2 g $CO_2$-eq/MJ up to 150 g $CO_2$-eq/MJ**, or even 730 g $CO_2$-eq/MJ in one case, depending on the feedstock (and probably also the modelling assumptions). Savings compared to fossil jet baseline collected from two publications are between 35%, and going up to ca. 98%. Significant decarbonisation of aviation via biofuels therefore needs careful evaluation of the feedstocks used. Further, dedicated energy crops inevitably raise concerns with regards to competition on land and water use of food production versus feedstock production, which imposes limits to scaling up of biofuels from dedicated crops.

A study by the Argonne National Laboratory (United States) provided a techno-economic analysis and LCA of **synthetic fuels** from Methanol or Fischer-Tropsch production (Zang et al. 2021c, b, a). This includes a detailed analysis of the availability of $CO_2$ from high or low concentration point sources in the United States (Zang et al. 2021c). Life cycle GHG emissions for synthetic methanol produced in a two-step pathway vary between **14 and 85 g $CO_2$-eq/MJ** for the modelled cases (cradle-to-grave), compared to 92 g $CO_2$-eq/MJ for conventional natural gas based methanol. This somewhat complements figures summarised in (Dieterich et al. 2020) for methanol production with wind energy or Icelandig grid electricity, resulting in 14 g $CO_2$-eq/MJ and 9 g $CO_2$-eq/MJ, respectively. The well-to-wheel results for synthetic “Fischer-Tropsch fuels” vary between **-9 g $CO_2$-eq/MJ and 44 g $CO_2$-eq/MJ** for the modelled cases.

A study commissioned by the German Environment Agency and performed by researchers at ifeu, DLR and Johanneum Research Forschungsgesellschaft has been published in 2021, based on work completed in 2019 (Liebich et al. 2021a). It contains life cycle assessment for comparison of the environmental impacts of specific production pathways including transportation of Fischer-Tropsch fuels, methanol, synthetic natural gas, biomethane, and hydrogen. Results for climate change impacts of **FT synfuels** vary between **carbon neutrality** (with residual straw as carbon source) **and ca. 20 g $CO_2$-eq/MJ** for the modelled cases. **Methanol production** comes with again nearly **carbon neutrality up to 25 g $CO_2$-eq/MJ**. Reduction potentials of up to 80% are identified already for today, increasing to a maximum of 95% for PtL pathways based on specific biomass. Kerosene was not part of the conventional reference products to which the synfuels were compared to (e.g. diesel, petrol).

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[8] https://www.solarpaces.org/cemex-and-synhelion-to-demo-zero-co2-cement/

## 1.4 Research questions

Synfuels from both PtL and StL pathways may show closed $CO_2$ cycles. This means that they are potential candidates for $CO_2$ neutral fuels in case the $CO_2$ input to the synthesis processes stems from direct air capture (DAC), biomass sources, or is regarded as “recycled” $CO_2$ from Carbon Capture and Utilisation (CCU) connected to industrial processes. However, a closed $CO_2$ cycle is not a guarantee for an overall beneficial environmental performance compared to fossil kerosene. Complete Life Cycle Assessments (LCA) are needed which include use of infrastructure, energy, materials, transportation, and also emissions to air, soil or water. This way, not only potential impacts on climate change can be quantified, but also other impacts on our environment such as land use or ecotoxicity. Trade-offs between such impact categories can be identified and considered in decision making processes.

This project is on life cycle assessment of synthetic kerosene produced via PtL or StL pathways. The goal of this study is to quantify the environmental impacts related to the Sun-to-Liquid and Power-to-Liquid processes. In particular, this study wants to answer the following three questions:

1. Which are the potential **life-cycle related environmental impacts of the production of synthetic kerosene via Power-to-Liquid and the Sun-to-Liquid (StL) pathways**?

2. How large is the potential **reduction of greenhouse gas emissions** per unit of fuel produced and combusted from PtL compared to StL and compared to conventional fossil kerosene? **Under which conditions** can these reductions be reached?

3. Does such a reduction of greenhouse gas emissions lead to an increase in negative environmental impacts of any other type (**“trade-offs”**)?

These questions tackle comparison of conventional versus synthetic kerosene production (1. and 2.), and ensures that trade-offs between environmental impact categories may be discovered (3.). Life Cycle Assessment (LCA) is best suited to do such comparative analyses. The study intends to inform both decision makers at governmental level and within industry. Even if LCA encompasses a variety of environmental impact categories, the focus of this report is on impacts on climate change.

Methodological choices have to be made with regards to multi-functional processes (see chapter 2.2.2). These are present during production of synthetic kerosene when a cement plant produces both clinker and $CO_2$, and with the refining process generating several co-products. In such cases, a decision has to be made how the environmental impacts caused by the underlying processes are distributed between (=”allocated” to) the various co-products, if product-specific environmental footprints are required.

Chapter 3 will explain that detailed data on the FT and the MeOH pathways are scarce and solely available for very case-specific configurations for synthetic kerosene production. No assertions can be made on the variability of potential other FT and MeOH production pathways. The StL pathway is modelled with detailed data specific to the engineering at Synhelion. Consequently, variation of technical efficiencies, size of the production processes, or scaling up are not shown in this report in order to not artificially increase the uncertainties. Still, the modelling is set up such that it embraces a large potential range of climate change impacts from kerosene from PtL or StL pathways. It further allows identification of the process elements driving the environmental impact scores.

The research does not include site-specific evaluation or specific potential supply chains of synthetic kerosene from the European region to Switzerland.

# 2 Methodology – Life Cycle Assessment

## 2.1 LCA and its impact categories shortly explained

Life Cycle Assessment (LCA) is regulated in the ***ISO standards 14040 and 14044***, and this work is based on those standards. LCA works such that after ***goal and scope definition***, all data necessary to model the processes under research are collected, resulting in the so-called ***"Life Cycle Inventory" (LCI).*** This encompasses not only all material or energy flows, transports, infrastructure and emissions in the foreground system (= the processes under research), but also all these aspects in the background of the system, such as all flows related to the production of steel used as an input to the foreground datasets.

Then, these flows are translated into environmental impacts in the ***Life Cycle Impact Assessment (LCIA)*** by aggregating them into impact categories and relating them to one reference flow. For instance, in the case of impacts on climate change, all emissions of greenhouse gases are compiled and put into relation to the radiative forcing of 1 kg $CO_2$ (in air) with factors (global warming potentials) specified by IPCC and based on physical measurements (IPCC 2021). Not all LCIA categories are so easily explained and show the same robustness. For example, the category "freshwater ecotoxicity" contains over 1000 substances emitted to various compartments (air, soil, water), and their exact toxicity compared to the reference substance may not be well known or directly measurable. Further, there exist various approaches for LCIA modelling. In this work, the **LCIA categories** as suggested in a handbook by the **International Reference Life Cycle Data System (ILCD)** are assessed (JRC 2010). The main part of this report focuses on a set of selected LCIA categories on the level of the kerosene production, excluding the end-use as discussed in section 3.7. Not all impact categories possess the same level of quality, due to e.g. complexity (thousands of substances with various (combined) toxic effects for ecosystems), data gaps (e.g. toxicity level not known for all substances), or data uncertainties (e.g. exact level of toxicity not known). Further, some of the impact categories contain redundant information, for instance when comparing "fossil fuel depletion" with "climate change impacts", as the latter are often driven by the combustion of fossil fuels. Results in chapter 5.1 are discussed for the following impact categories, all assigned with level of recommendation I ("recommended and satisfactory") or II ("recommended but in need of some improvements") in (Fazio et al. 2012) (Table 1). Land use is only of unsatisfactory quality (level III "recommended, but to be applied with caution") due to issues within the LCIA method itself and also due to inconsistencies within the implementation in the background Life Cycle Inventory databases. As a consequence, the results for land use have been assessed but have not been judged to be robust enough to be shown here.

*Table 1: Description of the life cycle impact assessment categories shown in the main body of this report.*

| **Impact category** | **Indicator** | **(Reference) Unit** | **Description** | **Example flows** |
|---|---|---|---|---|
| **Climate change** | Radiative forcing as Global Warming Potential, taken from IPCC with a 100 year time horizon | kg $CO_2$ eq | Human emissions have an effect on the heat radiation absorption which causes temperature rise and change of climate behavior on Earth. | $CO_2$, $CH_4$, $N_2O$, $SF_6$ |
| **Acidification** | Accumulated Exceedance | mol H+ eq | Atmospheric deposition in soil, water, ecosystems, organisms of pollutants with acid behavior. Measured in hydrogen ion concentration. | $SO_2$, $NO_X$, $NH_X$ |
| **Ozone depletion** | Ozone Depletion Potential | kg CFC-11 eq | Emissions of chlorinated fluorocarbons cause thinning of the stratospheric ozone layer, hampering the protective effect with regards to ultraviolet light. | CFC-12, HCFC-22 |
| **Respiratory effects, inorganic** | Human health effects associated with exposure to $PM_{2.5}$ | Disease incidences | Potential harm of the uptake of substances to the human body. | $NH_3$, $NO_X$, $SO_2$, $PM_{2.5}$ |

A word on the **time horizon** chosen for the **Global Warming Potential (GWP)** indicator, which gives the relative effect of a pulse emission by quantification of the energy trapped by this emission over a certain time horizon. The related future global warming impacts are aggregated over time, so that specification of a time horizon over which future warming is looked at is required. IPCC has defined these time horizons to be 20 years, 100 years, or 500 years, respectively. The GWP of $CO_2$ is always set to 1 as the reference substance. The related GWP value for all other substances varies with the chosen time frame, as the decay or adsorption of the gases in the atmosphere happens at different rates – and with that the relative energy absorbed by a gas over a certain time frame. For many substances, the GWP-20 value is higher than the one for GWP-100, which means that relative to the release of 1 kg of $CO_2$, the effect of releasing such a substance on the climate is high in the beginning of its life. For instance, $CH_4$ emissions come with a factor of 27.9 for GWP-100, while this increases to 81.2 for GWP-20 due to the relatively short atmospheric lifetime of methane of around twelve years (IPCC 2021). This means that the temperature change caused by a one-off pulse of methane is actually highest at the time of emission, and declines with time.

The choice of the time horizon thus can change LCA results for climate change drastically when large volumes of $CH_4$ are emitted during the life cycle analysed. This can for instance be the case in the natural gas supply chain. There is no general correct approach for the choice of the time horizon. As described in (Bauer et al.), “a focus on stabilizing the climate at below 2°C warming in 2100 implies a longer time horizon such as that incorporated in the GWP-100 index, which is commonly used in long-term scenario analysis and LCA. With the 2015 Paris Agreement as well as increasing awareness about near-term climate damages and potential tipping points, the scientific and political debate have shifted to limiting peak warming to close to 1.5°C. As 1.5°C will likely be reached before 2050, this shift emphasizes the importance of avoiding warming in the next decades, which supports using shorter global warming potential time horizons such as GWP-20 in addition to GWP-100 and thus balancing short-term with longer-term emissions.” The latest IPCC report points out that the focus needs to be laid on mitigating both short-lived species and long-lived species to reach a temperature peak and a decline (IPCC 2021).

Most LCA studies in the past, and still today, choose a 100 years time horizon with the corresponding GWP values as given by the IPCC. The “CORSIA methodology for calculating actual life cycle emissions values” (ICAO 2021b) correspondingly asks for the use of the 100 year time frame. This study adopts the choice of 100 years time frame, and only shows few selected climate change impact scores for the 20 years time horizon in Figure 19. However, political decision makers should be made aware that the coming few decades will be decisive for the climate on our planet, and that looking at a duration of 100 years might be too far reaching when it comes to release of specific greenhouse gases today in the coming years.

All LCA calculations are performed in the open source software “Brightway 2”[9] (Mutel 2017) combined with the user interface “Activity Browser”[10]. Ecoinvent version 3.7.1, system model “cut-off” is used as background Life Cycle Inventory Database (Wernet et al. 2016). Further, a framework by one of the authors has been used to make consistent use of several LCI datasets set up by the authors of this report or their colleagues in previous work (PREMISE[11]).

## 2.2 Goal and scope

The goal of this study is to quantify the environmental impacts related to the synthetic kerosene production via specified Power-to-Liquid and Sun-to-Liquid processes. In particular, this study aims to answer the three questions as formulated in chapter 1.4.

The study intends to **inform decision makers** at governmental level and within industry, and is carried out on behalf of the Swiss Federal Office of Civil Aviation (FOCA) without third party review.

This study aims to “compare fuels with identical chemical structure and composition to their conventional counterparts” (Müller et al. 2020). Thus, all compared fuels “will behave identically in all potential applications”. A ***process oriented cradle-to-gate approach*** is chosen for answering the above questions, allowing producers of synthetic kerosene to identify environmental hotspots in their production chain. However, this would neglect release of embedded $CO_2$ to the air when combusting the fuel, which is relevant for the comparison with conventional kerosene based on crude oil. Thus, the carbon embodied in the fuel is modeled as additional $CO_2$ emission to air, representing the use as jetfuel. ***No additional emissions from combustion of synthetic kerosene in aircafts*** could be included in this study, which is discussed in more detail in section 3.7.

No product system as modelled for this LCA exists in reality yet on a large scale, so that the ***complete process chains are hypothetical***. However, individual elements of the PtL and StL pathway are well-known from existing industrial processes.

The ***geographical scope*** of this study is primarily Switzerland. As it is likely that the production of synthetic kerosene for Swiss use will also take place in other countries especially but not only for the StL pathway, the scope is extended to Europe. This mainly affects the electricity mixes and the fact that the StL pathway is not suited for Northern countries. In contrast, Southern countries, countries of the Middle East and the Saharian region are part of the regions on the World with highest solar irradiance. Also here, the focus was kept on European countries, namely Spain, where a test site of Synhelion is already present and more are planned. Datasets from Spain are used to model electricity

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[9] https://brightway.dev/
[10] https://github.com/LCA-ActivityBrowser/activity-browser/i
[11] https://github.com/romainsacchi/premise

sources for all pathways evaluated in order to be consistent with a potential Synhelion site in Spain. It is not likely that a specific production process based on wind or PV would be placed at a location which does not provide good conditions, as this would by no means be economic. As such, unrealistic cases of StL in Northern countries or a wind based case with bad wind turbine performance are not modelled. ***No transport*** of the synthetic kerosene from the origin country to Switzerland was accounted for in this study. Results by (Liebich et al. 2021b) hint that omitting the transport data won't lead to completely different findings. It is not the aim of this study to provide estimates of the theoretical and technical potential, or economic feasibility of individual location-specific supply chains. Rather does it give general information and a comprehensive overview on the environmental impacts of the production of synthetic kerosene ***without specific geographical details of potential supply chains of synthetic kerosene to Switzerland.*** For instance, no information has been collected on where cement plants are located in Europe, how much biowaste is available at various locations, or where renewable electricity is most abundant from a specific renewable energy source; and the LCA model is not run depicting the wind load hours or solar irradiance on a European map with the corresponding environmental impacts of synthetic kerosene production. Similar questions are discussed in a report on a detailed analysis of "the system comparison of storable energy carriers from renewable energies" issued for the German Environment Agency published in 2021 based on work up to 2019 (Liebich et al. 2021a, b) .

The ***temporal scope*** is today and the near future (5-10 years).

***End-of-life or circular handling of infrastructure*** in 20-40 years is neglected due to high uncertainties with regards to recycling and circular economy efforts in the coming decades. Circular economy may be most relevant for the StL pathways which use in absolute amounts large masses of steel and glass, compared to the PtL pathways which are performed within simple gas-to-liquid plants.

### 2.2.1 System boundaries and functional units

Figure 3 depicts the system boundaries and various perspectives which are adopted for the LCA at the example of the Sun-to-Liquid pathway in order to also include the origin of methane in addition to $CO_2$ and other energy or material inputs.

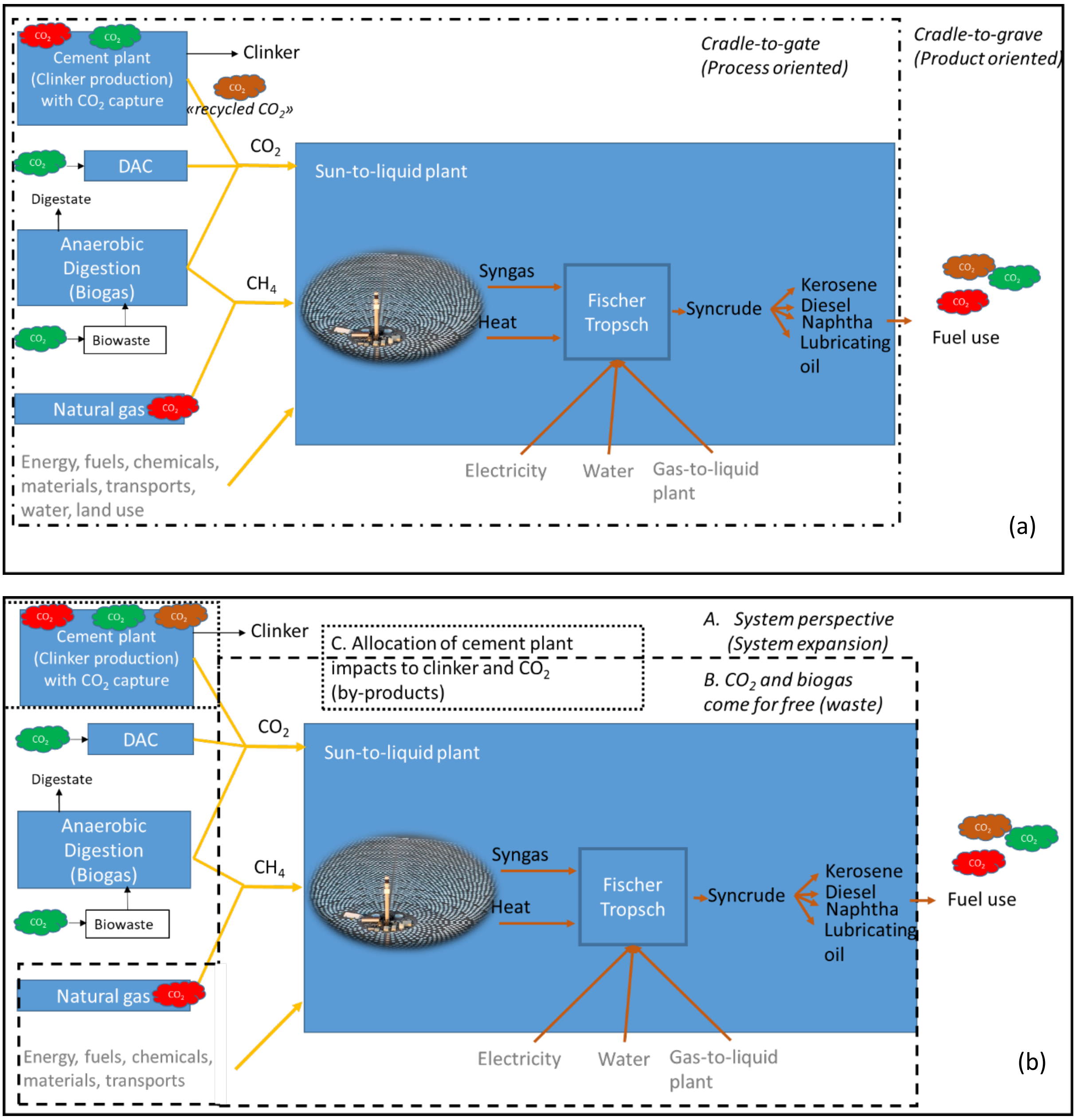

*Figure 3 System boundaries chosen to model synthetic fuel production via the Sun-to-Liquid pathway. The upper figure (a) shows the two perspectives of the fuel producer (cradle-to-gate, oriented for optimizing the producing process) on the one hand, and the fuel user perspective on the other hand (cradle-to-grave, oriented to comparing a product with others fulfilling the same need). The figure at the bottom (b) shows a zoom on the various approaches which can be adopted to solve multi-functionality. Grey processes represent background processes, which are taken from databases or previous work by the authors. Processes within the blue boxes are foreground processes. Red $CO_2$ emissions stand for fossil $CO_2$, while the green clouds represent biogenic carbon. "Recycled" $CO_2$ from CCU is represented with a brown cloud.*

The system boundaries in LCA include all (background) transportation processes, inputs of materials, energy or fuels, construction of required infrastructure, and emissions of substances to air, soil or water.

The **functional units** chosen to answer the three research questions are the following:

- **Product perspective** – PtL or StL producing synthetic kerosene for sale – Cradle-to-gate:

> “The production of 1 kg or 1 MJ (lower heating value LHV) synthetic kerosene via a specific Power-to-Liquid or Sun-to-Liquid pathway, including the release of the embodied carbon to air during the fuel combustion.”

Energy based allocation is performed for the products of the Fischer-Tropsch process (see section 2.2.2.2), and substitution is used for the $CO_2$ captured in the cement plant. To be able to reach any conclusions on the overall carbon balance, one more functional unit should be defined to be “Travelling 1 person-km (pkm) in a passenger aircraft on short/medium/long haul”. Due to lack of a suitable methodology as discussed in section 3.7 (i.e. transposing pollutant emissions changes from synthetic kerosene combustion into impacts on climate change beyond those caused by direct $CO_2$ emissions of the aircraft), this functional unit will not deliver valid and robust results. Thus, it is chosen to be “combusting 1 MJ of (synthetic) kerosene considering $CO_2$ emissions only”; combustion related $CO_2$ emissions are added on top of the kerosene production LCIA scores.

- **Process perspective** – here the overall system perspective, as shown in Figure 4: This uses **system expansion** to answer the question how the PtL and StL production pathway system performs compared to a conventional system. The expanded system includes production of all useful products from all multi-functional production processes, here namely the clinker production with a carbon capture unit added, and the production of all process by-products. Allocation with regards to the various co-products from refining is avoided. The conventional system produces all these products in the conventional way, while the PtL or StL introduces a new pathway for some of these products. The functional unit is thus defined as follows:

> a) **$CO_2$ from cement plant, Fischer-Tropsch PtL and StL**: “The production of 1 kg or 1 MJ (lower heating value LHV) (synthetic) kerosene, and the production (related to 1 kg kerosene) of 2.1 kg (synthetic) diesel, 1.3 kg (synthetic) naphtha, 1.3 kg (synthetic) lubricating oil (all including the release of the embodied carbon to air during fuel combustion), and production of clinker corresponding to the required input amount of $CO_2$ (1.35 kg clinker/kg $CO_2$ captured).”
>
> b) **$CO_2$ from cement plant, MeOH PtL**: “The production of 1 kg or 1 MJ (lower heating value LHV) (synthetic) kerosene, and the production (related to 1 kg kerosene) of 0.8 kg (synthetic) Diesel, 0.4 kg (synthetic) gasoline, (all including the release of the embodied carbon to air during fuel combustion), and production of clinker corresponding to the required input amount of $CO_2$ (1.35 kg clinker/kg $CO_2$

The clinker amount is calculated such that its production and related $CO_2$ capture covers the required amount of $CO_2$ input. Data from (Meunier et al. 2020) are used, which give a $CO_2$ flow of 2745 t/d for a total clinker capacity of 3000 t/d. As will be explained in chapter 3.3.1, a capture rate of 90% is applied.

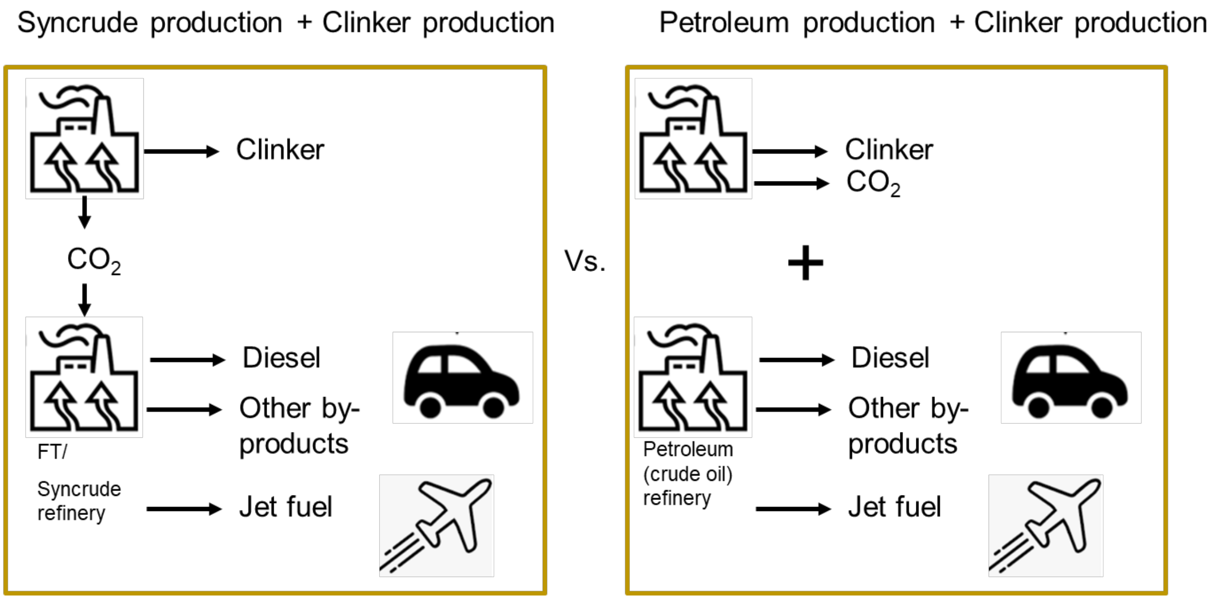

*Figure 4: Depicting the system expansion approach for comparison of a conventional system (right) and with the introduction of PtL or StL (left).*

This process perspective refers to the entire production chain of the kerosene. This includes all other by products of the Fischer-Tropsch process (Diesel, Naphtha, Lubricating oil), production of the syngas (FT/MeOH) or Syncrude (StL), production of either natural gas or biomethane to supply the required methane to the solar reforming process, and supply of $CO_2$ as a side-product of clinker production in a cement plant or direct air capture. The environmental impacts of this whole process combination is compared to a "conventional reference system" where the respective amounts of clinker, kerosene, Diesel, Naphtha, and lubricating oil are produced via conventional production routes. The relative difference between these two systems will provide insights in potential reduction or increase of various environmental impacts, thus depicting which change is introduced to business-as-usual when installing the novel processes.

Research question 3 may be answered by calculating not only the greenhouse gas emissions, but also the scores for other environmental impacts for the functional units as defined above for the cradle-to-gate perspective (production of kerosene without end use). As mentioned before, the cradle-to-gate approach neglects burning the fuel, and thus release of embodied fossil and biogenic carbon, to the atmosphere.

### 2.2.2 Multifunctionality of processes

Multi-output processes require decisions on how to attribute the sum of the related environmental impacts from the whole production chain to the individual products, if product-specific environmental burdens are of interest. Handling such multi-functionality of processes in LCA is framed in the standard ISO 14044 (ISO 2006), which indicates a preference for system expansion, and only if this is not possible, allocation ("partitioning") is recommended according to physical (preference 1) or other (e.g. economic) relationships. Performing such allocation means that the life cycle inventories are partitioned according to criterions such as the mass, energy content, or the economic revenue of the individual co-products. It is usually a subjective choice of the LCA practitioner which approach is chosen, but it is good practice to depict the importance of such a choice by showing the influence of the possible approaches on the findings.

#### *2.2.2.1 The multifunctional processes in PtL and StL pathways*

First, the **production of kerosene** both via Fischer-Tropsch and from processing of methanol is a multifunctional process, with kerosene/jet fuel always coming with other fuels as by-products.

Second, **cement plants** may produce not only clinker, but also captured $CO_2$ for further use. This is a case of $CO_2$ capture and utilization (CCU), which means that cement production is equipped with a carbon capture unit, and the captured $CO_2$ is used as feedstock in further industrial processes (and is not only present in the LCA as uptake to biomass or emission to air) (Mueller et al. 2020). In order to harmonise the modeling approach of such combined CCU systems, methodological guidelines have recently been published, which will be followed in this study (Müller et al. 2020). These guidelines discuss several approaches, including system expansion, substitution, and allocation using underlying physical or other relationships.

The third multi-functional process involved in this project is **production of biogas** from anaerobic digestion of biowaste. The main functionality of this digestion process is waste disposal (i.e. to get rid of biowaste), with biogas and digestate as by-products. The latter may substitute mineral fertilisers. Modelling such substitution is challenging due to the varying nature of the input biowaste and thus the modelling of potentially substitute mineral fertilisers and their properties. In this analysis, datasets set up by some of the authors and published in two publications are used (Antonini et al. 2020, 2021). These data start from picking up the biowaste, thus attributing all previous agricultural and societal activities related to the biomass to the agricultural sector. Fully closed carbon balance is ensured. It is assumed that all carbon embodied in the digestate will be emitted to atmosphere within a time frame of 100 years. This may be decreased through good management of the digestate in soil. No substitution of mineral fertilisers is considered. All activities for upgrading of the biogas to biomethane, or separation of the contained $CH_4$ and $CO_2$, respectively, are the burden of the fuel producer.

**Water electrolysis** stands for splitting $H_2O$ molecules into $H_2$ and $O_2$ molecules. In this work it is assumed that the $O_2$ is simply released to air as waste product, i.e. no economic use of the $O_2$ is considered and thus no allocation issue is tackled. This may be a little too simplified, as the economic value of $O_2$ can improve the economic performance of $H_2$ production (e.g. (Van Der Giesen et al. 2014)). Future well-optimised $H_2$ electrolysis processes might profit both in environmental and in economic terms from a use of $O_2$ on a case by case basis.

### 2.2.2.2 Solving multifunctionality

As mentioned above, such multi-functional problems can be solved with various approaches in LCA.

Option 1 (system expansion) will be applied to all pathways investigated in this work. For the cement plant specifically, option 2 (substitution) is chosen. Option 3 (allocation) will be applied to the Fischer-Tropsch and refining process, with a preference for energy allocation. Integrating all these options allows to follow both the ISO 14044 guidelines, and also the recommendations on LCA of CCU-based fuels which require that first substitution shall be applied, but that system expansion results shall always be computed "to assess the overall effect of introducing the CCU technology"(Müller et al. 2020).

#### Option 1: System expansion

**Option 1** is the ISO 14044-preferred **«System expansion»**, in which the environmental impacts of all processes involved in the production of conventional kerosene are compared to those of the production of synthetic kerosene. However, ***this approach is not suited when impacts per unit of kerosene are needed***, as only entire systems with multiple products can be compared. Environmental impacts of the product «kerosene» cannot be extracted, instead it can be ***quantified by how much the conventional system changes when the PtL or StL pathways are introduced***.

#### Option 2: Substitution

**Option 2 is «Substitution»:** All environmental impacts of the process chain are allocated to the kerosene alone, but in turn all by-products substitute conventional products (diesel etc.), so that impacts from production of these are saved (subtracted). Correspondingly, for the cement plant, all impacts from clinker production and carbon capture are attributed to the captured $CO_2$, but the production of conventional clinker is then subtracted so that only the impacts of the carbon capture process itself (infrastructure, material inputs, but NOT the remaining direct $CO_2$ emissions to air) are left to the captured $CO_2$ as illustrated in Figure 5.

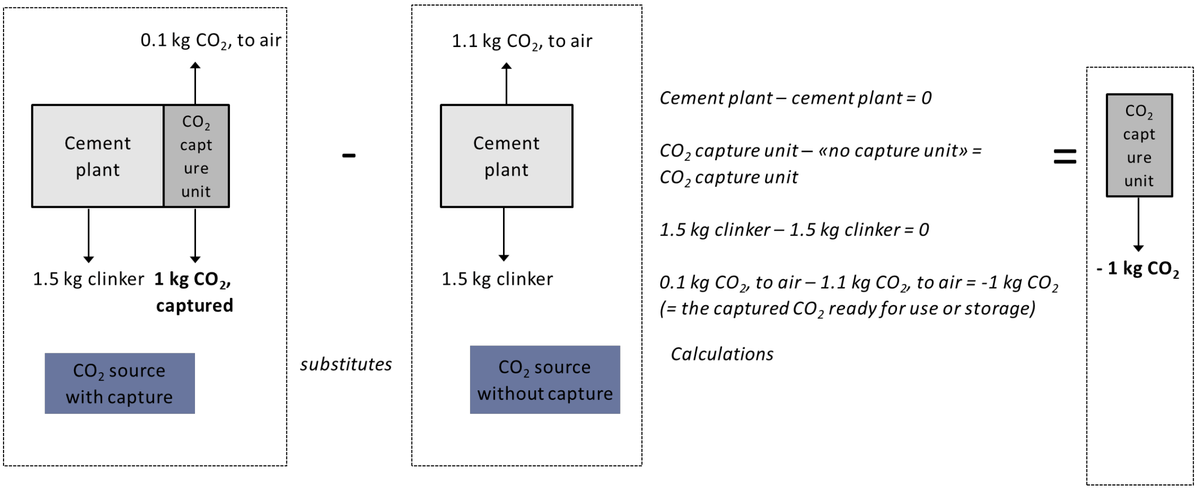

*Figure 5: Calculation of environmental impacts per 1 kg $CO_2$ captured and ready for use via the substitution approach according to* (Mueller et al. 2020)*. The capture unit includes infrastructure, material use, and energy flows for the capture process. The example is shown for a capture rate of 90%.*

Please note that after that, **the question still remains whether the cement plant owner (point of capture) or the fuel user (i.e. emitter of combustion emissions) will get credited for having saved $CO_2$ emissions.** While the cement plant exhibits lower physical $CO_2$ emissions due to the capture of $CO_2$, the fuel emitter obviously also wants to get fully credited for using "recycled" $CO_2$. However, it is not possible to credit the same molecule of $CO_2$ saved at two places. This fact and ambiguity is solved here by considering three perspectives:

1) First, the **perspective of the fuel user** who wants to get full credit for using recycled $CO_2$, thus the cement plant will still have to bear the full burden in terms of $CO_2$ emissions even if it has physically reduced the local emissions. This corresponds to a **100% allocation of the $CO_2$ emissions to the cement plant** as $CO_2$ supplier, or **100% credit to the fuel user**. The fuel user bears the impacts of the carbon capture process only. The $CO_2$ emissions would have "happened anyway" directly at the cement plant, and the fuel user does not influence the availability of $CO_2$ point sources in any way – at least as long as the $CO_2$ demand does not exceed the $CO_2$ "production" at point sources.

2) Second, **a 50:50 approach** where both the point of capture and the fuel emitter get credited and save 50% of their emissions, and both bear half of the impacts related to the carbon capture process. This further corresponds to the idea that **using the $CO_2$ present in a fossil fuel twice** – once for e.g. production of cement, and a second time to power an airplane – should halve the impacts of each of these steps. Further, this procedure seems to represent a fair approach e.g. when the transport sector will also be part of the EU ETS.

3) Third, the **perspective of the cement plant** which implements the carbon capture process and reduces its $CO_2$ emissions. In such a situation, the fuel user has to bear all emissions physically happening at the point of fuel combustion **(100% allocation to the fuel user)**, but does not have to "pay" for the carbon capture process. This acknowledges the physical realities of the fate of the $CO_2$ captured, and released to air due to combustion of the fuel. The cement plant (point source) has physically reduced the direct $CO_2$ emissions to air, so that it may claim successful reaching of climate goals, and/or the company does not have to purchase $CO_2$ allowances e.g. through the EU Emission Trading System (ETS). This perspective specifically also holds true when the **industrial $CO_2$ is captured for subsequent storage** (**CCS**), or when the cement plant finds ways other ways to permanently immobilize $CO_2$ such as by mineralization (Tiefenthaler et al. 2021): It is because of the fuel producer that this $CO_2$ will be released to air near time (CCU) instead of being stored (CCS). It is however unlikely that any producer of synthetic kerosene would buy $CO_2$ which comes with full climate change impacts to account for, and such a producer would find a source of $CO_2$ which would be emitted anyways.

### Insertion: Fossil, biogenic, geogenic, or recycled $CO_2$

A note on the ***fossil, biogenic, or geogenic*** nature of the carbon: Not all carbon released from a cement plant is fossil, i.e. stems from carbon sources which have been buried down in the Earth crust. Around two thirds of $CO_2$ emissions during clinker production stem from the calcination process and are sometimes described as "geogenic emissions" from burning limestone. Cemsuisse estimates that 20% of these emissions will be compensated by natural carbonation[12] during the lifetime of the cement (Cemsuisse 2020). The remaining 30-40% of direct $CO_2$ emissions from a cement plant are mostly due to the combustion of fuel. Biogenic fuels are projected to represent 60% of the total fuel supply to Swiss cement plants by 2050 according to the roadmap by Cemsuisse (Cemsuisse 2020). As a consequence, the 100% allocation of emissions to the fuel user needs to carefully differentiate between fossil carbon and biogenic carbon, as the latter has been taken up from the atmosphere only recently, and emissions back to the atmosphere through burning of the fuel should be considered as neutral. The case as modelled in this report shows 100% fossil carbon in order to represent the possibility that the $CO_2$ from CCU comes from an industry where no biogenic C is present. Higher shares of biogenic C accordingly decrease the net emission value. This aspect deserves more attention with ongoing decarbonisation activities in industry.

No differentiation between these $CO_2$ origins is made in this report when it comes to dealing with $CO_2$ coming from a cement plant, but the $CO_2$ is just labelled with "***recycled***" in case of CCU. This approach corresponds to the requirements in the **EU "Directive on the promotion of the use of renewable sources" (so-called RED II 2018)** (EC 2018). There, annex V states the "rules for calculating the greenhouse gas impact of biofuels, bioliquids and their fossil fuel comparator". This directive is currently proposed for amendment to include the assessment of greenhouse gas emission savings from renewable liquid and gaseous transport fuels of non-biological origin (RFNBOs) and recycled carbon fuels (RCFs).

The formula to calculate the greenhouse gas emissions is the following:

$$E = e_i + e_p + e_{td} + e_u - e_{ccs} - e_{rc} \qquad (1)$$

With

E = total emissions from the use of the fuel; $e_i$ = emissions from supply of inputs; $e_p$ = emissions from processing; $e_{td}$ = emissions from transport and distribution; $e_u$ = emissions from combusting the fuel in its end-use; $e_{ccs}$ = emission savings from carbon capture and geological storage; $e_{rc}$ = emissions saved by recycling carbon.

This corresponds to the "100% credit to fuel user ($CO_2$ emitter)" approach as presented before, where the fuel user bears the impacts of $CO_2$ capture, but emissions of «recycled» carbon are subtracted, which means that the cement plant still needs to pay for those saved $CO_2$ emissions (as not both the cement plant owner and the fuel emitter can claim that credit).

Carbon uptake from the atmosphere via direct air capture or removal by biomass ("biogenic $CO_2$") is modeled with a negative sign for $CO_2$ emissions in the LCA calculations. The same modeling approach is taken for recycled $CO_2$, following the substitution approach as suggested in the authors of the guidelines for LCA of CCU application (Mueller et al. 2020). This leads to partially heavily negative climate change impact scores due to the use of such "negative" $CO_2$. Such carbon will be released back to the atmosphere during fuel combustion, which is modeled with a positive sign to reach carbon neutrality within the carbon balance.

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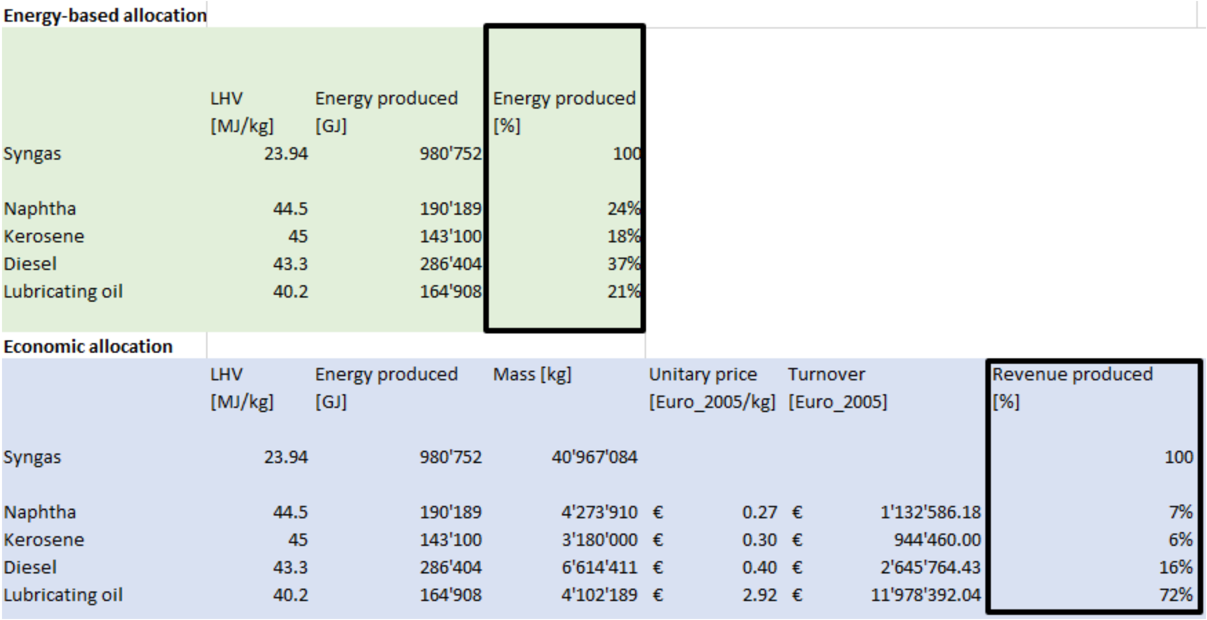
[12] Absorption of $CO_2$ by cement during its life.

### Option 3: Allocation

**Option 3 is «Allocation».** This means that environmental impacts and benefits of a multi-output process are attributed to several by-products based on **physical properties** such as the energy content, **or economic value**. However, this involves subjective choices on the chosen allocation key, and the results can differ heavily depending on the chosen approach. This is illustrated in Figure 6, where kerosene receives 18% of the environmental impacts of the whole FT process for energy-based allocation, while this decreases to 6% for the economic approach. This is due to the high economic value of lubricating oil, which actually is not a product of priority when the process is aimed for production of jet fuel. Lubricating oil is even not present as by-product in all refining processes which target for kerosene (e.g. (Klerk 2011)). It does not seem meaningful to allocate a large portion of the environmental impacts to a product which would be minimized as much as possible in a refinery for e-kerosene production. In addition, according to the ISO standard for LCA, physical allocation should be preferred to economic allocation, so that this approach is followed in this report.



**Energy-based allocation**

| | LHV [MJ/kg] | Energy produced [GJ] | Energy produced [%] |
|---|---|---|---|
| Syngas | 23.94 | 980'752 | 100 |
| Naphtha | 44.5 | 190'189 | 24% |
| Kerosene | 45 | 143'100 | 18% |
| Diesel | 43.3 | 286'404 | 37% |
| Lubricating oil | 40.2 | 164'908 | 21% |

**Economic allocation**

| | LHV [MJ/kg] | Energy produced [GJ] | Mass [kg] | Unitary price [Euro_2005/kg] | Turnover [Euro_2005] | Revenue produced [%] |
|---|---|---|---|---|---|---|
| Syngas | 23.94 | 980'752 | 40'967'084 | | | 100 |
| Naphtha | 44.5 | 190'189 | 4'273'910 | € 0.27 | € 1'132'586.18 | 7% |
| Kerosene | 45 | 143'100 | 3'180'000 | € 0.30 | € 944'460.00 | 6% |
| Diesel | 43.3 | 286'404 | 6'614'411 | € 0.40 | € 2'645'764.43 | 16% |
| Lubricating oil | 40.2 | 164'908 | 4'102'189 | € 2.92 | € 11'978'392.04 | 72% |

*Figure 6: Allocation based on energy content and economy value (revenue) of by-products in the Fischer-Tropsch process as shown in* (Van Der Giesen et al. 2014) *and adopted in this study. Unitary prices are taken from the ecoinvent database* (Wernet et al. 2016).

### Insertion: Carbon correction

A full carbon balance has been established for all modelled variations of PtL and StL pathways. Due to the application of energy allocation for the production of kerosene as single product (instead of a mix of fuels resulting from one refining process), this mass balance is distorted. For instance, the allocated input of syngas per 1 kg kerosene may be higher than in physical reality, because it is distributed to the kerosene based on the energy content of the kerosene. Thus, the syngas per 1 kg kerosene comes with an amount of embodied carbon which is higher than the actual carbon content of kerosene. An artificial carbon correction needs to be introduced to correct the corrupted C balance to compensate for over- or underestimations of emissions from combustion of the modelled kerosene. Note that both FT PtL and StL processes are modelled based on the products in (Van Der Giesen et al. 2014), but the calculated $CO_2$ content of the input syngas (2.35 kg syngas/kg kerosene) is different in FT PtL (1.38 kg $CO_2$/kg syngas) than in StL (1.16 kg $CO_2$/kg syngas). This leads to a different carbon correction (see results in section 5), even if the same process is assumed.

## 2.3 Life Cycle Inventories

Data for the PtL pathways have been collected from literature. Data for the StL pathways have been provided by Synhelion, without data inputs on the refining of the syncrude to the kerosene. The resulting Life Cycle Inventories can be made available for interested parties upon request for the PtL pathways, while the StL LCI contains confidential data, so that a case-by-case solution will have to be found when providing these datasets to an external party.

Major data uncertainties are the variability of the processes themselves, and the fact that the information used for the datasets stem from few (but recent and partially high-quality) literature sources. This may hamper the representativeness of the datasets set up within this project. We compensate for this by exploring variants of the designed processes. Besides, data gaps are present for the methanol-to-kerosene pathway, for a Fischer Tropsch process optimised for kerosene production, and for the syncrude-to-kerosene process.

Table 2 gives a qualitative overview on the quality of the inventories. Please note the existing data gap for refining of the synthetic crude oil to kerosene for all pathways.

## 2.4 Reduction of greenhouse gas intensity compared to reference value

An important benchmark with regards to certification or receiving financial or tax support of the synthetic kerosene is the reduction of the greenhouse gas intensity when using the synthetic kerosene compared to a conventional fossil kerosene. In the **Renewable Energy Directive by the European Commission,** such a fossil fuel comparator is mandatory to use and is quantified to amount to life-cycle greenhouse gas emissions of ***94 g $CO_2$-eq/MJ (4.1 kg $CO_2$-eq/kg)*** (including fuel combustion related $CO_2$ emissions). The reduction must be larger than 70% so that the fuel is elective for counting towards the targets for greenhouse gas reduction in the EU (EC 2018). Compared to the climate change impact of kerosene as present in ecoinvent v3.7, which amounts to 81 g $CO_2$-eq/MJ (3.6 kg $CO_2$-eq/kg), this fossil fuel comparator seems to be rather high. Further, the explanations of how this value has been calculated indicates that it is based on road fuels only (Commission 2015).

There exists a reference value as global standard for air traffic by the international aviation regulator ICAO. They use the typical Jet A1 kerosene within the frame of the **global CORSIA standard** for the calculation of eligible fuels. The value to be used is ***89 g $CO_2$-eq/MJ (CORSIA 2019) (3.9 kg $CO_2$-eq/kg)***. The ”CORSIA Sustainability Criteria for CORSIA Eligible Fuels” demands for “net greenhouse gas emissions reductions of at least 10% compared to the baseline life cycle emissions values for aviation fuel on a life cycle basis”. Biomass obtained from land with high carbon stock must not be used for the production of the fuel (ICAO 2019). This value is within the range of carbon intensities shown in various publications, going from 85 to 95 g $CO_2$-eq/MJ (Pavlenko and Searle 2021). The exact value is anyways subject to uncertainties and variabilities in the LCA modelling on the one hand, and on the other hand related to the actual physical properties of the jet fuel. The direct emissions due to the carbon content of the jet fuel are around 70-75 g $CO_2$/MJ, and the fuel supply chain contributes the remainder.

Obviously the choice of the reference value is important when a specific reduction is intended. In this work, the official CORSIA standard value is used. However, fuels within the EU are benchmarked to the higher RED value, which should be taken into account when comparing results of this report to work performed within the EU.

*Table 2: Qualitative overview on the quality of the inventories compiled for the three production pathways in this work.*

| | Fischer-Tropsch PtL | Methanol PtL | StL |
|---|---|---|---|
| **Syngas/ Methanol/ Syncrude production** | Based on detailed information in (Van Der Giesen et al. 2014). Novel, rather optimised design is shown in this reference. | Based on detailed technical modelling for a specific methanol production chain in a cement plant (Meunier et al. 2020), and compared to the information given in (Hank et al. 2019). No big differences found between these two references. | Detailed information from project partner based on calculations and demonstration sites. |
| **Processing to kerosene (Refining)*** | Based on information in (Van Der Giesen et al. 2014), however, this is not optimised for kerosene production; and the mass and energy balance stops at the level of the "liquid fuel", and does not go to the level of individual fuel products. The general description includes the split of the liquid fuel into diesel, kerosene, lubricating oil, and naphtha. It is not clear if all energy and mass flows required for refining are included. Syngas, FT and liquid fuel production are modelled in one box with no energy/water flows or emissions. | This process is not yet developed. Rough assumption data have been applied in this work (Albrecht et al. 2013). | No information given by project partner, as their expertise lies in the production of syncrude, and not its refining. Same modelling as in the Fischer-Tropsch process chain with regards to the split of the syncrude into individual products.* |
| **Infrastructure** | Described in detail in (Van Der Giesen et al. 2014), but may only be representative for that specific case. | Based on (Hank et al. 2019), but rather high level of uncertainty. | Detailed information on material inputs except for the CSP plant and electrolyser where own data was at hand; no information on energy required to build the infrastructure. |
| **$CO_2$ capture, cement plant** | Taken over from the MeOH chain. | Based on detailed technical modelling for a specific methanol production chain in a cement plant (Meunier et al. 2020). Input of energy sources, exact type of $CO_2$ capture system etc. are still subject to site-specific variation. | Taken over from the MeOH chain. |
| **$CO_2$ capture, DAC** | Detailed life cycle inventories published by part of the authors of this work, based on Climeworks technology and adapted to various designs to represent potential geographical locations of the DAC (Terlouw et al. 2021). | | |
| **Temporal validity** | Most references used are very recent (2019-2021) or from industrial project partner. They mostly represent current or optimised designs. | | |
| **Overall rating** | Specific data for syngas production and the FT process, however, the latter is not optimised for kerosene production. | Very specific data for methanol production and $CO_2$ capture combined with a cement plant, thus very realistic case. Comparison with other publication on methanol production does not result in large differences. Poor data for methanol to kerosene. | Detailed and case-specific data from industrial partner. Combination of StL with cement plant not yet modelled on the same level of detail, but with decent hints by the project partners on how to do that. |

# 3 Modelling of processes for production of synthetic kerosene

## 3.1 Power-to-Liquid

### 3.1.1 Fischer-Tropsch process

First, the Fischer-Tropsch process as such is discussed, while chapter 3.1.2 shows the complete Fischer-Tropsch Power-to-Liquid pathway.

A Fischer-Tropsch based facility includes the syngas producing and purifying unit and the actual Fischer-Tropsch synthesis of syncrude and its refining to fuels. Syncrude synthesis can be high-temperature (ca. 300-350°C) or low-temperature (200-240°C) (Doliente et al. 2020). It is mainly the catalyst type (often cobalt or iron catalysts) which determines the composition of the syncrude. However, the molecular composition of syncrude is always quite different from that of crude oil, so that the process needs to be adapted in order to be efficient(de Klerk 2008).

As shown in Figure 1, the process of turning syngas into syncrude and hydrocarbon fuels is in theory the same for both the PtL Fischer-Tropsch pathway and the three StL pathways. No reliable information could be found in literature on the energy balance of the syncrude refining process without syngas production, as usually the several steps are modelled in the same box, or the refining process is not included (e.g. in (Marchese et al. 2020)). As a result, this energy and material consumption for turning syncrude into kerosene can currently not be modelled, so that the full FT process as modelled in (Van Der Giesen et al. 2014) is used as a proxy. That work shows the three steps of syngas production, FT and refining as one single box with no additional inputs of energy or water, and no emissions, but a suggestion for the split of the syncrude into individual fuels.

As indicated in a detailed study (de Klerk 2011), cobalt-based low-temperature FT optimised for jet fuel can result in 64% jet fuel and 32% gasoline, with 4% other products[13]. However, iron-based FT may result in better applicability of the jet fuel and gasoline products in reality. Further, ***the integration of syncrude in the European refining industry needs to be well studied***, as many dependencies between the syncrude composition and the choice of co-production products exist (Ervasti and Wuokko 2019). This is evaluated in detail in the European project FLEXCHX[14].

According to a study for a Gas-to-liquid plant in Danish conditions (Rasmussen 2019), large amounts of excess heat are present from the highly exothermic process, which can either be used, have to be distributed to a heat network, or released via a cooling system. In this work, some of the references used as data input treat this excess heat as waste heat, or use this heat internally for driving processes. No cooling activity is explicitly modelled.

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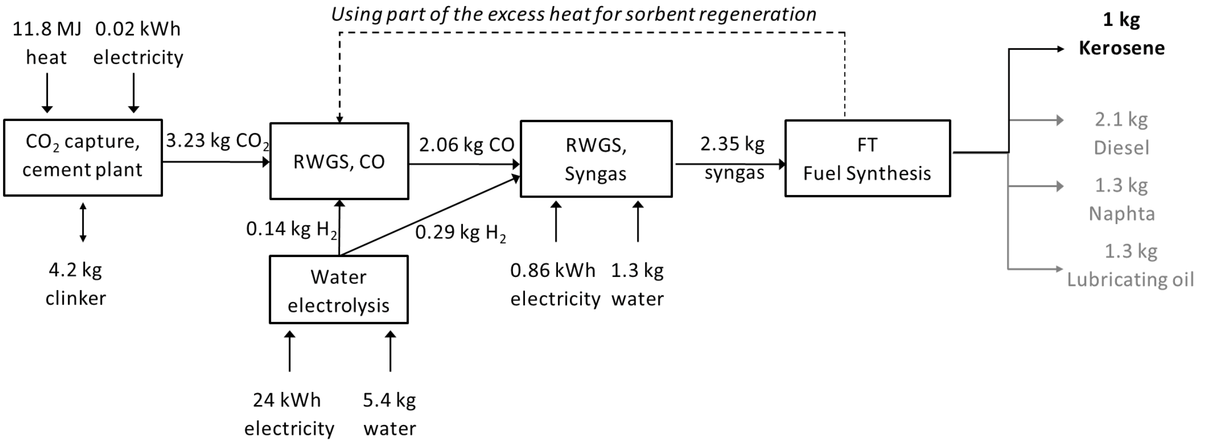
[13] This study is not used as basis for the FT process modelling and allocation as no further information on energy and mass balances is given.

[14] http://www.flexchx.eu/

### 3.1.2 Fischer-Tropsch Power-to-Liquid (FT PtL)

The complete “Power-to-Liquid” Fischer-Tropsch pathway includes syngas production from reverse water gas shift, the actual Fischer-Tropsch synthesis of syncrude and subsequent hydrocracking and distillation. (Van Der Giesen et al. 2014) present a life cycle assessment for such a specific production pathway, including detailed life cycle inventory datasets in the supplementary information. The latter is adapted for the purpose of this work as summarized in Flow scheme 1.



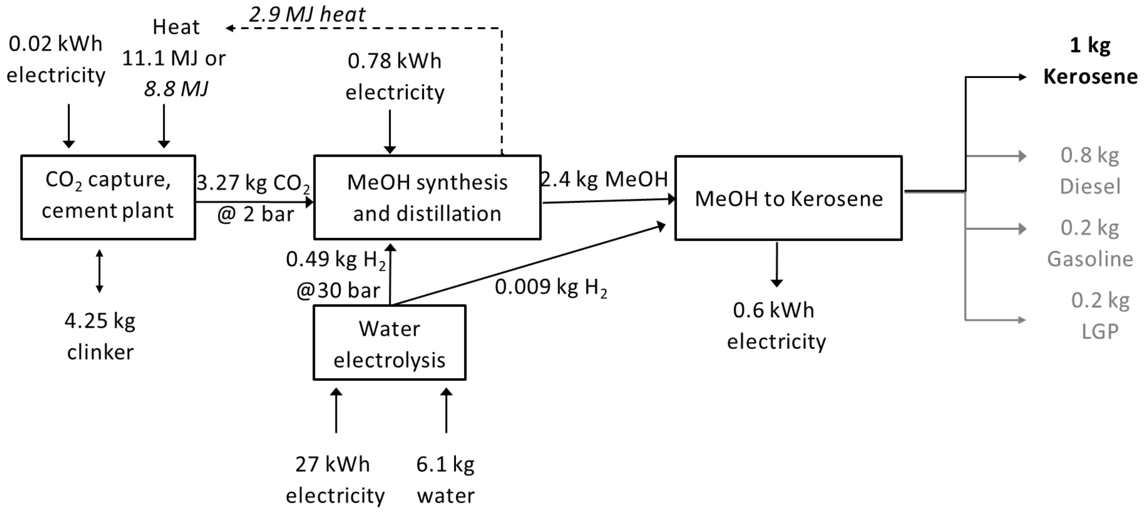
- PEM electrolysis (55 kWh/kg $H_2$)
- RWGS: fixed bed reactor; catalyst 57% CuO, 31% ZnO and 11% $Al_2O_3$; sorbent = zeolite
- FT-process: 25 bar; 230°C; 80% efficiency; i.e. 20% of the energy is converted to heat which is removed via water cooling (exothermic process); 2.3 kg syngas/kg FT fuel (syncrude) output
- Plant capacity: 140’000 barrels FT fuel per day
- Average lower heating value FT fuel: 43.2 MJ/kg

*Flow scheme 1: Modelling of the FT PtL pathway in this work. The $CO_2$ may also come from DAC. The provision of 3.23 kg $CO_2$ is connected to the production of 4.2 kg clinker in the cement plant. RWGS = Reverse Water Gas Shift; CO = Carbon Monoxide. The dotted line indicates that excess heat may be used in the CO production step, which is not accounted for in this study due to lack of data. The output of the full process chain is 1 kg kerosene. Energy and mass flows represent the values as allocated to the production of 1 kg kerosene. The products in grey indicate to which outputs of other fuels this amount of kerosene corresponds, however, no energy or mass flows are included in the flow scheme for these products. The latter is done in the system expansion modelling. These products are simply shown to point out that the production of kerosene is always linked to other co-products.*

The modelling of the construction of the fixed bed reactor and the gas-to-liquid plant is taken over without change from (Van Der Giesen et al. 2014). Processing of the syngas to kerosene is as well taken from that reference, with energy allocation applied as shown in Figure 6. This means that all environmental impacts from the production of syngas are allocated with a factor of 0.18 to the kerosene.

### 3.1.3 Methanol Power-to-Liquid (MeOH PtL)

The process for the methanol production and distillation modelled in this work is based on two publications with modelling of a specific methanol production pathway integrated into a cement plant (Meunier et al. 2020) and modelling of methanol synthesis for production of Poly(oxymethylene) dimethyl ethers (OME) for use in vehicles (Hank et al. 2019). Hank and Meunier provide quite similar information, so that Hank was used for validation of the Meunier data, but the results in this work are shown for application of the Meunier data only for consistency reasons. Further, a "methanol-to-synfuels" pathway from a German study is used to model the further processing of methanol into kerosene (Albrecht et al. 2013). The resulting flow scheme is shown in Flow scheme 2.



- PEM electrolysis (55 kWh/kg $H_2$)
- Catalyst: $CuO/Al_2O_3/ZnO$
- Integration of MeOH conversion and $CO_2$ capture leads to savings in heat inputs (33% energy savings)
- Inlet temperature to MeOH synthesis is 250°C, pressure is 80 bar. Temperature for distillation is 90°C, pressure is 1 bar
- 2.42 kg MeOH/MJ fuel mixture

*Flow scheme 2: Modelling of the MeOH PtL pathway in this work. The $CO_2$ may also come from DAC. The provision of 3.27 kg $CO_2$ is connected to the production of 4.2.5 kg clinker in the cement plant. The dotted line indicates that excess heat may be used for sorbent regeneration, which is not accounted for in this study due to lack of data. The output of the full process chain is 1 kg kerosene. Energy and mass flows represent the values as allocated to the production of 1 kg kerosene. The products in grey indicate to which outputs of other fuels this amount of kerosene corresponds, however, no energy or mass flows are included in the flow scheme for these products. The latter is done in the system expansion modelling. These products are simply shown to point out that the production of kerosene is always linked to other co-products.*

Please note that there might exist many more process designs, and that the methanol-to-synfuels pathway is scarcely present in literature, being a rather novel process under research. No official certification scheme exists yet for synthetic jetfuel from this process route, so that it is subject to rather large uncertainties. In principle, two options for further processing of the methanol exist: A) Methanol to gasoline (MTG) (applied in this work) or B) Methanol to Olefins (MTO). Turning the methanol to jet fuel is not yet well described in literature. A first approximation is made in this work based on (Albrecht et al. 2013).

Further, there exists a variety of possible catalysts for the process, which will have an effect on the efficiency of the process (Dieterich et al. 2020). In this work, a CuO/Al2O3/ZnO catalyst as suggested by (Meunier et al. 2020) is used.

The modelling of the methanol pathway in (Meunier et al. 2020) includes the $CO_2$ capture in a cement plant, without special integration of excess heat as one option or going for an integrated design between the $CO_2$ capture unit and the conversion process. Such heat integration saves roughly 25% of the required steam/heat input to the $CO_2$ capture process. Similarly, water input can be decreased by integration of the $CO_2$ capture and the conversion processes.

## 3.2 Sun-to-Liquid: Three production pathways by Synhelion

The Sun-to-Liquid pathways described and modelled in the following are the technologies developed by Synhelion. They are based on the usage of $CO_2$ and water combined with solar high-temperature process heat generated via a solar concentrating plant. Heat is stored so that continuous fuel production will be possible.

The Synhelion plant is the solar part in the Sun-to-Liquid pathway. It provides the process heat to start the chemical reaction to produce syngas. Synhelion is currently planning to reach a production volume of 700’000 t/a fuel by 2030 while entering the market within two years from now[15]. This volume would cover roughly half of the kerosene used for Swiss civil aircraft, or 15% of the Swiss diesel and gasoline use. In order to ensure constant supply of process heat to the industrial processes, the Synhelion plants will be equipped with a thermal energy storage and be located at sites with high solar irradiation.

"Synhelion uses solar heat to convert $CO_2$ into synthetic fuels – so-called solar fuels. Solar radiation is reflected by the mirror field, concentrated onto the receiver, and converted into high-temperature process heat. The generated heat is fed to the thermochemical reactor that turns $CO_2$ and $H_2O$ into syngas, a mixture of $H_2$ and CO. The syngas is then processed by standard gas-to-liquids technology into fuels, such as gasoline, diesel, or jet fuel. Excess heat is saved in the thermal energy storage (TES) to enable continuous 24/7 operation”[16]. Figure 7 depicts this principle.

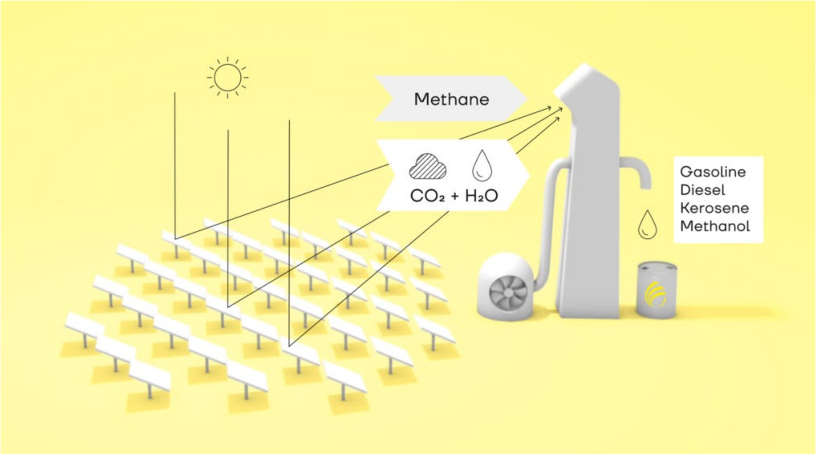


*Figure 7: Production scheme of the Synhelion plant.*

Three configurations are currently being designed: Solar reforming; Solar reforming plus; and Pure thermochemical reaction. Table 3 gives an overview on the various technology designs. All three production pathways include the conversion of $CO_2$, $H_2O$ (and $CH_4$) to syngas with the input of solar process heat supplied by solar concentrators. The choice of the site and its Direct Normal Irradiation (DNI) affect the size of the heliostat area, but not the design of the receiver, thermal storage, reactor, or input molecules origin choice. Potential sites evaluated are located in Spain (DNI 2330 $kWh/m^2*a$), the United States (DNI 2940 $kWh/m^2*a$), or Chile (3350 $kWh/m^2*a$). Only the case for Spain has been considered in this study.

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[15] https://energeiaplus.com/2021/03/15/wie-die-sonne-die-zementproduktion-klimafreundlicher-machen-kann/
[16] https://Synhelion.com/technology

*Table 3 Summary of Synhelion technologies for Sun-to-Liquid pathways.*

| | **SOLAR REFORMING** | **SOLAR REFORMING PLUS** | **PURE SOLAR THERMOCHEMICAL** |
|---|---|---|---|
| **TECHNOLOGY** | Based on conventional reforming technology but integrating solar energy, and using $CH_4$ as additional input.<br>The syngas resulting from reforming is converted to syncrude through industrial Fischer-Tropsch synthesis. | Similar to solar reforming with a slightly different reforming process (solar dry reforming). Further, hydrogen is produced from an electrolyser powered by a concentrated solar power (CSP) plant so that the $CH_4$ input is reduced.<br>The resulting syngas is converted to syncrude through Fischer-Tropsch synthesis via reverse water gas shift (rWGS). | Producing syngas from $CO_2$ and water with high-temperature solar energy.<br>The syngas is converted to syncrude through conventional Fischer-Tropsch synthesis. |
| **SIMPLIFIED CHEMICAL PATHWAY** | **Thermochemical**:<br>$0.75\ CH_4 + 0.25\ CO_2 + 0.5\ H_2O$ + solar energy<br>-> $CO + 2\ H_2$ | **Thermochemical**:<br>$0.3\ CH_4 + 0.3\ CO_2$ + solar energy<br>-> $0.6\ CO + 0.6\ H_2$<br>**Electrochemical**:<br>$1.8\ H_2O$ + solar electricity -> $1.8\ H_2$<br>**rWGS**:<br>$0.4\ H_2 + 0.4\ CO_2 \rightarrow 0.4\ H_2O + 0.4\ CO$ | **Thermochemical**:<br>$CO_2 + 2\ H_2O$ + solar energy<br>-> $CO + 2\ H_2 + 1.5\ O_2$ |
| **SYNTHESIS** | $CO + 2\ H_2$ → Syncrude → Fischer-Tropsch → kerosene and other hydrocarbons | | |
| **CATALYST** | Mixture of Fe, C, Cr, Ni, Nb, Ti | | No reforming, thus no catalyst required |
| **TEMPERATURE** | 800 – 1200 °C | 800 – 1200 °C | 1500°C |
| **RENEWABLE CARBON** | - 25% (with biogenic or recycled $CO_2$ )<br>- 100% (with biogas as $CH_4$ and $CO_2$ source) | - 70% (with biogenic or recycled $CO_2$)<br>- 100% (with biogenic or recycled $CO_2$ and biogas as $CH_4$ source) | 100% with biogenic or recycled $CO_2$ |
| **CAPACITY [MT/A]** | 0.5 | 0.5 | 0.5 |
| **INPUTS** | $CO_2$ 0.7 kg/kg syncrude<br>$H_2O$ 1.1 kg/kg<br>$CH_4$ 0.8 kg/kg | $CO_2$ 1.9 kg/kg syncrude<br>$H_2O$ 2.2 kg/kg<br>$CH_4$ 0.35kg/kg | $CO_2$ 2.8 kg/kg syncrude<br>$H_2O$ 2.3 kg/kg |
| **DESIGN** | 13 heliostat solar tower plant modules | 6 heliostat solar tower plant modules for reforming<br>+ 20 heliostat solar tower plant modules as CSP | 345 heliostat solar tower plant modules |

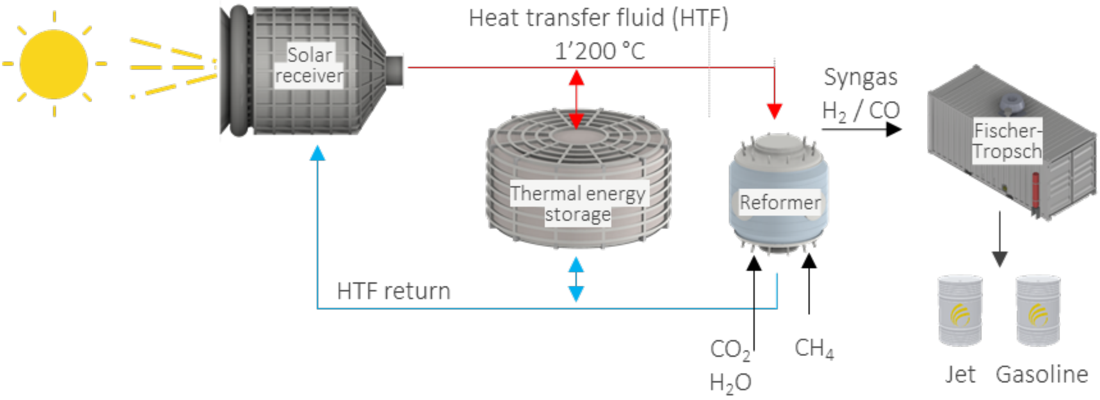
| | | | |
|---|---|---|---|
| **TOTAL LAND AREA [KM$_2$]** | 9.2 | 6.7 | 68.6 |
| **CO$_2$ SOURCE** | - Industrial point source, e.g. cement plant (possibly powered by Synhelion plant)<br>- DAC (external, i.e. not within Synhelion plant)<br>- Biogas | - Industrial point source, e.g. cement plant (possibly powered by Synhelion plant)<br>- DAC (external, i.e. not within Synhelion plant)<br>- Biogas | - Industrial point source, e.g. cement plant (possibly powered by Synhelion plant)<br>- Integrated DAC could be possible here due to high temperatures present |
| **CH$_4$ SOURCE** | Natural gas, Biogas | | Not required |

### 3.2.1 Solar reforming (SR)

Within this process, methane (from natural gas or biogas) is combined with $CO_2$, water ($H_2O$) and solar energy to produce syngas (CO and $H_2$). The reforming catalyst is a mixture of Fe, C, Cr, Ni, Nb, Ti. The resulting syngas is converted to syncrude through conventional Fischer-Tropsch synthesis, i.e. through reacting of the syngas with the help of heat, electricity, and water (Flow scheme 3).

The reforming process can take various degrees of gas purities. Biogas contains considerable amounts of $CO_2$ (42% in this work[17], versus 58% $CH_4$). According to Synhelion, the $CO_2$ can easily be separated and used to cover all required $CO_2$ input in this process design. The use of biomethane as $CH_4$ source was initially also investigated in this work. Biomethane is upgraded biogas, thus providing much higher purity (91% $CH_4$ in this work, and 8% $CO_2$ with the remainder being $O_2$ and CO). Several upgrading techniques exist, including amine scrubbing, membrane separation, or PSA (Zhang et al. 2017; Liebich et al. 2021a). In this case, the gas mixture as such does not contain enough $CO_2$ for separation and covering the $CO_2$ needs of the Synhelion process. Additional $CO_2$ would have to be bought from external sources. This doesn't seem to make sense, as biogenic $CO_2$ has been removed from the gas one step ahead. Thus, it is more likely that Synhelion would use biogas and make use of both the $CH_4$ and the $CO_2$ contained, instead of buying upgraded biomethane with a lower $CO_2$ content from a supplier. Depending on the source of the methane and the $CO_2$, the share of renewable carbon may vary between 25% to 100%, assuming that the input $CO_2$ is treated as "recycled" or is biogenic. However, uncertainties exist on the scalability of the production of substantial amounts of synthetic fuels for aircraft with methane from waste biomass sources.

All production steps are already mostly well-known except for the step from syncrude to kerosene, and combination of them should be feasible within the coming years.



*Flow scheme 3: Design of a Synhelion solar reforming syncrude production pathway. High-temperature solar reforming of $CH_4$ takes place together with its reaction with $CO_2$ and $H_2O$ to produce syngas. The syngas of all towers is centralized and processed to syncrude at one single location in conventional Fischer-Tropsch synthesis plant. The solar field not shown includes the heliostats. Figure: Courtesy of Synhelion.*

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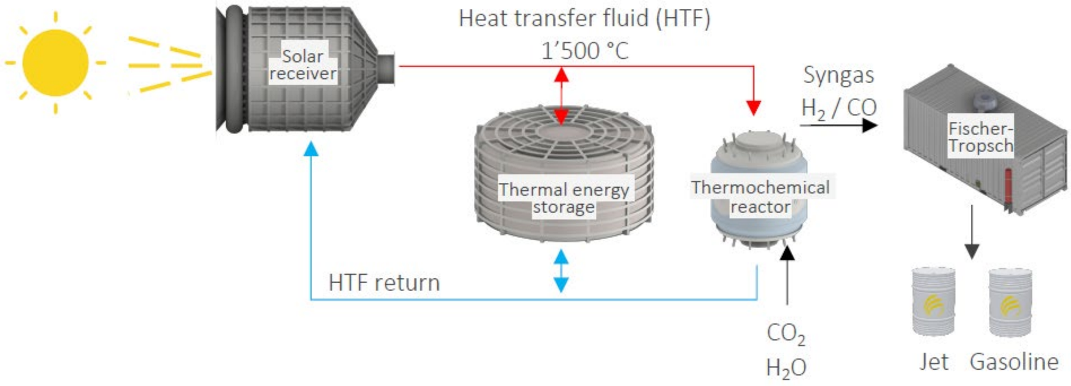
[17] Commonly, the $CO_2$ content in biogas is between 30 and 45% (Kober, Tom; Bauer, Christian; Bach, Christian; Beuse, Martin; Georges, Gil; Held et al. 2019)

### 3.2.2 Solar reforming plus (SR+)

A process called “solar reforming plus” is developed by Synhelion, where part of the required hydrogen is produced in an electrolyser powered by a concentrated solar power plant. A reverse water gas shift process is then combined with the Fischer-Tropsch synthesis to produce syncrude. Due to the significant reduction of required $CH_4$ input, the share of renewable carbon increases to 70%-100%. Again, the required $CH_4$ input may be covered with either natural gas or biogas. However, in this case, the required $CH_4$ input is reduced compared to the required $CO_2$, so that the $CO_2$ content in the biogas is not high enough to fully cover the $CO_2$ amount. The biogas input is thus calculated according to the required $CH_4$ amount, and the contained $CO_2$ contributes to a reduction of external $CO_2$ supply.

### 3.2.3 Pure solar thermochemical (ST)

In the pure solar thermochemical pathway, the Synhelion plant is used to produce syngas from $CO_2$ and $H_2O$ only in a two-step redox process, without the addition of methane and thus without fossil feedstock. The share of renewable carbon may thus be 100%. The syncrude is produced through conventional Fischer-Tropsch synthesis. This production pathway is under development and may reach larger scales by 2030.



*Flow scheme 4: Design of a Synhelion pure thermochemical syncrude production pathway. $CO_2$ and $H_2O$ are split in a ceria-based redox process to produce syngas. The syngas of all towers is centralized and processed to syncrude at one single location in conventional Fischer-Tropsch synthesis plant. The solar field not shown includes the heliostats for the reforming. Figure: Courtesy of Synhelion.*

## 3.3 $CO_2$ sources

### 3.3.1 $CO_2$ from industry: Capture at cement plant

Point sources from industry (e.g. iron and steel mills, oil refineries, ammonia plants) are well suited for targeted $CO_2$ capture, and are expected to be more and more available in the coming years due to stringent goals for climate change reduction. The concentration of $CO_2$ in the emitted gas from industries varies significantly, and with this the required energy input and technology for $CO_2$ capture (Zang et al. 2021c). Often, chemical scrubbing with methyldiethanolamine (MDEA) is chosen. The cement industry is responsible for 8% of worldwide $CO_2$ emissions (Lehne and Preston 2018) and is actively seeking to decrease these emissions (IEA 2018; Lehne and Preston 2018; Cemsuisse 2020). Switching to alternative fuels with less carbon intensity (natural gas, biomass, waste) should help in these efforts, together with potential CCS or CCU.

The captured $CO_2$ may be of fossil or biogenic origin (see section "Insertion: Fossil, biogenic, geogenic, or recycled CO2"), and the utilized $CO_2$ may be regarded as "recycled", thus being modelled as uptake with a negative sign. Generally, $CO_2$ emissions from a cement plant origin from the chemical decomposition of calcite (2/3) and from burning fuel to supply the required process heat (1/3). On average, roughly 15%-25% of the $CO_2$ are biogenic from burning biogenic waste or natural rubber. It may be possible to provide the required heat by a solar concentrating plant so to combine heat production, $CO_2$ capture and use of $CO_2$, and thus get rid of fossil fuel combustion. A pilot plant of Synhelion built at a cement plant of CEMEX will be built until end of 2022.

$CO_2$ capture in a cement plant combined with MeOH synthesis is modelled in (Meunier et al. 2020), who present a detailed techno-economic study of methanol production combined with carbon capture at a cement plant. Integrated process design making use of excess energy from the exothermal methanol conversion reactions show potentials for heat or electricity input reduction. This is only applied to the MeOH PtL pathway, while $CO_2$ supply from cement plant for the FT PtL and the StL pathways cannot profit from this integrated design as modelled in this work. The $CO_2$ capture process modelled is conventional amine-based absorption with monoethanolamine (MEA) (aqueous solution with 30 wt% MEA) with a capture rate of 90% and a resulting $CO_2$ purity of 98 mol%.

### 3.3.2 $CO_2$ from DAC

This process is modelled based on a paper partly written by the authors of this report, modelling in detail many different possible system configurations based on the Climeworks technology (Terlouw et al. 2021). Capture capacity is 100 kt $CO_2$ per year. The technology is modular, running at low temperature. The greenhouse gas removal efficiency amounts to up to 93%. Sorbents are cellulose-based solid sorbent functionalized with amines (3 kg/t $CO_2$ captured). The required energy input per t $CO_2$ captured amounts to 1500 kWh heat and 500 kWh electricity (without any subsequent $CO_2$ compression).

Various systems have been sized to provide a specific mass of $CO_2$ per year, including all necessary capture infrastructure, energy provision and storage infrastructure. Storage of electricity is modelled with a Lithium nickel-manganese-cobalt oxide battery; latent heat is stored in a steam drum tank. The most important design challenge is the heat and electricity supply. The designs included in the above reference and this work namely include:

A) **Autonomous solar** design with *heat from a solar Fresnel plant* and *electricity from photovoltaics*
B) *Heat from (grid-connected)* ***high-temperature heat pump*** and *electricity (from grid)*
C) Assumption that ***industrial waste heat*** can be used coming with no environmental burdens and *electricity (from grid)*

The publication finds that infrastructure usually does not drive the results, but the source of the input energy. Figure 8 visualizes this fact.

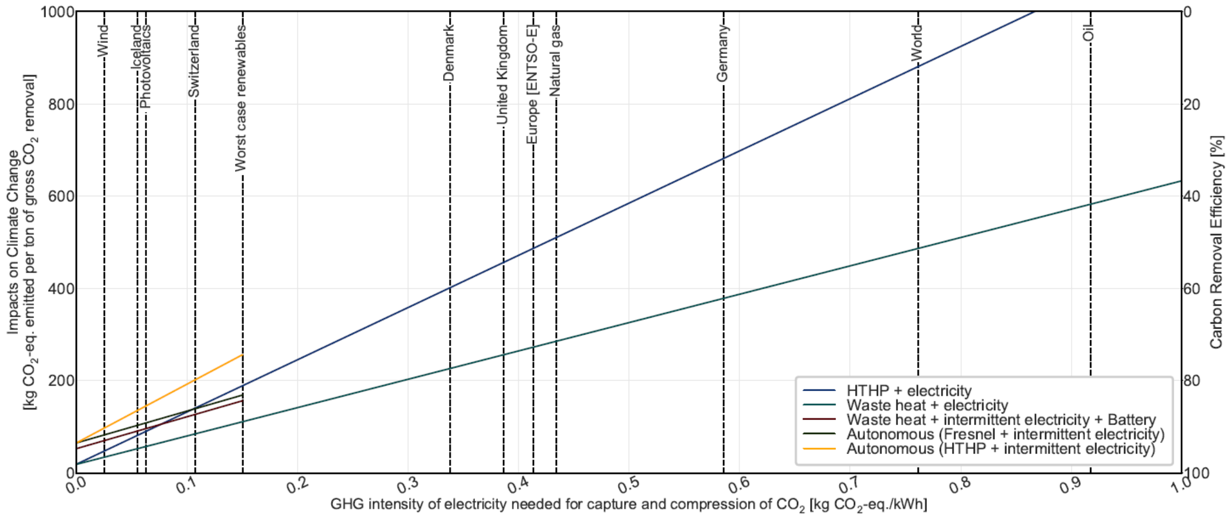


*Figure 8: Impacts on climate change per ton $CO_2$ removed from the air with various DAC plant configurations shown as a function of the greenhouse gas intensity of the input electricity for capture and compression of $CO_2$. Taken from* (Terlouw et al. 2021). *HTHP + electricity = Heat from High-temperature heat pump with electricity as input to the HTHP and to electricity needs.*

### 3.3.3 $CO_2$ from biogas

Biogas contains considerable amounts of $CO_2$ (42% in this work, versus 58% $CH_4$). Upgrading of this gas via e.g. Pressure Swing Adsorption or chemical scrubbing (MEA) separates the $CO_2$ from the $CH_4$, so that these can be used to (partially) cover all required $CO_2$ input in the solar reforming pathways (see discussion in chapter 3.2.1).

A biogas and biomethane process chain as modelled in (Antonini et al. 2020) is used. The biowaste is treated via anaerobic digestion with biogas and digestate as products. The impacts of growing and using the biomass are allocated to the food and agricultural sector, so that the biowaste comes with zero environmental impacts. Even though, it comes with embodied carbon, which is modelled with negative emissions (uptake from the atmosphere to biomass). Additionally, the treatment of the biowaste is as well allocated to the food and agricultural sector, as it is a process which inherently takes places when food is produced. The biogas thus comes with zero additional processing emissions, but embodied carbon taken up recently from atmosphere by the biomass. Any environmental impacts caused by further transport and treatment of the biogas (e.g. upgrading to biomethane) are allocated to the biogas user.

## 3.4 Hydrogen sources

The production of hydrogen is modelled based on own work published in (Antonini et al. 2020, 2021). The technical modellings on various $H_2$ production technologies and production configurations was performed in Aspen Plus® and subsequently coupled to Life Cycle Assessment (LCA), which allows not only for inclusion of direct and indirect emissions of greenhouse gases, but also trade-off assessment regarding environmental impacts other than climate change. The technologies included are Steam Methane Reforming (SMR) and Autothermal Reforming (ATR) with natural gas or biomethane from anaerobic digestion of biogenic waste as well as gasification of wood from dedicated sustainable forestry. Water electrolysis with PEM electrolysers was included for comparison based on previous work.

Figure 9 and Figure 10 show a summary of the results as shown in (Antonini et al. 2020, 2021), first for the reforming and gasification cases, and in the latter figure giving a summary of how the climate change impacts of $H_2$ production with PEM electrolysis change as a function of the greenhouse gas intensity of the input electricity.

Figure 9 shows the contributions of processes involved in the production of the hydrogen. In the climate change category, it is the direct $CO_2$ emissions and the fuel supply chain, which dominate the result. For these cases, a $CO_2$ capture rate of 98% is assumed. The error bars in the biomethane case depict a potential range of biowaste composition and corresponding carbon uptake from the atmosphere to biomass as well as differences in handling of the digestate. Both with reforming of biomethane as well as with gasification of wood, the combination of the process with carbon capture and storage results in negative greenhouse gas emissions, i.e. actual carbon removal from the atmosphere.

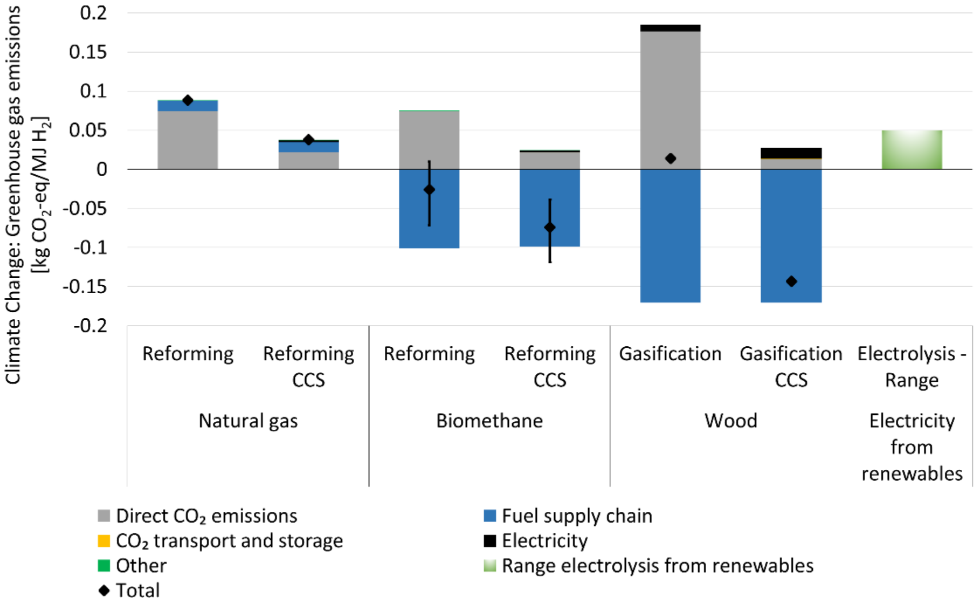


*Figure 9: Climate change impacts of production of 1 MJ hydrogen via reforming of natural gas or biomethane with or without CCS as well as the gasification of wood. The black error bar in the biomethane cases represent the variability in the carbon balance from biomass (with highly varying C content and fate of C in the digestate co-product of biogas) up to hydrogen. The potential range of climate change impacts from electrolysis depending on the input electricity is shown for comparison on the right side. Based on* (Antonini et al. 2020, 2021).

Figure 10 shows the climate change impacts of $H_2$ production with PEM electrolysis, varying the greenhouse gas intensity of the input electricity. A very small base climate change score comes from the electrolyser infrastructure as such, but the input electricity has the highest influence on the overall performance of the process. Note that the use of intermittent renewable energy sources (namely wind and PV) may require additional storage infrastructure, which is not yet included in this figure.

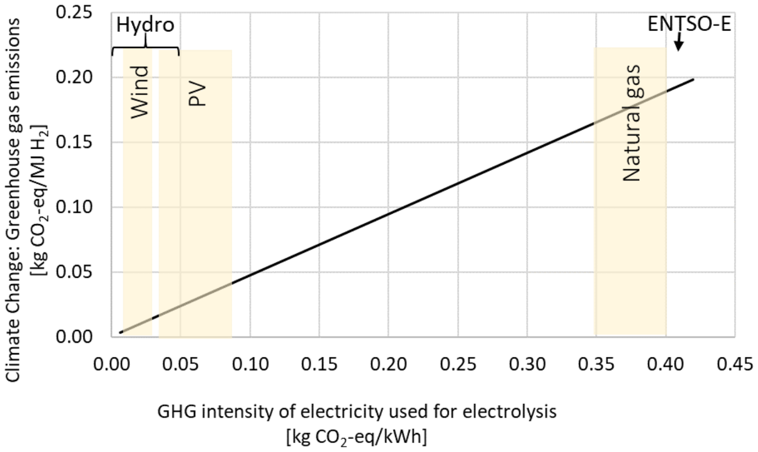


*Figure 10: Climate change impacts of the production of 1 MJ hydrogen via water electrolysis in a PEM electrolyser as a function of the greenhouse gas intensity of the input electricity. No storage is considered for the pure renewable cases. Taken from own publication* (Antonini et al. 2020).

Obviously the focus of this work is on Power-to-Liquid fuels, thus using electricity as input to the hydrogen production, and not primarily hydrogen from reforming of gas or gasification of wood. However, in order to give an idea of how the transition to a pure electrolysis-based PtL pathway may look like, conventional hydrogen production (SMR of natural gas) and novel solutions (combination with carbon capture and storage, use of biomass) are included.

## 3.5 Electricity production

Electricity production is modelled with datasets from the ecoinvent database v3.7, except for electricity from the Fresnel plant (own work). Spain is used as base case, ensuring consistency (only one country considered) and comparability with electricity from concentrated solar power. The main information are shown in Table 4.

*Table 4: Specifics of the datasets used for modelling the electricity inputs to all processes. The climate change impacts are calculated on the level of net electricity produced and ready for use or transmission/distribution. All information are from the ecoinvent database v3.7. CSP = Concentrated Solar Power*

| | Location | Technology | GHG intensity g $CO_2$-eq/kWh |
|---|---|---|---|
| **Hydropower, run-of-river** | ES | Various types of run-of-river power plants in Switzerland and Austria are the basis for this dataset. Overall efficiency is between 82% and 91%. | 0.4 |
| **Hydropower, reservoir** | ES | 52 dams in Switzerland are the basis for this dataset. Natural emissions of methane and carbon dioxide are included as an average of emissions from 89 reservoirs in temperate non-alpine regions. | 52 |
| **Wind, onshore** | ES | Modelled with a Vestas V80 wind power plant with a rated capacity of 2 MW. The wind load hours in Spain are calculated to be 2150 h/a on average. | 13 |
| **Photovoltaics** | ES | 570 kWp open ground photovoltaic plant with multi-Si panel modules. An average solar yield of 1200 kWh/kWp has been calculated for Spain | 64 |
| **CSP plant, tower** | ES | A 20 MW solar tower power plant in South Africa is the basis for this dataset. | 44 |
| **Switzerland** | CH | Average grid mix in Switzerland based on guarantees of origin. | 96 |
| **Spain** | ES | Average grid mix in Spain based on physical production and imports. | 370 |
| **ENTSO-E mix** | Europe | Electricity production mix in Europe including imports. | 400 |

It is important to recognise that the greenhouse gas intensity of electricity production with renewables heavily depends on the location (and with that the intensity of the renewable energy source, i.e. wind speed and solar irradiation) and the chosen technology (e.g. small vs. large wind turbine, PV cell type). For instance it generally holds true that wind power causes lower climate change impacts than PV electricity production. However, there might be overlaps, e.g. for a less windy location with high solar irradiation.

**Some facts on Swiss PV and wind power plants.** For photovoltaics, the solar yield factor in the dataset used amounts to 1200 kWh/kWp. This value is around 920-970 in the Swiss Mittelland, 1200-1400 in the Swiss Alps, 1400-1700 in Southern Europe, and 2500 in the Sahara (Bauer et al. 2017). The PV technology as well as the PV supply chain have made big progress in the past years, e.g. with regards to electrical efficiency or material efficiency as well as decarbonisation of energy input for manufacturing of components (Frischknecht (treeze Ltd.) and Krebs (treeze Ltd.) 2020). The environmental impacts thus show in general a decreasing trend. The climate change impacts lie roughtly between 30-80 g CO2-eq/kWh for silicium cells, and 5-30 g CO2-eqkWh (CdTe) (not Swiss-specific).

Swiss wind turbines have reached 2600 h/a in the past. The Jura comes with 1300-2000 h/a, Swiss Mittelland 1000-1644 h/a, Swiss Alps 1300-2500 depending on the altitude and location (Eymann et al. 2015). The climate change impacts have been calculated to be between 8 and 32 g $CO_2$-eq/kWh for large turbines, with a decreasing trend again (Eymann et al. 2015).

It is important to note that these figures don’t include any storage or capacity oversizing needed to satisfy the average electric power demand of a production plant. The design of a fully reliable power provision and thus the resulting environmental impacts heavily depend on the specific solutions found by e.g. a fuel producer. These aspects will shift the GHG intensity of the net electricity consumption to higher values, and thus increase impacts on climate change. **Please see the discussion in the box in chapter 5.1.1** for implications of the above presented facts on the climate change impacts of synthetic kerosene produced with these renewable resources in Switzerland.

## 3.6 Water sources

Water is needed at various locations within the PtL and StL pathways, namely as input to the water electrolysis, and potentially for cooling of processes, as process water, or for cleaning purposes for photovoltaic panels or heliostats (see Table 7). This water may be used directly from surface waters, or needs to undergo treatment depending on the application. For synthetic kerosene production happening in desert regions with high solar irradiance and close to the sea, seawater desalination may be necessary. No such process has been included in the present LCA. Some discussion of this topic is shown in (Liebich et al. 2021b). With climate change, water scarcity may also increase in other regions on the world, or water supply may be a challenge for other reasons. High water recycling rates should be achieved.

## 3.7 Combustion of kerosene

The emissions profile of current in-production aircraft gas turbines using fossil kerosene (typically Jet A1) is well known and published based on the ICAO emissions regulation. $CO_2$is proportional to the fuel burn determined or modelled for particular aircraft and the carbon content of the fuel. Synthetic kerosene potentially emits less hydrocarbons, CO and particles (Dieterich et al. 2020). Cruise emission profiles for pollutants have to be calculated from static ground tests using specialized correlations. Pollutant emissions can vary significantly between engines. Looking at climate impacts, in addition to $CO_2$, non-greenhouse gas emissions can trigger additional climate impacts. During cruise, current aircraft gas turbine engines combust the fuel basically 100% complete, this means that CO and hydrocarbon species emissions are around zero. This combustion behavior does not degrade with use of PtL and StL fuel. Due to the high thermal efficiency of gas turbines during cruise, NOx is produced. Modern gas turbines, which are more fuel efficient than previous generations, are burning the fuel at higher temperatures, therefore tend to emit more NOx. The use of PtL and StL kerosene (with similar heating value) has a more or less neutral effect on this behavior and will in consequence not reduce NOx emissions. The importance of aviation cruise NOx with respect to climate impact is currently debated. Most recent climate science about aviation NOx emissions total impact on climate tends to conclude that high altitude aviation NOx may produce a more or less neutral effect in the future, also due to changing background (Skowron et al. 2021). Extremely small fractions of the fuel are converted into soot particles, which are a trigger for contrail formation together with sulfur. Main drivers for soot formation in fossil fuels are aromatics. Since PtL and StL fuels do not contain aromatics, the use of these fuels has a co-benefit of reducing particle emissions (in terms of mass and number of emitted particles), which has been demonstrated for different low aromatic kerosene fuels in recent years (Durdina et al. 2021). The reduction of soot particles and the missing sulfur in PtL and StL fuels leads to less ice nuclei concentrations and favorable optical properties of condensation trails (less warming) (Voigt et al. 2021). The amount of (soot) particle reduction from a fossil fuel blend with PtL and StL fuel or 100% PtL and StL fuel can be estimated. However, there is no methodology to convert emission reductions into environmental impact weighted emissions in terms of $CO_2$ equivalents for the emissions involved. Hence, quantification of emissions related to the end use of synthetic kerosene, and thus the translation of such emissions into life cycle environmental impacts is not possible at this point in time. In agreement with the commissioner of this report, the combustion phase is thus solely represented by emitting the carbon embodied in the fuel to air as $CO_2$. This results in the fact that LCA results including the combustion phase can only be interpreted for the climate change impact category, but not for any other impact category, as for the latter the modelling is incomplete.

# 4 Definition of base cases and variations

## 4.1 Process design variations

As has been shown in Figure 1, various design choices can be taken for both PtL and StL pathways with regards to the synthesis processes themselves, but also with regards to the choice of how the required educts are produced and supplied. In this project, we namely model this variability by the following:

- **Hydrogen** from water electrolysis in a Protone Exchange Membrane (PEM) electrolyser. Electrolysis in an alkaline electrolyser (AEL) or Solid Oxide Electrolyser Cells (SOEC) are not modelled. A comparison of these three electrolyser types is provided in (Dieterich et al. 2020). As hydrogen is currently mostly produced via steam methane reforming of natural gas, results are also shown using this pathway (with and without carbon capture and storage (CCS)) for benchmarking and to show an additional potential transition scenario.
- **Electricity** input to processes in the foreground, namely $CO_2$ capture, $H_2$ production, production of the kerosene: This is modelled with electricity from renewables (hydropower, wind power, photovoltaics, concentrated solar power) and electricity from grid (Switzerland (CH), Spain (ES) and the ENTSO-E[18] grid mix as a higher bound case). Note that the exclusive use of electricity from fluctuating renewables may require the addition of ***energy storage*** (electricity and/or hydrogen) to the system and/or may call for oversizing some process capacities. This has been included in the DAC cases and the modelling for StL, but not in all other production pathways (namely not for $H_2$ from electrolysis).
- **Steam/heat is needed as** input to $CO_2$ capture and conversion processes. In todays industry, this mostly stems from burning fossil fuels. However, the use of waste or renewable heat may decrease the input of fossil-based heat, or even cover all heat needs. Heat pumps or solar

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[18] European association for the cooperation of transmission system operators (TSOs) for electricity.

energy may be other sources of heat. In this work, the heat either comes from A) an industrial, fossil-based heat source, B) is assumed to be free of emissions, or C) comes from a Fresnel Solar Power plant as modelled by the authors with data based on Industrial Solar[19] (Terlouw et al. 2021).

- **$CO_2$** stems A) from direct air capture (DAC) in various configurations according to previous work by the authors (Terlouw et al. 2021). This has the advantage that $CO_2$ in the atmosphere is abundant, and $CO_2$ can be removed from the atmosphere geographically independent of existing infrastructure depending on the configuration. B) From a CCU process at concentrated $CO_2$ sources, here represented by carbon capture at a cement plant. This seems to be a reasonable choice as the cement industry is actively seeking a reduction of their $CO_2$ emissions, and the $CO_2$ is present in relatively high concentrations in the flue gas, thus making it possible to capture it with lower energy input compared to e.g. from the flue gas in a natural gas power plant.
- **Methane ($CH_4$)** is needed as an input to the solar reforming pathways in form of natural gas or biogas. A very recent published life cycle inventory database on natural gas production and transport is used to model natural gas input from various countries (Bussa et al. 2021; Meili et al. 2021). A biogas and biomethane process chain as modelled in (Antonini et al. 2020) is used.

It should be noted that some of these inputs can be chosen by design and engineering, while others may not be possible to be influenced by the producer of the synthetic kerosene – for instance the source of the electricity input to specific processes[20]. Further, both electricity from renewables as well as biomass-based resources may be limited and not accessible in volumes big enough to ensure production of large amounts of synthetic kerosene. Even more, the electricity grid mixes may evolve towards decarbonisation, while technologies will become more efficient. It was not the purpose of this project to model such potential upscaling pathways for increasing penetration of syncrude to the refining sector and of the volume increase of synthetic kerosene on the aircraft fuel market. Instead, the results will be shown for selected case combinations. This gives a perspective on how production based on a business-as-usual behaviour may look like, how this can be improved already today by conscious choices on key parameters (potential good practice today), and how best cases in future may look like.

Table 5 presents a summary of these qualitative choices that can be made when modelling the PtL and StL pathways.

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[19] https://www.industrial-solar.de/

[20] Of course an operator of an industrial process may be free to choose to either produce electricity on-site, or buy guarantees of origin for a specific electricity supplying technology or electricity mix.

*Table 5: Summary of input data variations, which can be combined in many different ways mostly independently.*

| **Input** | **Origin** | **Technology/Modelling** | **Specifics** | **Reference used as basis** |
|---|---|---|---|---|
| $CO_2$ | CCU – Cement plant | a) Integrated design (methanol pathway) / «normal» carbon capture.<br>b) Credit for capturing $CO_2$: 100% to fuel//50% to fuel//100% to cement plant<br>c) Steam origin: Industrial fossil-based or waste heat with zero impacts | Amine-based absorption process with 90% capture rate | (Meunier et al. 2020) |
| | DAC | Climeworks technology<br>Energy supply via:<br>- High-Temperature Heat Pump (HTHP) + grid electricity<br>- HTHP + PV electricity<br>- Fresnel + PV | Low-temperature DAC; 1500 kWh heat and 500 kWh electricity per ton of $CO_2$ | (Terlouw et al. 2021) |
| | Biogas | Treatment of household waste by anaerobic digestion | Upgrading of biogas to separate $CO_2$ and $CH_4$ | (Zhang et al. 2017) |
| $H_2$ | Electrolysis, PEM | Electricity supply:<br>- Hydropower, run-of-river<br>- Wind, PV<br>- Grid (ES, ENTSO)<br>- Natural gas | Per kg $H_2$:<br>- 55 kWh electricity, low voltage<br>- 12.3 kg water, deionised | (Zhang et al. 2017; Dieterich et al. 2020) |
| | Other | - SMR of natural gas or biomethane<br>- Gasification of Wood | With and without CCS, amine-based with 98% capture rate.[21] | (Antonini et al. 2020, 2021) |
| Electricity (for electrolysis, $CO_2$ capture, processing) | | Renewables Hydro run-of-river/reservoir, wind, photovoltaics, CSP (all modelled for Spanish conditions)<br>Grid: Switzerland, Spain, ENTSO-E | Intermittent power supply will require some kind of storage, which is not considered in this study except for DAC. | Ecoinvent v3.7.1 cut-off |
| Methane (input to StL reforming) | Natural gas | - Netherlands: Country with lowest methane emission rate (MER) (0.04%)<br>- Libya: Country with very high MER (8.5%)<br>- RER market mix (1.3%)<br>- US mix (Synhelion sees potential for their technology in the US) (1.3%) | The underlying includes many origin countries and transport distances for natural gas. The main difference is the methane emission rate over the whole chain. | (Bussa et al. 2021; Meili et al. 2021) |
| | Biogas | Treatment of household waste by anaerobic digestion | Upgrading of biogas to separate $CO_2$ and $CH_4$ | (Zhang et al. 2017) |

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[21] We don't analyse a case of hydrogen production from reforming with carbon capture and subsequent use of the $CO_2$ for the synfuels process.

## 4.2 Base cases

Two base cases are defined as follows (Table 6):

a) **Business-as-usual (BAU)**: This represents a “current” production of synthetic kerosene without specific decarbonisation aims of side processes such as electricity inputs other than electrolysis. On the one hand, this depicts a process design where the fuel producer does not have full control of all processes in the foreground chain, or does not aim for full decarbonisation e.g. for economic reasons.

b) **Decarbonisation (Decarb)**: This represents a “current” production of synthetic kerosene where the fuel producer shows interest in high reduction of climate change impacts, e.g. due to compulsory reduction targets by policy makers. It underlines intrinsic motivation of fuel producers to not only do it better, but as good as possible, given all the efforts made towards reduction targets. This scenario is modeled by a **solar driven cement plant** and electricity from concentrated solar power plants for two reasons: First, it is planned by Synhelion to collaborate with a cement plant and run it fully on solar energy to cover the required electricity and heat inputs with a CSP plant. Second, climate change impact scores of heat and electricity from Fresnel or CSP plants can be looked at as in the medium range of heat/electricity from renewables, thus representing well an average and thus realistically achievable renewable case.

*Table 6: The base cases «Business-as-Usual” (BAU) and “Decarbonisation” (Decarb): $CO_2$ input, $H_2$ electricity source, electricity in all other processes, heat origin, and natural gas origin.*

| | **BAU** | **Decarb** |
|---|---|---|
| **$CO_2$** origin, crediting and energy supply | CCU from cement plant, 100% credit to fuel user who bears the impacts of carbon capture (“recycled $CO_2$“). The latter is run by electricity from grid (ENTSO-E) and heat from a fossil-based production mix. | CCU from cement plant, 100% credit to fuel user who bears the impacts of carbon capture (“recycled $CO_2$“). The latter is purely solar driven (Fresnel solar plant and CSP plant). |
| **$H_2$** electrolysis electricity source (PtL) | PEM with run-of-river hydropower | PEM with run-of-river hydropower |
| **Electricity** in all other processes (Carbon Capture, Processing) | European (ENTSO-E) mix | Solar (CSP) |
| **Heat** origin (Carbon Capture, processing) | Industrial, fossil-based production mix ($CO_2$ capture) // Internal excess energy (waste heat from exothermic processes) | Solar (Fresnel) // Internal excess energy (waste heat from exothermic processes) |
| **Natural gas** origin<br>(StL reforming cases) | European market mix (NG)<br>or biogas from biowaste (BG) | The Netherlands (very low methane emission rates in supply chain) (NG)<br>or biogas from biowaste (BG) |

## 4.3 Comparability of results calculated for the various pathways

**Comparability of the results** between the different pathways is enhanced due to the harmonized modelling choices. However, it should be noted that comparability is at the same time still distorted by several issues, with the major ones being the following:

- **No details on the refining process of syncrude are known** for both FT PtL/StL as well as the upgrading of MeOH, as this is currently still under investigation and no applicable data could be found. Furthermore, the molecular composition of syncrude is significantly different from crude oil, so that the FT process needs to be adapted in order to be efficient(de Klerk 2008).
- While the **FT PtL pathway is modelled resulting in syngas** and then running through Fischer-Tropsch for syncrude production and refining, the **StL pathways directly result in syncrude** for further refining. Due to the above mentioned data gap, this should not distort comparability between the FT PtL and the StL pathways.
- Novel process chains are considered, with the underlying data taken from publications and not from real proof of concepts (except for the StL pilot plant). No future developments considered due to lack of data.
- The **PtL pathways are not modelled with biogenic carbon sources** (other than biogenic waste burnt in cement plants), while the StL reforming pathways include biogas as $CO_2$ and $CH_4$ source.
- The **StL data received from Synhelion are more detailed** and valid for well-developed process designs. This includes e.g. optimised water recycling or handling of emissions from the Fischer-Tropsch process. The FT PtL and MeOH PtL data are from publications with partially no in-depth discussion.
- The Methanol to gasoline process is little known, and only one reference could be found so that no validation could take place.
- Various kerosene types or qualities may be produced via the various production pathways, while we assume the product from all modelled processes results in the exact same kerosene. However, the effect of various kerosene properties on the LCIA results are probably minor.

The base case will be varied with combinations of input data choices as presented in Table 5. This does not account for the above mentioned uncertainties, which cannot be addressed better at present due to the need of further research and need of receiving real-life data from industry. This would lead to higher accurateness and robustness of the values shown in Table 7. As example, the input data to FT and MeOH are rather similar, and so are the LCIA results. However, it is unknown yet whether these two production pathways are indeed so similar, or if they would show larger differences in reality.

## 4.4 Summary of inputs to the pathways and carbon balance

Quantitative input data for the production of 1 kg kerosene via all modelled pathways are summarized in Table 7. We additionally show the carbon contents so that the carbon balance can be followed.

*Table 7: Summary of inputs modelled for the production of 1 kg kerosene via various PtL and StL pathways. Values in brackets indicate the amount of C (kg) so that the C balance is easily visible for the reader. C inputs from $CO_2$ and CH4 minus $CO_2$ emissions plus the carbon correction amount equal the C content of kerosene (0.86 kg C /kg). Processing electricity is electricity for the core processes in each pathway, without power needs of electrolysis or $CO_2$ capture. Total electricity includes all these. FT = Fischer-Tropsch, MeOH = Methanol, SR = Solar reforming, SR+ = Solar reforming plus, ST = Solar thermochemical, NG = natural gas, BG = biogas, BM = biomethane (upgraded biogas).*

| | | **FT** | **MEOH** | **SR** | **SR** | **SR+** | **SR+** | **ST** |
|---|---|---|---|---|---|---|---|---|
| | | | | NG | BG | NG | BG | |
| **Kerosene production** | kg | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **$CO_2$ (Carbon)** | kg | 3.23<br>(0.88) | 3.27<br>(0.89) | 0.67<br>(0.18) | 0 | 1.88<br>(0.51) | 1.19<br>(0.32) | 2.73<br>(0.74) |
| **Hydrogen** | kg | 0.44 | 0.49 | 0 | 0 | Produced internally | | 0 |
| **Natural gas /Biogas (carbon)** | $m^3$ | 0 | 0 | 0.97<br>(0.57) | 1.87<br>(0.99) | 0.44<br>(0.26) | 0.84<br>(0.45) | 0 |
| ***of it $CH_4$*** | *kg* | *0* | *0* | *0.97<br>(0.57)* | *0.76<br>(0.57)* | *0.44<br>(0.26)* | *0.34<br>(0.26)* | *0* |
| ***of it $CO_2$*** | *kg* | *0* | *0* | *None* | *1.53<br>(0.42)* | *None* | *0.69<br>(0.19)* | *0* |
| **Electricity, processing** | kWh | 0.9 | 0.2 | 0.02 | | 0.002 | 0.002 | 0.32 |
| **Electricity, electrolysis** | kWh | 24.1 | 27.0 | 0 | | 0 | 0 | 0 |
| ***Electricity, total*** | *kWh* | *25.0* | *27.2* | *0.02* | | *0.002* | *0.002* | *0.32* |
| **Water, processing**** | L | 1.3 | 0 | 1.0 | | 2.2 | | 2.2 |
| **Water, electrolysis** | L | 5.4 | 6.1 | 0 | | 0 | | 0 |
| **Water, mirror cleaning** | L | 0 | 0 | 0.2 | | 0.1 | | 1.3 |
| ***Water, total*** | *L* | *6.7* | *6.1* | *1.2* | | *2.3* | | *3.5* |
| **$CO_2$ emissions** | kg | 0 | 0 | 0.03<br>(0.01) | 0.90<br>(0.24) | 0.1<br>(0.03) | 0.1<br>(0.03) | 0 |
| **Carbon correction** | kg | -0.09<br>(-0.02) | -0.13<br>(-0.03) | | | 0.41<br>(0.11) | | |

** Water inputs to (chemical) processes.

In the SR and SR+ BG cases, all or part of the $CO_2$ input is covered by the biogas, respectively. The StL designs mostly cover their electricity needs internally from solar energy, so that only a small amount of electricity needs to be taken from the grid (potentially including certificates). $CO_2$ emissions are emissions from natural gas or biogas used as backup firing. Note that these emissions are biogenic when biogas is used.

# 5 Results

All results are in general shown for climate change impacts, expressed in total greenhouse gas emissions (using GWP factors for a time horizon of 100 years) over the whole life cycle (kg $CO_2$-equivalents per functional unit). Contribution analysis visualizes which processes contribute to the total score with their individual impact. The figures differentiate between the $CO_2$ supply chain in blue shades, the $H_2$ supply chain in green, the $CH_4$ supply chain in brown, and the processing of these inputs via syngas/syncrude to kerosene.

Results are first shown for production of 1 kg kerosene modelled with the base cases as an overview over the various production pathways. Then, variations for the FT PtL and the MeOH PtL are shown. Due to similarities in the input data for the FT and MeOH pathways – and the resulting similar LCIA results – variation of specific parameters is exemplified at the example of FT PtL or MeOH PtL, and the findings can be applied to both PtL pathways. Details are then given for the StL cases. Results are further shown for the system expansion approach. All figures include the climate change impact scores per kg kerosene and per MJ kerosene, and show the reduction potential of the synthetic kerosene compared to the CORSIA reference value (section 2.4).

The **contribution categories** shown in the figures are the following:

a) **$CO_2$ supply chain**:
  - Required input of electricity and heat, respectively;
  - $CO_2$ other = $CO_2$ leakage (fossil and biogenic), tap water, monoethylamine, infrastructure
  - $CO_2$ credit/uptake: This visualizes that the $CO_2$ is from recycling or from direct uptake from the air, thus comes with negative climate change impacts.

b) **$H_2$ chain**: This includes the PEM electrolyser infrastructure and the input electricity.

c) **$CH_4$ chain**: This includes the extraction, processing and transport of the natural gas, or the production of biogas. Due to the fact that with the chosen modelling of the latter, the uptake of $CO_2$ from atmosphere to biomass is larger than the greenhouse gas emissions of the required processing of the gas, biogas comes with negative emissions.

d) **Plant infrastructure** for the syngas/methanol/syncrude production and processing to kerosene.

e) **Processing, electricity**: Necessary power input for the syngas production and FT process (FT PtL); MeOH synthesis, distillation and conversion (MeOH PtL); and syncrude production and refining (StL)

f) **Processing, direct emissions** (for StL reforming only): Direct emissions of $CO_2$ from backup gas burning. Further direct emissions may be possible from losses which potentially occur during reforming and Fischer-Tropsch. For the PtL Fischer-Tropsch pathway and the MeOH pathway, no information was available on such losses, other than the fact that around 20% of the input energy is lost according to (Van Der Giesen et al. 2014). For StL, the process design is optimised such that these direct process emissions are impeded.

g) **Carbon correction** as explained to correct the distorted C balance due to allocation (see section "Insertion: Carbon correction")

h) **Combustion/Total**: The kerosene production comes in most cases with negative climate change impacts, i.e. embedded carbon which has been gained through recycling or direct uptake from the atmosphere. The embedded carbon is then released back to air during combustion of the fuel in the aircraft engine (shown with a grey bar), which results in the final total greenhouse gas emissions shown with the black cross. A carbon content of 0.86 kg C/kg kerosene is assumed. Please keep in mind the limitations of calculating the overall impacts of the combustion phase on climate change as discussed in section 3.7.

i) The **reduction** of the greenhouse gas emissions of each synthetic kerosene life cycle compared to the CORSIA benchmark is added for both the BAU and the Decarb cases. The CORSIA reference value for life cycle greenhouse gas emissions including combustion is 89 g $CO_2$-eq/MJ (3.9 kg $CO_2$-eq/kg) (see chapter 2.4).

## 5.1 Base cases comparison

In order to establish a first overview on climate change impact results, the BAU and Decarb base cases are calculated for all pathways (FT PtL, MeOH PtL, StL). Impacts on climate change, the potential reduction compared to the CORSIA benchmark, and the contribution of processes related to the production of 1 kg synthetic kerosene are shown in Figure 11.

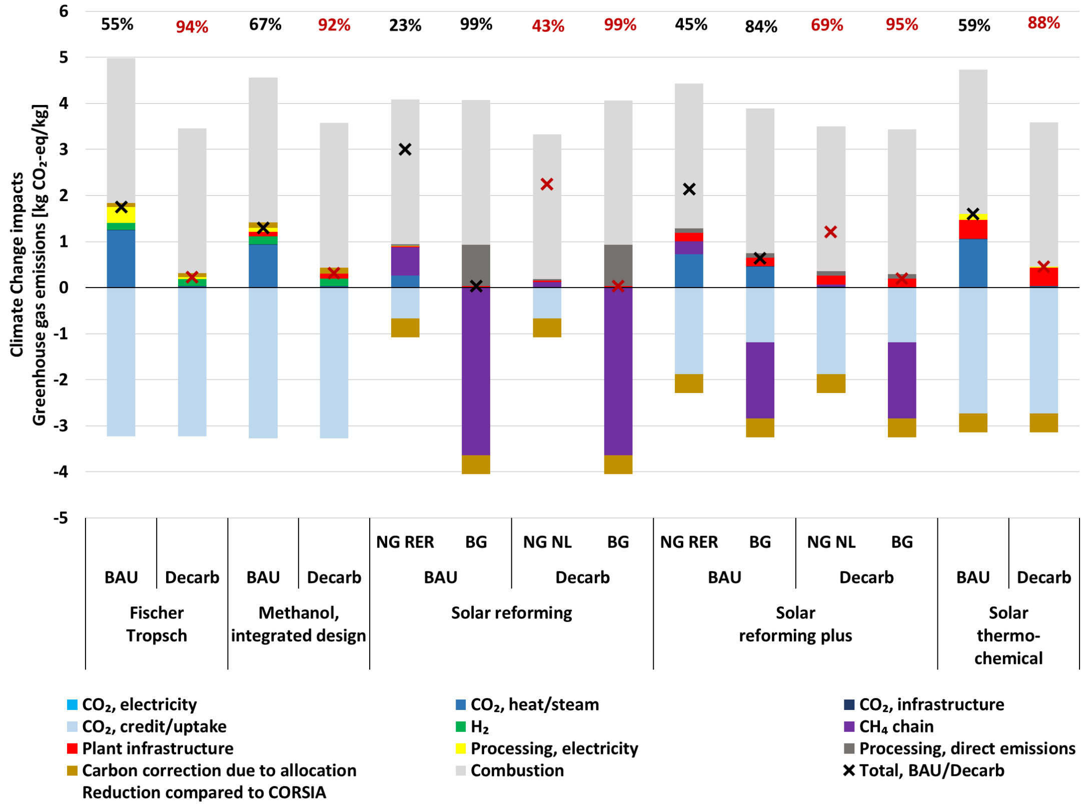


*Figure 11: Contribution analysis of climate change impacts of the production of 1 kg kerosene via various PtL and StL pathways. Combustion of the kerosene in an aircraft engine is considered only via emission of $CO_2$ to air associated with carbon embodied in the kerosene; no other climate effects of aircraft are considered. The red figures indicates the reduction of greenhouse gas emissions compared to the CORSIA benchmark. BAU = Business-as-usual scenario; Decarb = Decarbonisation scenario. NG = Natural gas, BG = Biogas, RER = Europe, NL = The Netherlands. Conventional kerosene comes with 3.9 kg $CO_2$-eq/kg.*

KEY MESSAGES:

- The use of synthetic kerosene can result in significant reduction of impacts on climate change when decarbonisation in the supply chain is an integral part of the process design.
- Using biogenic carbon sources brings the fuel close to carbon neutrality.
- No pathway shows clear advantage over the others based on the modelled input data.

The climate change impacts of kerosene production are dominated by the $CO_2$ supply chain in these base cases, where $CO_2$ is from a cement plant (considered as “recycled $CO_2$”) and the electrolysis is driven by run-of-river hydropower. Within the supply chain of $CO_2$, the main contributor is the provision of heat to $CO_2$ capture from an industrial, fossil based energy mix in BAU, which can be significantly lowered in the Decarb variant using solar energy. For PtL, the reduction potential thus is increased to over 90% for Decarb compared to 55-67% in BAU, which corresponds to climate change impacts between ca. 5-40 g $CO_2$-eq/MJ. Electricity required as input for processing is assumed to be a rather greenhouse gas intensive European market mix in BAU, which is visible for the FT and the MeOH pathway, respectively. The electrolysis runs on run-of-river hydropower in both the BAU and the Decarb case.

For StL, the technical optimisations of solar reforming plus compared to solar reforming indeed lead to lower climate change impacts (50 g $CO_2$-eq/MJ instead of 70 g $CO_2$-eq/MJ for BAU) for the natural gas consuming pathways. A complete solar energy supply and monitoring of the methane emissions in the natural gas supply chain allow a reduction potential of up to 70% (27 g $CO_2$-eq/MJ) for SR+. The use of biogas as carbon source (providing both the required $CH_4$ and the $CO_2$) allows for factual carbon neutrality in the SR model, as only very little greenhouse gas emissions from infrastructure and energy input are left per MJ. Thus, the decarbonisation of this remaining very small electricity input does not influence the reduction potential significantly. This increases slightly for SR+ where not all $CO_2$ input can be covered through the biogas, and additional $CO_2$ has to be purchased or captured. Due to the uptake of $CO_2$ to biomass and as the processing greenhouse gas emissions are lower than that uptake, biogas comes with negative emissions. Hydrogen produced with hydropower does not add much greenhouse gas emissions, and the plant infrastructure also plays a minor role (see Box 2). This is slightly different for the solar reforming plus and the solar thermochemical cases, where the impacts from material use for the large plants are well visible due to production of large amounts of mainly steel and aluminium oxide. The solar thermochemical design doesn’t require an input of $CH_4$. In a full solar and thus for Synhelion very realistic configuration, 88% of the GHG emissions of conventional kerosene can be avoided, and only 10 g $CO_2$-eq/MJ are left mainly from plant infrastructure.

Reduction potential is present for all pathways assessed, and is significantly higher for the decarbonisation scenario. The relatively small differences between the individual pathways seem not to point to a specific favourable pathway (except the use of biogas in SR). Further, the results have to be interpreted in the light of the uncertainties and variabilities as discussed in chapter 4.3.

### 5.1.1 Greenhouse gas intensity of the electricity source

**One important aspect when electrolysis comes into play is the electricity source used as input.** However, this may also play a role in the remaining foreground processes. Figure 12 assesses the climate change impacts of the production of 1 kg kerosene as a function of the GHG intensity of electricity used for electrolysis, $CO_2$ capture and processing in figure (a). GHG emissions of the FT and the MeOH PtL pathways are very sensitive to this GHG intensity. In contrast, the StL consumes little external electricity (i.e. not solar energy) (see Table 7) and thus the choice of the input electricity does not play a major role. Part (b) of the figure showcases that it is solely the electrolysis step in the PtL pathways which drives this high interdependency between climate change impacts and GHG intensity of input electricity.

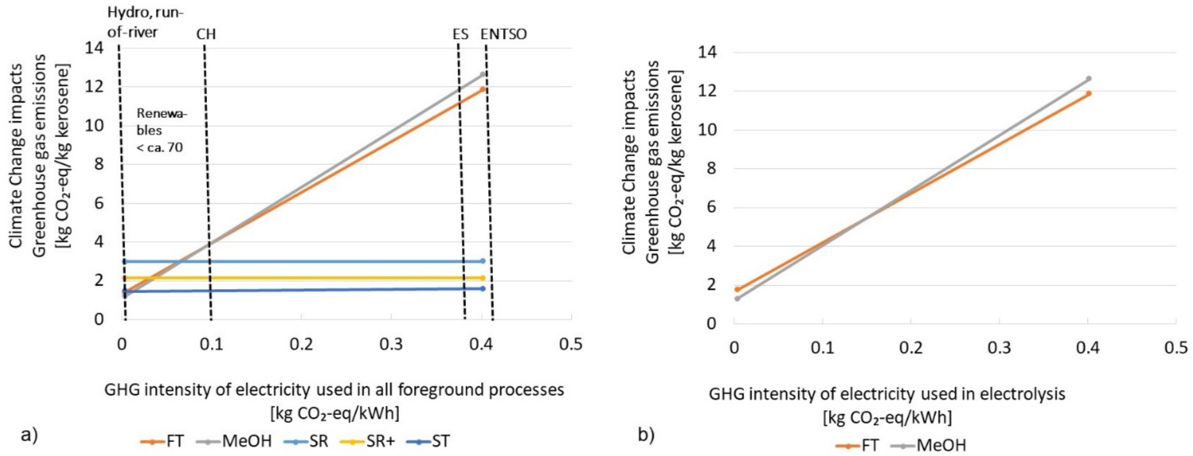
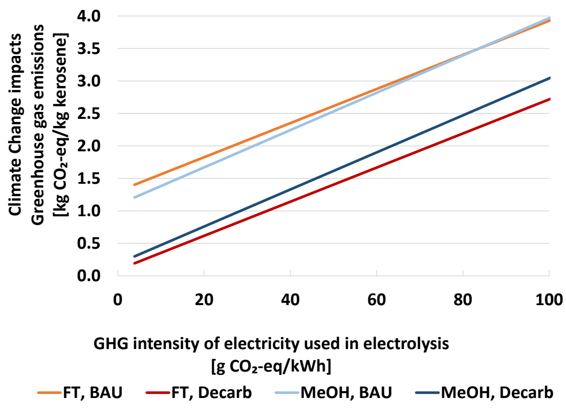


*Figure 12: Performance in climate change impacts of the production of 1 kg synthetic kerosene via various PtL or StL pathways in relation to the input electricity used a) in foreground processes, namely $CO_2$ capture, $H_2$ production, and processing, or b) in electrolysis (thus only shown for PtL). CH = Switzerland, ES = Spain, ENTSO = European electricity mix*

It will be illustrated even more impressively in Figure 14 and Figure 15 that there is only a small margin for the choice of electricity input to the electrolysis in PtL when significant reduction of climate change impacts compared to conventional kerosene wants to be reached. This even rules out the use of PV or wind electricity from sites which are not very optimal (see also the GHG intensities related to PV and wind electricity presented in chapter 3.5).

**Box: Power-to-Liquid with electricity from PV or wind in Switzerland**

Any fuel producer needs to know the greenhouse gas intensity of the input electricity chosen, and to include environmental impacts of eventual storage of electricity (or hydrogen) or oversizing of capacities. This allows a first estimate where the climate change impacts of the resulting fuels would lie on the lines in the figure below (which is an excerpt with extension from Figure 12), in comparison to the fossil benchmark of 3.9 kg $CO_2$ -eq/kg kerosene. In order to reach a reduction of ca. 70%, the input electricity should not come with more than around 5 g $CO_2$-eq/kWh (BAU, where 70% are possibly not feasible at all in any case) or ca. 30-40 g $CO_2$-eq/kWh (Decarb). The latter has been proven easily feasible with Swiss wind power, where greenhouse gas emissions between 8 and 32 g $CO_2$-eq/kWh have been calculated (Eymann et al. 2015). For photovoltaics, the choice of type, technological development, and location of the PV module are decisive to get into the mentioned range. Remember that any environmental impacts from storage etc. needs to be added on top of these values, which will shift the GHG intensity of the input electricity to the right!



### 5.1.2 Selected environmental impact categories

LCA does not only calculate a “carbon footprint”, but provides quantification of a variety of environmental impacts. A selection of those results is shown in Figure 13 as discussed in chapter 2.1, namely for potential acidification, ozone depletion, and effects on the respiratory ways of human beings. As discussed in chapter 3.7, data to include the combustion phase were not available. The results shown here thus have to be regarded as cradle-to-gate only. In all three impact categories, decarbonisation not only lowers climate change impacts, but also decreases the load in these categories. For acidification and respiratory effects, electrolysis plays a more important role than for climate change and ozone depletion. Heat based on fossil fuels for $CO_2$ capture again proves to be malign for environmental impacts, so that decarbonsiation is heavily needed and brings major benefits. Production of the materials for the StL infrastructure (SR+ and ST) is most important for acidification and respiratory effects. The SR pathway is dominated by emissions in the natural gas supply chain with regards to ozon depletion, which again underlines that a functioning monitoring of all emissions related to oil and gas extraction and processing is of high importance in order to avoid negative impacts on the environment.

In order to be able to somewhat classify the results, the comparison to combusting conventional kerosene in a medium haul passenger aircraft is added. This should be interpreted with care, as these benchmark values include the end use of the kerosene, while no data on this are presented for the synthetic kerosene. Still, the impact scores for synthetic kerosene are lower than those for fossil-based kerosene. It is likely that adding the end use of synthetic kerosene will not lead to heavy exceedance of these benchmark values.

KEY MESSAGES, figure 13:

- Decarbonised pathways lead to lower acidification, ozone depletion, and effects on the respiratory ways compared to BAU. No trade-off has been identified.
- The combustion phase is highly likely to come with reduced particle emissions compared to conventional fuel. The impacts on the environment could not be modeled due to lack of methodology.
- Heat supply to carbon capture and materials for StL infrastructure play a major role, as well as the natural gas supply chain with regards to ozone depletion.

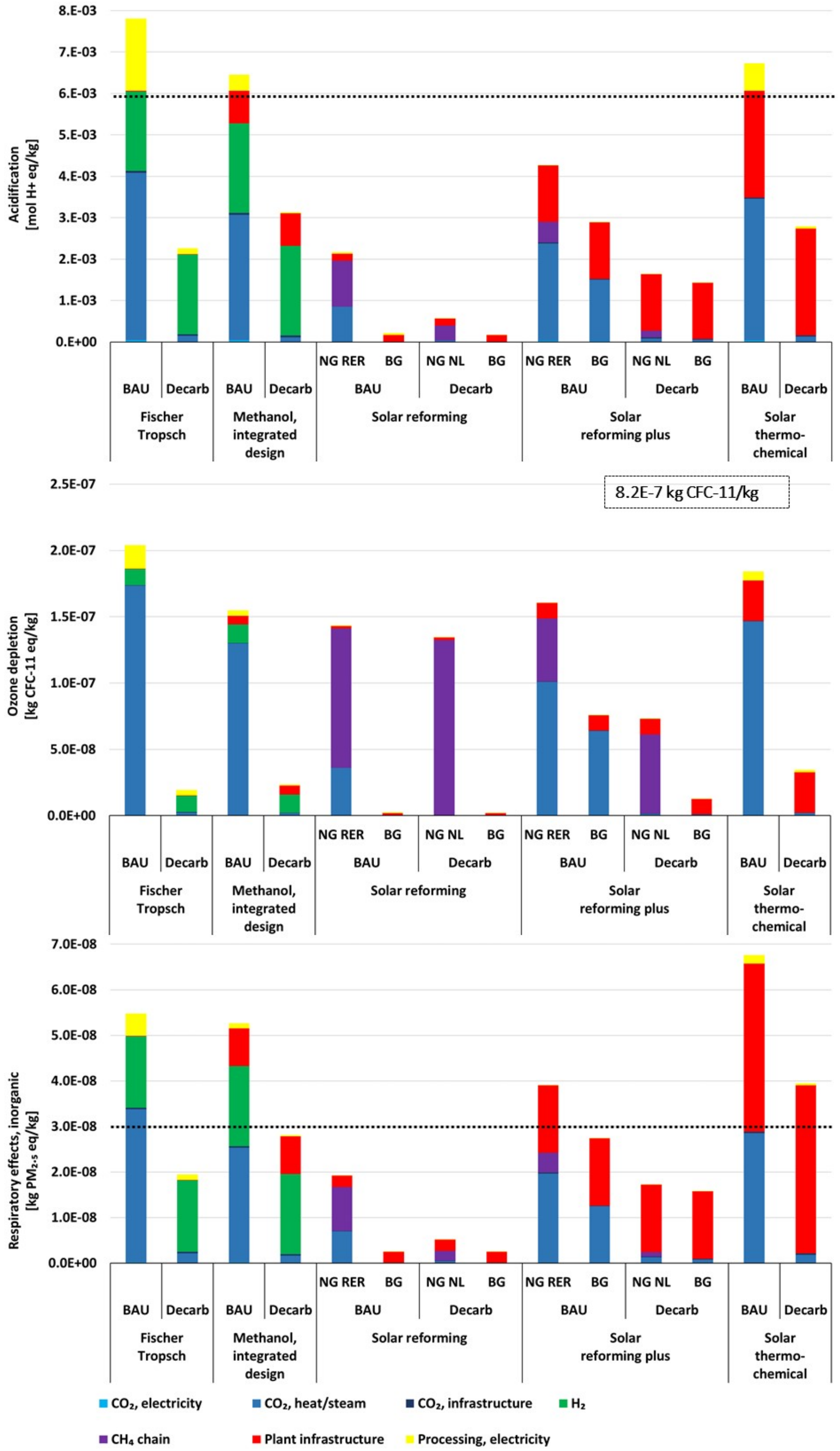


*Figure 13 Results for selected life cycle impact assessment categories fort he production of 1 kg synthetic kerosene. The dotted line (or the value in the dotted box, respectively) shows the score for conventional kerosene.*

## 5.2 Fischer-Tropsch PtL (FT PtL)

Figure 14 shows variations for the Fischer-Tropsch PtL pathway. The BAU case uses electricity from ENTSO unless otherwise mentioned (and run-of-river hydropower for electrolysis), while decarb uses solar heat and electricity.

First, the origin of the $CO_2$ is varied, and the electrolysis is powered by run-of-river hydropower unless specifically mentioned. Second, the influence of the origin of the electricity used as input to electrolysis is shown:

a) $CO_2$ sources:
   i. Varying the **crediting scheme for the $CO_2$ from industry:** 100F = 100% credit to fuel, 50F = equal credit to fuel and cement plant, and 100C = 100% credit to cement plant. 100F is the base case for all other variations
   ii. Exploring the potential of **using waste heat for $CO_2$ capture** instead of fossil heat
   iii. **$CO_2$ from DAC** in various configurations: Pure autonomous solar electricity/heat sources; heat from high-temperature heat pump (HTHP) driven by varying electricity; use of waste heat with varying electricity source.

b) $H_2$ production:
   i. Electrolysis with varying electricity source
   ii. Steam methane reforming of natural gas with and without CCS (SMR NG w and w/o CCS)

Climate change impacts of kerosene from the assessed FT PtL configurations range between **5 and 80 g $CO_2$-eq/MJ for BAU and 5 and 42 g $CO_2$-eq/MJ for Decarb** in general, with outliers from not crediting the fuel user for the use of recycled $CO_2$ (100C, ca. 78-85 g $CO_2$-eq/MJ), and the use of electricity from the European grid for electrolysis (up to ca. 270 g $CO_2$-eq/MJ). Reduction potentials of up to 95% have been found.

First, the **credit of the captured $CO_2$** in the cement plant is given either to 100% to the fuel producer (100F), distributed to both the fuel producer and the cement plant (50F), or the credit is given to the cement plant which can then claim improvement in their carbon emission reduction targets (100C). In case the $CO_2$ is considered a normal industrial, marketable product (100C), the reduction potential is minor (5% to 13%). This increases to 55% (BAU) and up to 94% (Decarb) when all credit for the reuse of the $CO_2$ goes to the fuel producer. As discussed before in this report, this aspect is still to be handled in reality via conventions or treaties between economic partners. As the **steam/heat source for $CO_2$ capture** plays a major role, in one case it is assumed that heat can be internally recovered for the $CO_2$ capture process, or is taken from another excess heat source for free. This leads to a total reduction in climate change impacts of 87% and 95%, respectively, compared to the initial setting. Switching the cement plant to a fully solar energy powered site (i.e. electricity and heat supply from Fresnel plant; "Decarb" scenario) benefits even more with 94% reduction potential (decreasing to 13% in the 100C case).

The ambiguity on who may get which credit for reusing $CO_2$ can be solved by choosing **$CO_2$ from DAC**. This leads to reduction of at least 47% in all analysed cases. Obviously, a high-temperature heat pump running with a rather greenhouse gas intensive European electricity mix generated higher GHG emissions (40 to 47 g $CO_2$-eq/MJ, 47% to 55% reduction) compared to a case where the HTHP and the DAC electricity input are running on run-of-river hydropower (6 to 13 g $CO_2$-eq/MJ, 85% reduction even in BAU). The use of a waste heat sources combined with run-of-river hydropower used for electrolysis leads to kerosene reaching a reduction of max. 90% compared to the CORSIA reference value. When this scenario is combined with the assumption that all electricity supply in the complete FT PtL pathway is replaced with run-of-river hydropower, this can even be increased to 94%.

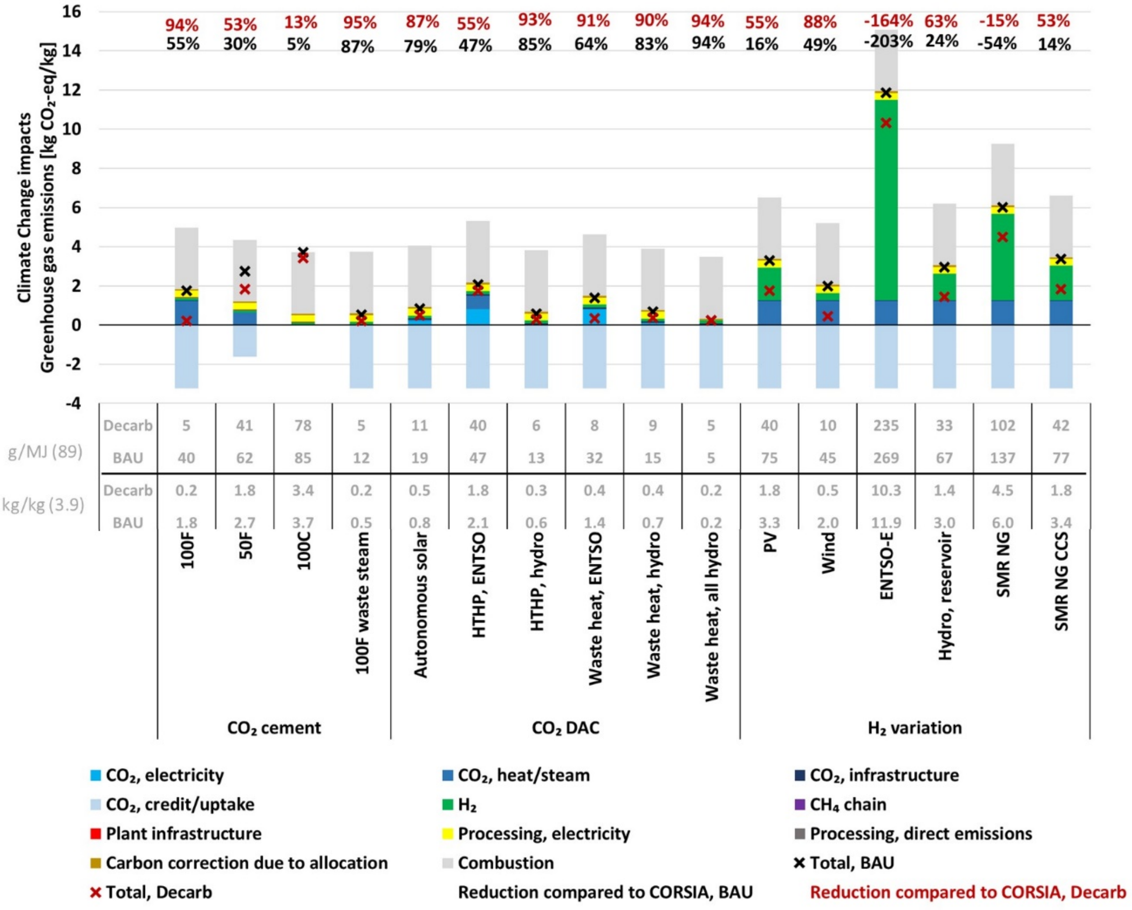


*Figure 14: Contribution analysis of climate change impacts of the Fischer-Tropsch PtL pathway with various variations of input parameters to explore potential optimisation possibilities.*

KEY MESSAGES:

- The way $CO_2$ is credited and $H_2$ origin drive the climate change impacts. Processing them into synthetic kerosene causes minor amounts of greenhouse gas emissions, but data gaps are still present for this step..
- Specific configurations for $CO_2$ from DAC come with significant reduction potential.
- There is little margin for the electricity source to electrolysis. Only extremely low-carbon electricity sources are suitable.

Next, the **electricity source for the electrolysis process** is varied. Obviously, the results linearly correlate with the greenhouse gas intensity of the input electricity, as depicted already in Figure 12. Using PV electricity in Spain for electrolysis results only in a minor reduction of GHG emissions compared to fossil kerosene for BAU (16%), but this can be increased to 55% for Decarb. Using wind power in Spain at least halves the climate change impacts (88% for Decarb). However, these results do not include any electricity storage for the electrolysis process, which might be required for direct coupling of intermittent renewable power generation with electrolysis and a FT process.

An important note is made here on the topic of **greenhouse gas emissions from hydropower**. While these are indeed very low for run-of-river power plants, direct emissions of greenhouse gases (calculated per kWh electricity produced) can be significant from a hydropower reservoir, especially in tropical regions and/or when a lot of biomass is buried during the construction of the reservoir (dos Santos et al. 2006; Hertwich 2013; Scherer and Pfister 2016). No “blank cheque» can thus be issued for electrolysis from hydropower in general. Already when switching from run-of-river electricity to a hydropower from reservoirs in Spain as supply to the electrolysis, the reduction potential decreases by around 30%, lowering it to only 24% (BAU) or 63% (Decarb).

Using **hydrogen from the current hydrogen market** (which is mostly based on steam methane reforming of natural gas without CCS) is not an option, as it would lead to increased climate change impacts. Even when adding CCS, the performance of hydrogen from hydro-based electrolysis cannot be reached and should not be considered for this application. This is different when pure biomethane-based hydrogen could be produced. However, due to the limited availability of biomass, this is not a case which is suited for scaling up of synthetic kerosene from Fischer Tropsch PtL.

## 5.3 Methanol PtL (MeOH PtL)

Figure 15 shows variations for the methanol PtL pathway. The BAU case uses electricity from ENTSO unless otherwise mentioned (and run-of-river hydropower for electrolysis), while Decarb uses solar heat and electricity.

First, the origin of the $CO_2$ is varied, and the electrolysis is powered by run-of-river hydropower unless specifically mentioned. Second, the influence on the origin of the electricity used as input to electrolysis is shown. Then we explore if MeOH PtL could be run on a country grid mix.

a) $CO_2$ sources:
    *i.* Two different **designs of the $CO_2$ capture process**: One where the Methanol production is not well integrated into the cement plant, and one with an optimised integration of waste heat for partial or full coverage of heat needs from excess heat. The integrated design is used as base case for the $H_2$ variations and the electricity variations as there would be no reason to not make use of this benefit in real world *under the condition that coupling the MeOH production and the cement plant is possible.*
    ii. **$CO_2$ from DAC** in various configurations: Pure autonomous solar electricity/heat sources; heat from high-temperature heat pump (HTHP) driven by varying electricity; use of waste heat with varying electricity source.
b) $H_2$ production: Electrolysis with varying electricity source, and ENTSO electricity for $CO_2$ capture and processing.
c) Electricity source in all processes ($CO_2$ capture, electrolysis, processing).

Climate change impacts of kerosene from the assessed MeOH PtL configurations range between **8 and 70 g $CO_2$-eq/MJ for BAU and 7 and 46 g $CO_2$-eq/MJ for Decarb** in general, with outliers from the use of electricity from the European grid for electrolysis (up to 287 g $CO_2$-eq/MJ). Reduction potentials of up to 93% have been found.

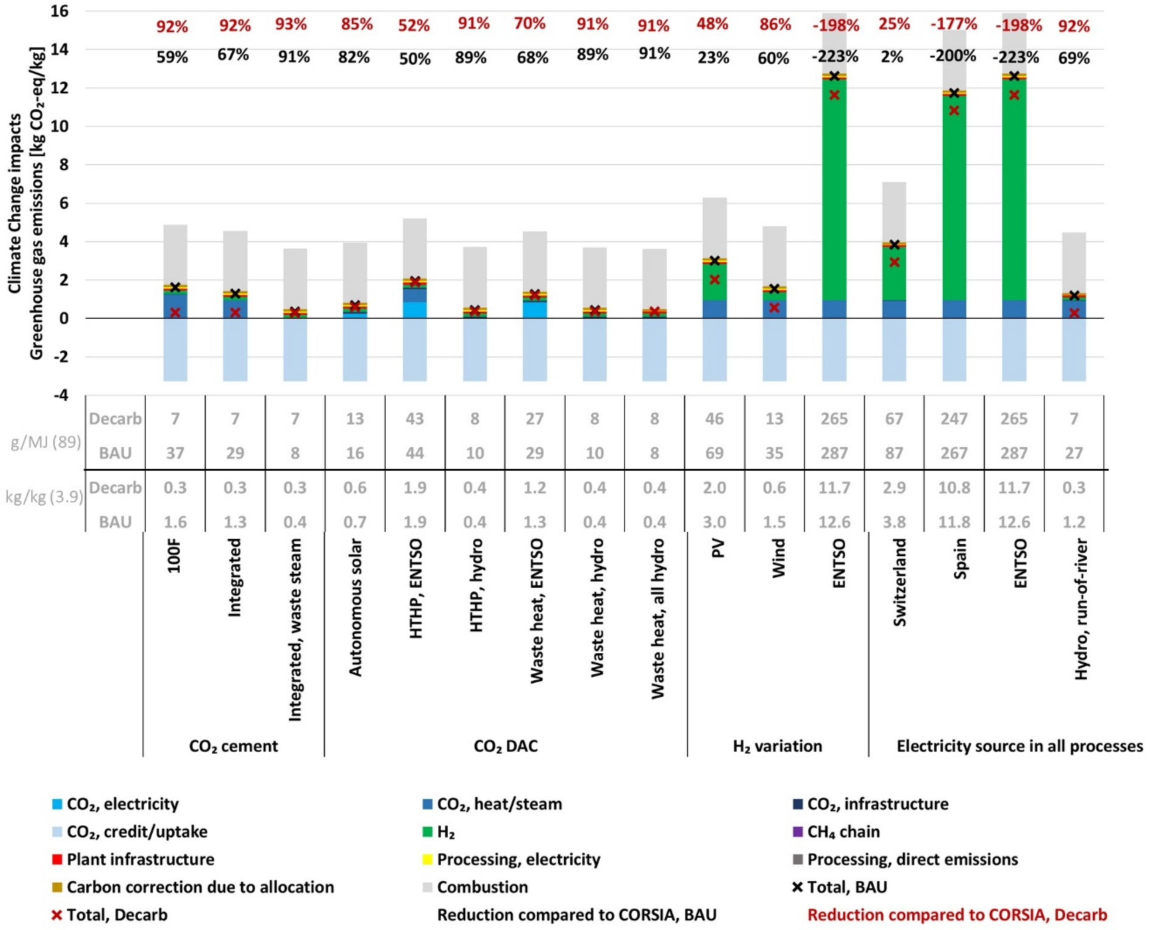


*Figure 15: Contribution analysis of climate change impacts of the Methanol PtL pathway with various variations of input parameters to explore potential optimisation possibilities.*

KEY MESSAGES:

- Optimised process design can result in significant reduction potential (integrated design) even for BAU, which supports the feasibility of low-carbon synthetic kerosene already today.
- Low-carbon electricity must either be produced locally, or be bought via certificates of origin, as the margin for using electricity with slightly increased GHG emissions is low.

It is interesting to see the effect of an **integrated design** within the combined cement – methanol plant, which increases the reduction potential from 59% to 91% for BAU, indicating that a combination of potential design improvements here and there could in sum lead to significant benefits. This effect is not visible in Decarb, as the use of very low-carbon energy allows for taking less care on the actual amount of energy used in the process. In view of a general pressure on the energy networks in future, saving energy should nevertheless remain a top goal of process design. In case all steam input could be replaced by waste steam, this would even go up to 91%, reaching nearly the performance of a purely solar driven cement and PtL plant.

Again, the use of **direct air capture of $CO_2$** is a good option for reduction of GHG emissions, if supplied by low-carbon energy, reaching 91% reduction potential at most, but staying also below 45 g $CO_2$-eq/MJ for less optimal configurations.

For this pathway, a variation of the electricity input was carried out, as this pathway showed highest sensitivity with regards to the greenhouse gas intensity of the input electricity (see Figure 12). Running all processes ($CO_2$ capture and MeOH conversion processes) on the current Swiss electricity mix would hardly reduce GHG emissions (Decarb), or even be worse than conventional kerosene with 87 g $CO_2$-eq/MJ for BAU. Conversely, using hydropower as the only electricity input would decrease the climate impact of synthetic kerosene even further compared to the BAU base case.

## 5.4 Synhelion StL

Synhelion provided all data related to the production of a specific amount of Syncrude, which is the synthetic counterpart of petroleum and can be benchmarked against this without encountering the allocation choices which need to be done when proceeding with the modelling to kerosene production. Hence, Figure 16 shows the climate change impacts of syncrude production, while Figure 17 allows comparison of the StL pathways with the PtL pathways on the level of kerosene production, and makes it possible to quantify reduction potentials compared to e.g. the CORSIA reference value for life-cycle greenhouse gas emissions of jet fuel.

Again, variations are only shown for selected cases in order to keep the figure readable.

First, the origin of the $CH_4$ is varied for the solar reforming cases. Second, DAC configurations for $CO_2$ capture are shown for the more advanced solar reforming plus (SR+) and the solar thermochemical (ST) pathways.

a) $CH_4$ sources ($CO_2$ is from cement plant with 100F crediting scheme):
  i. Natural gas: From the average European market with intermediate lower bound methane emission rate (MER); Netherlands with very low MER), LY with very high MER, US as potential market for Synhelion with intermediate lower bound MER.
  ii. Biogas from biowaste, which also serves as partial (SR+) or full (ST) $CO_2$ source.

b) $CO_2$ from DAC in various configurations: Pure autonomous solar electricity/heat sources; heat from high-temperature heat pump (HTHP) driven by varying electricity; use of waste heat with varying electricity source.

Climate change impacts from the assessed StL configurations are in general lower than those from the fossil benchmark. Interesting reduction potentials are present for SR+ with $CO_2$ from DAC, and for ST configurations. The use of biogas allows reaching out for climate neutrality.

First, Figure 16 is discussed. Within the solar reforming case, improvements compared to conventional petroleum (ca. 3 kg $CO_2$-eq/kg or ca. 68 g $CO_2$-eq/MJ syncrude) are barely possible, unless biogas is used as $CH_4$ and $CO_2$ source. When using natural gas from a country with old infrastructure (Libya), the climate change impacts are even significantly higher compared to conventional petroleum. This is different for the solar reforming plus case, where clearly a reduction potential can be identified. A design with natural gas from a technologically well-developed natural gas supply chain (Netherlands NL) and a pure solar driven cement plant results in climate change impacts of 33 g $CO_2$-eq/MJ syncrude, which is roughly 50% of petroleum impacts, being a realistic near-future case. A wise design choice for $CO_2$ from DAC can also support a low carbon footprint of syncrude. The use of biogenic sources obviously leads to even lower, close to carbon neutral results – but again the availability of biomass needs to be considered when thinking of a scale-up.

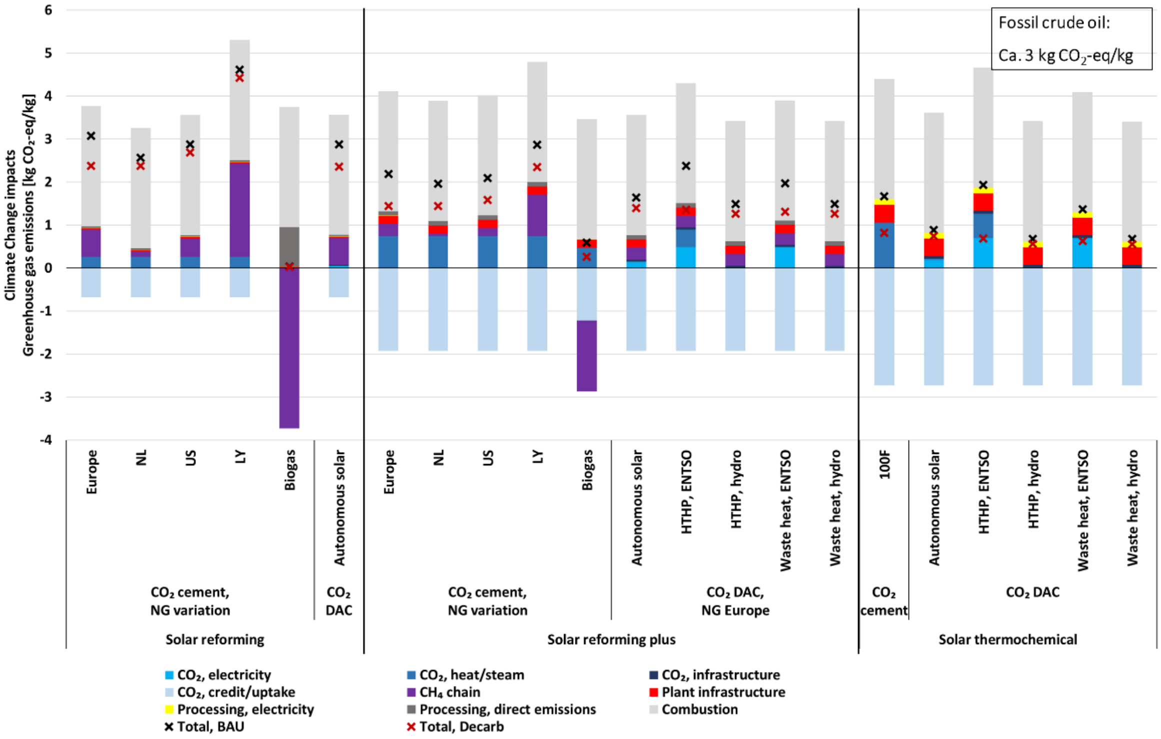


*Figure 16: Contribution analysis for climate change impacts of the production of 1 kg syncrude via the StL pathways. Bars show contributions to total BAU scores. Refining to useable fuels is not included.*

KEY MESSAGES:

- Syncrude causes less impacts on climate change than crude oil in most configurations, but only reaches significant reductions in SR+ and ST.
- The use of biogas as carbon sources nearly allows carbon neutrality.
- Solar thermochemical syncrude production in a decarbonised setting comes with high reduction potential (>70%).

Syncrude from the solar thermochemical pathway can also come closer to the region of carbon neutrality, with impacts as low as 19 g $CO_2$-eq/MJ syncrude for the realistic pure solar cement scenario. This can be decreased even more to around 13 g $CO_2$-eq/MJ for DAC designs with hydropower driven heat pumps or using waste heat.

Moving to Figure 17 and the production of kerosene, the increase of the reduction potential from SR over SR+ to ST is easily visible. The solar reforming configuration can be well regarded as transition design where reductions up to one third (BAU) or ca. 43% (Decarb) compared to conventional fossil kerosene are possible, with a readily available technology and as planned by Synhelion. However, the natural gas source needs to be carefully evaluated, as the related greenhouse gas emissions depend heavily on the infrastructure and technologies used on the extraction site as well as on the state of the transport infrastructure.

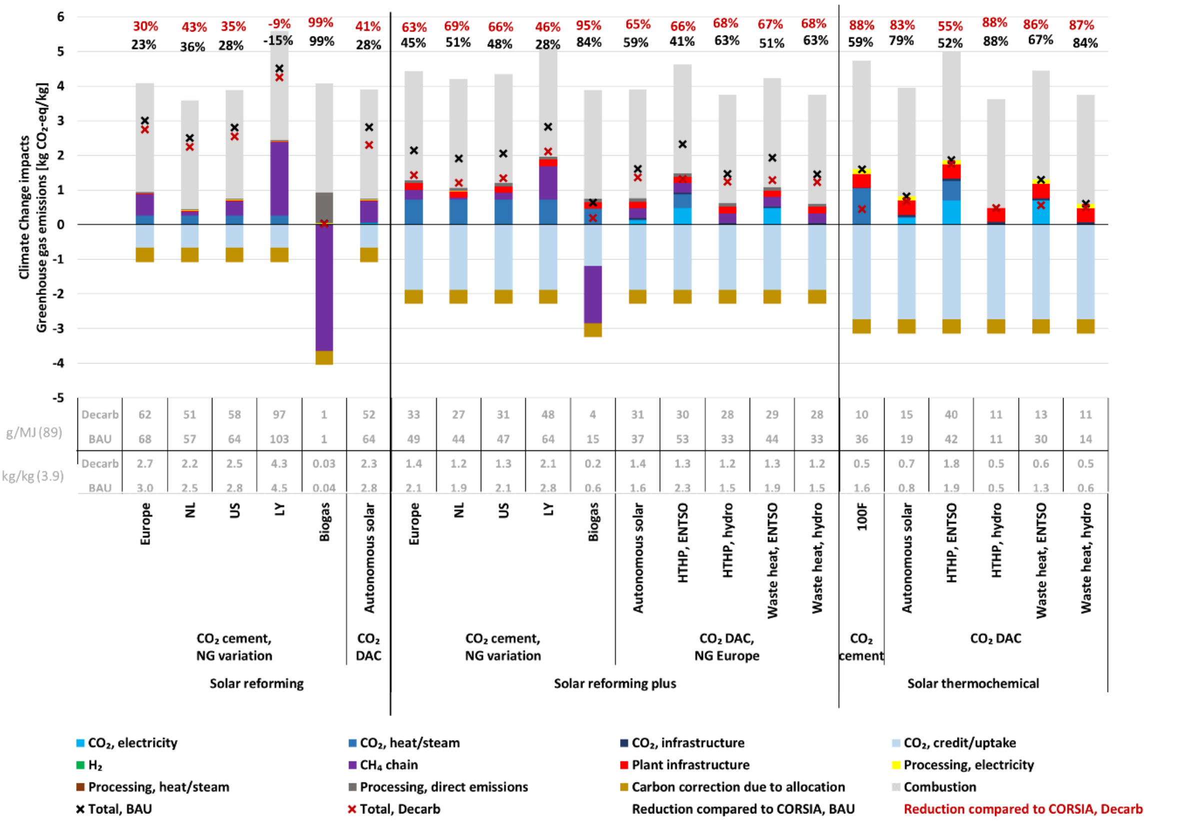


*Figure 17: Contribution analysis of climate change impacts of the Synhelion StL configurations with various variations of input parameters to explore potential optimisation possibilities. Results are shown for all three configurations, with variation of the natural gas source, DAC design, and integrated pure solar cement plant.*

KEY MESSAGES:

- The origin and supply chain of natural gas need to be closely monitored.
- Solar thermochemical production is most promising and reaches low values for greenhouse gas emissions.
- Solar reforming with biogas from biowaste nearly reaches carbon neutrality.

More variations are explored for the solar reforming plus case, as this already shows higher reduction potentials. An integrated design with a pure solar cement plant in Spain and average European natural gas supply ("Europe Decarb") reaches a 63% reduction, and switching to natural gas from the Netherlands leads to a reduction of max. 69% compared the CORSIA reference value. It can be stated that the SR+ configuration can easily at least half the $CO_2$ related climate change impacts of kerosene use in aircraft. When biomass is used as carbon source, this can be increased to 84-95%. DAC configurations with natural gas from the Netherlands allow for a two thirds cut of climate change impacts.

Finally, the pure solar thermochemical pathway leads to lowest climate change impact scores. Reduction of at least 52% under not very optimal conditions are a good start, which can easily be driven up to close to 90% compared to the CORSIA benchmark.

The contribution of the StL plant infrastructure visibly increases from SR over SR+ to solar thermochemical. Figure 18 shows which components and materials mostly influence the total greenhouse gas emissions of the construction of the planned Synhelion plants. As can be seen from Table 3, the SR plant is the smallest of the three designs. SR+ comes with a combination of the Synhelion plant and a CSP plant. ST has again a similar design as SR, but with a reactor instead of a reformer. Any energy inputs for construction and also maintenance of the StL plants has not been modelled. Further, the end of life has not been included, i.e. no benefits or burdens from recycling and treating the used materials could be modelled.

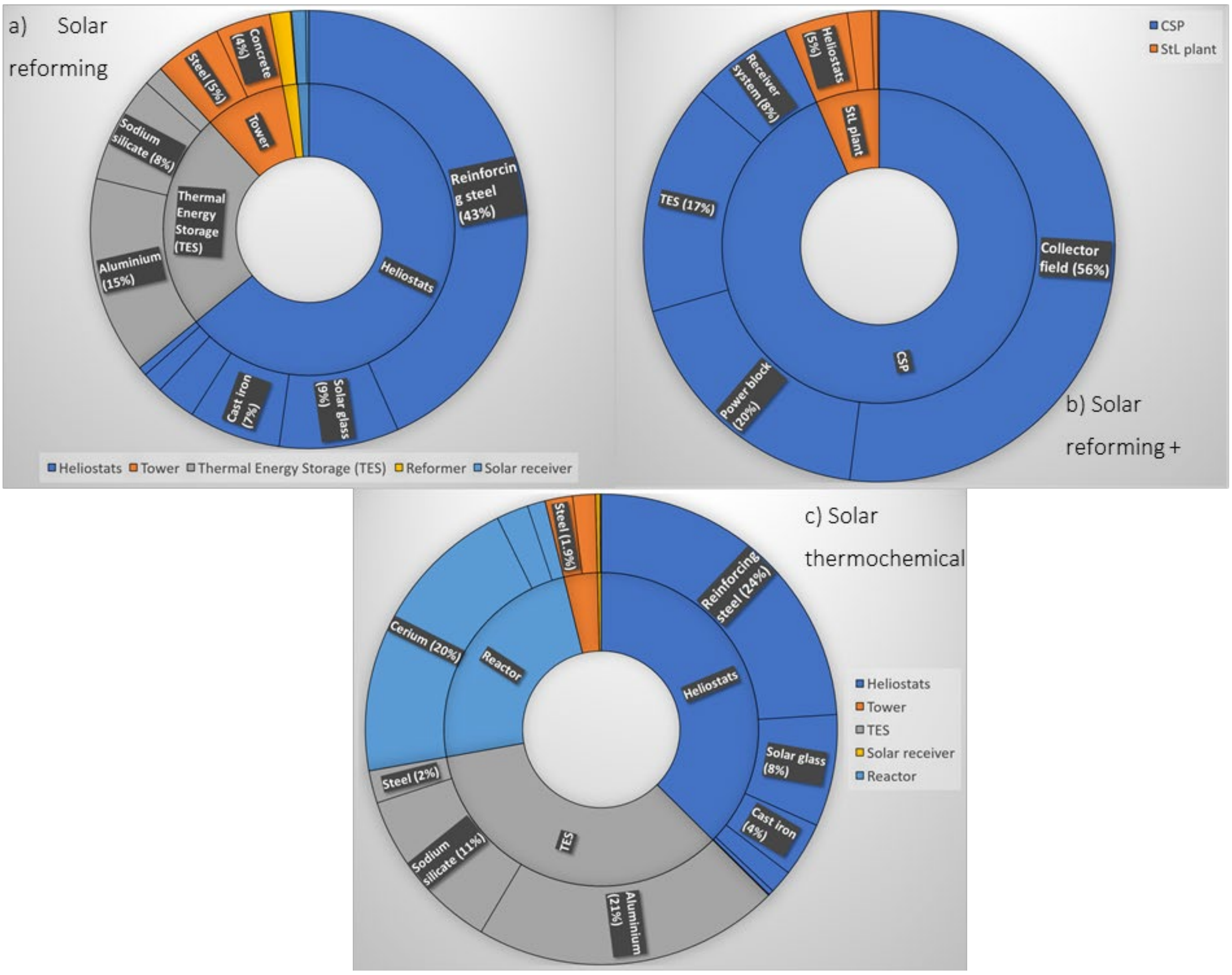


*Figure 18 Contribution analysis of climate change impacts of a Synhelion plant for production of syngas: a) Solar reforming with a Synhelion plant; b) Solar reforming plus wich a Synhelion plant combined with CSP; and c) Solar thermochemical.*

For the SR plant, the heliostats dominate the climate change impact score by using large masses of steel and solar glass. This may be reduced by choosing circular end-of-life processing, depending on the exact process, recycling product, and allocation scheme. The Thermal Energy Storage (TES) is second important via its use of aluminum and sodium silicate. The solar receiver, tower, and the reformer are of lower importance.

Due to the large size of the CSP plant in SR+, it is responsible for most of the climate change impacts, again driven by the collector field materials. In contrast, the climate change impacts of the ST plant is mostly split into three components: The heliostats, the TES, and the reactor. For the latter, it is the rare-earth metal cerium which is an important emitter of greenhouse gases and consumer of fossil fuels during mining of the rare earth oxides.

A word should be said on the land use of the Synhelion plants. They are sized to a capacity of 0.5 Mt syncrude per year and occupy 9 km$^2$ (SR), 7 km$^2$ (SR+), and 69 km$^2$ (solar thermochemical), respectively (see Table 3). With a plant lifetime of 20 years and a capacity of 0.5 Mt per year, around 60 km$^2$ (SR), 40 km$^2$ (SR+) or 350 km$^2$ (ST) would be needed to produce 300 Mt/a of jet fuel. This translates to a (reversible) land usage of 0.9 m$^2$/kg syncrude (SR), 0.7 m$^2$/kg syncrude (SR+), and 6.9 m$^2$/kg syncrude (ST), respectively. The global jet fuel demand could easily be covered in countries like the United States, Australia, or Saudi Arabia. The consumption of aviation fuel and kerosene in Europe in 2018 amounted to 63 Mt.[22].

A discussion on the time horizon for evaluation of climate change impacts was raised in chapter 2.1. Depending on this, the methane emissions (amongst others) come with a much higher characterization factor for the 20 year time frame compared to the 100 year time frame. The effect of this is evaluated for the SR and the SR+ pathways with natural gas origin variation (Figure 19).

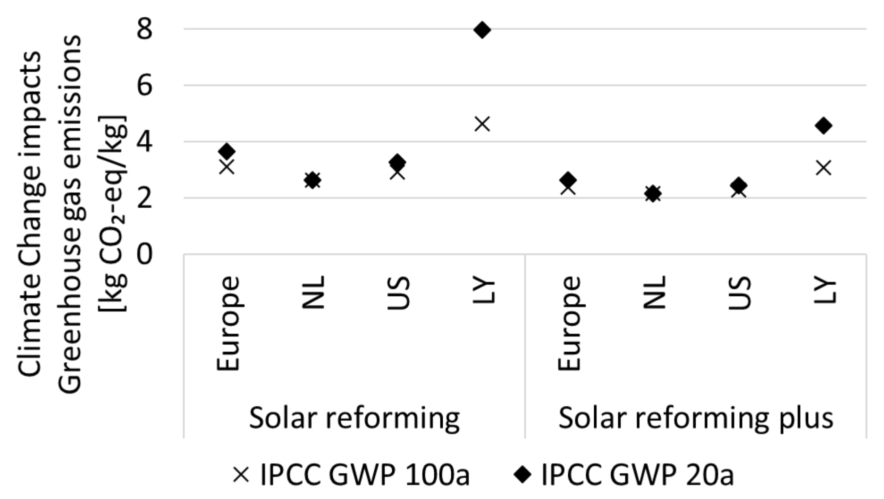


*Figure 19 Climate change impacts of synthetic kerosene produced via solar reforming of natural gas with varying origin, calculated with a time horizon of 100 years and of 20 years, respectively, as suggested by the IPCC.*

For natural gas supply chains with intermediate or low methane emission rates, the effect of switching to a 20 years time horizon is low, but still may decrease the reduction potential by few percentage points. However, higher methane emissions are heavily penalized and are devastating for the climate performance of synthetic kerosene. This again underlines the importance of a close monitoring of the natural gas supply chosen as input to kerosene production in SR and SR+ plants.

## 5.5 Kerosene production, system perspective

The system perspective avoids allocation and thus allows for a global view on the potential savings when introducing a new production pathway into existing markets. This is shown for the two PtL pathways at the top of Figure 20, and for StL at the bottom. As described in the methodological section, the system is trimmed to produce 1 kg kerosene, and takes into account all other products, which are related to this production. These are, namely, the by-products from the refining process (diesel, naphtha and lubricating oil for FT, and diesel, liquefied petroleum gas (LPG), and gasoline in the case of the MeOH processing to fuels) as well as the co-production of clinker and $CO_2$ for the case

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[22] https://renewable-carbon.eu/news/can-the-european-unions-kerosene-demand-be-met-by-the-amount-of-biomass-produced-in-the-eu/

where the $CO_2$ is from a CCU process. In case of direct air capture, no clinker is involved in the system. The respective amounts are also shown in Flow scheme 1 and Flow scheme 2, and in chapter 2.2.1.

The combustion of each fuel is modelled based on the carbon contents as used for the carbon correction in the allocation case. These are 3.37 kg/kg Naphtha, 3.16 kg/kg diesel, 2.75 kg/kg lubricating oil, 3.01 kg/kg LPG, and finally 3.14 kg/kg gasoline.

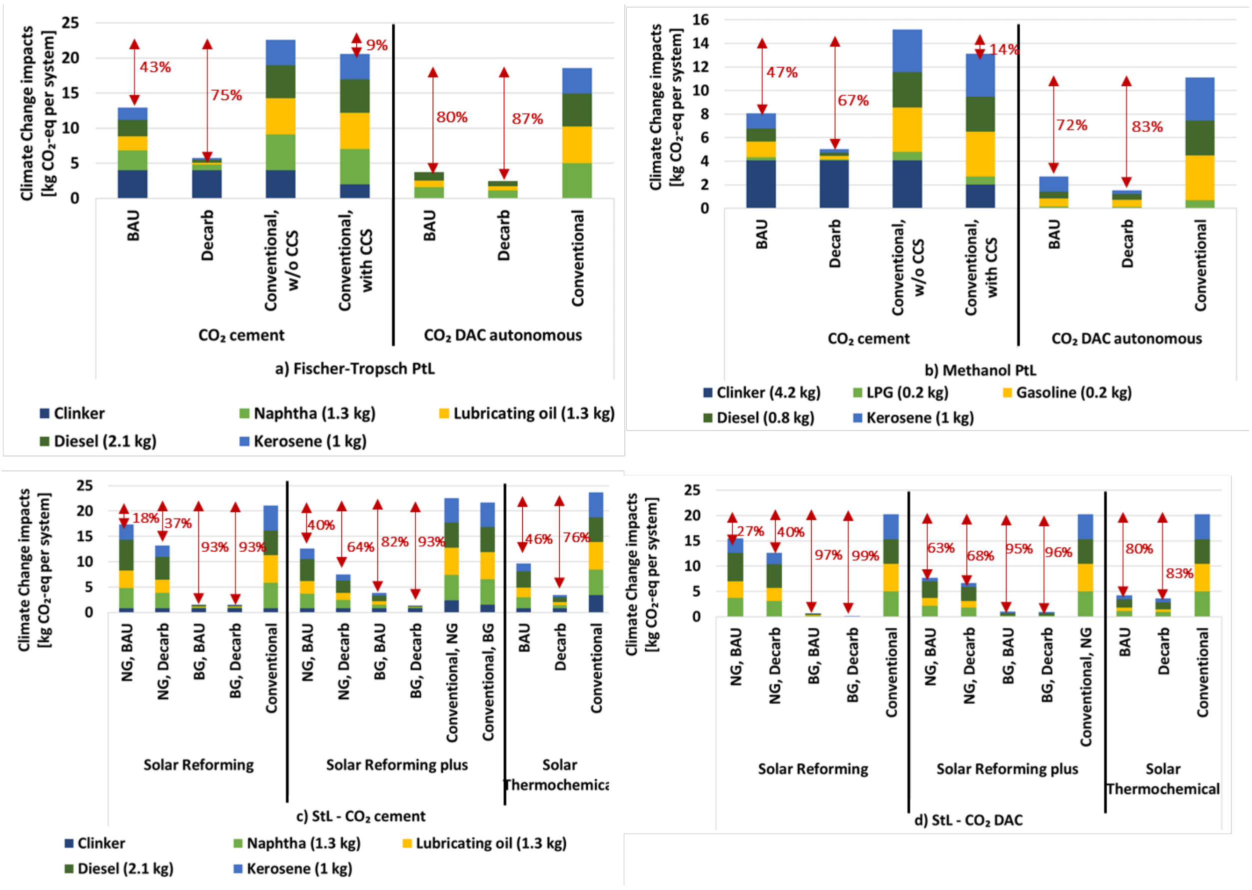

*Figure 20: System perspective on climate change impacts of fulfilling a demand in fuels with conventional production pathways or via PtL (top, (a) and (b)) or StL (bottom, (c) and (d)). The PtL figures are again split into two parts: One for a system where the $CO_2$ comes from the cement plant, and one where it is captured from air (thus no clinker involved). The reduction potential is shown with red arrows.*

KEY MESSAGES:

- Introducing the production of synthetic fuels into the current fuel production pathways leads to partially significant reduction of the system wide climate change impacts for selected PtL and StL systems compared to conventional systems.
- The reduction potential is higher with $CO_2$ from DAC than with industrial $CO_2$ recycling from cement plants as the system does not have to produce any clinker.

Savings of up to close to 90% of the greenhouse gas emissions compared to a current production system are possible in decarbonisation scenarios. Equipping the cement plant with a CCS unit would also already show some benefit, though way too low to contribute significantly to the necessary reduction in $CO_2$ emissions.

# 6 Discussion and conclusions

The aviation sector needs to be decarbonised in order to contribute to the international goal of reducing climate change caused by human activities. Synthetic kerosene can support the decarbonization activities coordinated by ICAO. Reduction potentials regarding impacts on climate change[23] of at least 20% for current, non-optimised pathways have been found, going up to 95% when relying on highly low-carbon energy sources such as run-of-river hydropower or solar energy and with optimised system design. Carbon neutrality can nearly be reached for the investigated StL pathways using biogas as carbon source. Major differences between the FT PtL pathway, the MeOH PtL pathway and StL don't seem to exist based on the available data used in this work. Results indicate that the specific design of synthetic kerosene production has a larger influence on life-cycle GHG emissions than the pathway type. The reduction potentials found in this work correspond well with the reduction potentials as calculated in (Liebich et al. 2021a) of almost 80% for today, and just below 90% for 2050.

Data for StL were most detailed in this analysis, and the solar thermochemical pathway looks very promising (up to nearly 90% reduction potential). "Solar reforming" comes with lowest reduction potentials even with heavy decarbonisation in the background (41%). This is anyway only seen as a starting pathway, and the following "Solar reforming plus" pathway already allows for reduction of up to nearly 70% compared to the CORSIA benchmark. The use of biogas from biowaste even allows for going close to carbon neutrality in a heavily decarbonised setting, which is easily feasible when using abundant solar energy. Availability of such biomass based feedstock may be a challenge in future, when more and more applications will look out for such renewable waste biomass.

For both FT PtL and MeOH PtL, $CO_2$ from DAC seems to allow for higher reductions than $CO_2$ from cement plants. It is absolutely necessary to use a very low-carbon electricity source for the electrolysis process.

The main conclusions of this study are the following:

- Provided that energy supply used as input to both the PtL and the StL pathways causes low GHG emissions**, the production of synthetic kerosene with the processes as presented in this report leads to partially significant reductions in climate change impacts compared to conventional kerosene** at least during the production phase. The combustion phase comes with question marks. Whereas a $CO_2$ reduction potential could be shown, the modelling of impacts from the reduction of particle emissions is currently not possible. Some data gaps and uncertainties are left when modelling the various production pathways. As a consequence, the presented absolute numbers for climate change impacts and reduction potentials should be interpreted with an understanding of the open questions. Still, **the trends shown in this report are promising**, and clearly indicate that it is worthwhile investing into specific optimised and low-carbon development of PtL and StL production pathways for synthetic fuels. Collaboration between synfuel producers and existing industry should be seeked in order to make the best use of existing heat and $CO_2$ point sources. The use of $CO_2$ from DAC gives some more flexibility with regards to the location of PtL or StL plants, and can lead to even higher reduction of climate change impacts compared to the CORSIA reference value for aviation fuels.
- The **system perspective confirms** the findings presented on the level of kerosene, showing overall **reduction of climate change impacts** when production of synthetic kerosene enters the current system.

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[23] Excluding non-$CO_2$ related impacts on climate change of aviation.

- **No pathway seems to generally outperform the others**, taking into account the various data sources, data gaps and variations in potential system designs in reality. $CO_2$ from DAC, if supplied with low-carbon energy, seems to be slightly beneficial compared to $CO_2$ from industry, and all discussions on credits and double counting are avoided. However, DAC is still very expensive, and it seems illogical to first emit $CO_2$ from a point source to atmosphere to capture it again in diluted form.
- The **origin of the $CO_2$ and the electricity source for the electrolysis process play major roles** for reaching the reduction goals. For $CO_2$, the choices with regards to allocation of environmental burdens for $CO_2$ from industrial processes are of utmost importance both in real life and in the LCA modelling, and can change the reduction potential significantly. No $CO_2$ saving must be counted twice, so the different supply chain stakeholders have to agree on who gets the credit of using captured $CO_2$ otherwise emitted to atmosphere. This in view of the fact that more and more industries will seek for cutting their $CO_2$ emissions due to increasing $CO_2$ price. Further, the energy sources used for driving the $CO_2$ capture process both in industry as well as for DAC are of crucial importance.
- The electricity sector, and in general the **electricity sources, need to be heavily decarbonised**. When switching to renewables, burden shift needs to be controlled, so that environmental or social impacts of e.g. increased mining activities in China are minimised. As many human activities will rely on electricity in future, the pressure on the power system needs to be decreased by minimization of electricity consumption. Due to the very high share of auto-production of electricity in the StL pathways, these are more beneficial regarding this aspects than PtL pathways, which might also have to seek own power plant construction to power all involved processes, mainly the electrolysis. (Industrial) waste heat or solar heat should be used as input to the production pathways of synthetic kerosene in order not to release even more carbon so far bound to fossil resources.
- **Environmental impacts other than climate change impacts cannot yet be quantified** for a cradle-to-grave (cradle-to-cradle) perspective, i.e. including the combustion of synthetic kerosene. Research and real-life measurements are needed to learn more about emissions related to the combustion of synthetic kerosene, and to get deeper insights into the effect of those emissions in the atmosphere.
- The environmental impact categories presented for cradle-to-gate clearly favor the decarbonised cases and did not show any trade-offs.
- All pathways which don’t use biogas from biowaste as carbon source will always come with **certain net $CO_2$ emissions left which will have to be compensated to reach net zero emissions (climate neutrality)** in the aviation sector. DAC with CCS (DACCS) may have to close the gap, which was not considered in this study. These efforts will cause some additional environmental impacts and costs.

It is the duty of decision makers to ensure that

a) the energy sources for the production of synthetic kerosene are highly decarbonised, i.e that renewable energy is used
b) the use of such energy does not increase the environmental or social burden at places supplying input materials for making use of such energy, e.g. mining of metals for the photovoltaics sector, or water supply in deserted regions.
c) carbon accounting prevents double counting of avoided emissions.

Future work and transition to synthetic kerosene in aircraft may include the following aspects:

- **Transport and storage of the fuel** is not yet included. These processes in general won't differ from the handling of conventional kerosene. The results as shown in (Liebich et al. 2021a) indicate that transportation of the end product is not an important contributor to the end result, adding nearly zero or only few grams of $CO_2$-eq/MJ. This finding is shown to also hold true for other life cycle impact categories. In the conventional fossil-based system, storage infrastructure and fuel handling for storage don't really show up in LCA studies as well. Transport and storage of $CO_2$ and/or $H_2$ have not been included as well. In total, the effect of neglecting all these will be in the range of few grams.
- No **specific supply chains** have been evaluated in this preparatory basic work. Future analyses need to investigate the geographical availability of the required $CO_2$, water, and energy supplies as well as transportation possibilities.
- **Flexibility** of all processes to indeed act as POWER-to-Liquid technology, making use of intermittent renewables, needs to be investigated in more detail with regards to technical **feasibility of dynamic operation and energy storage requirements**.
- **Collaboration with stakeholders in research, governments and industry** should be seeked to collect and harmonise supply chain specific data and the ongoing developments within the field of SAFs so that a roadmap can be created on how to proceed in the coming few years. This should lead to availability of better and more sophisticated input data to future LCA studies, such as site-specific Fischer Tropsch PtL scenarios, FT process tailored for maximized jet fuel output, and more data for the methanol to kerosene reaction steps. Even with improved input data quality, the general trend of the results presented in this report will assumingly hold true, and any design focused on carbon reduction will lead to decreased greenhouse gas emissions from synthetic kerosene compared to the status quo.
- With regards to the $CO_2$ source, this work has not looked at **industries other than cement**, e.g. iron & steel mills, or ammonia plants. Detailed information are needed on the **concentration, purity, amount and durability of $CO_2$ at the industries' outlets**. For instance, the Argonne National Laboratory has compiled such data for the United States, differentiating between high-concentration sources with a purity of more than 87% (corn ethanol plant, ammonia plant, natural gas processing plant), and low concentration sources with purities of less than 35% (cement plant, hydrogen production SMR plant) (Zang et al. 2021c).
- Further process variants have not been assessed in this work, such as the co-production of syngas and carbon to improve the $CO_2$ balance or the solar cracking of methane. In addition, this work did not intend to model potential environmental impacts of a transition from the current fossil-based aviation fuel market to a potential fully synthetic jet fuel coverage in few decades. Such transition includes blending conventional and synthetic kerosene, use of industrial excess heat possibly only available currently but not in few decades anymore, capacity requirements in future, logistics of the transport of the synthetic fuel, just transition for current conventional fuel producers to potentially switch to synthetic fuel production, or similar.

Economic aspects have not been taken into account in this report. Economics will naturally support optimisation of processes on the one hand, but also potentially lead to ruling out expensive new technologies such as DAC. Evaluation of sustainable alternative fuels (SAFs) calls for in-depth sustainability assessment of such fuels, thus including not only environmental and economic aspects, but also social aspects in the whole supply chain, and considering and implementing the aspects of circular economy.

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