CIRCULAIR

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*Public report*

# Pre-evaluation of key economic and environmental parameters

CIRCULAIR

# Public report: Pre-evaluation of key economic and environmental parameters

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## Abstract

CIRCULAIR investigates the conversion of manure and straw into sustainable fuels for aviation and shipping via hydrothermal liquefaction (HTL). This report provides a pre-evaluation of key economic and environmental parameters for HTL jet fuel production via the CIRCULAIR fuel production scheme. The results within this public report are NOT the final results of the techno-economic and environmental analyses of CIRCULAIR, which will be published in consecutive reports. Instead, this pre-evaluation provides an intermediate and preliminary estimate of fuel production cost and life-cycle greenhouse gas emissions, in order to guide the future research within the project.

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# Project information

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# Glossary

| Acronym | Signification |
|---|---|
| AP | Aqueous phase |
| APOS | Allocation at the point of substitution |
| CAPEX | Capital Expenditures |
| CORSIA | Carbon Offsetting and Reduction Scheme for International Aviation |
| DK | Denmark |
| EASA | European Union Aviation Safety Agency |
| EL | Electrolysis |
| EU | European Union |
| GC | Gas Cleaning |
| GHG | Green House Gas |
| GLO | Geographical Location Global |
| GWP/GWP100 | Global Warming Potential / over 100 years |
| HT | Hydrotreatment |
| HTL | Hydrothermal Liquefaction |
| ICAO | International Civil Aviation Organization |
| IPCC | Intergovernmental Panel of Climate Change |
| ISO | International Organisation for Standardization |
| LCA | Life-Cycle Assessment |
| LCI | Life-Cycle Inventory |
| LCIA | Life-Cycle Impact Analysis |
| LCOE | Levelized Cost of Energy |
| MeOH | Methanol |
| OPEX | Operational Expenditures |
| PFR | Plug Flow Reactor |
| PNNL | Pacific Northwest National Laboratory |
| PtX | Power-to-X |
| RoW | Rest-of-the-World |
| SMR | Steam Methane Reforming |
| UG | Upgrading |
| VFA | Volatile Fatty Acid |
| WO | Wet Oxidation |

# Executive summary

CIRCULAIR investigates the conversion of manure and straw into sustainable transport fuels via hydrothermal liquefaction (HTL). This public report provides a pre-evaluation of key economic and environmental parameters for HTL jet fuel production via the CIRULAIR concept. The intermediate evaluation at project mid-term is based on plant configurations as well as preliminary mass and energy balances that have been published in prior reports. The final results of the techno-economic and environmental analyses of CIRCULAIR will be published at later stages of the four year project, based on refined modelling. This report provides a first estimate of fuel production cost and life-cycle greenhouse gas emissions in order to guide the future research within the project.

As high-level intermediate results, both fuel production costs and the global warming potential (GWP100) were evaluated. Due to the multi-product nature of CIRCULAIR, average fuel costs were evaluated for a mix of fuel products. The techno-economic results of 99 €/MWh and 62 €/MWh stem from two distinct approaches for capital expenditure (CAPEX) estimation. In terms of environmental impact, a reduction of the GWP100 by 84% compared to fossil jet fuel was estimated using an energy allocation based attributional life cycle assessment (LCA) approach.

The CIRCULAIR concept represents a multi-product system, in consequence, selling prices for co-products and allocation of environmental burdens to the respective product streams have profound impact on the results. Some variations of jet fuel production cost and global warming potential depending on co-product revenues and LCA methodology are discussed is this report, but proper accounting for the multi-product nature of the process requires further considerations.

The pre-evaluation identified important drivers of fuel production cost and life cycle emissions. CAPEX is a key consideration, especially for early implementation, and a prime target for more detailed techno-economic investigation. Significant cost stem also from green hydrogen generation, where the majority of green hydrogen is needed for methanol synthesis from evolving $CO_2$ streams. This indicates that the intended coupling of HTL with PtX schemes requires access to green $H_2$ at sufficiently low cost.

# 1. Introduction

CIRCULAIR[1] is a collaborative Research and Innovation Action that is funded by the European Union. The renewable fuel production scheme that is investigated in the CIRCULAIR project is sketched in Figure 1.

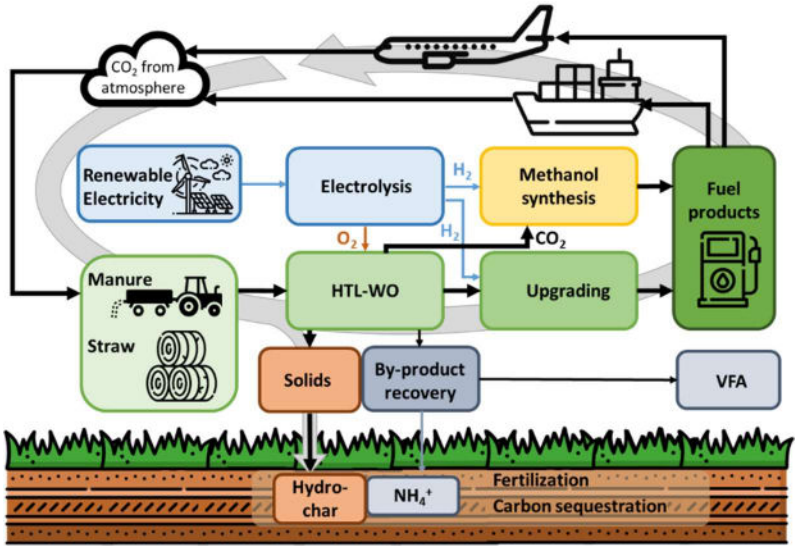

Figure 1: Sketch of the CIRCULAIR concept. The central conversion step is hydrothermal liquefaction (HTL) coupled to wet oxidation (WO) of the HTL process water. All product phases of HTL conversion are utilized. Coupling with green $H_2$ aims at almost complete carbon to product conversion.

## 1.1. CIRCULAIR System analyses

This public report “Pre-evaluation of key economic and environmental parameters” is the third out of a series of eight public reports from the CIRCULAIR system analysis work package that will be published over the four year project duration:

1. Assessment framework for CIRCULAIR process [1]
2. Process model (for pre-evaluation) [2]
3. **Pre-evaluation of key economic and environmental parameters (this report)**
4. Optimized process model
5. Techno-economic evaluation and market analysis
6. Socio-economic impact assessment
7. Life cycle analysis
8. Trade-off studies, synthesis of results and roadmap

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[1] See: https://project-circulair.eu for more information on the CIRCULAIR project (roles of consortium partners, expected innovations, results, progress of project implementation). Additional administrative information can be retrieved via https://cordis.europa.eu/project/id/101083944

The titles of this series of reports indicates an iterative approach where an initial quantification of key performance characteristics guides the more detailed development of an optimized process model that serves as a basis for a final evaluation of a more robust and holistic set of results.

## 1.2. Main objective

The main objective of this report is a first evaluation of fuel production cost as a key economic and GWP as a key environmental performance parameter. The evaluation is based on preceding reports that defined a baseline configuration [1] and evaluated energy and mass streams from a simplified process model [2] (see also Section 2.2). The purpose of this pre-evaluation is to guide the further research within the system analysis work package and to complement the technical project implementation by identifying key drivers of future economic or environmental performance.

One consequence of this two-step procedure is that the results of CIRCULAIR's experimental campaigns cannot be reflected by the preliminary model as they become available at a later stage of the project. Therefore, the quantitative values in this report need to be handled with care and should be considered as preliminary indications until the final results become available.

# 2. Baseline case definition and process modelling

The pre-evaluation of production cost and GWP requires the definition of baseline configurations and a background system for the investigation. Techno-economic and environmental modelling is also dependent on a suitable representation in the form of a process model that reflects the chosen configuration and is capable to quantify energy and mass streams. This preparatory work was subject to the preceding public reports "Assessment framework for CIRCULAIR process" [1] and "Process model (for pre-evaluation)" [2] that are shortly reviewed in the following sections.

## 2.1. Baseline case scenario

The previously published CIRCULAIR report *"Assessment framework for CIRCULAIR process"* [1] contains the definition of a baseline case for initial evaluation. This baseline case serves as context for the economic and environmental analysis, and defines a background system, which is needed e.g. to retrieve country specific input data such a labour rates or entries from life-cycle inventories.

The geographical context of the evaluation is central Denmark, where high feedstock densities for agricultural residues meet good wind power potentials for green $H_2$ generation (Figure 2, left and right).

Figure 2: Geographical context and logistic concept. Central Denmark is chosen due to high feedstock density for agricultural residues (left) and good wind power potential (right). The baseline configuration foresees several HTL plants for biocrude production and a central upgrading facility.

The supply concept for the baseline case foresees a hub and spoke approach. Seven HTL plants supply HTL biocrude to a central upgrading facility (Figure 2, middle), where individual HTL plants aggregate feedstock at a local level. The capacity of each of the distributed HTL plants was chosen to be 7650 kg/h wet biomass slurry (1000 kg/h on a dry basis) throughput. The central upgrading unit treats the biocrude from all seven HTL plants, which corresponds to an overall fuel production capacity of 2400 kg/h (jet fuel share: about 600 kg/h). This concept implies that HTL plant sites and the central upgrading facility are locally separated, which excludes thermal integration of HTL and upgrading plants and requires separate $H_2$ supply at HTL and upgrading sites, compared to the simplified sketch of the CIRCULAIR concept in Figure 1.

Figure 3 provides an overview of the major building blocks of the baseline configurations at the HTL and upgrading plant sites. Important methodological choices include pressurized alkaline electrolysis and a combination of fixed bed hydrotreating with hydrocracking at the upgrading plant. For more detailed considerations, we refer to the previously published CIRCULAIR reports [1, 2].

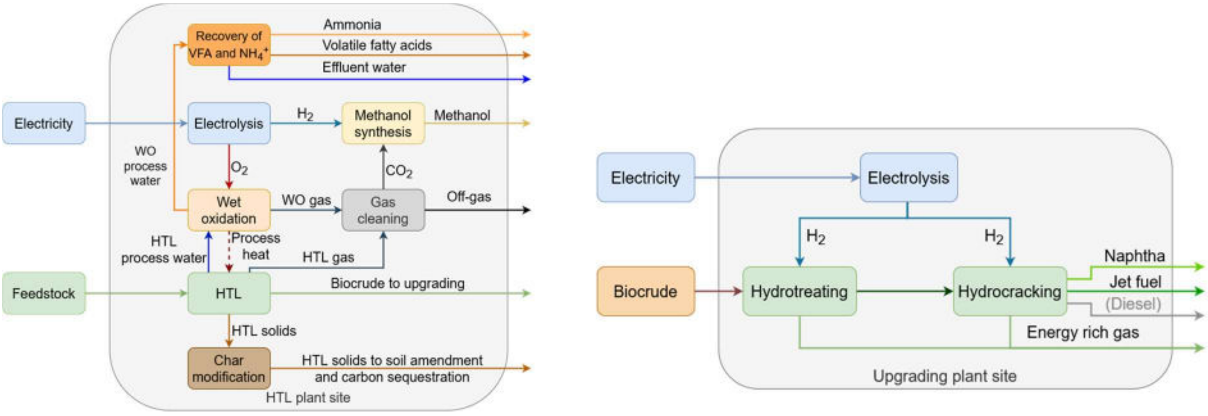

Figure 3: Sketches of the baseline configuration at HTL plant sites (left) and the central upgrading plant (right). Grey boxes indicate the system boundary of the plant sites. Taken from Figure 3 and Figure 4 in [1].

## 2.2. Preliminary process model

The previously published CIRCULAIR report *"Process model (for pre-evaluation)"* [2] discussed the development of a process model that is capable to derive a first version of energy and mass streams for the baseline plant configurations in Figure 3. This preliminary process model has focussed on three main process steps of the CIRCULAIR concept, HTL conversion, WO of HTL process water, and upgrading via hydro-processing.

Figure 4 shows the overall mass balance of the modelled process. Streams with high water content are the dominating contribution to the total mass flow, illustrating that large quantities of aqueous streams have to be heated, cooled, and treated, which has a significant impact on operating and investment costs. This also highlights the importance of heat exchange and thermal management in hydrothermal liquefaction.

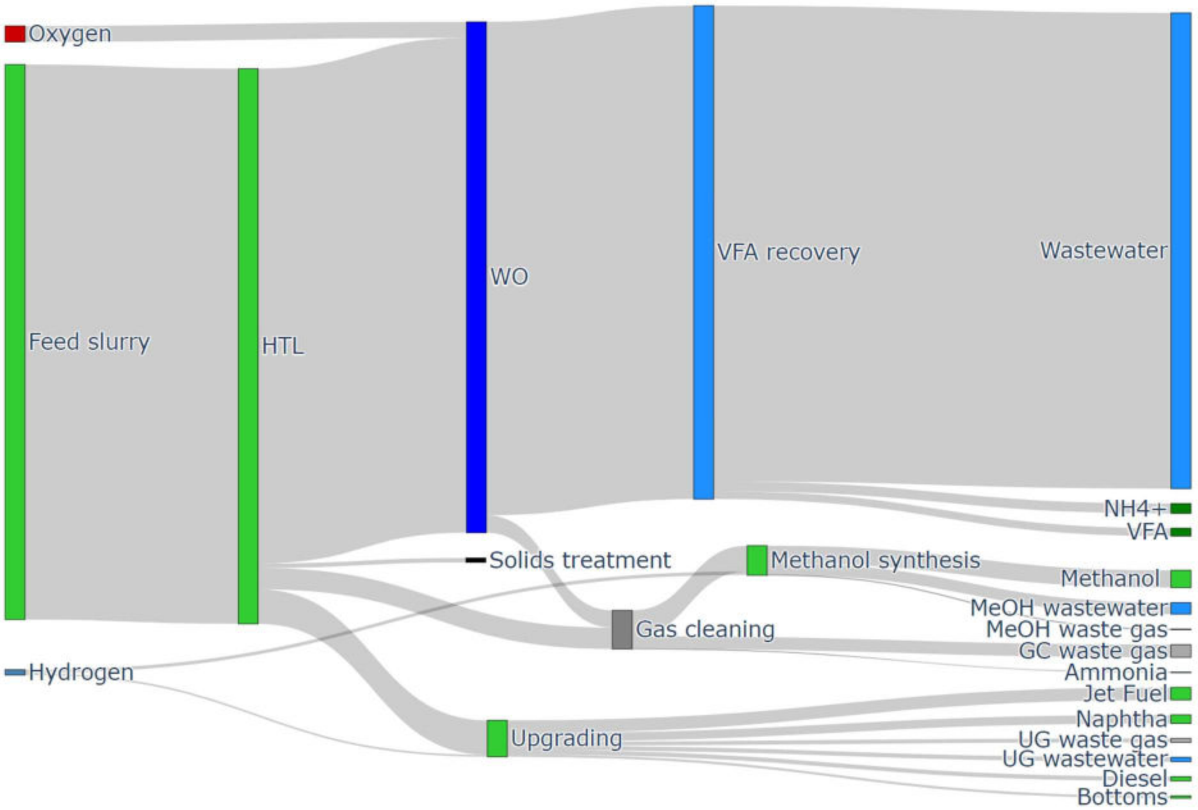

Figure 4: Preliminary mass balance of the overall CIRCULAIR process based on the biomass input. In the baseline scenario several HTL plants feed one upgrading plant.

The role of carbon containing streams and energy products becomes more apparent in the carbon and energy balances, which are shown in Figure 5 and Figure 6, respectively.

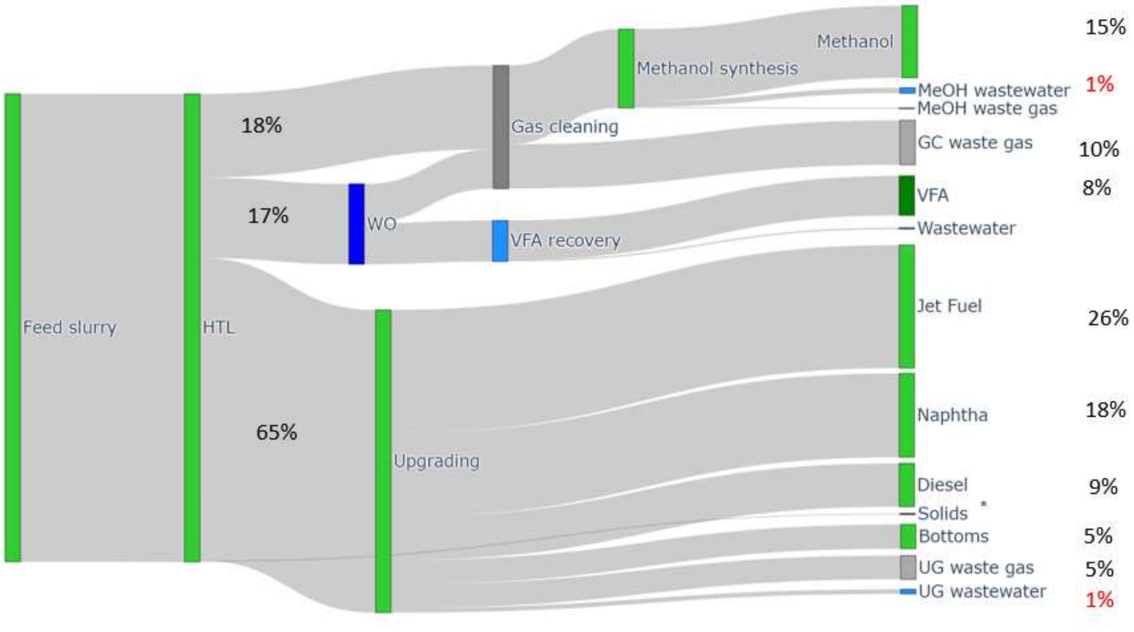

Figure 5: Carbon balance of the overall CIRCULAIR process (*Value for solids is underestimated in the preliminary modelling, see discussion in CIRCULAIR report "Process model (for pre-evaluation)" [2]).

The carbon balance illustrates the relevance of carbon containing compounds in the aqueous phase that results from HTL conversion. A proper set of processes for carbon utilization from the HTL aqueous phase can significantly increase the carbon efficiency of the overall process. Furthermore, treatment procedures are also needed to clean-up the water phase before disposal. The energy balance also shows that the energy content of carbon compounds in the HTL aqueous phase can play a significant role for the overall energy efficiency of the process. In CIRCULAIR, wet oxidation (WO) of the HTL aqueous phase is integrated with HTL conversion, thereby it is possible to utilize the exothermic process heat from WO in order to elevate the temperature of the feed slurry to process temperatures.

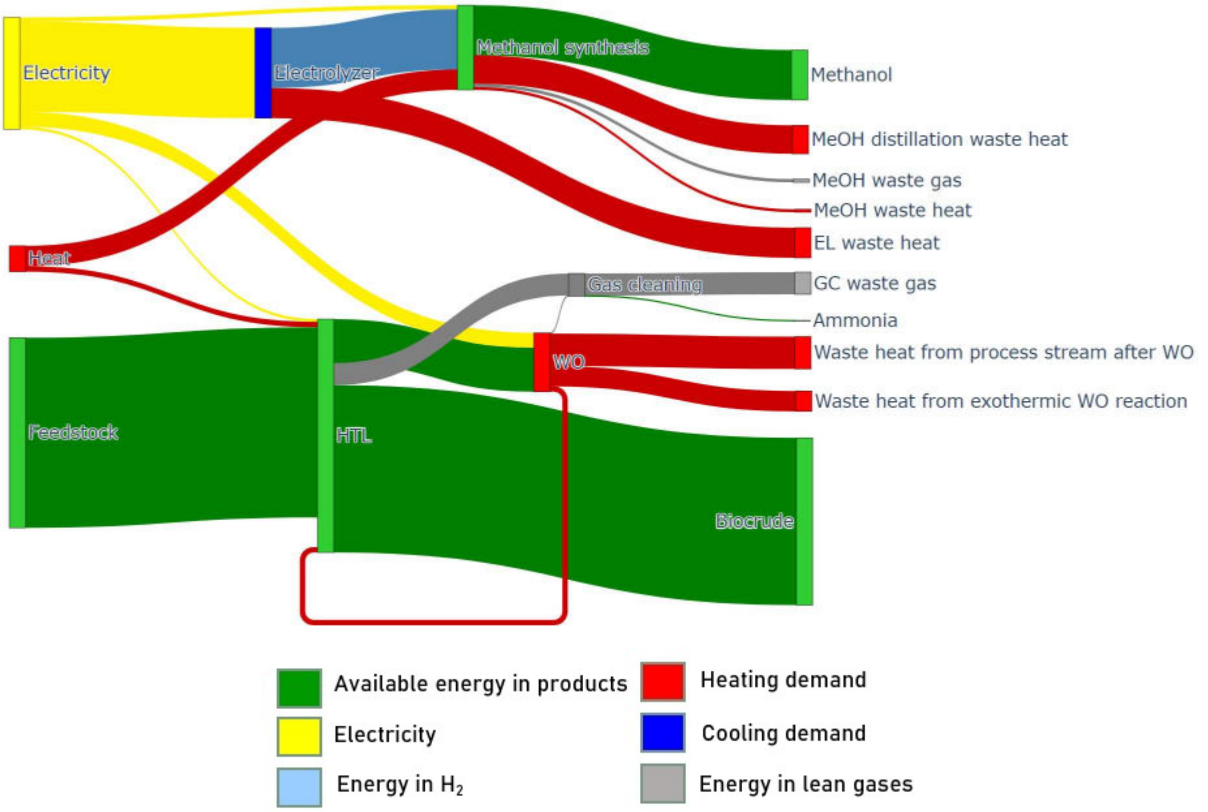

Figure 6: Preliminary energy balance of the CIRCULAIR process at the HTL plant site (upgrading of the biocrude is not shown in this figure).

The carbon and energy balances in Figure 5 and Figure 6 also show that a high fraction of the carbon that is initially contained in the feedstock is transferred to various final products. However, synthesizing methanol from $CO_2$ streams that are released both from HTL conversion and WO, requires the provision of major amounts of additional energy in the form of hydrogen. Consequently, the electricity demand for the operation of electrolysis becomes the dominating contribution of the overall electricity consumption of the process, which has profound consequences for plant economics (see Section 4). The process model cannot representatively account for the solids formation, in consequence only a small share of the carbon in Figure 5 goes into the solid fraction (see CIRCULAIR report “Process model (for pre-evaluation)” [2] for more detailed discussion). The process model will be adjusted by implementing experimental CIRCULAIR results for solids formation. For the pre-evaluation of the global warming potential within this report it was assumed that about 3 % of the carbon in the initial feedstock is sequestered via soil application of HTL solids.

# 3. Methodology

## 3.1. Techno-economic assessment

### 3.1.1. Levelized Cost of Energy approach

The techno-economic assessment was performed by applying the Levelized Cost of Energy (LCOE) approach. Thereby, energy production costs for the integrated CIRCULAIR process are evaluated, where energy refers to the total amount of energy that is stored in the fuel products. LCOE are calculated by dividing the discounted costs over the lifetime of the plant by the discounted fuel production, according to the following equation:

$$LCOE = \frac{\sum_{t=0}^{n} \frac{I_t + A_t + C_t}{(1+i)^t}}{\sum_{t=0}^{n} \frac{E_t}{(1+i)^t}}$$

where:

$LCOE$ = Levelized Cost of Energy [€/MWh]
$I_t$ = Capital expenditures (CAPEX) [€/y]
$A_t$ = Operational costs [€/y], excluding costs for commodities.
$E_t$ = Total amount of energy in fuel products [MWh/y]
$C_t$ = Commodities [€/y]
$i$ = Discount rate [%]
$n$ = Economic lifetime [y]
$t$ = Year of lifetime

The LCOE approach is a typical choice in energy economics and reflects both CAPEX and operational expenditures (OPEX). In this specific case, OPEX is separated into annual operational costs excluding commodities ($A_t$) and commodity costs ($C_t$). This separation is based on the methodology of OPEX estimation, where a certain fraction of the CAPEX investment is used as a fixed annual OPEX contribution, while commodities are defined as material and energy flows of economic value that enter or leave the system boundary. Consequently, commodity costs are evaluated from the preliminary energy and mass balances (see Section 2.2).

The total costs over the entire lifetime of the system are either allocated to all fuel products, namely naphtha, jet fuel, diesel, heavy fuel oil and methanol, or specifically to the target product jet fuel.

### 3.1.2.Estimation of Capital expenditures (CAPEX)

The results in Section 4 indicate that CAPEX represents a decisive contribution to fuel production cost, especially during the early phase of commercialization. Many CAPEX estimations for future fuel production pathways take an n-th plant approach that represents a future scenario where the respective technology has already evolved over an initial development phase. However, the CAPEX for early commercial implementations of novel fuel production pathways is usually much higher as key learnings and optimizations still need to take place. For this reason, two different approaches are chosen to estimate the CAPEX of a coupled HTL-WO plant, a high lump sum estimate that may be representative for a near-term implementation, and a lower estimate from a bottom-up approach. The material based bottom-up approach may be representative for a distant future as it estimates CAPEX from a sum of subsystem contributions, assuming typical cost for established processes in the petrochemical industry. The lump sum estimate resulted from discussions within the CIRCULAIR consortium. The bottom-up approach is addressed in more detail in the following.

**HTL-WO reactor geometry and material based bottom-up CAPEX estimate**

A plug flow reactor (PFR) design is used for the continuous sub-critical HTL and WO reactor, essentially consisting of a long tube [3]. In order to enable heat exchange between the two reactors, they are implemented as a closely coupled reactor system.

The investment cost of the plant components are evaluated with literature values for total capital investment of established commercial process steps. This methodology is similar to a prior techno-economic evaluation of HTL conversion within the EU-funded project HyFlexFuel [4].

The cost for the required components were modelled using an economy-of-scale approach. Values for the respective components are based on those published by Towler et al. [5].

$$C_e = a + b\,S^n$$

where:

$C_e$ = purchased equipment cost

$a, b$ = cost constants

$S$ = size parameter

$n$ = exponent for equipment type

The equation used to determine the equipment cost is valid for a certain range of sizes. Constant *a* describes a fixed part of the equipment cost, factor *b* the variable part that depends on the size of the process. The effect of scaling is taken into account by the exponent *n* depending on the respective component. In addition, 20% off-site cost are added to the actual plant components and installation cost in order to reflect the additional need for peripheral components such as pipes, measuring and control equipment in the balance of plant cost. Further installation factors account for expenses that relate to the integration and installation of each component.

$$C_{ie} = IF * C_e$$

where:

$C_{ie}$ = purchased and installed equipment cost
$IF$ = Installation factor

Table A1 (in the Appendix) provides a summary of the installation factors used to estimate investment costs for different process components. In addition to the direct plant cost, a share of 15% of the plant cost for contingence, as well as 5% for balance of plant cost are taken into account.

## 3.2. Life cycle assessment

In order to analyse environmental impacts the methodology of life cycle assessment (LCA) is applied. Global warming potential (GWP) is chosen as a key parameter for a first evaluation of environmental impact. LCA is standardized in ISO 14040 [6] and ISO 14044 [7], the software Brightway2 [8] is used for the evaluation. In the following, the four stages of an LCA are listed and explained shortly:

- Goal and scope definition.
- Inventory analysis (LCI).
- Impact analysis (LCIA).
- Interpretation.

### 3.2.1. Goal and scope

The goal of this assessment is a first indication of the greenhouse gas (GHG) emission reduction potential compared to conventional fuels and to identify the main GHG emission drivers of the CIRCULAIR process (global warming potential over 100 years (GWP100)). The assessment is applied to the CIRCULAIR baseline scenario, and it is not the goal to deliver a fully detailed quantitative assessment. The latter will be the goal of an upcoming final assessment. Two different system models are applied, an attributional system model, and a consequential system model, which shows the impact of avoided emissions from common practices. Within the attributional approach, again two different system models are investigated, a cut-off approach, where all emissions are allocated to the main product and an allocation approach, where the emissions determined with the cut-off approach are allocated between the different fuel products. The energy content of the fuel products is used as allocation key.

It should be noted that other, non-energy by-products are always considered to replace their respective current fossil equivalents on the market and that the substitution of current manure handling practices and the adapted treatment of manure for HTL use is not considered yet, but will be part of the final assessment.

### 3.2.2. Inventory analysis (LCI)

Material and energy inputs/outputs for the life cycle of HTL fuel production are the basis for the LCI, these streams have been determined as described before (see Section 2.2). For the background activities, the Ecoinvent 3.10, APOS system model is used, while the foreground activities are modelled in Brightway2.

### 3.2.3. Impact analysis (LCIA)

The focus of the impact analysis is the impact category of climate change. Characterization factors from the IPCC 2021, climate change, Global Warming Potential (GWP100) method are used [9]. The functional unit of 1 kg of jet fuel produced is chosen, however a fuel mix is produced. The fuel mix consists of the following fuels: naphtha, jet fuel, diesel, heavy fuel oil (HFO) and methanol. Their respective energy share as listed in Table 2 in Section 5.1 are used as allocation key in the attributional, allocation based system model.

### 3.2.4. Interpretation

Section 5 discusses the LCIA results. As noted before, the work described in this report is not intended to reflect a fully detailed quantitative LCA of the CIRCULAIR process, rather an indication of the GHG emission reduction potential should be generated, whereas key GHG emission drivers can be identified. In order to do so, the results of the attributional, allocation based system model are most suitable and therefore defined as the main result in this assessment, while the other two system model approaches are designed to give an impression of either allocating the emissions to only jet fuel as the main product and neglecting the production of co-products (attributional, cut-off based), or show the implications that the substitution of the respective fossil fuel products would have on their respective supply chains (consequential approach). Evaluating different model approaches highlights the importance of the model approach for the interpretation of LCA results from multi-product pathways.

# 4. Pre-evaluation of key economic parameters

This chapter presents the preliminary results from the evaluation of fuel production cost using the LCOE approach and discusses the preliminary results of the economic analysis of the CIRCULAIR process in light of different scenario assumptions for the economic value of co-products.

## 4.1. Fuel production cost

Figure 7 shows the high-level LCOE results of the techno-economic analysis consisting of CAPEX, OPEX and commodity costs. The values of 99 €/MWh for the lump sum approach and 62 €/MWh for the bottom-up approach correspond to a normalization based on the mix of fuel products that result from the CIRCULAIR baseline configuration, where the difference arises from two distinct methods of CAPEX estimation (see Section 3.1.2 and Section 4.2). With a share of 51%, CAPEX is the dominating contribution in the lump-sum case, while CAPEX and commodity costs contribute about equally in the bottom-up case. In both cases, OPEX as percentage values of CAPEX account for a lower share of cost (annual subsystem OPEX costs were assumed to be 5% of CAPEX for HTL-WO and 3% of CAPEX for all other subsystems).

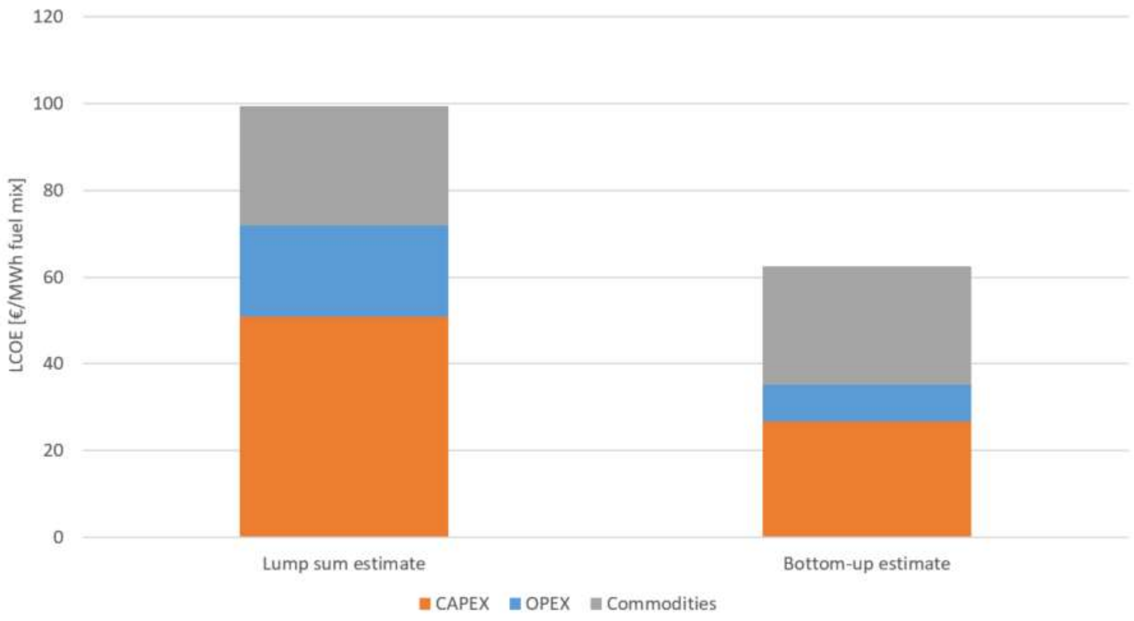

Figure 7: Cumulated production cost (CAPEX, OPEX and commodities) for the mix of fuel products evaluated for two distinct methods of CAPEX estimation.

Figure 8 shows a break-down of subsystem CAPEX and OPEX contributions for the lump-sum estimate normalized to the sum of the energy contained in all fuel products. The CAPEX/OPEX cost break-down is dominated by the cost for the HTL-WO subsystem, which is evaluated from a lump-sum CAPEX estimate for an early commercial system that can be implemented in the near-term future. Subsystem OPEX cost in Figure 8 and Figure 9 follow a similar trend as CAPEX cost items, as annual subsystem OPEX costs are estimated as a fixed fraction of CAPEX[2].

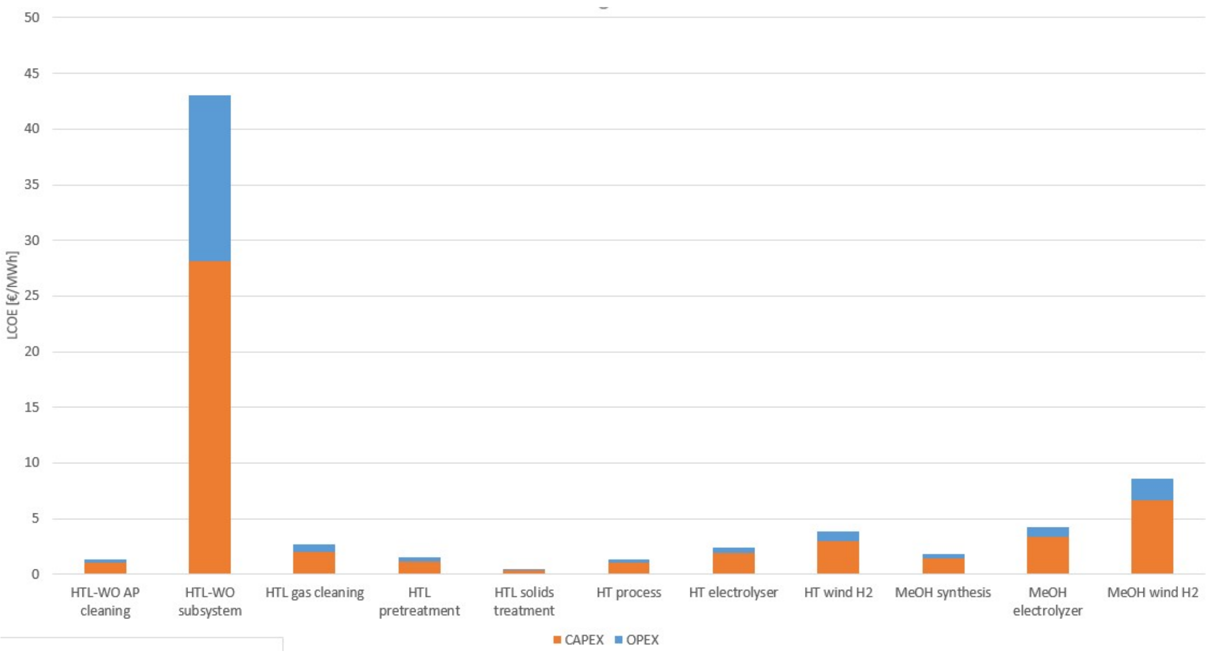

Figure 8: Break-down of cost contributions for various subsystems in the lump sum approach, normalized to the sum of the energy contained in all fuel products. Orange: CAPEX, blue: OPEX.

Significant cost contributions are also associated with green hydrogen production for hydrotreatment (HT) and Methanol (MeOH) synthesis.

Figure 9 indicates that green hydrogen generation cost can become the dominating cost contribution in the bottom-up scenario where HTL-WO costs are reduced by learning effects.

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[2] Annual subsystem OPEX costs were assumed to be 5% of CAPEX for HTL-WO and 3% of CAPEX for all other subsystems. See also Figure 11 for additional OPEX contributions at system level.

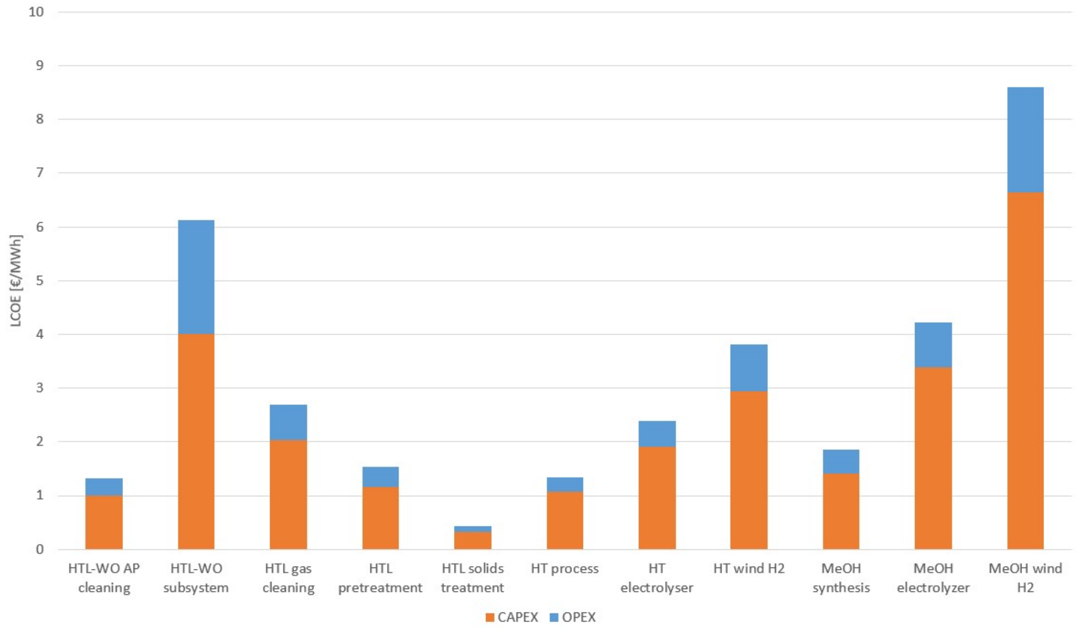

Figure 9: Break-down of cost contributions for various subsystems in the bottom-up approach, normalized to the sum of the energy contained in all fuel products. Orange: CAPEX, blue: OPEX.

Figure 10 shows additional OPEX contributions at system level that mainly relate to feedstock supply, commodity and labour cost, as well as revenues that were attributed to the utilization of low-grade process heat for district heating and carbon sequestration via HTL solids. Transport cost for manure and labour cost at the location of the distributed HTL plants are the dominating contributions to the additional OPEX at system level, indicating the need for a balanced supply chain that limits the transport requirements for wet feedstock but ensures a sufficiently large capacity of the individual HTL plants, here in terms of labour costs, but also more generally with respect to economies of scale.

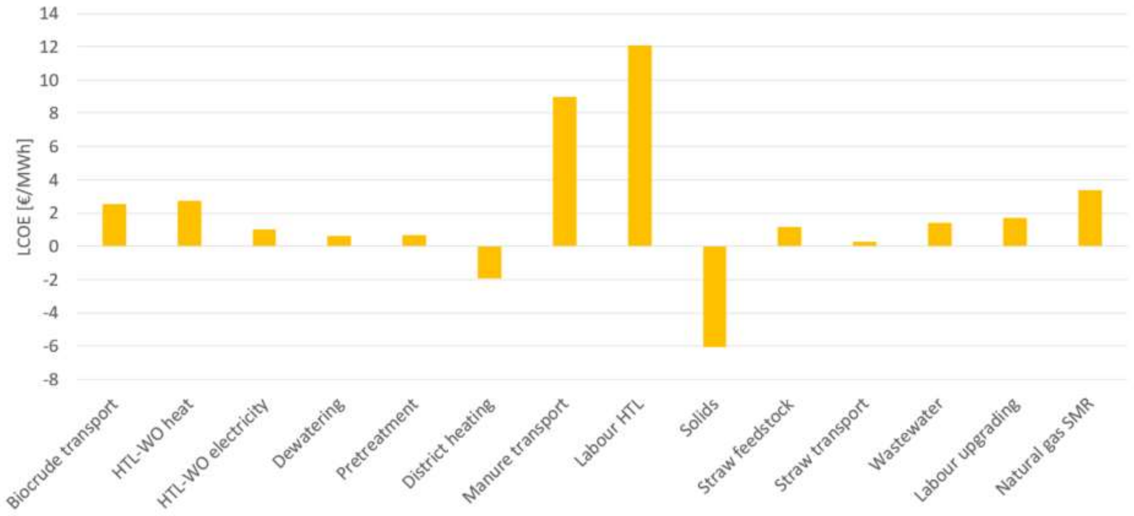

Figure 10: Break-down of cost contributions for various commodities in the bottom up approach, normalized to the sum of the energy contained in all fuel products. (SMR: Steam methane reforming to produce hydrogen for biocrude upgrading from natural gas).

## 4.2. Different estimations of capital expenditure

The results that were shown in Section 4.1 indicate that the CAPEX estimate for the HTL-WO subsystem plays a key role for techno-economic analyses of the CIRCULAIR concept. Two distinct methods for CAPEX estimation were described in Section 3.1, a lump-sum expert estimate, that may be representative for the near-term implementation of an early commercial plant, and a material-based bottom-up estimate, that may be representative for a longer-term future potential (n-th plant approach). Table 1 shows CAPEX estimates from this report in comparison to CAPEX estimates from literature sources. In particular, the CIRCULAIR estimates that are based on two entirely different methodologies differ by a factor of about seven, which has profound consequences on the techno-economic results and their interpretation.

Table 1: Different CAPEX estimates for HTL and HTL-WO plants normalized to slurry throughput according to PNNL [10] .

| Scenario or literature reference | Normalized CAPEX € / (kg slurry / h) |
|---|---|
| CIRCULAIR lump sum estimate: HTL - WO | 2400 |
| PNNL HTL SOT 2018/19 | 2095 |
| PNNL HTL SOT 2020 | 609 |
| PNNL HTL SOT 2021/22 | 520 |
| CIRCULAIR bottom-up estimate: HTL – WO | 337 |

## 4.3. Role of co-product value on jet fuel production cost

The target product of the CIRCULAIR project is jet fuel, however, the techno-economic results that were shown so far were normalized to the energy content of the mix of fuel products that result from the CIRCULAIR concept. This was necessary since the energy content of the jet fuel product is only 30% of the overall energy contained in all fuel products (see Table 2 in Section 5.1.1). Consequently, if LCOE are normalized to only one target product, e.g. jet fuel, production cost become very sensitive to the market values of the co-products.

Figure 11 shows the LCOE for the jet fuel product as a function of co-product revenues (shown as a multiplication of the current fossil fuel prices with the indicated value on the x-axis). Again, a distinction is made between the lump-sum and the bottom-up approach. With current market prices for co-products, both cases display significantly higher jet fuel production costs compared to the fuel production cost of the product mix (see Section 4.1). However, it is conceivable that significantly higher market prices can be achieved for renewable fuel products (jet fuel, methanol, naphtha and diesel) compared to current prices of conventionally produced fossil fuels. This is confirmed by the observation that renewable diesel is already being traded at significantly higher market prices than conventional fuels. In addition, price premiums for various fuel products may be expected in the future due to mandates (e.g. ReFuel EU aviation for jet fuel), penalties or $CO_2$ taxes [11].

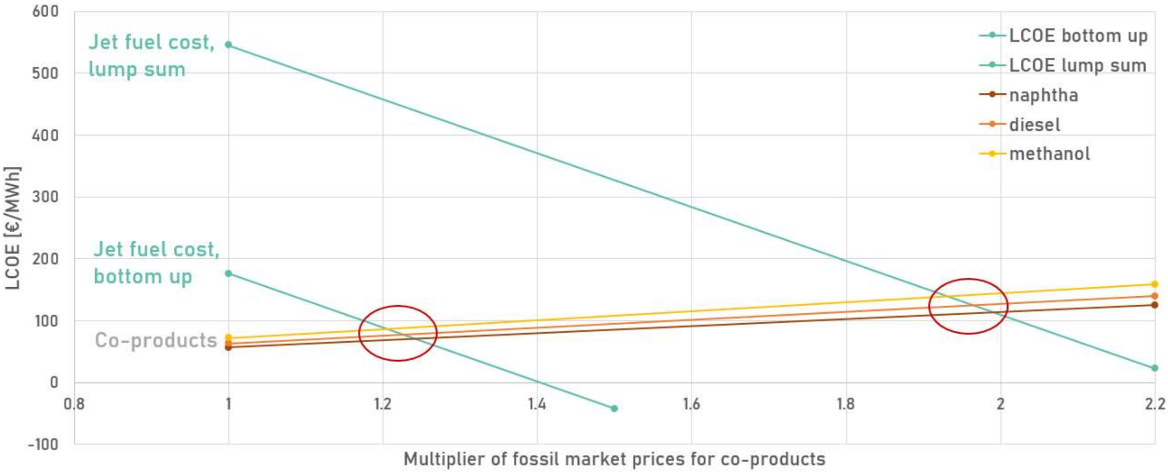

Figure 11: Jet fuel production cost (LCOE) for different co-product prices. A multiplier of 1 corresponds to the current market value of conventional fuel products. Red ellipses roughly correspond to the results for the fuel mix that are shown in Figure 7.

Figure 11 illustrates the strong sensitivity of the jet fuel production cost (LCOE) to the revenues that may be received for the co-products. Jet fuel contains about 30% of the energy that is stored in all fuel products (see Table 2), therefore, jet fuel production costs are significantly higher than the average values for the mix of fuel products if co-products products need to be sold at the price level of conventional fuels. The average values for the mix of fuel products (see Figure 7) correspond to scenarios where all fuel products can be marketed as a price level that is almost double the current fuel prices (lump sum CAPEX estimate) and slightly more than 20% higher than current fuel prices (bottom-up CAPEX estimate), respectively. This highlighting the importance of marketing co-products at premium price levels, especially for early commercial implementations.

The European Aviation Safety Agency (EASA) has recently announced aviation fuel reference prices for ReFuelEU Aviation [12]. The 2024 market price for aviation biofuels[3] was set to

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[3] This market price will be used to calculate the penalty for non-compliance with ReFuelEU aviation.

2085 €/tonne (174 €/MWh at 12 MWh/tonne), this market price is based on a production cost estimate of 1461 €/tonne (122 €/MWh). The same reference [12] also provides production cost estimations for advanced aviation biofuels of 1915-3655 €/tonne with an average of 2715 €/tonne (226 €/MWh). Jet fuel production via the CIRCULAIR pathway may be competitive in comparison to these reference prices and production cost even in case of the higher lump sum CAPEX estimate, provided that co-products can also be marketed at a sufficient premium.

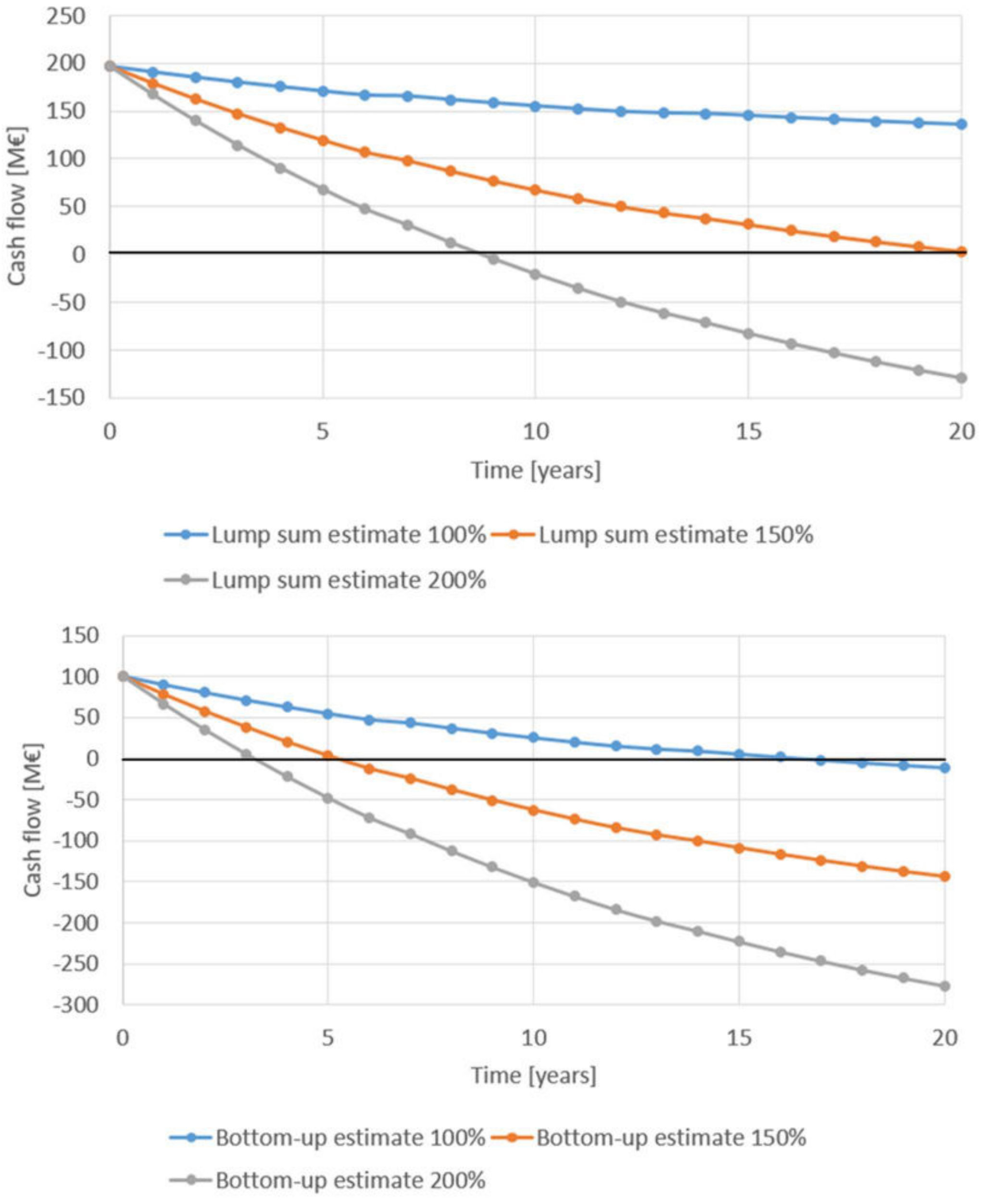

Figure 12: Cash flow analysis of over a lifetime of 20 years for six different scenarios. Top: Lump-sum approach with 100% (blue), 150% (orange) and 200% (grey) of current fossil product prices as revenues for co-products.; Bottom: Bottom-up approach with 100% (blue), 150% (orange) and 200% (grey) of current fossil product prices as revenues for co-products.

Another perspective on the techno-economic results is provided in Figure 12, which shows cumulative costs by year. In year zero, investment cost are shown, while in the following years, additional CAPEX cost for replacements, OPEX cost for maintenance, commodity and labour costs as well as revenues are considered. Depending on initial investments and market value of the various products, it can be seen that the initial investment cost cannot be recovered by the revenues made (lump-sum CAPEX estimate, co-product revenues at conventional fuel prices) or that initial investment and revenues are about equal after the lifetime of 20 years (lump sum CAPEX estimate, co-product revenues at 150% of conventional fuel prices; bottom-up CAPEX estimate, co-product revenues at conventional fuel prices). Significant profit can be made if co-product revenues are at a level of 200% of the conventional fuel prices, or ≥150% of the conventional fuel prices for the lump-sum and the bottom-up CAPEX estimate, respectively.

# 5. Pre-evaluation of key ecological parameters

In the following, the preliminary results of the life cycle assessment (GWP100) of CIRCULAIR are displayed and discussed. Figure 13 shows a high-level representation of the main LCA result of this report, a comparison between the GWP100 of the CIRCULAIR baseline scenario using an attributional allocation based system model and conventional jet fuel production as comparator. The CIRCULAIR baseline case emits 14 $g_{CO2\text{-}eq.}/MJ_{jet\ fuel}$ (0.6 $kg_{CO2\text{-}eq.}/kg_{jet\ fuel}$) and thus reduces the GWP emissions by 84% compared to conventional jet fuel production. The attributional approach corresponds to an allocation of the environmental credits and burdens to all fuel products based on energy content. This approach is in line with the methodologies to evaluate life-cycle GHG emissions of aviation fuels for important regulation such as the EU Renewable Energy Directive (RED) or the CORSIA scheme by ICAO[4] [13, 14]. The approach is consistent with the evaluation of fuel production cost in Figure 7, however, jet fuel is chosen as a comparator as it is the target product of CIRCULAIR.

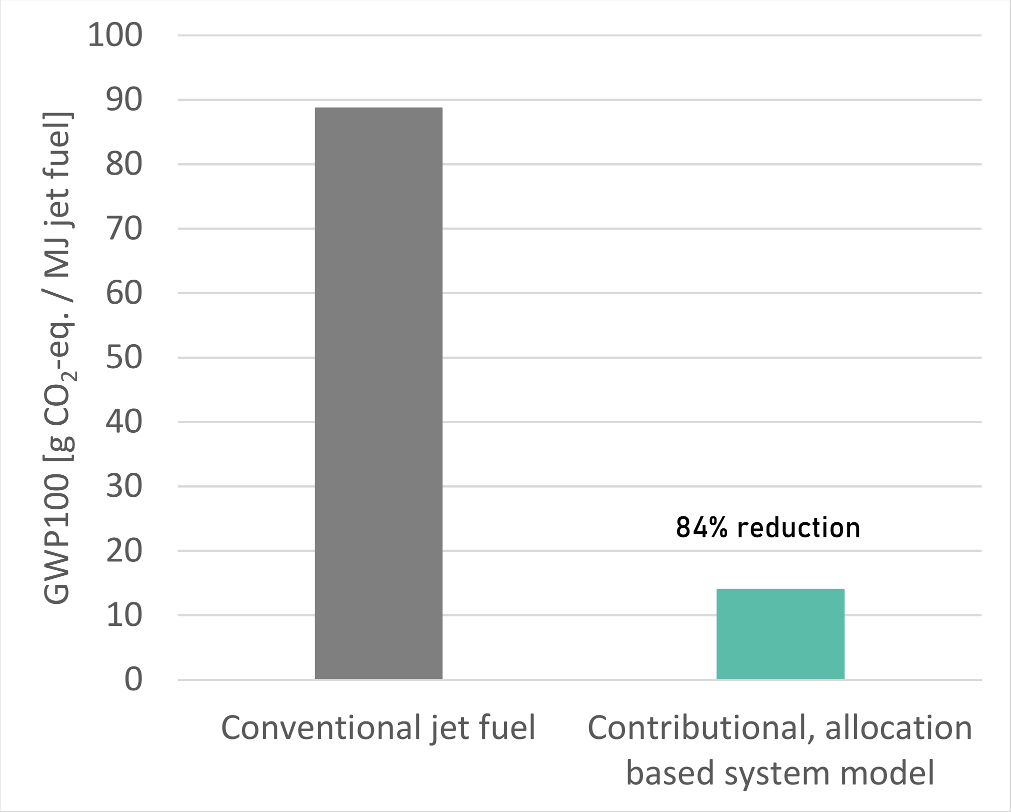

Figure 13: Comparison of GWP100 emissions of conventional jet fuel production and the CIRCULAIR baseline scenario (attributional approach, energy based allocation).

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[4] CORSIA: Carbon Offsetting and Reduction Scheme for International Aviation; ICAO: International Civil Aviation Organization. Note that the ICAO comparator of 89 $g_{CO2\text{-}eq}$/MJ is displayed in Figure 13, while RED uses a more general fossil fuel comparator of 94 $g_{CO2\text{-}eq}$/MJ for various fuels.

The CIRCULAIR baseline scenario represents a multi-product system (see Figure 5). Section 5.2 show alternative representations of GWP100 results of the same system using a cut-off system model (47 g $CO_2$-eq. / MJ jet fuel or 2.0 $kg_{CO2\text{-}eq.}/kg_{jet\ fuel}$), which allocates all emissions to the jet fuel product alone, as well as a consequential system model (-23 $g_{CO2\text{-}eq.}/MJ_{jet\ fuel}$ or -1.0 $kg_{CO2\text{-}eq.}/kg_{jet\ fuel}$) that accounts for co-products replacing the conventional products in the market. It is pointed out that the mentioned cut-off and consequential approach represent different methodologies to investigate the same system, these alternative methodological approaches are not compliant with reference regulations in the transportation fuel sector, such as RED and CORSIA, and should in particular not be directly compared to the comparator values that are given in these reference regulations. The respective system model results will be discussed in more detail in the following sections.

## 5.1. Attributional system model

The main goal of the LCA section of this report is to give an indication of the GWP100 reduction potential of the CIRCULAIR baseline case and furthermore to identify the key parameters that drive GHG emissions. The attributional system model allows to identify these key emission drivers and is therefore applied to target this goal. The Sankey diagram in Figure A 1 (see Annex) illustrates the complexity of the evaluation that leads to the high-level result that was shown in Figure 13. The main process steps along the process chain are identified for better visibility. As can be seen, the CIRCULAIR process has several interlinked process steps, especially connected to the co-product recovery.

### 5.1.1. Key ecological parameters of the CIRCULAIR baseline scenario

Figure 14 shows the main process contributions to the GWP100 of the CIRCULAIR baseline case, calculated with the attributional system model. Negative contributions to the net emissions stem from the fixed carbon in the HTL solids (-17%), while avoided emissions (~ -2% each) correspond to a replacement of heat production from natural gas and to liquefied petroleum gas production (Rest of World / RoW and Europe without Switzerland). It is known that avoided emissions from a change in manure storage and handling can result in a significant negative contribution [15], however, this effect is not yet considered in the pre-evaluation within this report.

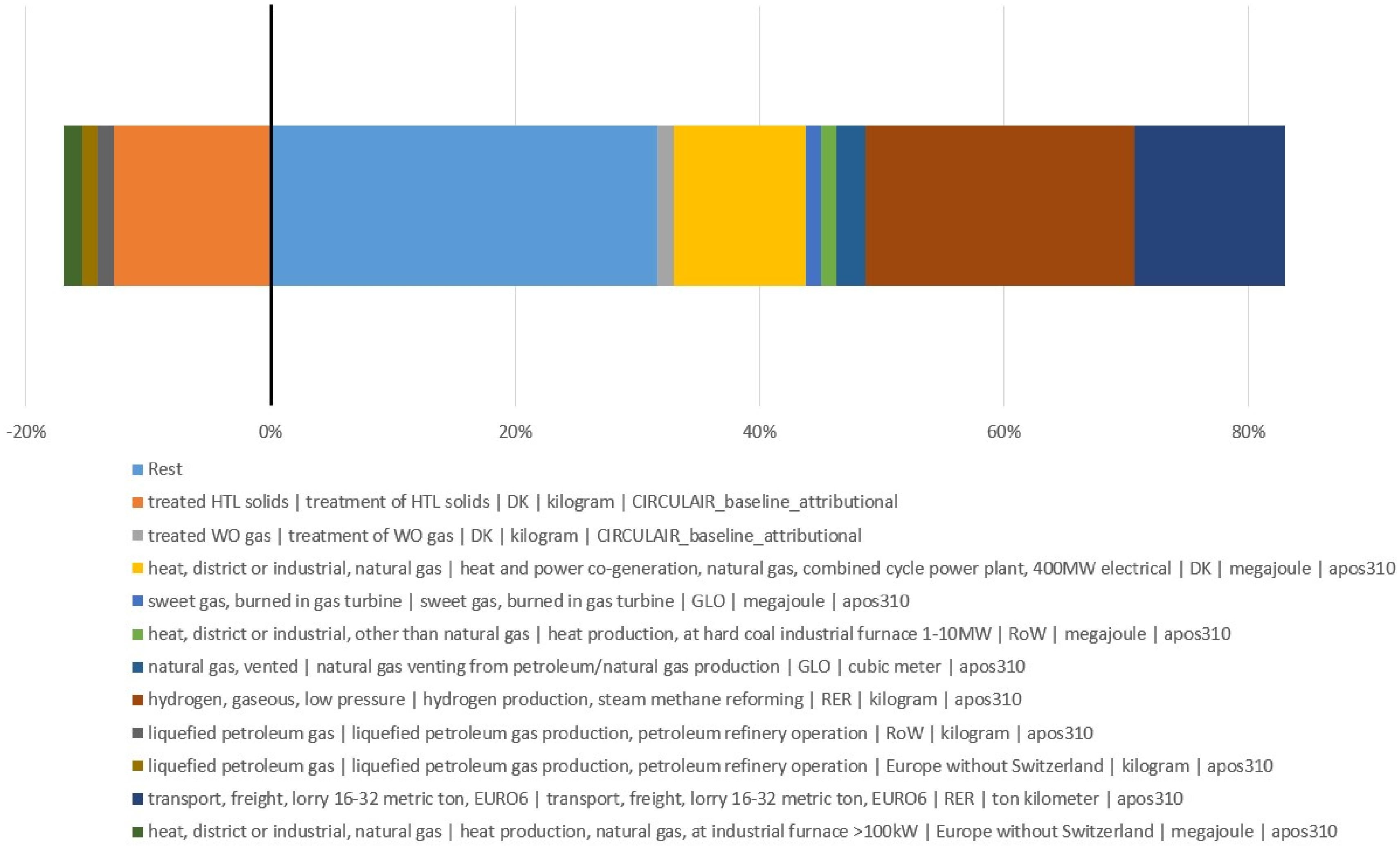

Figure 14: Process contributions to the GWP100 emissions calculated with the attributional, cut-off based system model. The “Rest” consists of more than 900 process contributions that make up almost 30% of the emissions, however all individual contributions within this “Rest” are smaller than the smallest contribution that is individually shown in this figure. DK = Denmark, GLO = global, RER = Europe, RoW = rest of world, apos 310 = “allocation at point of substitution” Ecoinvent database 3.10.

The carbon balance that is derived from the process model (see Figure 5) underestimates the solids formation, furthermore it is not yet known if the carbon in the solids is sufficiently stable when sequestered in soils. For the pre-evaluation in this report, it was assumed that about 3% of the initial carbon contained in the feedstock is sequestered. A more accurate estimation will be part of the project work and will be included in the final LCA report. The largest contribution of the net positive emissions in Figure 14 is attributed to the "rest" (~42%), which consists of more than 900 small and very small contributions. A detailed analysis of these contributions is beyond the scope of this report, nevertheless, this "rest" plays an important role towards the long-term target of achieving net-negative emissions[5] as it surpasses the scenario assumption for the negative contribution that is associated to the HTL solids.

The largest individual contribution stems from hydrogen production for HTL upgrading via steam methane reforming (SMR, ~29%). This contribution stems from the assumption that the upgrading plant needs to run continuously[6], which would result in high hydrogen storage cost if only green hydrogen from intermittent wind energy is used. Therefore, hydrogen production from SMR is assumed for time periods, when renewable electricity from wind energy is not available. Taking into account the capacity factor of electricity production from wind at the baseline location (51.7%), this would correspond to 48.3% of the hydrogen being produced from SMR.

The second largest share of emissions is attributed to transport activities (~16%), resulting mostly from the transport of manure with minor contributions for the transport of biocrude and jet fuel. Heat demand for different operations is the third largest contributor (~14%). Currently, most of this heat demand is used for pyrolysis of the HTL solids. However, the exact preparation and treatment method of the HTL solids as application for soil amendment is yet to be investigated and will be part of the further work in the project. Notably, the contribution of treating HTL solids is almost as large as the assumed negative contribution from HTL solids separation. Improved estimates both on HTL solids treatment and solid sequestration credits will be provided in the final LCA results of CIRCULAIR.

Further minor contributions (2-3% each) are attributed to natural gas that is vented during petroleum/natural gas production, sweet gas burning in a gas turbine and emissions due to leakage during the WO gas cleaning. For HTL gas cleaning, also a leakage is considered,

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[5] The contribution of this "rest" will likely decrease in the longer-term future as many individual contributions that are linked to energy use or material use (such as steel) decrease due to decarbonization efforts in various sectors of the economy.

[6] Large amounts of hydrogen are also needed for methanol synthesis. For methanol synthesis it is expected that the reactor can be operated in a mode that follows the intermittent wind profile.

however, the impact is lower and it is therefore found in the "rest" contribution. Besides the leakage, most of the non-$CO_2$ gas streams get burned to produce $CO_2$, which is then released into the atmosphere. The produced heat is not considered to be usable in this case. Not burning the produced $H_2$ and $CH_4$ would yield in significantly increased GHG emissions, which is why the production of $CO_2$ as a less potent GHG is considered here.

The evaluation of the multi-product CIRCULAIR baseline scenario using an attributional system model results in a GWP100 of 0.6 $kg_{CO2\text{-}eq.}/kg_{jet\ fuel}$ if the emissions are distributed over all fuel products performing energy-based allocation. The GWP100 corresponds to 2.0 $kg_{CO2\text{-}eq.}/kg_{jet\ fuel}$ respectively, if all emissions are solely allocated to the jet fuel product. For both cases, the emission drivers are the same, only the allocation is changed.

### 5.1.2. Allocation of emissions based on produced energy of fuel products

As described above, the CIRCULAIR baseline scenario produces a basket of different fuels, including naphtha, jet fuel, diesel, heavy fuel oil and methanol. The produced energy amounts of these fuel products are used as allocation key in the attributional, allocation based system model. They are listed in Table 2 alongside their respective allocated emissions. On an energy basis, methanol (36.4%) is the fuel which is produced the most, followed closely by jet fuel as the main product of the process (30.0%). Naphtha is also produced with a significant share (19.8%), while the other two products only contribute less than 10% each.

Table 2: Fuel products of the CIRCULAIR baseline scenario with their respective energy shares and their allocated GWP100 emissions.

| Fuel product | Energy share [%] | Allocated emissions [g $CO_2$-eq. / MJ jet fuel] | Allocated emissions [kg $CO_2$-eq. / kg jet fuel] |
|---|---|---|---|
| Naphtha | 19.8 | 9.2 | 0.4 |
| Jet Fuel | 30.0 | 14.0 | 0.6 |
| Diesel | 9.6 | 4.5 | 0.2 |
| Heavy Fuel Oil | 4.2 | 2.0 | 0.1 |
| Methanol | 36.4 | 17.0 | 0.7 |

The energy-based allocation of the GWP100 emissions calculated with the attributional, cut-off-based approach results in the emissions given in Table 2, giving methanol the highest share of emissions, closely followed by jet fuel. The GWP100 emissions of naphtha are around 50% of those of methanol, while those of diesel and HFO are significantly smaller.

## 5.2. Consequential system model

The consequential system model approach is often used to consider market effects and system-wide cause-and-effect relationships. In the context of fuel production and regulatory frameworks that demand a certain share of renewable fuels being introduced into the markets, as well as a global view on the development of Global Warming, this viewpoint can have its justification. However, the approach can also mask the emission drivers of a process and thereby hide potential for improvement. Furthermore, the interpretation of a comparison to a fossil comparator is tricky and therefore the results should be taken with care.

Figure 15 shows the process contributions to the GWP100 emissions for the consequential system model, however due to the complexity of the system and the high resulting number of process contributions, many small impacts cannot be displayed on both ends of the spectrum. The big impacts on the net positive side correspond to the attributional approach that was discussed in the preceding section, hydrogen production via SMR, transport of goods and heat supply. Likewise, one of the large contributions on the net negative side stems from the carbon that is fixed in the HTL solids, which was again discussed before. Using the consequential system model however, this is only the third highest impact on the net negative side. The highest amount of avoided emissions stem from the replacement of fossil methanol production via natural gas reforming (-17.6 $g_{CO2\text{-}eq.}/MJ_{jet\ fuel}$), followed closely by vented natural gas (-16.7 $g_{CO2\text{-}eq.}/MJ_{jet\ fuel}$). Smaller, but still significant avoided emissions can be attributed to sweet gas and natural gas burned in gas turbines, heat production from natural gas, pipeline transport of natural gas and the fuel products naphtha and diesel. Overall it becomes clear that a number of fossil processes could be avoided by the implementation of HTL fuel production, but the most significant finding is the high amount of emissions avoided from fossil methanol production via natural gas reforming. Due to its significance, a short comparison of different methanol production routes in different countries based on the available models in Ecoinvent has been performed and is displayed in Figure 16. It can be clearly seen that there are huge differences between the different production routes but also between different countries / regions. In the current model for pre-evaluation, the process of methanol production via natural gas reforming in the region "Rest of World, RoW" has been selected as a mean value. For the detailed LCA analysis later in the project, an analysis of the market composition of different production routes and countries / regions may be performed in order to more accurately display the effect of methanol production displacement.

Another very important part of the consequential analysis, which is not yet implemented in the results from this report, is the avoidance of emissions that results from current manure handling practice and subsequent usage. These emissions would change when manure is being used in the HTL process (or any other process, e.g. anaerobic digestion) without the need for storage over prolonged durations. It is known that long-term storage of manure, e.g. for application as fertilizer, is associated with large amounts of GHG emissions. In consequence, alternative use cases can result in large amounts of avoided GHG emissions. This topic has already been discussed before [16], but needs to be addressed in more depth in the final LCA deliverable of this project.

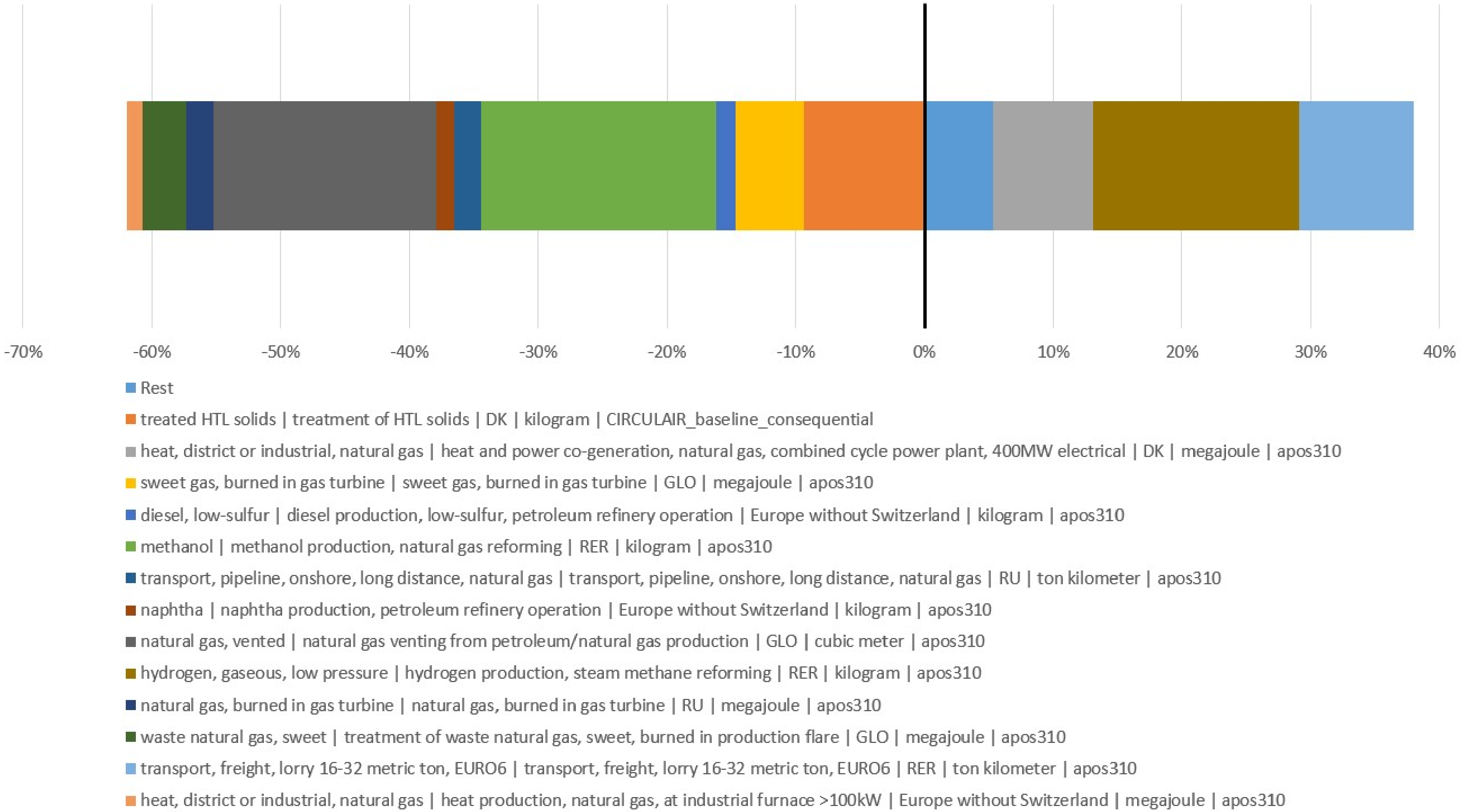

Figure 15: Process contributions to the GWP100 emissions calculated with the consequential system model.

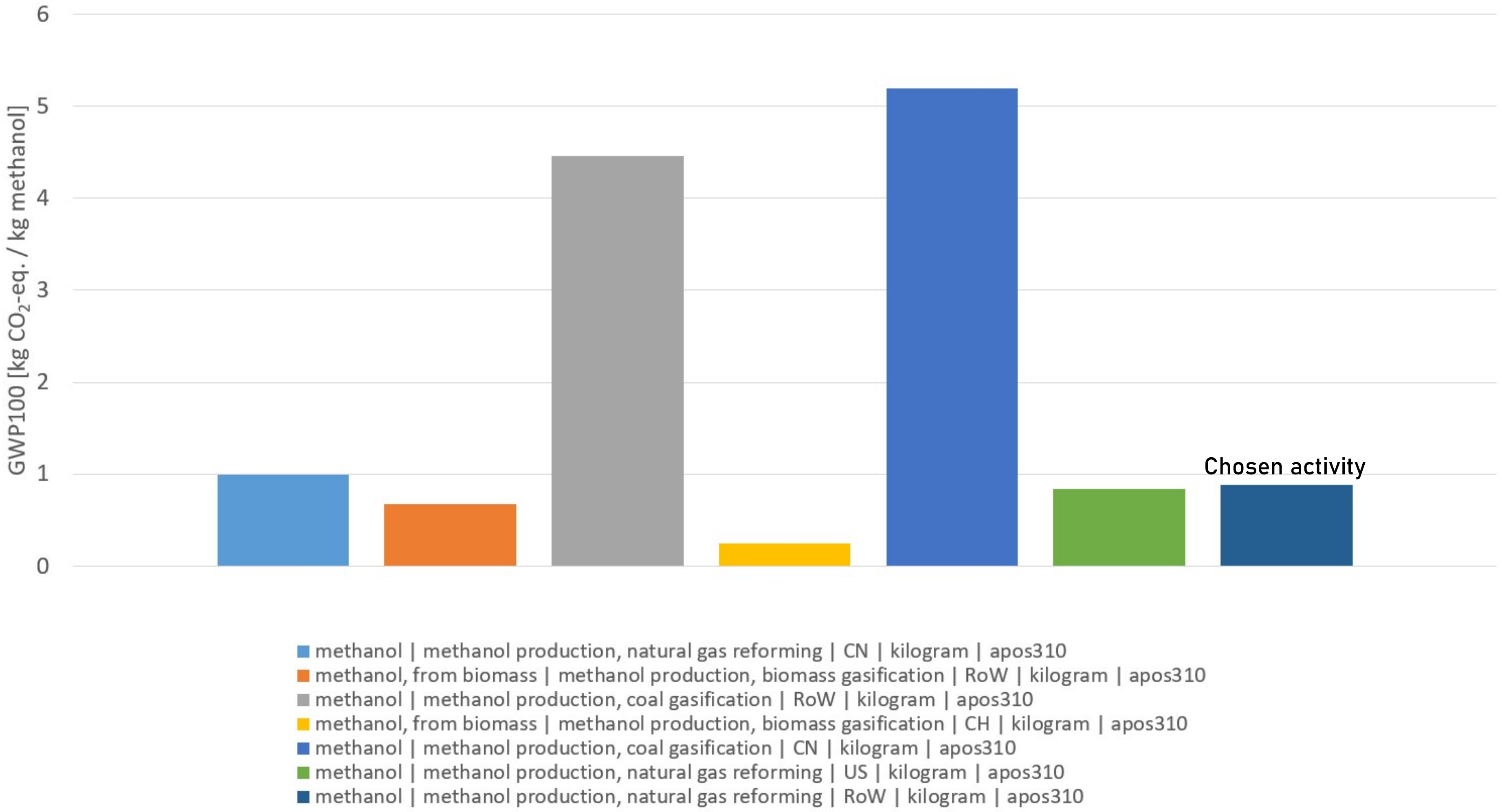

Figure 16: GWP100 emissions for different methanol production routes in different countries / regions.

# 6. Conclusions and Outlook

This report presented a pre-evaluation of the key economic and environmental parameters in form of fuel production cost and global warming reduction potential of the fuel production pathway that is investigated in the CIRCULAIR project. The preliminary results are a LCOE of 99 €/MWh (lump-sum CAPEX estimate) and 62 €/MWh (bottom-up CAPEX estimate) for a mix of fuel products that result from the CIRCULAIR concept, as well as a reduction of global warming potential by 84% compared to conventional jet fuel as a reference (attributional allocation). A recent publication by EASA [12] announced a 2024 market price reference for aviation biofuels of 2085 €/tonne (174 €/MWh at 12 MWh/tonne), based on a production cost estimate of 1461 €/tonne (122 €/MWh), indicating that the CIRCULAIR production pathway may be competitive with current aviation biofuel pathways. Another outcome of the pre-evaluation of techno-economic and life cycle parameters is the derivation of first take away massages and the identification of subjects that need refined analysis:

- HTL-WO reactor CAPEX is the key cost driver especially for early implementation of HTL plants.
- Likewise, CAPEX is an important consideration for WO as treatment and valorisation option of the HTL aqueous phase.
- Green hydrogen generation is another major cost driver. It is anticipated that green hydrogen cost will play a pivotal role in the trade-off studies that are subject to an upcoming report.
- The economic values of co-products play a crucial role for the multi-product fuel production scheme of CIRCULAIR.
- The reduction in GWP100 of 84% with respect to a conventional jet fuel reference is in line with the renewable energy directive (> 65% reduction), but falls short of the CIRCULAIR target of negative emissions.
- The LCA results point to levers to achieve net-negative emissions by addressing major contribution to positive emissions.
- Furthermore, LCA methodology, in particular with respect to the multi-product nature of the investigated fuel pathway can push the net-result in the negative regime. This needs to be carefully discussed and investigated in the more detailed LCAs within CIRCULAIR.

Further techno-economic modelling within CIRCULAIR should aim at a more detailed understanding of HTL-WO CAPEX and its potential for future reduction. Furthermore, the pivotal role of green hydrogen generation, especially for methanol synthesis, but also for hydrotreatment of HTL biocrudes deserves more considerations. Green hydrogen generation is also a prime target for studies that consider trade-offs between fuel production cost, carbon conversion efficiency and global warming potential. It is also important to note that methanol synthesis from evolving $CO_2$ streams is an optional opportunity and it may be interesting to investigate HTL fuel production without methanol synthesis as an alternative to the coupled approach.

The LCA results already indicate a deep reduction potential compared to fossil fuel, as well as pathways to achieve net-negative emissions. One key lever are avoided burdens that result from changes of manure handling practices in the agricultural sector. Avoiding emissions, mainly by avoiding long-term manure storage, does not physically create negative emissions, but the emission avoidance in another sector may be reflected as a credit for the fuel product. Another important lever is a more rigorous evaluation of the carbon that can indeed be physically stored below ground by sequestration of HTL solids. Furthermore, the main contributions to the GWP should be addressed in more detail and options to reduce these contributions should be identified.

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# 8. Annex

Table A1: Considered installation factors chosen for individual process components [1].

| Equipment type | Installation factor |
|---|---|
| Compressors | 2.5 |
| Reactors, columns | 4 |
| Heater | 2 |
| Pressure vessels | 4 |
| Miscellaneous equipment | 2.5 |
| Pumps | 4 |
| Instruments | 4 |
| Heat exchangers | 3.5 |

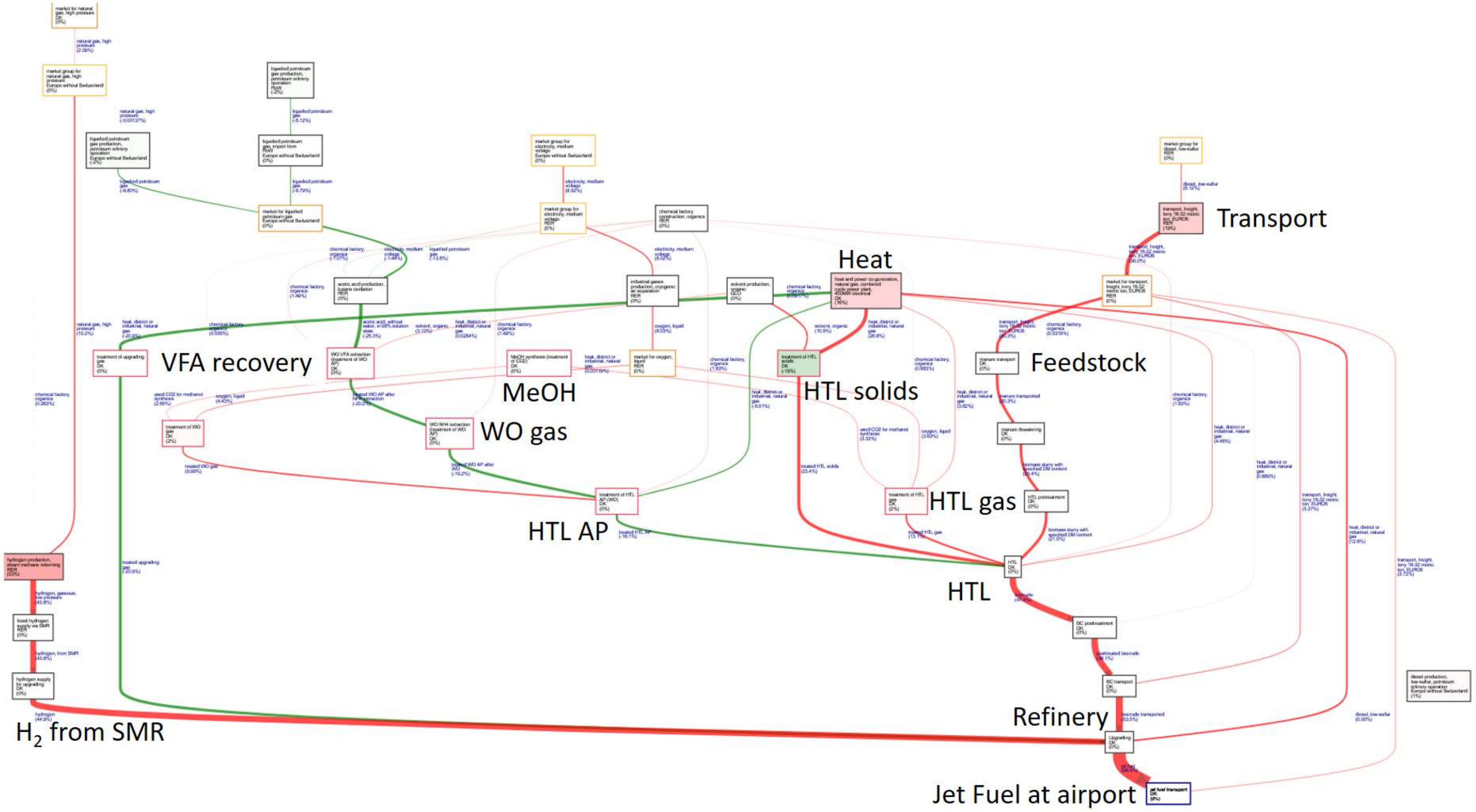

Figure A 1: Sankey diagram of the CIRCULAIR baseline scenario modelled with the attributional approach. Streams (and boxes) in red correspond to burdens, streams (and boxes) in green correspond to credits. The largest negative contribution in Figure 14 is associated with negative emissions for the fixed carbon content (10% of total carbon) in the HTL solids and is visualized here as the green box close to the HTL solids.