HyFlexFuel

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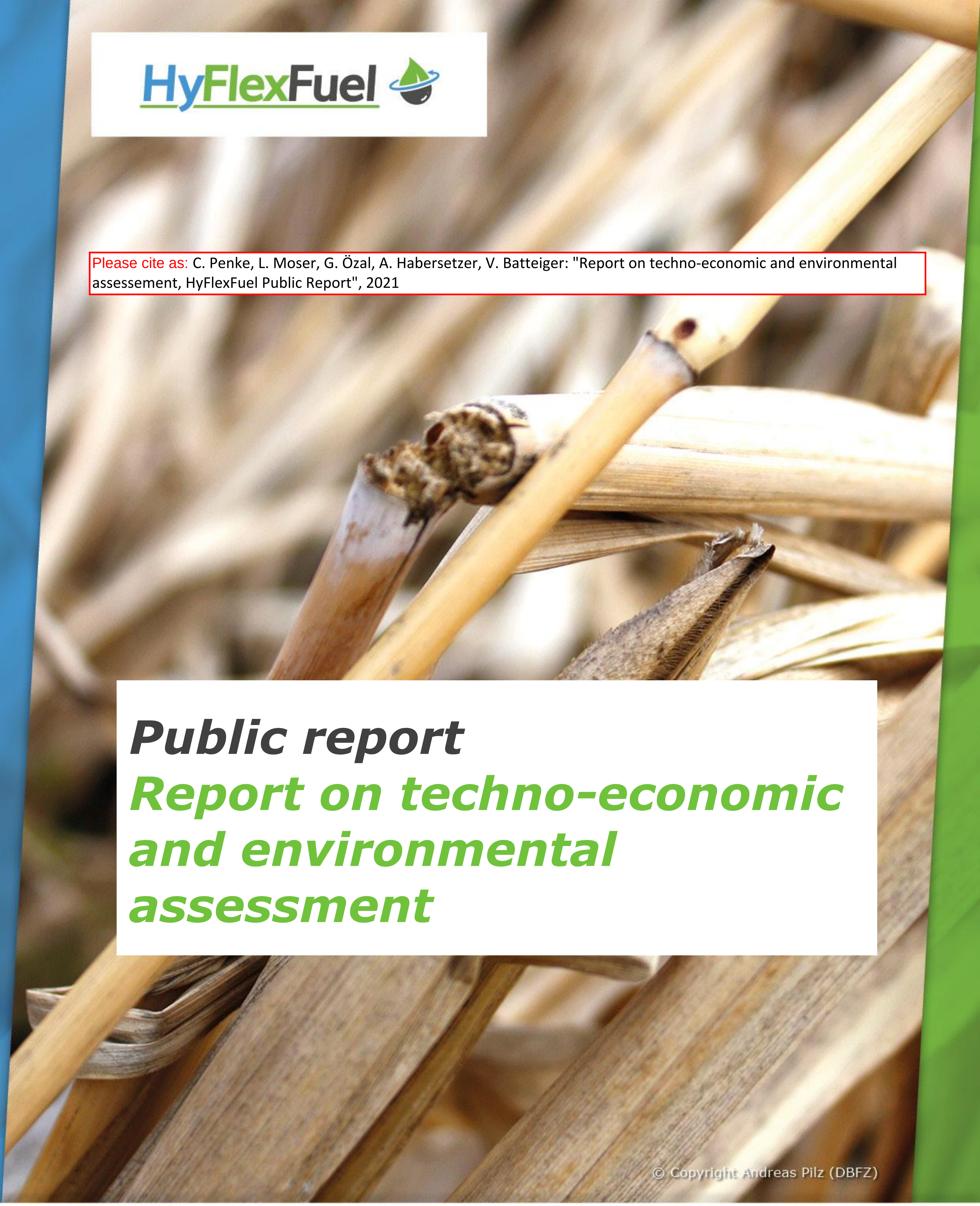

Public report

Report on techno-economic and environmental assessment

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Project Information

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Public Report – Report on techno-economic and environmental assessment

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Abstract:

The HyFlexFuel project demonstrates the key subsystems of a hydrothermal liquefaction (HTL) based fuel pathway towards high quality transportation fuels. The experimental implementation within HyFlexFuel is accompanied by analyses of the simulated system that investigate the performance of the fuel conversion technology in a future commercial-scale plant with respect to a number of key indicators. Within this public report, techno-economic and environmental performance indicators are evaluated based on a numerical system model that was developed earlier in the project. The techno-economic assessments (TEA) show that minimum fuel selling prices are well below 1 €/kg fuel for sewage sludge, straw and miscanthus, whereby sewage sludge and straw are more cost effective. HTL of microalgae seems to be unattractive from an economical point of view, due to high microalgae production costs. The key direct investment cost driver is identified as the HTL process, while other sub-processes of the fully integrated plant also account for a large part. Indirect investment cost drivers are found to be dependent on the HTL plant site location since interest rates, expressed by weighted average cost of capital, vary significantly. The environmental performance shows the same trend as the TEA data. Sewage sludge shows the best performance, followed by straw and miscanthus. HTL with microalgae shows the highest emissions, due to high emissions from microalgae production. Main emission drivers are found to be direct emissions from off-gases from the process, heat demand and hydrogen production. These main drivers also present the key levers for future emissions reductions. This could include using the CO_2 off-gases, producing heat in an environmentally friendly way and producing hydrogen by electrolysis with renewable electricity. The results suggest that HTL is a promising technology option for the production of sustainable transportation fuels.

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Executive Summary

Hydrothermal liquefaction (HTL) can convert a broad range of organic feedstock into intermediate biocrudes. These biocrudes can be subsequently upgraded to transportation fuels via hydrotreatment. One key advantage is that hydrothermal processing can handle organic feedstock without excessive drying, which potentially enables advanced biofuel production from wet waste streams, such as sewage sludge or food wastes, at competitive costs. Another potential advantage is a low projected capital investment compared to competing advanced biofuel pathways, which may lead to competitive advantages for an even broader range of feedstock classes including lignocellulosic residues or aquatic biomass.

This report presents the techno-economic and environmental assessment of a large-scale integrated HTL plant based on the technology and process path investigated in the HyFlexFuel project. Key economic and environmental parameters of future HTL fuel production are quantified to underpin the mentioned benefits of the process and to guide the further development of the fuel path. For the evaluation, it is assumed that the key process steps, which are promoted within HyFlexFuel to a technological readiness level of TRL 5, are further developed to a commercial maturity level in a 2025-2030 timeframe. In particular, it is assumed that all major subsystems can be continuously operated for a duration of months without extensive off-time or maintenance work. Furthermore, it is assumed that the capacity is scaled from the current pilot-scale demonstration to a future capacity, which is essentially defined by the potential availability of the investigated feedstocks sewage sludge, *Spirulina* and wheat straw at representative plant locations in Europe. These assumptions are necessary to compare the performance potential of HTL fuels with conventional fuels and biofuels that are already available on the market. In contrary, only minor improvements are assumed for technical parameters that govern the process efficiency such as biocrude yields.

The results support the hypothesis that wet waste streams such as sewage sludge are an appropriate feedstock for the commercialization of HTL technology. Given that technological maturity is achieved by continued research and development effort, upgraded HTL products may be produced at a production cost (i.e. minimum selling price) of 0.44 €/kg. The relatively low fuel production cost in the sewage sludge case study results from additional revenues for waste management services. In particular, a gate fee of 60 €/t for the thermal treatment of sewage sludge is assumed based on a comparison with typical sewage sludge disposal costs in Europe.

Agricultural residues such as wheat straw or advanced energy crops such as miscanthus are potentially available in much larger quantities than wet waste streams. However, reasonable estimates of feedstock costs at European plant locations lead to slightly higher production costs of about 0.44 € / kg and 0.75 € / kg for cereal straw and miscanthus, respectively. Much higher production costs of 8.26 €/kg are estimated in case of HTL fuel production from the microalga *Spirulina*, which indicates that the cost of microalgae cultivation need to be reduced significantly.

The environmental assessment indicates that the global warming potential is significantly reduced compared to crude-oil based fuels. However, the remaining global warming potential (GWP) that is found for the baseline assumptions is still significant. Dominating contributions to the global warming potential stem from internal emissions of CO_2, process energy and hydrogen generation from natural gas. Providing the process energy (mainly to serve the heat demand of the HTL and catalytic hydrothermal gasification (cHTG) subsystems) and hydrogen (mainly for hydrotreating) from natural gas is a reasonable assumption for near-term implementations in Europe. Nevertheless, this result is a clear indication that the provision of renewable heat and renewable hydrogen are important levers to further reduce the GWP of HTL future fuel production.

A much lower GWP is found when additional credits for the replacement of current sewage sludge disposal methods are factored in.

From an economic and environmental point of view no apparent show stoppers have been identified within the system analyses, consequently HTL fuel production may achieve competitive cost levels and significant GWP reductions in the future. Embedding HTL fuel production in waste management systems can create additional revenue and thereby enable low fuel production cost. Due to the large feedstock potentials, it is valuable to investigate HTL fuel production also from lignocellulosic feedstock.

Table of Contents

1. Introduction 1

1.1 HTL fuels in context of the energy transition in transportation 1

1.2 HyFlexFuel project implementation 1

2. Considered HTL scenarios 3

2.1 HTL of sewage sludge 3

2.2 HTL of cereal straw 5

2.3 HTL of miscanthus 6

2.4 HTL of microalgae 6

3. Methodology 7

3.1 Numerical system model 7

3.1.1 Hydrogen production 7

3.1.2 Nutrient recovery 8

3.1.3 Aqueous phase (AP) recycling 8

3.1.4 Mass and energy balances 9

3.2 Techno-economic assessment (TEA) 10

3.2.1 Determination of HTL investment costs 11

3.2.2 Determination of operating costs 12

3.2.3 Catalysts 13

3.2.4 Design of HTL reactor and heat exchanger 14

3.2.5 Determination of fuel production costs 15

3.2.6 Revenues 15

3.3 Life-cycle assessment (LCA) 16

3.3.1 Supply of residue feedstock streams 18

3.3.2 Supply of cultivated biomass 19

3.3.3 Struvite production 19

3.3.4 Allocation of heat and power 20

3.3.5 Selection of LCA data 21

4. Results of techno-economic assessment 22

4.1 HTL of sewage sludge 22

4.2 HTL of agricultural residues 24

4.3 HTL of miscanthus 25

4.4 HTL of microalgae 26

4.5 HTL fuel production costs in Europe 27

5. Results of life-cycle assessment 29

5.1 HTL of sewage sludge 29

5.2 HTL of agricultural residues 36

5.3 HTL of miscanthus 37

5.4 HTL of microalgae 38

6. Discussion 39

6.1 Numerical system model 39

6.2 TEA 39

6.2.1Assessment of HTL scenarios *39*
6.2.2Process design options for improved economic performance *40*
6.2.3Comparison with literature values *41*
6.3 LCA 42
6.3.1GHG in literature *42*
6.3.2Land use change *42*
6.3.3Fossil vs. biogenic carbon emissions *43*
6.3.4Process design options for an improved performance *43*
6.4 Economic and ecological trade-off 43
7. Conclusions 45
References 46
Appendix 49

Glossary

Abbreviation Acronym	Description
AD	Anaerobic digestion
AP	Aqueous phase
CHP	Combined Heat and Power Supply
cHTG	Catalytic hydrothermal gasification
CTU	Comparative Toxic Unit
DM	Dry matter
CAPEX	Capital Expenditures
GGE	Gasoline gallon equivalent
GHG	Greenhouse gas
GREET model	The Greenhouse gases, Regulated Emissions, and Energy use in Technologies Model
GWP	Global warming potential
H2020	Horizon 2020
HDO	Hydrodeoxygenation
HDM	Hydrodemetallization
HDN	Hydrodenitrogenation
HEFA	Hydroprocessed Esters and Fatty Acids
HEX	Heat Exchanger
HFO	Heavy Fuel Oil
HT	Hydro treating
HTL	Hydrothermal liquefaction
ILUC	Indirect Land Use Change
KOH	Potassium hydroxide (chemical formula)
LCA	Lifecycle assessment
LUC	Land Use Change
MFSP	Minimum fuel selling price
NPK fertilizer	Nitrogen (N), Phosphorus (P), and Potassium (K) fertilizer
OPEX	Operating expenditures
PC	Production costs
PNNL	Pacific Northwest National Laboratory
PSA	Pressurized swing adsorber
PTW	Product-To-Wake
RED II	Renewable Energy Directive II
SPV	Spent Catalyst Revenue

TEA	Techno Economic Assessment
TLCC	Total Life Cycle Cost
ubc	Upgraded biocrude
WACC	Weighted Average Cost of Capital
WGS	Watergas Shift
WTP	Well-To-Product
WTW	Well-To-Wake
WWTP	Waste water treatment plant

1. Introduction

1.1 HTL fuels in context of the energy transition in transportation

The European Green Deal aims to achieve climate neutrality for the European Union and its citizens by 2050. This ambitious target implies a deep decarbonization of all energy intensive sectors of the economy. So far, greenhouse gas (GHG) emissions from the EU transportation sector could not be reduced, instead they increased by about 30% over the past 30 years[1]. It is clear that timely action is needed to reverse this trend and enter a phase of steady decline of transport emissions. A good fraction of transportation can be decarbonized by battery electric vehicles, hydrogen and fuel cells. On the biofuel side, ethanol and biodiesel already contribute relevant shares to the European fuel consumption. However, a further increase of first generation biofuel production volumes has been limited by the availability of sustainable feedstock. Environmental concerns led to a revision of the EU renewable energy directive (RED II), which caps the share of conventional biofuels from food or feed crops, and foresees a gradual phase out of feedstock with high indirect land-use change (ILUC) risk. Instead, the current European regulation aims at an increased share of biofuel production from advanced feedstock.

Within the transportation sector, the decarbonisation of aviation is especially dependent on renewable drop-in fuels since the existing fleet and all large transport aircraft that are currently in production rely on kerosene-type turbine fuel[2]. Currently, jet fuel is mainly derived from crude oil and the small share of aviation biofuels (well below 1% in 2020) is mainly derived from plant oils and fats via the HEFA process. The main drawback of HEFA fuels is the limited availability of sustainable feedstock. Therefore, it is necessary to develop conversion technologies that can produce large additional volumes of kerosene range fuels from sustainable feedstock. The H2020 HyFlexFuel project addresses this challenge and further develops all major process steps of a hydrothermal liquefaction (HTL) process chain that can convert a broad variety of biomasses into a mixture of hydrocarbon fuels including kerosene and diesel as target products.

1.2 HyFlexFuel project implementation

Figure 1 introduces to the basic building blocks of the HyFlexFuel process chain. A broad variety of organic feedstock can be converted into an intermediate biocrude via hydrothermal liquefaction at pressures and temperatures in the range of 160-220 bars and 300°C- 350°C[3]. An intermediate biocrude is formed alongside with a process water phase, solids and a gaseous phase. The biocrude is further upgraded to a mixture of hydrocarbon fuels via catalytic upgrading. The process water is treated by catalytic hydrothermal gasification or anaerobic digestion to recover combustible gases from the admixed organic fraction. Depending on feedstock, phosphates may be recovered to yield a fertilizer by-product.

[1] https://www.eea.europa.eu/data-and-maps/indicators/transport-emissions-of-greenhouse-gases-7/assessment

[2] Prospects for battery-electric aircraft are limited to short distance flights. The entry into service of liquid hydrogen fueled transport aircraft, such as the Airbus ZEROe conceptual designs, are not expected before 2035

[3] These condition are near the critical point of water

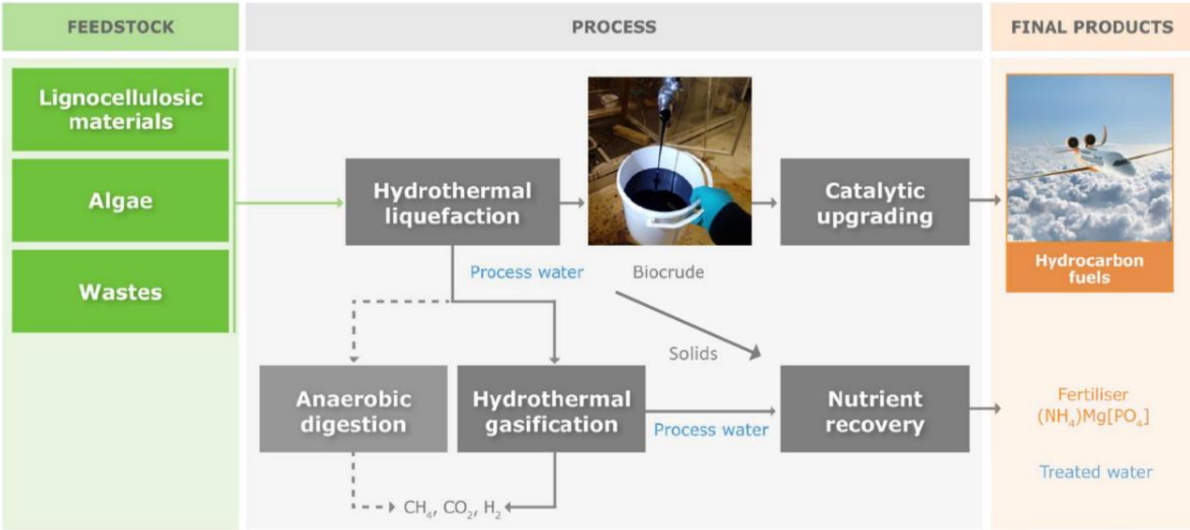

Figure 1: *Basic building blocks of the HyFlexFuel process chain.*

Within HyFlexFuel, various feedstock are investigated with regard to their availability and suitability for the HTL process. Three model feedstock, miscanthus and cereal straw (lignocellulosic biomass), *Spirulina* (microalga), and sewage sludge (waste) have been chosen to demonstrate the feedstock flexibility of HTL conversion. Bulk quantities of biocrudes were produced from all model feedstocks in the pilot-scale HTL plant of Aarhus University at Foulum, Denmark. Biocrudes from three out of four feedstock, *Spirulina*, cereal straw and sewage sludge, were upgraded at Aarhus University, in close collaboration with Haldor Topsoe, via continuous hydrotreatment. The resulting hydrocarbon fuel mixtures show promising compositions for transportation fuel production. The production of combustible gases from the organic content of HTL process waters was demonstrated by the project partners OWS and Paul Scherrer Institute PSI via anaerobic digestion and hydrothermal gasification, respectively. So far, these results stem from the pre-screening phase. Long-term cHTG and AD experiments remain as important objectives for the final project phase. Struvite, a fertilizer product, was precipitated at the University of Hohenheim, from a leachate of HTL solids.

2. Considered HTL scenarios

An environmental and economic analysis of a technical system requires the definition of its layout and size to be able to compile energy and mass balances, and to determine the costs and environmental impacts of processes and components. Therefore, a suitable location, a general size and layout of the fuel production plant is defined respectively for the different feedstock types sewage sludge, miscanthus, cereal straw and microalgae.

The respective location of the HTL fuel production plants was determined taking into account socio-economic aspects as well as feedstock availability, which was determined in [1].

2.1 HTL of sewage sludge

Sewage sludge is an attractive HTL feedstock, as it is usually available at very low cost. This is due to the fact that the disposal of sewage sludge, which is a waste product from the treatment of various types of wastewater, is usually cost-intensive [2]. Therefore, considering sewage sludge as feedstock, HTL presents, besides a fuel production process, also a disposal process.

The experimental campaigns in HyFlexFuel show that sewage sludge is suitable for HTL conversion. A biocrude that could be successfully upgraded to a fuel mix with low shares of oxygen and nitrogen has been produced [3,4].

Additionally the process steps of nutrient recovery [5] and anaerobic digestion of the aqueous phase have been demonstrated.

Within the HyFlexFuel project, the biomass potential of sewage sludge in Europe was determined to be 2.1 Mt/year [1]. The geographical representation of biomass availabilities shows that these are particularly significant for sewage sludge in urban, densely populated areas. This is associated with the fact that the largest volumes of wastewaters are treated in wastewater treatment plants (WWTPs) in these areas.

For this reason, in this report, an HTL scenario is developed in which the entire sewage sludge from a single WWTP is converted to fuels using HTL. The WWTP Emschermündung was selected as a suitable site to be considered as an example at this point. This WWTP treats the wastewater of about 950,000 inhabitants, which is associated with a sewage sludge production of 3.4 t (dry matter) per hour.

It is assumed that sewage sludge is produced with a dry matter (DM) content of 3 wt% at the WWTP and is subsequently upconcentrated to 20 wt% DM using a centrifuge. This stream represents the feed for the HTL. It is assumed that a HTL plant located on the site of the WWTP area converts the entire sewage available at the WWTP Emsdchermündung. For this reason, it can be concluded for later techno-economic calculations that large parts of the existing infrastructure (e.g. roads, electricity and gas connection) can also be used for the HTL process. The process considered in this scenario is shown in Figure 2.

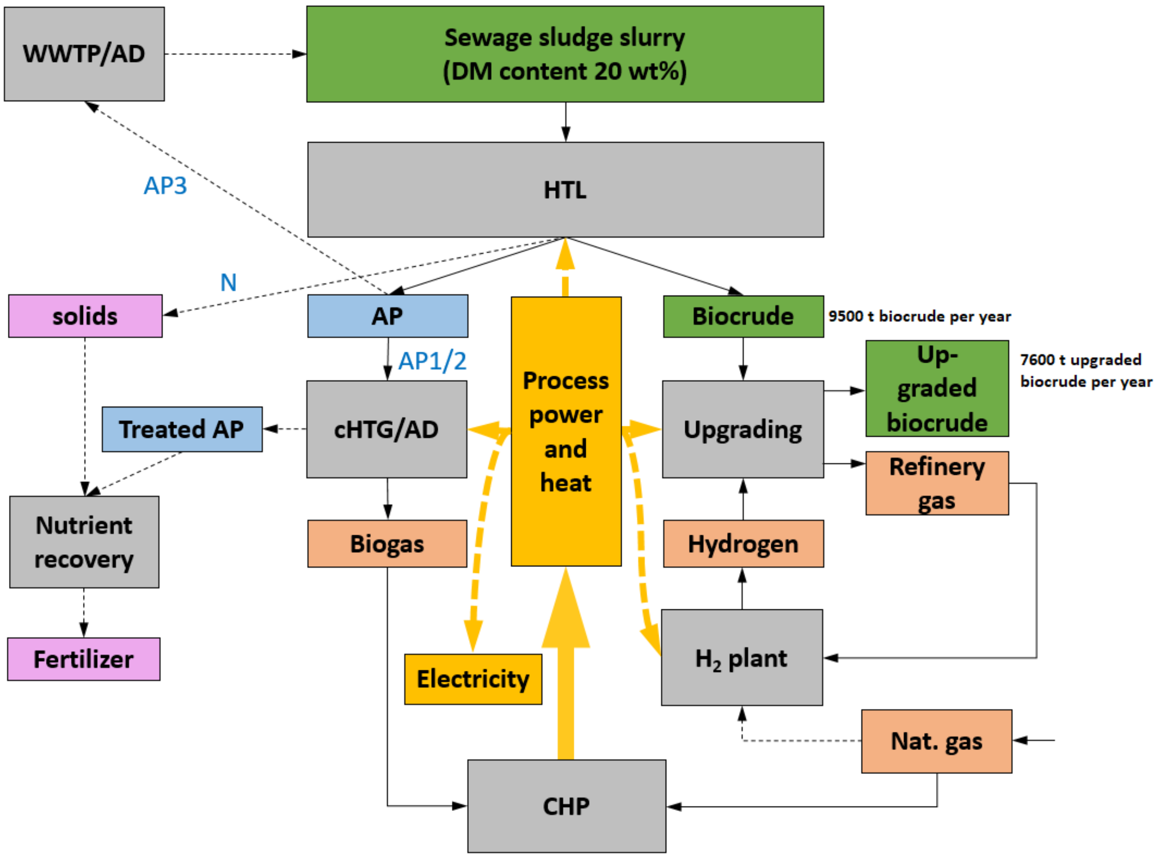

Figure 2: *Basic building blocks of the HyFlexFuel process chain for the HTL of sewage sludge: Sewage sludge is produced in a waste water treatment plant (WWTP). The WWTP offers the option of treating emerging wastewater (AP3). The possibilities of energetic utilisation of the aqueous phase through a cHTG (AP1) or AD (AP2) as well as the option of a nutrient recovery (N) are evaluated.*

The produced biocrude is hydroprocessed by an upgrading process using hydrogen. As a result, nitrogen and oxygen contents are reduced. Thus a fuel mix is available that can be separated into different transportation fuels (gasoline, jet fuel, kerosene and heavy fuel oil). In the studied HTL process chain, it is assumed that most of the excess hydrogen is recycled and the rest is provided by steam reforming of natural gas. Furthermore, it is assumed that the required process heat and electrical energy is provided by a combined heat and power plant. In addition to the biocrude, an aqueous phase is produced as HTL by-product. Different AP treatment methods are considered for an HTL sewage sludge process configuration. An HTL plant next to a WWTP offers the option of treating emerging wastewater. Additionally, the possibilities of energetic utilisation of the aqueous phase through cHTG or AD are evaluated.

Sewage sludge is a product that contains high levels of phosphorus. Since phosphorus is a limined resource, nutrient recovery in this scenario seems to be reasonable from an environmental point of view. Additional phosphorus recovery will become obligatory for wastewater treatment plants for many European countries in the near future. For the process developed in the HyFlexFuel project, it is considered that phosphorus and nitrogen can be be recovered from the aqueous phase and solids as struvite, which can be used as a long-term fertilizer [6].

2.2 HTL of cereal straw

Straw is an agricultural by-product that makes up a majority of the yield of cereal crops. In general, agricultural biomass has a high availability especially in intensively used agricultural areas. However, when looking at straw as potential HTL feedstock, it has to be noted that straw has a number of different uses, for instance livestock bedding, soil improver or as fuel (mono- or co-incenation for heat and power supply).

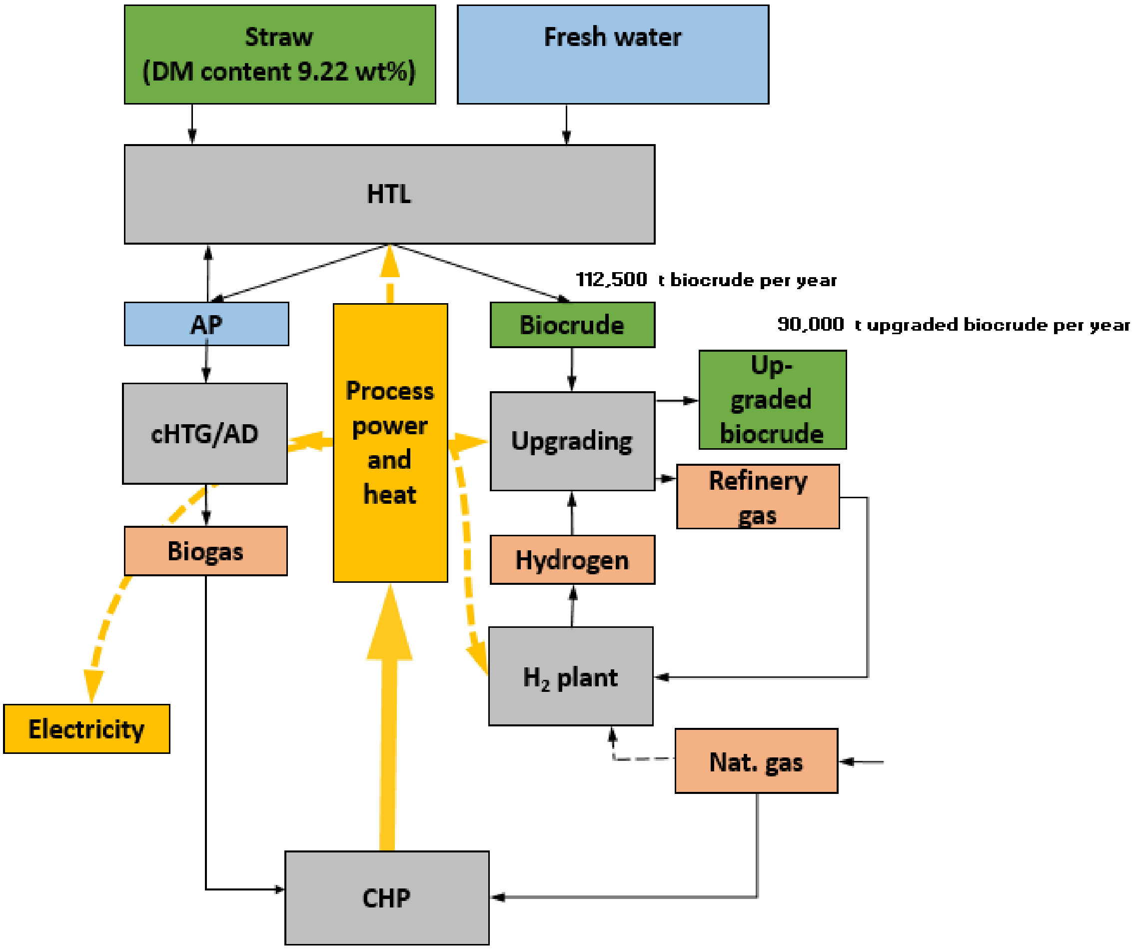

Figure 3: *Basic building blocks of the HyFlexFuel process chain for the HTL of cereal straw.*

For the assumed HTL scenario, in which biocrude is produced from straw, we consider a site in Romania, since feedstock availability is high at this location. Within a 50-km transport radius, there are 250,000 t (dry) of available cereal straw per year. This amount would contribute to an upgraded biocrude production of 90,000 t per year. The process configuration studied in the system analysis is shown in Figure 3.

Straw is assumed to have a moisture content of 9.22 wt%, delivered as straw bales via trucks, and stored on site. A biomass crusher with an electrical power of 25 MW is assumed as pretreatment process. As in the sewage sludge scenario, it is assumed that the HTL feed has a dry matter content of 20 wt%. This is achieved by adding fresh water to the straw. In addition, KOH is added to the biomass slurry to cause an increase in pH. This assists in the conversion of lignocellulosic biomass to minimize coke formation and increase biocrude yield.

Since the overall water requirement should be kept as low as possible and the carbon dissolved in the aqueous phase should be utilized, a recycling rate of the aqueous phase of 90% is assumed. The portion that is not recycled is converted energetically via cHTG.

The biocrude upgrading takes place along the lines of the process step described for the sewage sludge scenario.

Due to the negligible amounts of phosphorous present in straw, phosphorous recycling in the form of struvite precipitation is not considered in this case.

2.3 HTL of miscanthus

Miscanthus is a perennial energy grass. Its fast growth rate and high energy density make miscanthus a particularly attractive lignocellulosic feedstock.

In the scenario considered, it is assumed that 15 tons of miscanthus with a water content of 7.94% are harvested per hectare per year.

The configuration and size of the HTL process chain is treated along the lines of the process of HTL of straw described above.

Northern France was chosen as the location for this process, as there is a high potential of agricultural land in this area (land used for food or fodder production was not considered).

2.4 HTL of microalgae

By cultivating microalgae, large amounts of biomass can be produced on non-arable land [7].

Sun-intensive areas are suitable locations for such algae production. Southern Spain was chosen as the site considered for a cultivation of microalgae. In addition, it is assumed that the algae slurry is concentrated to a dry matter content of 20 wt%.

The configuration and size of the HTL process chain is treated along the lines of the process of HTL of sewage sludge described above.

3. Methodology

This section presents a brief description of the methodology that was used to assess a hydrothermal liquefaction process in terms of its economic performance and ecological footprint.

3.1 Numerical system model

Mass and energy balances were calculated based on the results of the Aspen Plus model. The Aspen Plus model is separated into the four different process steps hydrothermal liquefaction (HTL), catalytic hydrothermal gasification (cHTG), hydrotreatment (HT) and nutrient recovery (NR). In each process step, intermediate and output streams are generated. Intermediate streams are further processed in the subsequent process step. For all streams containing organic materials, the amount of feedstock can be used as basis for the mass balance calculations. The amount of struvite can be referred to the amount of solids or the amount of phosphorous present in the feedstock. The amount of hydrogen used in the upgrading section is based on the amount of biocrude produced during HTL, specifically, the molar amount of hydrogen is 25 times the molar amount of biocrude. Details of the used process model can be taken from Penke et al. [8] and Moser et al. [9].

3.1.1 Hydrogen production

Significant amounts of hydrogen are required for upgrading the produced biocrude to reduce the amount of heteroatoms in the biocrude and achieve a fuel containing a maximum amount of saturated hydrocarbons. The HTL process model therefore includes an on-site hydrogen production facility, shown in Figure 4.

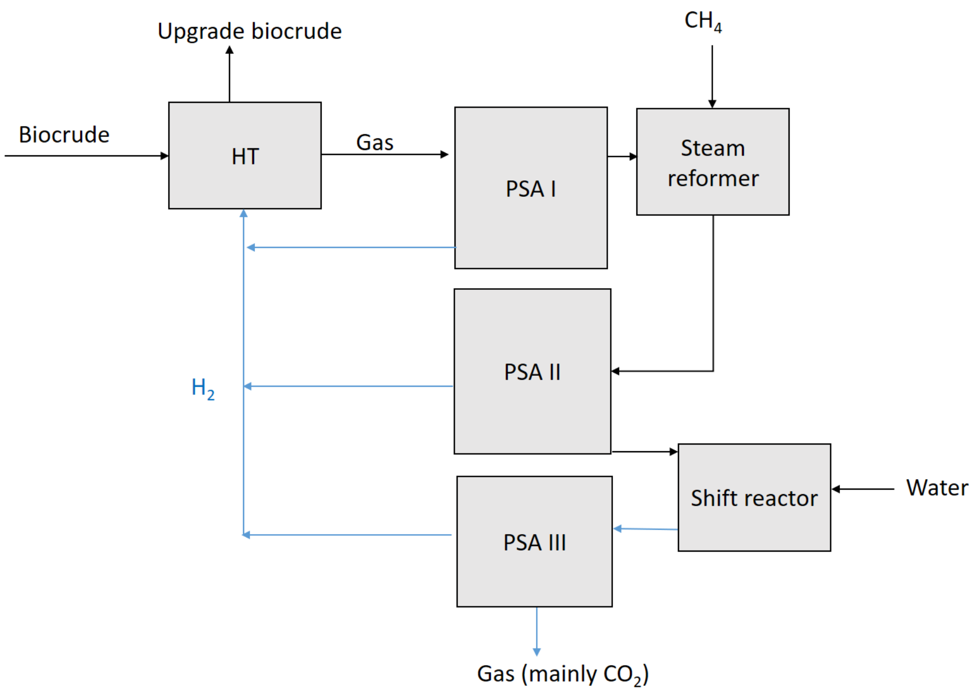

Figure 4: *Modeling of on-site hydrogen production for hydrotreating (HT). In addition to hydrogen recycling by pressurized swing adsorbers (PSA), a steam reformer and a shift reactor are part of the hydrogen production plant.*

Experimental results carried out at Aalborg University on upgrading show that about 40 to 50 g of hydrogen per kilogram biocrude reacts to the upgraded biocrude. However, it should be taken into account that a significant excess of hydrogen must be used to achieve a sufficiently good upgrading result. In the system analysis, it is assumed that 4 times this amount is introduced into the upgrading process. As a result, the off-gas released during the upgrading process consists largely of hydrogen (~40 wt%), in addition to short-chain hydrocarbons. To minimize the hydrogen demand, the system analysis assumes hydrogen recycling by using a pressurized swing adsorption unit (PSA). The recovered hydrogen is recycled back to the upgrading system. To meet the additional demand for hydrogen in the system, a steam reformer is also part of the modeled hydrogen system. This steam reformer produces the required hydrogen from methane and the remaining short-chain hydrocarbons and water. To optimize carbon efficiency, the exhaust gas streams are fed into a shift reactor, which provides additional H_2 output and produces almost pure CO_2.

3.1.2 Nutrient recovery

For the scenario of conversion of sewage sludge described above, the process of nutrient recovery is considered. This is based on the process applied at the University of Hohenheim [5]. The process flow diagram of the considered nutrient recovery is shown in Figure 5.

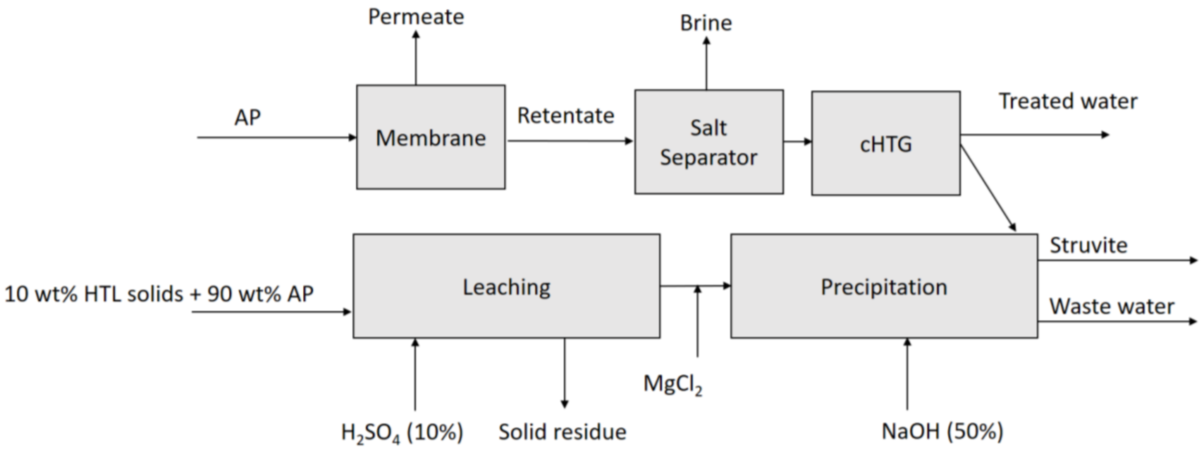

Figure 5: *Modeling of the nutrient recovery process. Solids are leached and, with addition of $MgCl_2$, parts of N-containing treated water and caustic, struvite can be precipitated.*

The mineral components of the solids are dissolved by a leaching process using acid. The insoluble components remain as solid residue. The liquid containing solved minerals and a part of the treated aqueous phase are mixed. With the use of $MgCl_2$ and an increase of the pH value by the addition of caustic solution (NaOH), struvite can be precipitated as a crystalline solid.

3.1.3 Aqueous phase (AP) recycling

Aqueous phase recycling can be a suitable option for dry feedstock to improve the biocrude yield and to reduce the fresh water demand.

In our model we assume, that the biocrude yield increases by 25% if we recycle 90% of the AP. We further assume that the solid yield remains constant. In addition, we make the simplified assumption that all product compositions remain the same regardless of recycling.

3.1.4 Mass and energy balances

The respective mass and energy balances for the investigated scenarios are given in Table 1 and Table 2.

Table 1: *Mass balances for the considered HTL scenarios.*

Process stream	Sewage sludge [kg/h]	Microalgae [kg/h]	Miscanthus [kg/h]	Cereal straw [kg/h]
HTL feedstock (dry), in	3359	2924	38995	30113
HTL water, in	13423	11295	5637	13697
HTL biocrude, out	1197	1033	16040	12910
HTL AP, out	10891	10735	256731	261879
HTL solids (dry), out	434	155	516	2225
HTL gas, out	349	900	8069	5592
HT biocrude, out	868	868	10273	10273
HT gas phase, out	358	437	4080	4535
HT hydrogen demand	46	83	721	800
H_2 unit methane, in	201	362	3168	3513
H_2 unit water, in	52	93	816	905
Total waste water, out	16499	5098	15822	13736
CHP natural gas, in	520	474	5620	5874
CHP off-gas, out	5724	5217	61822	64617
(Pure) Struvite, out	31	0	0	0
Solid residues (dry), out	43	155	516	2225
Additional chemicals, in	1289	0	625	613

The flows listed refer to the process diagrams described for dry and wet feedstocks in sections 2.1 and 2.2. The line "additional chemicals, in" summarizes the input of chemicals required for nutrient recovery and the requirement for KOH for lignocellulosic feedstocks. Heating demand in Table 2 refers to the heat demand of the respective process steps without considering heat recovery. In further modeling studies we assumed a heat recovery of 80% in the respective sub-processes.

Table 2: *Energy balances for the considered HTL scenarios.*

Process stream	Sewage sludge [kWh]	Microalgae [kWh]	Miscanthus [kWh]	Cereal straw [kWh]
HTL, heating	7132	6043	110645	117499
HT, heating	1174	9	14973	12051
H_2 unit, heating	402	480	1529	4862
AP treatment, heating	3776	4076	8903	9081
Electricity demand, total	13	11	135	138
CHP, heat supply	3999	3644	43191	45144
CHP, electricity supply	2113	1925	22818	23850

3.2 Techno-economic assessment (TEA)

To derive the total cost of products from plant, various cost items pertaining to the plant and its operation must be considered. Investment costs are incurred for the acquisition of buildings, machinery, equipment, piping, electrical equipment, service facilities, land, and other resources necessary for the plant. Additionally, there is a direct cost component, i.e., what is paid for the equipment that is actually supplied or the land that is acquired, and an indirect cost component, i.e., for services that are required for the installation and use of the plant, such as engineering, legal costs, and construction costs. These costs are therefore associated with the construction of the production facilities, including the related services.

Operating costs, on the other hand, are incurred during the plant's operating phase, i.e., when it is producing a product. Operating costs can be further divided into variable operating costs, or costs associated with the actual production process, e.g. raw materials, operating labor or operating supplies, and fixed operating costs, e.g. salaries, loans, insurance or certain taxes.

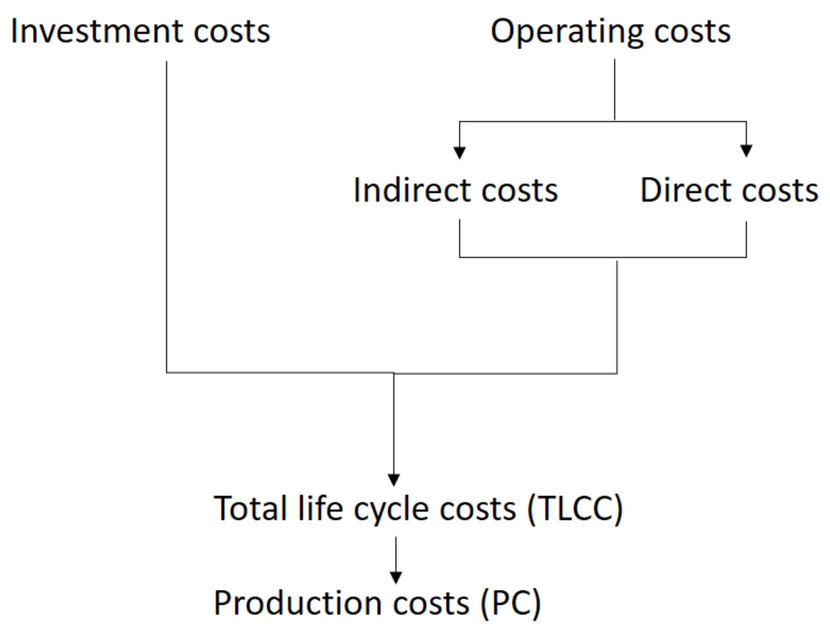

Figure 6: *Overview of investment and operating costs for the derivation of production costs of upgraded biocrude.*

The total life cycle cost (TLCC) of the production process is then a combination of investment costs and operating costs, taking into account the time value of money, which is found using the annuity method. The TLCC is then used to derive the upgraded biocrude production costs (PC) by dividing by the adjusted sum of fuel produced.

$$TLCC = \text{Investment cost} + \text{Direct operating costs} + \text{Indirect operating costs}$$

$$PC = \frac{TLCC}{\text{Fuel produced in plant lifetime}}$$

3.2.1 Determination of HTL investment costs

The investment costs of the plant components of established commercial process steps are chosen to be modeled with published values for total capital investment in literature.

A detailed list of the process equipment considered can be found in the appendix Table A1, Table A2, Table A3. Costs for the respective components were modeled using an economy-of-scale approach. Values for the respective components are based on those published by Towler et al. [10].

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

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 costs is valid for a certain range of sizes. Constant a describes a fixed part of the equipment costs, 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 costs are assumed to add to the actual plant components and installation costs in order to include smaller components such as pipes, measuring and control equipment in the balance of plant costs.

Installation factors were included in the calculation to account for the fact that the facility expense involves installation of each component.

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

where:

C_{ie} = purchased and installed equipment cost

IF = Installation factor

Table 3 provides a summary of the installation factors used to estimate investment costs for different process components.

Table 3: *Considered installation factors chosen for individual process components [10].*

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

In addition to the direct plant costs, a share of 15% of the plant costs for contingence, as well as 5% for balance of plant costs are taken into account.

3.2.2 Determination of operating costs

The operating costs of HTL-based fuel production are determined by considering the running costs. Besides the feedstock costs, these costs also include chemicals and catalyst, electricity, required methane and labor. Other plant-related costs are taken into account by calculating with fixed shares relating to investment costs. The following table shows which types of labor force were assumed for each HTL scenario.

Table 4: *Types and numbers of jobs considered for determing the operating costs for HTL based fuel production. Occupation class gives country specific labor costs.*

Type of job	Occupation class according to Ilostat [11]	Number of jobs for wet feedstock HTL scenario	Number of jobs for dry feedstock HTL scenario
Plant manager	1	1	2
Plant engineer	2	1	5
Lab manager	2	1	2
Lab technician	3	1	5
Shift supervisor	3	5	5
Shift operators	8	5	20
Facility	8	1	3
Administration	8	1	3

The costs for the workers are derived from data sets published by the International Labour Organization for various countries [11]. For this reason, an occupation class was assigned to the jobs taken into account. The feedstock costs have a decisive influence on the total costs of an HTL process. Depending on the feedstock used, they can vary greatly.

Sewage sludge represents a waste stream, as it is costly to dispose of. For this reason, we assume in our modeling that sewage sludge is available at negative feedstock costs. The revenues considered are described in section 3.2.6.

Since straw is a by-product in agriculture, only the costs for storage and transport of up to 50 km were considered for this raw material. Including the transport costs, feedstock costs of 36.46 €/t_{DM} were assumed in this study.

In contrast, miscanthus represents a crop biomass that would be cultivated with the goal of fuel production. In addition to transportation and storage costs, this feedstock incurs costs for cultivation and harvesting [12]. The costs for the feedstock miscanthus were modeled at 106 €/t_{DM}.

The most cost-effective way to cultivate algae on a large scale is offered by thin-layer reactors, where raw materials (CO_2, nutrients and fresh water) and labor costs account for a major part [13]. For the economic calculations, microalgae costs of 2.33 €/kg dry biomass determined for a baseline case scenario by Pandey et al. [13] were assumed.

The following prices are considered for the chemicals required depending on the selected process configuration: KOH with 0.80 €/kg, $MgCl_2$ with 0.49 €/kg, H_2SO_4 with 0.17 €/kg and NaOH with 2 €/kg. For the treatment of the wastewater produced at HTL, a cost of 1.77 €/m^3 is calculated.

3.2.3 Catalysts

In this study, costs of catalysts included in typical catalytic processes are considered. Costs of all catalysts were estimated with the CatCost tool [14]. The year 2020 was chosen as basis year. Table 5 lists all the relevant data used for the calculation of the catalyst prices for the case of sewage sludge. The masses of all catalysts were calculated based on the mass balance of the Aspen Plus model and typical space velocities for the respective operations.

Table 5: *Relevant variables for the calculation of catalyst costs based on the CatCost tool as well as calculated catalyst costs for sewage sludge.*

Catalyst	unit	HDM	HDO/HDN	Sulfur trap	cHTG	WGS
Composition AP	-	MoO_2	Ni Mo	ZnO	Ru	CuO
Weight percent of AP	wt%	17	4 13	90	5	52
Support	-	Al_2O_3	Al_2O_3	Al_2O_3	C	Al_2O_3 / ZnO_2
Space velocity	1/h	0.5	0.5	4	4	40
Mass of catalyst	kg	2,210	2,210	907.4	907.4	96.9
Cost of catalyst	€/kg	39.4	39.8	43.5	121.4	93.9
Lifetime	y	2	2	2	2	2
Cost of catalyst	€/y	43,490	43,976	21,765	60,695	4,696
Total	**€/y**	**174,622**				

Catalyst costs are calculated based on the sum of production cost and spent catalyst revenue (SPV). For all catalysts, except the ruthenium catalyst, the value of the recoverable metal is smaller than the total recovery fee. Therefore, the best option for those catalysts is to landfill them. For the ruthenium catalyst, a total catalyst cost of 390.2 € was calculated. Due to the high material cost of ruthenium (6892.4 €/kg), a value of 268.8 €/kg can be accounted for the recoverable metal. The effective catalyst cost can therefore be calculated as 121.4 €/kg. Furthermore, it should be noted, that the CatCost tool also includes variables like the selling margin, which is why the costs are not only influenced by the production and material cost itself, but also by the amount of ordered catalyst. Since the smallest amount that can be ordered in the CatCost tool is 1000 kg and the amount of water-gas-shift (WGS) catalyst only amounts to 96.9 kg, the costs for this catalyst were extrapolated with a fit based on data points obtained for different amounts of ordered catalyst between 1000 kg and 2000 kg.

3.2.4 Design of HTL reactor and heat exchanger

The HTL reactor is one of the most important components of an HTL fuel production process and accounts for a large part of the plant costs [15].

In order to represent the cost of the HTL reactor with a high degree of accuracy, this reactor was modeled including a suitable facility for heat recovery. We assume the reactor type to be a continuous plug flow tube reactor.

A tube-in-tube heat exchanger was chosen as heat exchanger, which can be implemented on industrial scale at low cost.

The HTL reactor as well as the heat exchangers consist of several tubes arranged in parallel. A value of 8 cm was identified as a suitable inner tube diameter and a value of 0.21 m/s as a suitable flow velocity.

To size the tube-in-tube heat exchangers, the modeling spreadsheet from Chemical Engineer's Guide [16] was used, taking into account the thermodynamic and fluid mechanics process data. The number of respective tubes is derived from the respective mass flow rates. The HTL reactor considered in this study with the arrangement of the respective heat exchangers is shown in Figure 7.

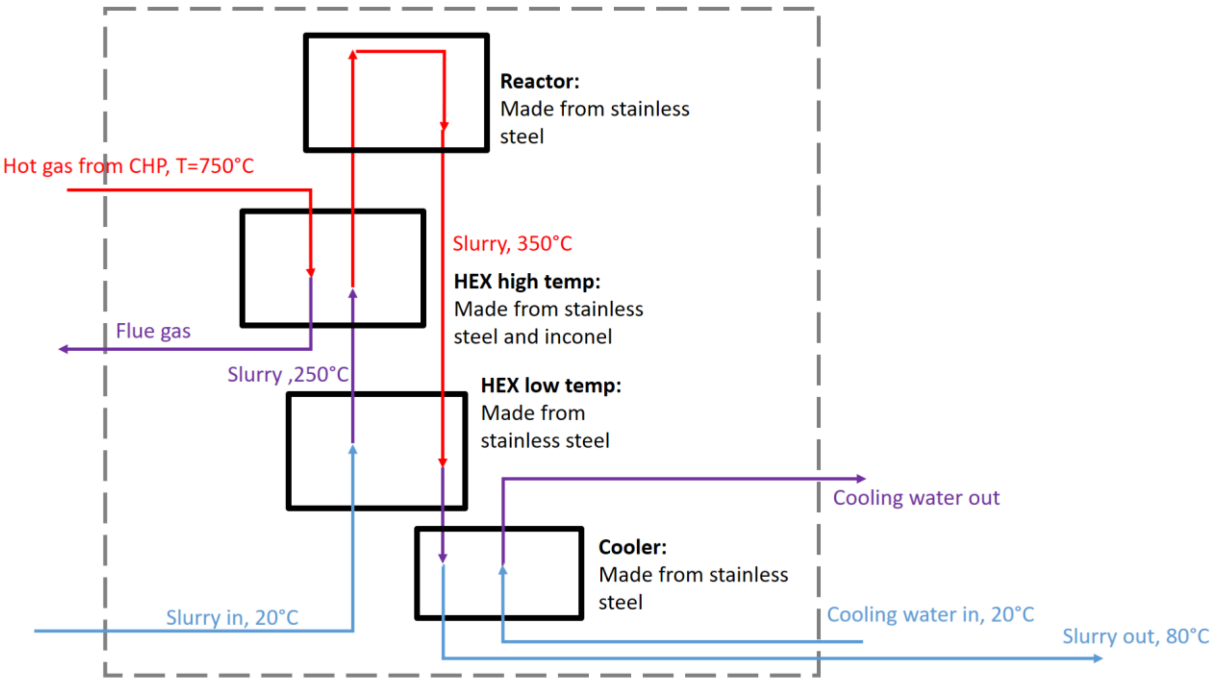

Figure 7: *Overview of the heat exchanger arrangement for the HTL reactor.*

To heat the HTL feed to a temperature of 350 °C, we model a "low-temperature heat exchanger" and a "high-temperature heat exchanger". In the low-temperature heat exchanger, the waste heat from the hot slurry heats the slurry to 250 °C. In the high-temperature heat exchanger, the hot exhaust gases from the CHP are used to reach the required process temperature of 350 °C. The heat from the CHP is used to heat the slurry. Cooling of the HTL product stream, which is necessary to realize the separation into the respective HTL products, is done by means of a cooler, where cooling water with a temperature of 20 °C is used.

The material chosen for the HTL reactor is mostly stainless steel 304. Only the components with temperatures higher than 350 °C are made of inconel in this study.

The investment costs for the HTL reactor result from the required tube materials (prices taken from Fastwell [17]), as well as costs for the assembly and installation of the reactor.

3.2.5 Determination of fuel production costs

For the determination of the total production costs (PC), operating and investment costs are related to the produced fuel.

In order to consider that the interest rate is variable depending on the country, as the investment risks are assigned a respective investment risk depending on the location. The country-specific weighted average costs of capital (WACC) are shown in Figure 8.

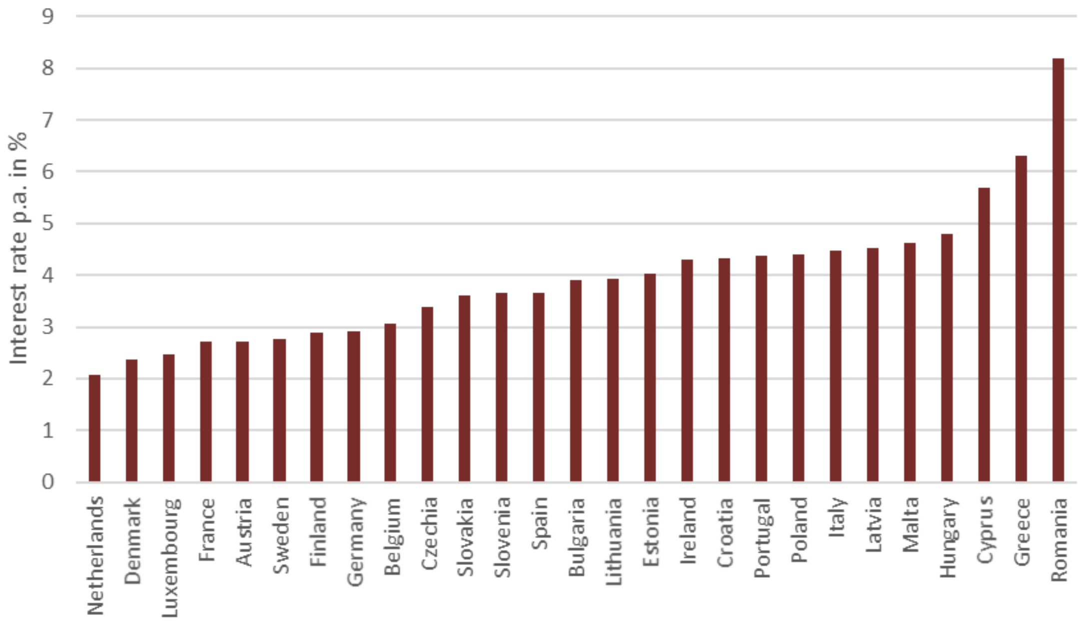

Figure 8: *Annual interest rate in European countries expresses as weighted average costs of capital (WACC).*

The figure shows that these rates can vary widely. For example, the Netherlands with WACC of 2.1% has a much lower interest rate than Romania with a value of 8.2%.

In order to relate OPEX and CAPEX to the amount of fuel produced, the interest rate (*WACC*) is taken into account, as well as the expected life of the plant in (*n*) years. $OPEX_{total}$ refers to the operating costs that can be expected during the entire plant lifetime.

$$PC = \frac{OPEX_{\text{total}} + CAPEX * (1 + WACC)^n}{\text{Fuel produced in plant lifetime}}$$

3.2.6 Revenues

Sewage sludge represents a waste stream, as it is costly to dispose of. For this reason, we assume in our modeling that sewage sludge is available at a negative cost, as HTL is a suitable disposal method for this process. To estimate the potential revenue, we used data published by the *Urban Waste Water Treatment Directive* [18], which provides information on which countries practice which sewage sludge generation and in what proportions. In a next step, the study shows that sewage sludge disposal practices vary greatly by location. The different disposal practices are associated with different disposal costs. The following costs were assumed for the type of disposal practice, consistent with Đurđević et al. [19]: landfilling (where allowed) with 62 €/t DM and mono incineration with 100 €/t DM. For the considered HTL Baseline Case szenario, possible profits from sewage sludge disposal under realistic conditions of 60 €/t were considered.

The profits from the marketing of transport fuels naphtha, jet fuel and diesel are determined by calculating the average market value to be achieved for a fuel mix (consisting of these three fractions). This results in a profit of 0.61 € per L fuel mix. Related to 1kg upgraded biocrude, this gives 0.36 €. For the marketing of heavy fuel oil (HVO), which is also a by-product depending on the quality of the biocrude, we assume a lower market price of 0.16 € per liter.

Furthermore, we assume that struvite from the nutrient recovery can be sold at prices of 0.47 € per kg. This price was determined by comparing the nutrient content of struvite with DAP fertilizers and it's respective market prices [20]. A feed-in tariff of 0.071 €/kWh is assumed for excess electricty produced in CHP.

3.3 Life-cycle assessment (LCA)

In order to compare different process configurations and feedstock, it is necessary to establish a common basis for the process chain. This is achieved by defining the functional unit and allocation methods and by identifying the system boundaries for the use of different feedstock types and process configurations.
The mass of upgraded biocrude (1 kg) is chosen as the functional unit, i.e., as the reference unit to which the emissions from the LCA are related to. The upgraded biocrude represents a preliminary stage of the final fuel products (jet fuel, gasoline, diesel and HFO), which can be technically used in different sectors.
The use phase considered includes transportation to the point of use and combustion of the fuel products. The system boundaries considered in this report are shown in Figure 1. In addition to the feedstock supply and transport to the HTL plant, the HTL process, comprising the entire processing of the feedstock to the fuel, represent essential steps of the fuel production process. These elements form the well to product (WTP) system boundaries. The product to wake (PTW) system boundaries take into account that the fuel is transported to the user and thermally converted. WTP and PTW together form the WTW (well to wake) system boundaries.

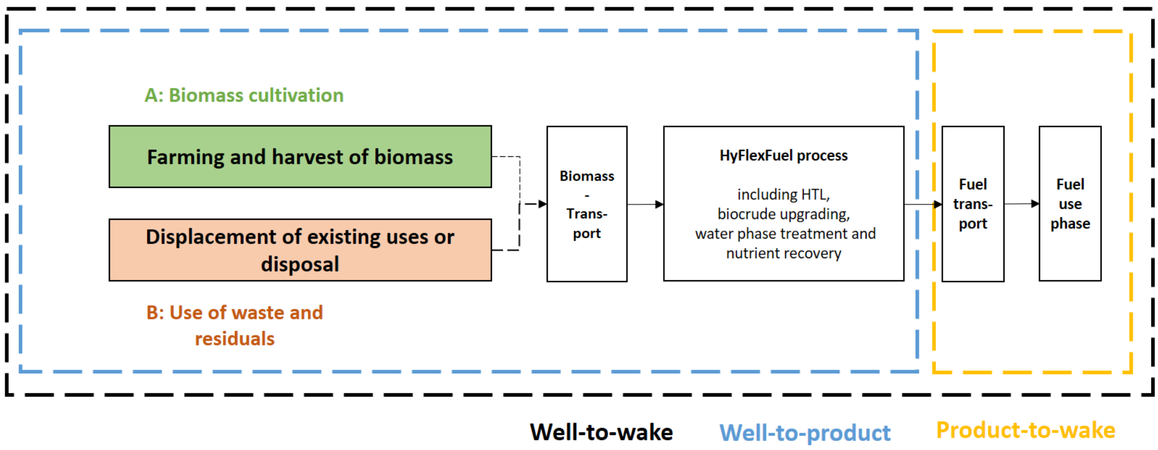

Figure 9: *LCA system boundaries for the studied HTL scenarios. Well-to-product (WTP) comprises the feedstock supply, feedstock transport and the fuel production via HTL. Product-to-wake (PTW) comprises fuel transport and the use phase.*

From Figure 9 it also becomes clear that we distinguish between two use cases in the provision of the HTL feedstock. On the one hand, we consider biomass that is produced with the target of converting it to fuel via HTL (A). On the other hand, we study available waste and residue streams (B).

Emissions associated with the cultivation of the biomass are attributed to the feedstock and thus also to the HTL fuel. These include all emissions associated with the cultivation and harvesting of the biomass as well as its transportation and storage.

The situation is different for residual materials and waste streams, which also represent a suitable type of HTL feedstock. These streams arise from other background-processes that are not further defined. For this reason, emissions from primary processes are not considered and we assume that waste is available for HTL without further restrictions. In addition, when waste materials are used, the disposal process that is omitted by converting the waste material via HTL is also considered. Thus, the emissions (*E*) of waste feedstocks can be accounted using the avoided-burden approach.

$$E_{\text{Feedstock}} = -\,E_{\text{Reference process}}$$

This means, when we want to replace the common disposal of a waste feedstock with HTL, we can subtract the emission from the corresponding reference process.

The software Brightway2 [21] is used integrating the data from Ecoinvent (V3.7.1.) to generate the LCA results. In order to achieve a broader overview of the environmental impacts of the HTL process, other environmental impacts than global warming potential are assessed as well. Therefore, three different impact categories from the International Reference Life Cycle Data System (ILCD) guidelines are applied. These include the following midpoint impact categories in the version ILCD 2.0 from 2018:

- climate change total
- ecosystem quality, freshwater ecotoxicity
- resources, dissipated water

Figure 10 shows all input and output streams considered in this LCA. Individual process steps, including feedstock supply, feedstock transportation, HTL, HT, fuel transport, H2 plant, cHTG, nutrient recovery, CHP and wastewater treatment are shown in different colours. Input streams are shown in green, output streams in red. Yellow boxes imply that the construction of the plant is considered. It should be noted, that not all process steps are used in all different configurations.

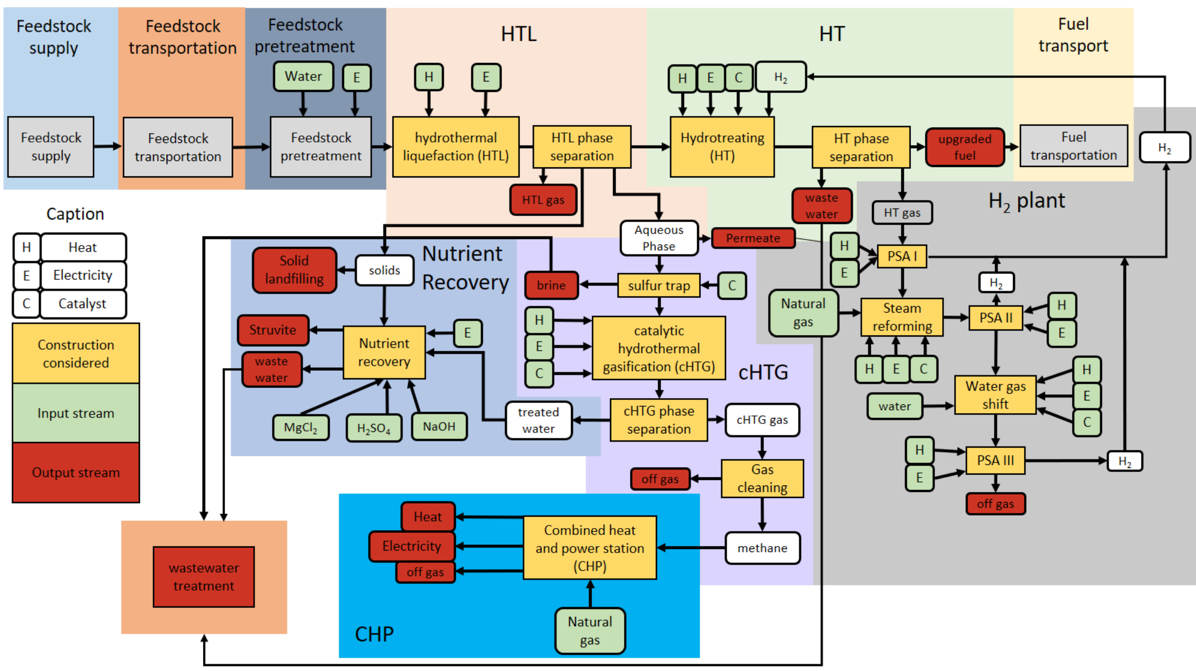

Figure 10: *Overview of all input and output streams considered in this LCA. Individual process steps are shown in different colors. Input streams are shown in green, output streams in red. Yellow boxes imply that the construction of the plant is considered.*

3.3.1 Supply of residue feedstock streams

Raw sewage sludge coming from a wastewater treatment plant consists of about 5 wt% dry matter (DM). In the most common reference process for Germany, the dry matter content has to be increased to up to 92 wt%, in order to enable an efficient incineration of the dried sewage sludge. This is achieved by a dewatering and drying process. Subsequently, the dried sewage sludge is burned. In the case of HTL as replacing disposal process, the DM content has to be increased in order to have a high share of organic material for the HTL process to be as efficient as possible. On the other hand, the DM content is limited by the need for the resulting slurry to still be pumpable. Therefore, a DM content of 20 wt% is chosen. This DM content can be achieved by a decanter centrifuge, which is significantly more efficient with regard to heat and electricity demand compared to the reference process.

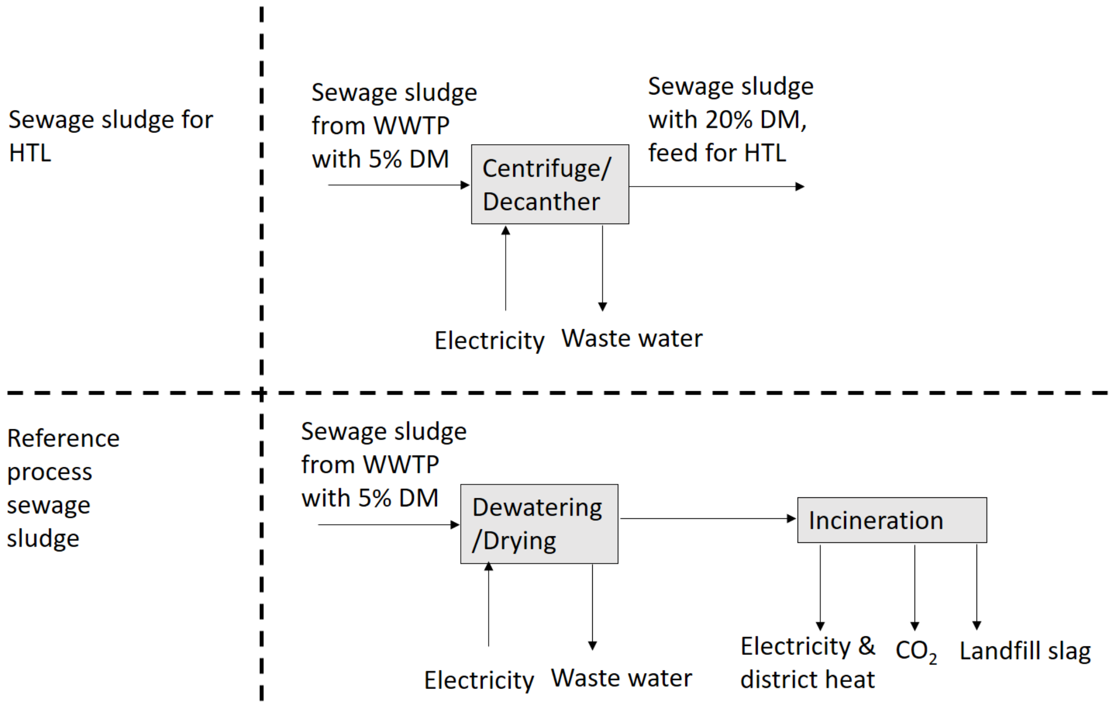

Figure 11: *Top: Considered process for the supply of sewage sludge for HTL. A centrifuge is used to increase the dry matter content in the raw sludge from 5 to 20%. Below: Considered current use-case scenario for sewage sludge: Raw sludge is dried and incinerated.*

Considering the above described processes, the emissions related to the reference case can be considered as avoided burden, while the emissions for the feedstock drying for the HTL process have to be accounted for. Therefore, the calculation of the emissions for the feedstock supply can be conducted as follows:

$$E_{\text{Sewage sludge, HTL}} = E_{\text{Pretreatment}} - E_{\text{Reference Disposal}}$$

with $E_{\text{Sewage sludge, HTL}}$ representing the emissions of the sewage sludge supply and pretreatment, $E_{\text{Pretreatment}}$ representing the emissions linked to the pretreatment and $E_{\text{Reference}}$ disposal process accounting for the avoided burden/emissions for the substitution of the existing disposal process. The pretreatment involves the dewatering of sewage sludge from around 5 wt% of dry matter to 20 wt% of dry matter needed for an efficient HTL treatment. The dewatering is realized via centrifugation. The existing process of sewage sludge disposal includes the drying of the sewage sludge from about 5 wt% of dry matter to about 92 wt% of dry matter. The dried sewage sludge is subsequently incinerated.

In the case of wheat straw, the ecoinvent activity “wheat production” was used to model the supply of wheat straw. This activity includes more than 150 technosphere exchanges, including markets for seeds, tillage, fertilizers, pesticides, other chemicals and irrigation as well as 120 biosphere flows that describe the pollution of the biosphere by metals, chemicals and greenhouse gases.

3.3.2 Supply of cultivated biomass

In the case of miscanthus, the ecoinvent activity “miscanthus production” was used to model the production of miscanthus. It comprises several exchanges including tillage, miscanthus rhizome, plant protection products, fertilizer and other chemicals. Furthermore, 32 biosphere exchanges describe how the environment is polluted by metals and other chemical groups. The product of the activity is chopped miscanthus. Further emissions for storage have not been accounted for.

The supply of microalgae is not modeled as an individual process in this study. To cover this part of the microalgae process chain, a literature value for microalgae cultivation as well as microalgae harvesting and dewatering have been used [Azari et al. 2018]. The associated greenhouse gas emissions are calculated as 4.67 kg CO_2-Eq/kg upgraded biocrude.

3.3.3 Struvite production

In the nutrient recovery, struvite is produced as by-product. Since struvite can find application as fertilizer, an equal amount of existing NPK fertilizer can be substituted, which results in an avoided burden in the LCA. Besides struvite, a solid and aqueous waste stream accumulate during nutrient recovery. The aqueous waste stream is treated as an average waste stream, while the solid waste is considered to be quite similar to the solid phase of sewage sludge. It is considered, that the solid waste can not be separated as dry matter, but rather as a 5 wt% dispersion of the solid in water. Furthermore, it is considered, that this waste stream is treated in the same way as a 5 wt% raw sewage sludge, except for the incineration process, which can be neglected due to the absence of organic material. This has been modeled by a combination of adapted ecoinvent processes, which are shown in Table 6. In total, the disposal of solids in the HTL consists of two sub-processes, first the drying of the dispersion and secondly the landfill of the residue. The drying process can be modeled with the pre-assembled ecoinvent process called “drying, sewage sludge”. It is assumed that the same amount of heat and electricity is needed to generate a DM content of 92 wt%, since the DM content of both streams is 5 wt%. In the reference case, all emissions are correlated with the incineration and landfill process. Since in the case of HTL, the incineration process is not performed, all technosphere inputs from the pre-assembled ecoinvent process “treatment of raw sewage sludge, municipal incineration with fly ash extraction” that are correlated with the incineration process are sorted out. Considering the biosphere inputs, those dealing with organic material were sorted out and in the case of inorganic biosphere inputs, only those associated with the compartment water were considered. Since the HTL waste stream only consists of a solid residue, it is assumed that no gases are produced from the waste. However, all considerations are assumptions and have to be investigated in detail in future work, since no reliable data are available up to now.

Table 6: *Adapted Ecoinvent processes for modelling the disposal of solid residues from the HTL process.*

Process	Technosphere inputs	Biosphere inputs
Drying, sewage sludge	All inputs considered	No entries
Incineration, sewage sludge	Incineration as well as landfill, only landfill considered	Entries associated with organics are sorted out, for entries associated with inorganics, only entries associated with water are considered

3.3.4 Allocation of heat and power

The heat and power supply for all processes is partly covered internally by the supply of biogas as well as externally by the supply of natural gas. The ratio of internal and external supply is feedstock and process dependent and listed in Table 7. In this LCA, all emissions coming from the heat and power supply are treated as fossil emissions, since the emission savings from the internal supply are already covered by the carbon capture credit assumed for the biomasses. The amount of carbon and carbon dioxide per kg of biomass and per functional unit are also listed in Table 7. The CHP unit is sized based on the heat demand of the whole process, the electricity demand is significantly lower however. Therefore, a significant amount of electricity is produced and not used. In the LCA model, this amount of electricity is neglected and the allocated emissions are substracted. Therefore, the amount of carbon dioxide fixed in the biomass is also corrected. Based on the functional unit of 1 kg of upgraded biocrude, the amount of biomass input can be calculated. Based on the input of biomass and the mass of carbon dioxide fixed in 1 kg of biomass, the amount of fixed carbon dioxide per functional unit (1 kg of upgraded biocrude) can be calculated. This amount of carbon dioxide is equal to the carbon capture credit that is accounted for as avoided burden in the LCA.

Table 7: *Internally produced heat, carbon content, mass of carbon dioxide, mass of corrected carbon dioxide, mass of feedstock and mass of carbon dioxide credit.*

Feedstock	Sewage sludge	Miscanthus	Wheat straw	Microalgae
Portion of internally produced heat [%]	50.9	13.2	14.9	47.1
Carbon content [wt%]	41.2	47.4	49.8	48.8
Mass carbon dioxide [kg]	1.51	1.74	1.83	1.79
Mass carbon dioxide corrected [kg]	1.44	1.72	1.80	1.72
Mass feedstock [kg]	3.87	3.80	2.93	3.37
Mass carbon dioxide credit [kg]	5.56	6.53	5.28	5.80

3.3.5 Selection of LCA data

Based on the process model and the modeled mass and energy balances, the different process steps and their respective exchanges have been recorded in an input-output table (SI/appendix). For the use phase, the combustion of the different fuel fractions, data from the GREET model [22] were used. Based on the specific composition of each upgraded biocrude, the emissions of the fuel mix is calculated by summing up the emissions calculated by the GREET model for each transportation fuel. The individual and total emissions are shown in Table 8. As can be seen, the different compositions do not have a major influence on the total emissions.

Table 8: *Total emissions as well as emissions for individual fuel fractions during combustion of the fuel mix for all feedstock.*

Feedstock	Gasoline	Jet fuel	Diesel	Heavy fuel oil	Total emissions
Emissons from GREET [kg CO_2 Eq./kg ubc]	3.39	3.37	3.47	3.43	**-**
Sewage sludge [%]	29.6	38.2	9.9	22.3	**3.40**
Lignocellulosic feedstock [%]	17.8	16.4	24.7	41.1	**3.42**
Microalgae [%]	35.1	20.0	38.7	6.2	**3.42**

4. Results of techno-economic assessment

This section presents the results of the techno-economic analysis for the HTL scenarios described above. The possible costs and revenues associated with HTL fuel production are presented in detail. In addition, the economic effects that can be expected with a variation of the process configuration or the location of the HTL plant are discussed.

4.1 HTL of sewage sludge

The total investment costs incurred over an assumed lifetime of 20 years for an integrated HTL plant and the operating costs that arise during plant operation were related to the quantity of upgraded biocrude (ubc) produced. The results related to 1 kg upgraded biocrude are shown in Figure 12.

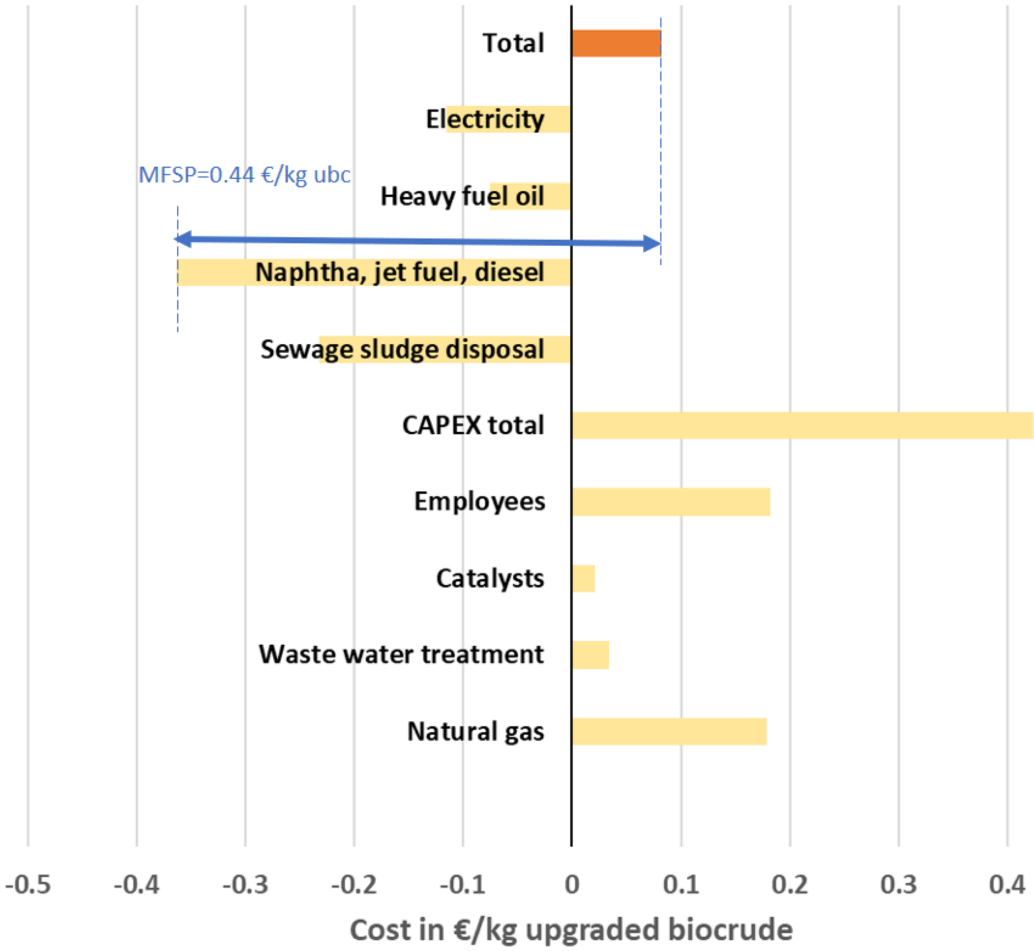

Figure 12: *Overall costs and revenues for HTL fuel (upgraded biocrude, ubc) production based on the conversion of sewage sludge.*

In the figure, it appears that the costs are composed of revenues that can be obtained for various HTL products and by-products and various expenses for the HTL process.

On the revenue side, the production of the fuel fractions naphtha, jet fuel and diesel accounts for the majority (0.36 €/kg ubc). Further revenues can be obtained from the marketing of heavy fuel oil and surplus electrical energy (0.08 €/kg ubc and 0.12 €/kg ubc). The disposal of sewage sludge is also reflected on the profit side. Per kg upgraded biocrude 0.23 € can be generated in disposal profits. The upgraded biocrude production costs are mainly dominated by capital expenditures (0.42 €/kg ubc). Large cost items are the employee costs with 0.18 €/kg ubc and the demand for natural gas, also with 0.18 €/kg ubc. Costs for catalysts (0.02 €/kg ubc) and wastewater treatment (0.03 €/kg ubc) rather play a minor role in the upgraded biocrude production costs.

The total cost for HTL conversion results with 0.08 €/kg upgraded biocrude from the sum of revenues and expenses. In order to make HTL conversion economic, we conclude that the target products (naphtha, jet fuel and diesel) need to be sold at a higher price. This MFSP is the difference between fuel revenues generated at market prices and the additional costs incurred. Thus, the MFSP for the sewage sludge scenario is 0.44 €/kg upgraded biocrude. The total capital cost for a HTL conversion of wet biomass was calculated to be 19 million €. The distribution of these costs is shown in Figure 13.

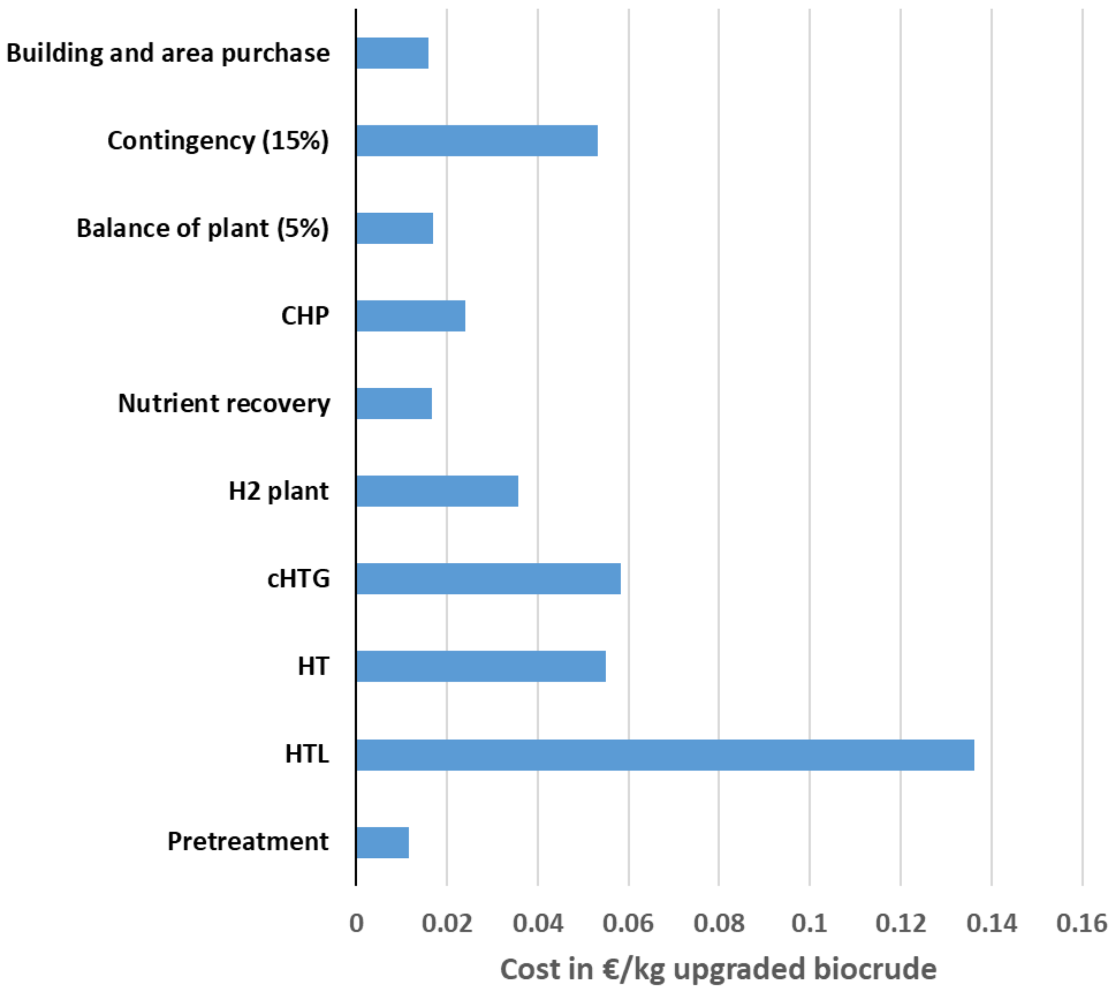

Figure 13: *Composition of the capital expenditures related to the quantities of produced biocrude for wet feedstocks related to 1 kg upgraded biocrude.*

The HTL plant itself accounts for the largest item. 40% of the capital expenditures are attributable to it. The reason for this is that the costs for the HTL process are primarily driven by the reactor. At the moment, no commercial solutions exist for the HTL tubular reactor with a necessary heat recovery, which is associated with an additional financial expense. In addition, parts of the reactor require material that can withstand high temperatures. Inconel was selected as a suitable material for the high-temperature heat exchanger in the HTL reactor. Also, the expenditures for the sub-processes cHTG as an AP treatment option (17%), the hydrotreating (16%) and the Hydrogen Production Facility (11%) make up a large portion of the capital expenditures. CHP, nutrient recovery, and pretreatment account for 7%, 2% and 3% of total capital expenditures, respectively.

4.2 HTL of agricultural residues

The calculated MFSP and the breakdown of costs incurred and revenues expected are shown in Figure 14.

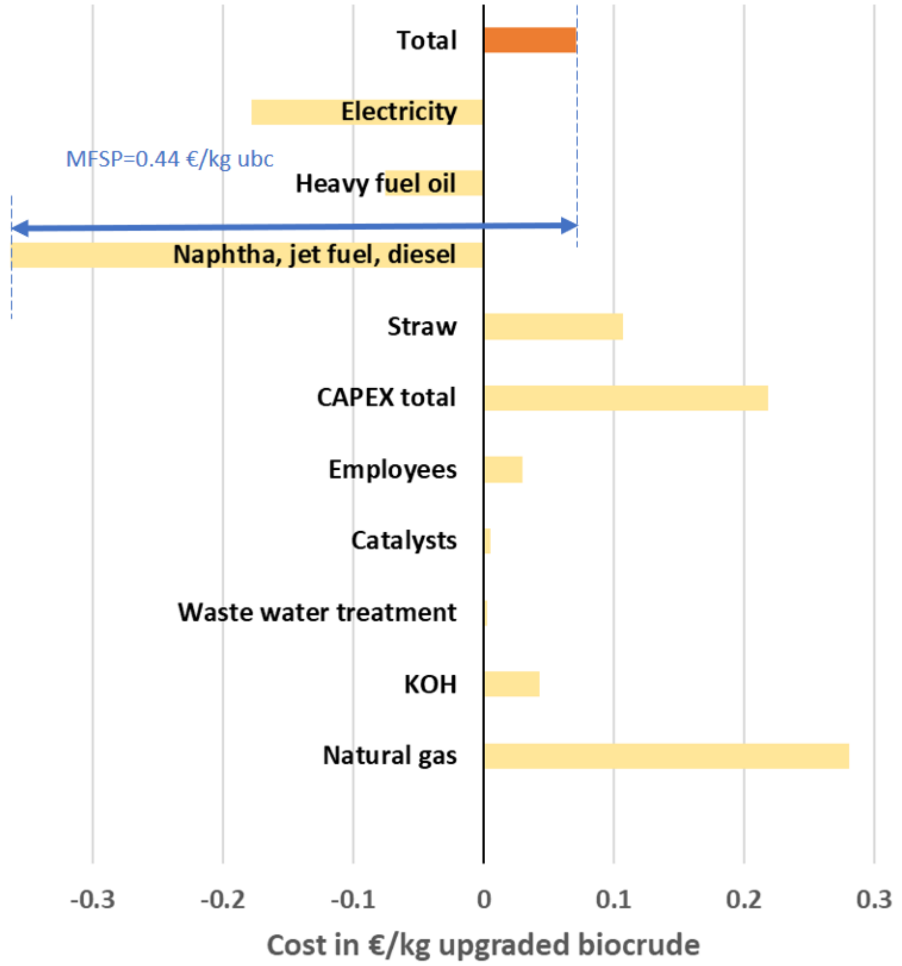

Figure 14: *Overall costs and revenues for HTL fuel production based on the conversion of cereal straw.*

If cereal straw is used and an accordingly large-scale plant is implemented (90 kt upgraded biocrude per year), a MFSP of 0.44 €/ kg upgraded biocrude can be achieved. In contrast to the sewage sludge scenario, the feedstock purchase of straw is associated with certain costs. Related to 1 kg upgraded biocrude, 0.11 € have to be spent for straw. In addition, the HTL conversion of lignocellulosic feedstock such as straw or miscanthus takes into account the addition of KOH, which is associated with costs of 0.04 €. Since the HTL conversion of dry biomass is based on the assumption that 90% of the AP is recirculated, the AP treatment system can be relatively smaller. Nutrient recovery is also not considered in this modeling. As a result, the investment costs are lower than for HTL conversion of sewage sludge.

In addition, the effect of economy-of-scale plays a role. This also contributes to the fact that the investment costs of 0.22 €/kg upgraded biocrude are lower than in the sewage sludge scenario.

On the other hand, AP recycling results in less methane being produced internally. This increases the need for additional purchased methane. The related costs are 0.28 € per kg upgraded biocrude

4.3 HTL of miscanthus

The costs and revenues for an integrated HTL plant processing miscanthus is shown in Figure 15.

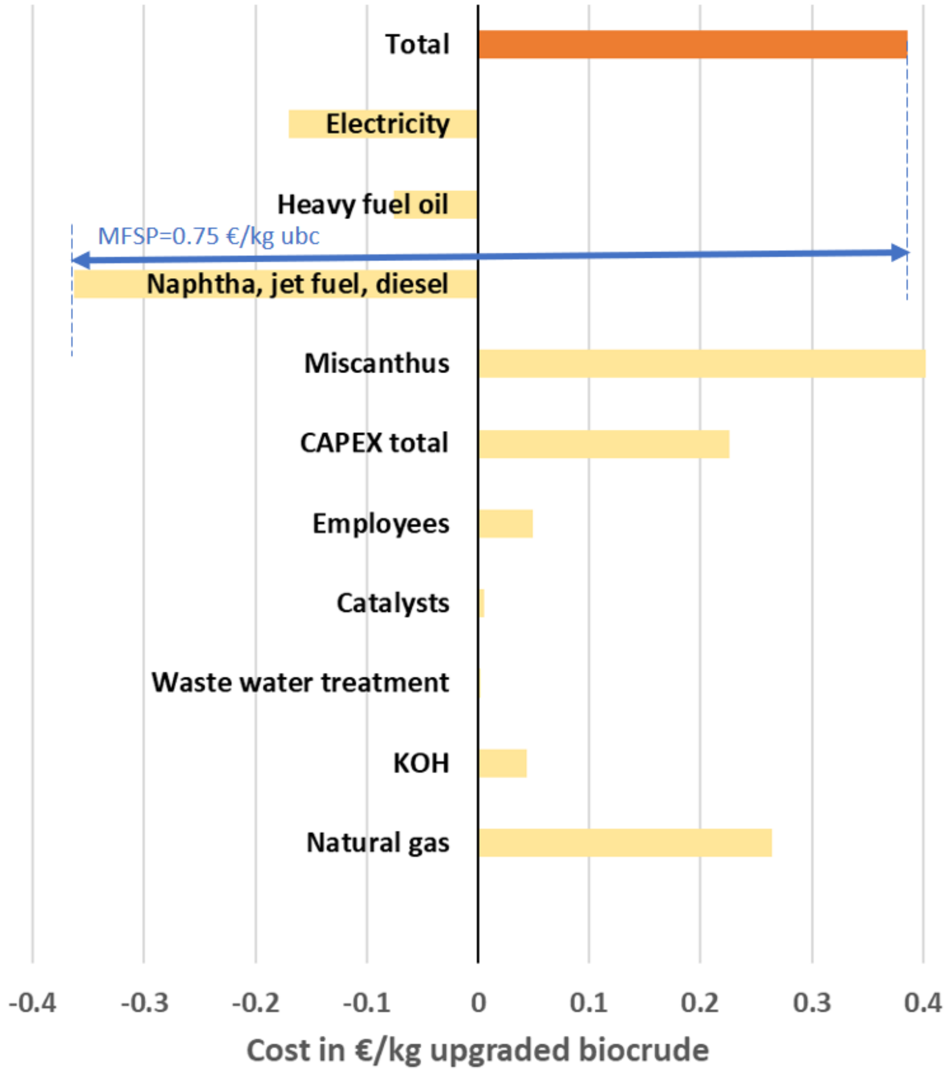

Figure 15: *Overall costs and revenues for HTL fuel production based on the conversion of miscanthus.*

Compared to the other two scenarios, the use of miscanthus as feedstock results in a higher MFSP of 0.75 €/kg upgraded biocrude. This is mainly due to the fact that miscanthus, which is a cultivated biomass, is available at a higher cost.

4.4 HTL of microalgae

The production costs of the upgraded biocrude were also calculated for the cultivation and conversion of microalgae. The results, which show how the production costs are composed in detail, are shown in Figure 16.

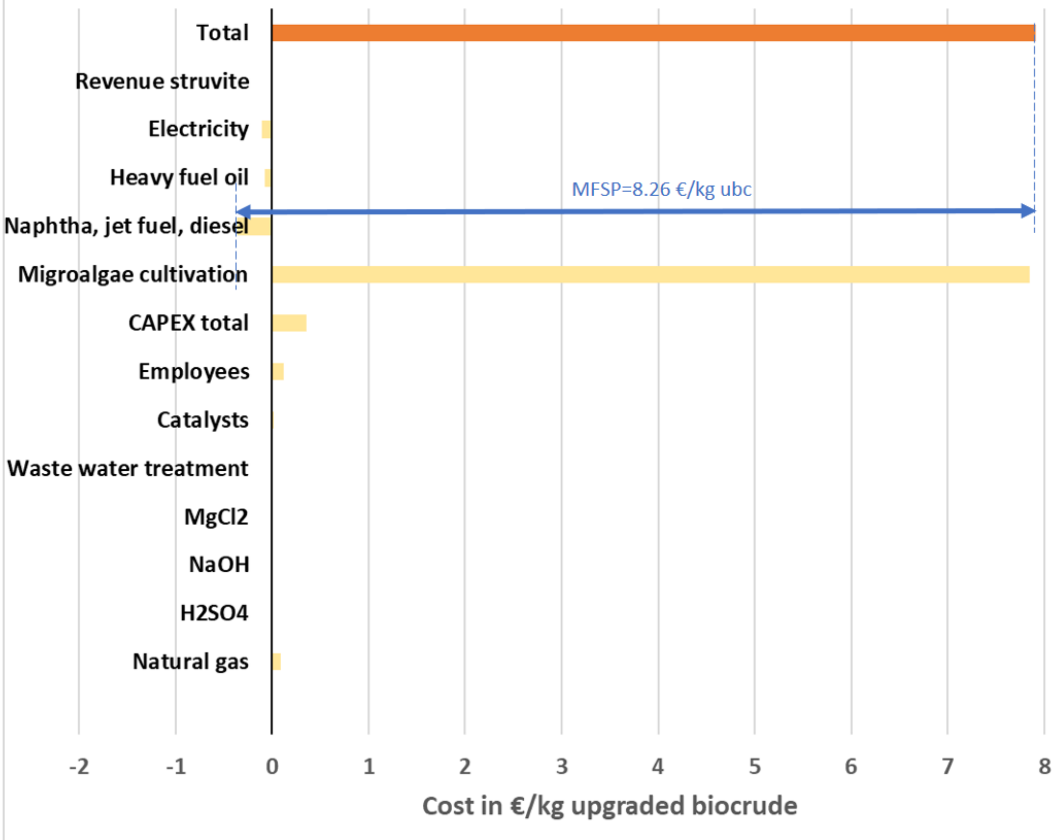

Figure 16: *Overall costs and revenues for HTL fuel production based on the conversion of microalgae.*

Compared to the other scenarios, the MFSP are expected to be much higher with a value of 8.26 €/kg upgraded biocrude. These high costs for a biocrude production of HTL based on microalgae are to a large extent attributable to the cultivation of microalgae. Algal cultivation itself was not modeled in this TEA study. However, various studies on the cultivation of microalgae on a large scale are available in literature, which provide information on production costs. Since production costs are dominated by feedstock costs in the case of microalgae conversion, the leverage that can be achieved with HTL process optimizations is significantly smaller than in the other considered HTL scenarios.

4.5 HTL fuel production costs in Europe

In order to identify a suitable location in Europe for future HTL projects, the impact of different site-dependent parameters on the production costs of upgraded biocrude was analyzed. This study was conducted for HTL scenarios of sewage sludge, miscanthus and straw. Microalgae were excluded from this analysis due to high feedstock costs.

Labor costs, weighted average capital costs, and natural gas costs were considered as country-specific costs. The profit that can be generated by disposal of sewage sludge is based on the usual country-specific disposal options and the associated costs. Straw and miscanthus costs were considered at country level by taking into account the specific feedstock density by allowing for a longer transportation distance than 50 km. Upgraded biocrude production costs in different countries are shown in Figure 17.

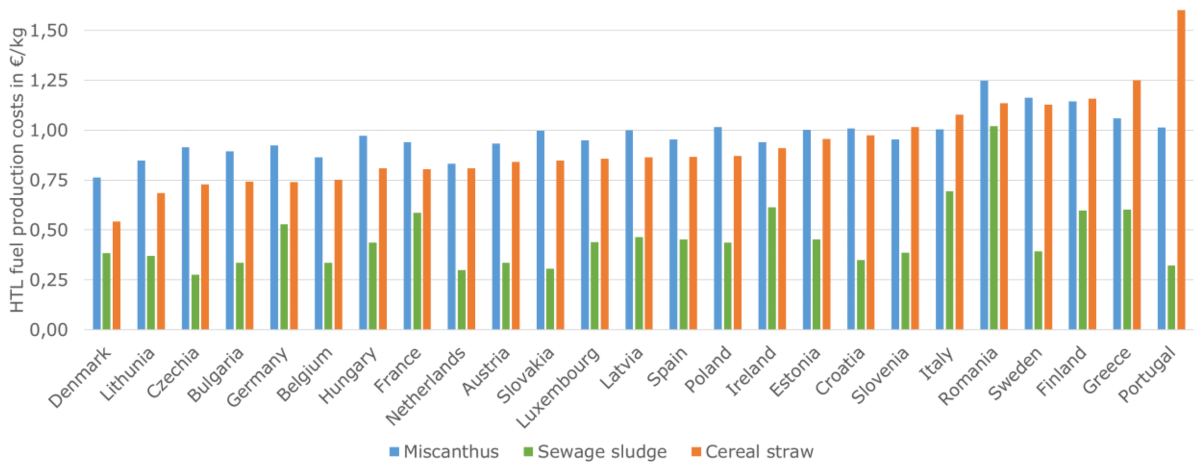

Figure 17: *Estimated HTL fuel production costs (mixture of hydrocarbon fuels) in EU countries for miscanthus (blue), sewage sludge (green) or cereal straw (orange) as feedstock.*

The results show that there are considerable price differences between the countries. The fuel production costs for the conversion of cereal straw vary from 0.54 € to 1.61 € per kg upgraded biocrude. For the use of sewage sludge, prices range from 0.28 € (Czech Republic) to 0.56 € in Romania. The fuel production costs when using miscanthus range from 0.76 € (Denmark) to 0.98 € (Romania) per kg upgraded biocrude.

In a next step, the upgraded biocrude potential was taken into account to estimate which quantities of fuel can be provided at which costs.

Average country specific HTL fuel production costs plotted against aggregated theoretical fuel production potentials are illustrated in Figure 18.

In this analysis, the assumption was made, that fuel volumes are purchased at the lowest possible cost. Smaller quantities of fuel are therefore produced at lower cost than larger quantities. With an increase in the produced fuel volumes, an increase in the production costs is therefore to be expected. It should also be noted at this point that theoretical fuel production potentials disregard competing demand from other sectors.

Figure 18 shows that even large fuel quantities (in the case of miscanthus up to 225 Mt/year) can be produced at tolerable production costs of less than 1 €/kg upgraded biocrude.

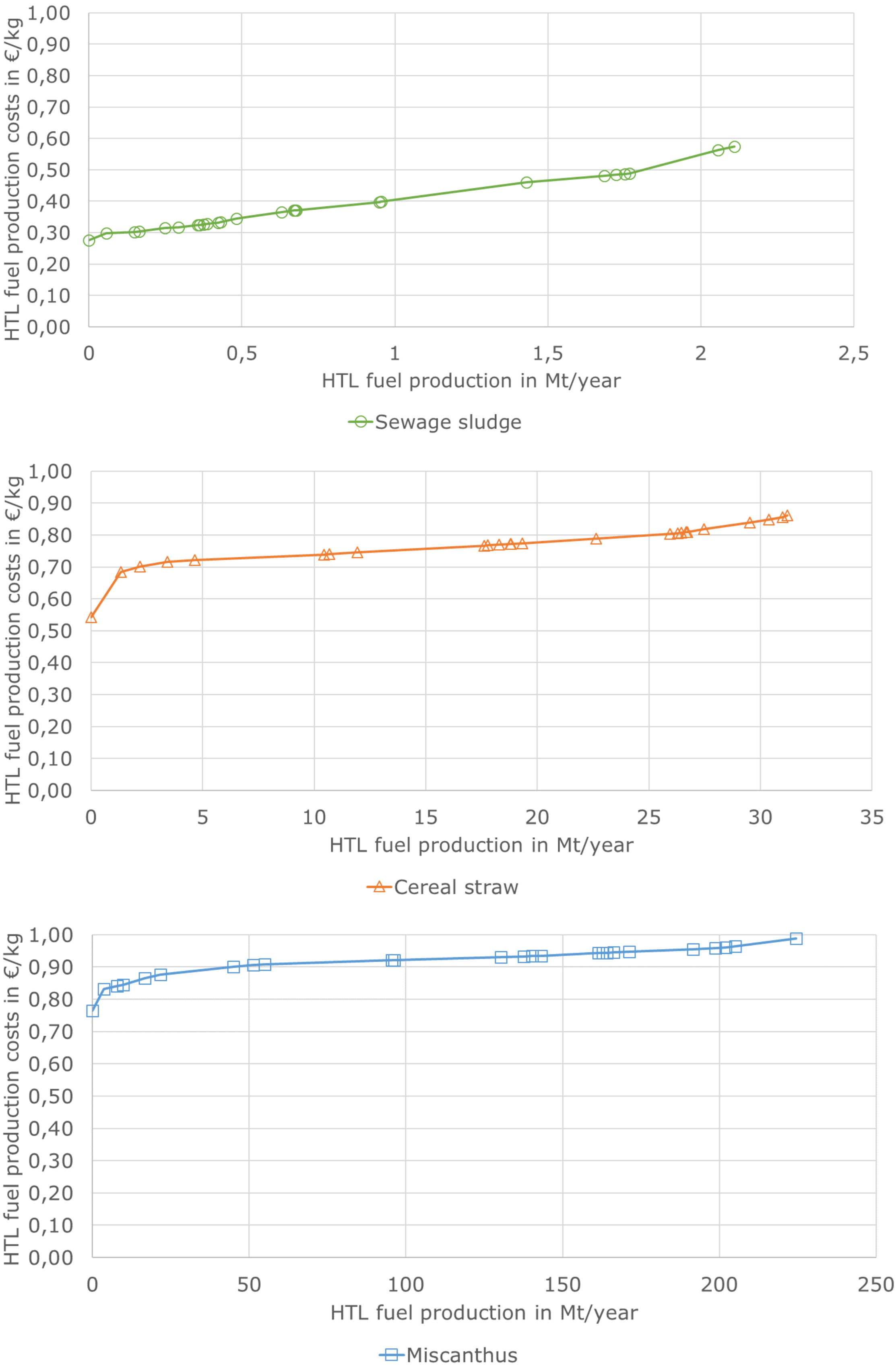

Figure 18: *Average country-specific HTL fuel production costs plotted against aggregated theoretical fuel production potentials. The theoretical fuel production potentials disregard competing demand from other sectors.*

5. Results of life-cycle assessment

5.1 HTL of sewage sludge

As described earlier, the whole well-to-wake (WTW) process can be divided into two different sub-processes, the well-to-product (WTP) and product-to-wake (PTW) process, which are shown here. The WTP sub-process describes the emissions that are associated with the production of the product, while the PTW sub-process shows the emissions that arise from transport and use of the product. In *Figure 19*, WTP emissions are shown in blue and PTW emissions are shown in red. The conventional pathway of fuel production (left) is compared with the HTL pathway for sewage sludge, whereat in the one case (middle), the avoided burden for substitution of the established disposal of sewage sludge is considered, and the other case (right), this is neglected.

The PTW emissions of 3.45 kg CO_2 Eq./kg ubc were calculated based on the results from the GREET model (3.40 kg CO_2 Eq./kg ubc) and the emissions for transporting the finished fuel (0.06 kg CO_2 Eq./kg ubc) [22]. The WTP emissions for the conventional pathway were also calculated based on the GREET model and amount to 0.59 kg CO_2 Eq./kg ubc. Therefore, the WTW emissions of the conventional pathway add up to 4.04 kg CO_2 Eq./kg ubc. If the disposal of sewage sludge is considered as an avoided burden, this adds a large negative contribution of -2.05 kg CO_2 Eq./kg ubc to the WTP part. The net emissions for this case add up to -1.39 kg CO_2 Eq./kg ubc. Neglecting the negative emissions of the avoided burden leads to net emissions of 0.65 kg CO_2 Eq./kg ubc. Compared to the conventional case, this relates to savings of 83.8 %.

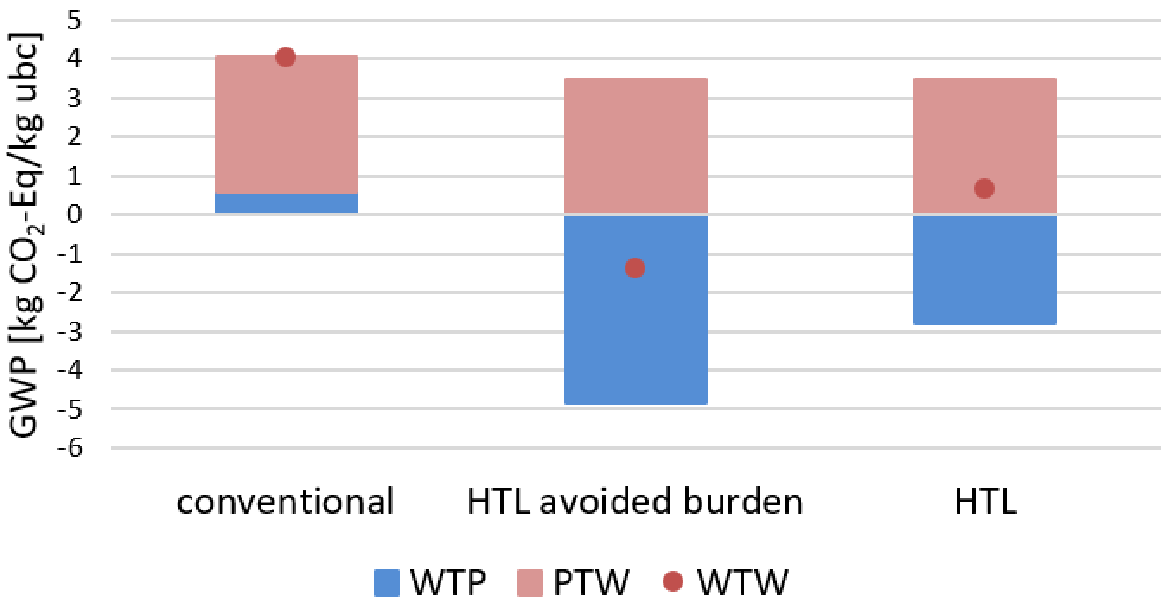

Figure 19: *Impact of climate change total emissions for a fuel mix based on the conventional pathway (left), the HTL pathway with sewage sludge considered as a fossil resource and the HTL pathway with sewage sludge considered as a renewable feedstock.*

In the following, the emissions of the individual sub-processes of the HTL pathway will be shown in more detail. *Figure 20* shows the contributions of the individual sub-processes of which the HTL fuel production pathway is comprised. As can be seen, the total emissions are clearly dominated by the emissions of the fuel combustion (use phase), the carbon capture credit and the avoided burden of the sewage sludge supply. Less important contributions can be observed for the HTL and cHTG process steps.

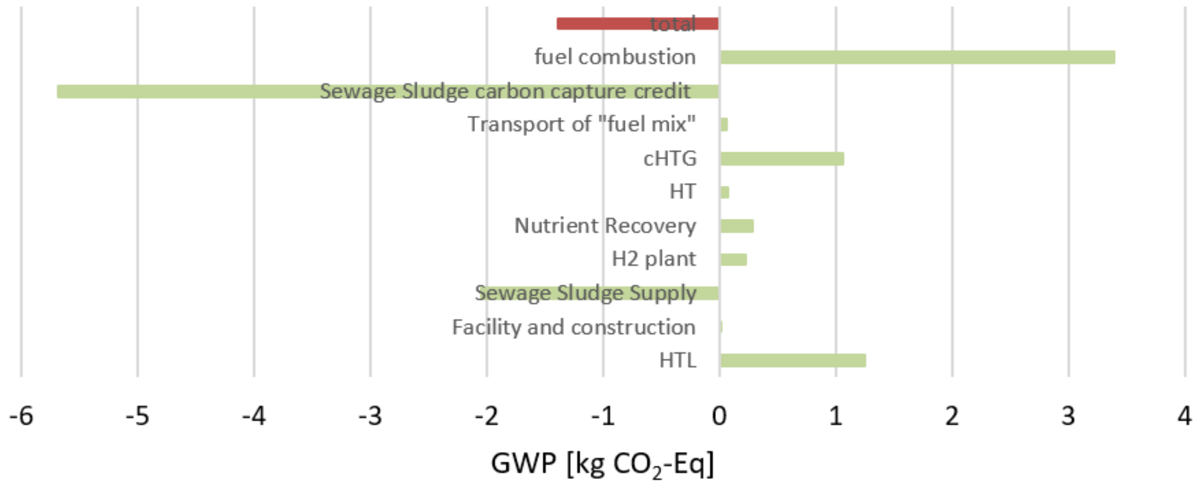

Figure 20: *Contributions of the individual sub-processes to GWP of the HTL pathway for sewage sludge as renewable feedstock including the avoided burden for sewage sludge supply.*

In order to understand the sub-process of sewage sludge supply in more detail, the contributions of the individual inputs are shown in *Figure 21*. As described earlier, the process of sewage sludge supply is modeled by three different inputs. The first two inputs represent the reference processes of drying and incineration of sewage sludge, while the third input describes the actual preparation of feedstock for the HTL process (feedstock drying). It can be seen, that the impact of the latter input is negligible in comparison to the two reference inputs. The impact of the combined reference process is dominated by the impact of drying sewage sludge, while the incineration of the dried sewage sludge only has a minor contribution to the carbon footprint of the reference process. Since the HTL process substitutes the reference process, the emissions shown in *Figure 21* can be credited as avoided burden (negative emissions).

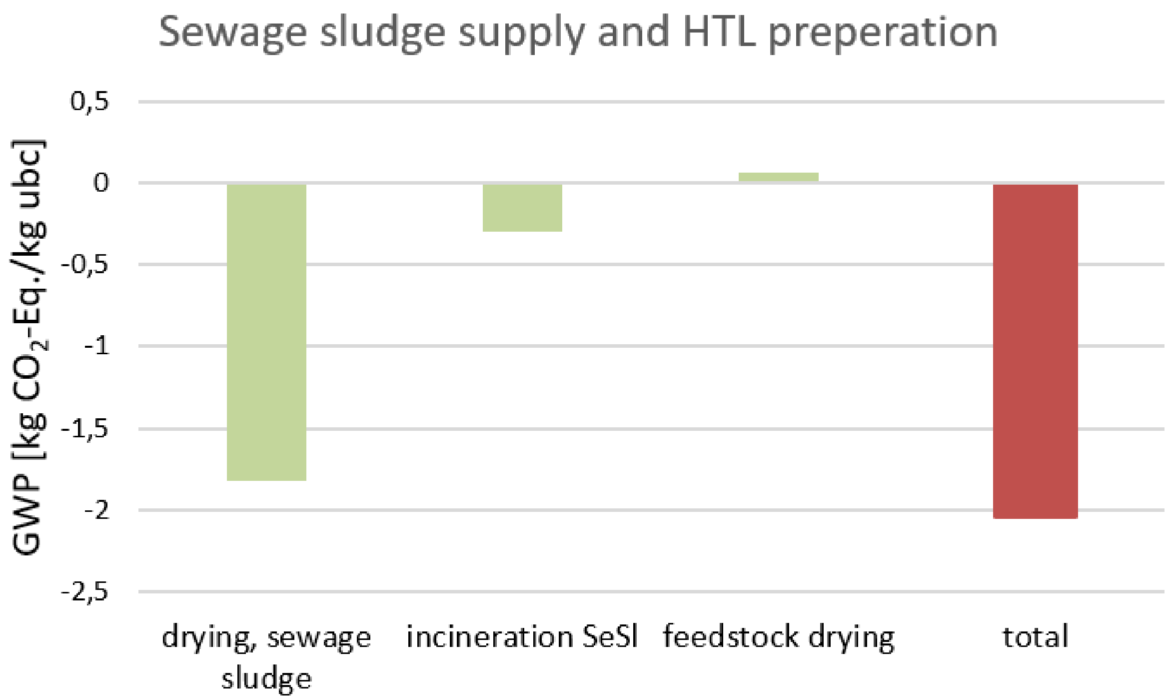

Figure 21: *Contributions of the individual inputs of the subprocess sewage sludge supply.*

In *Figure 22* and *Figure 23*, the contributions of the individual inputs for the two reference processes drying of sewage sludge and incineration of sewage sludge are shown.

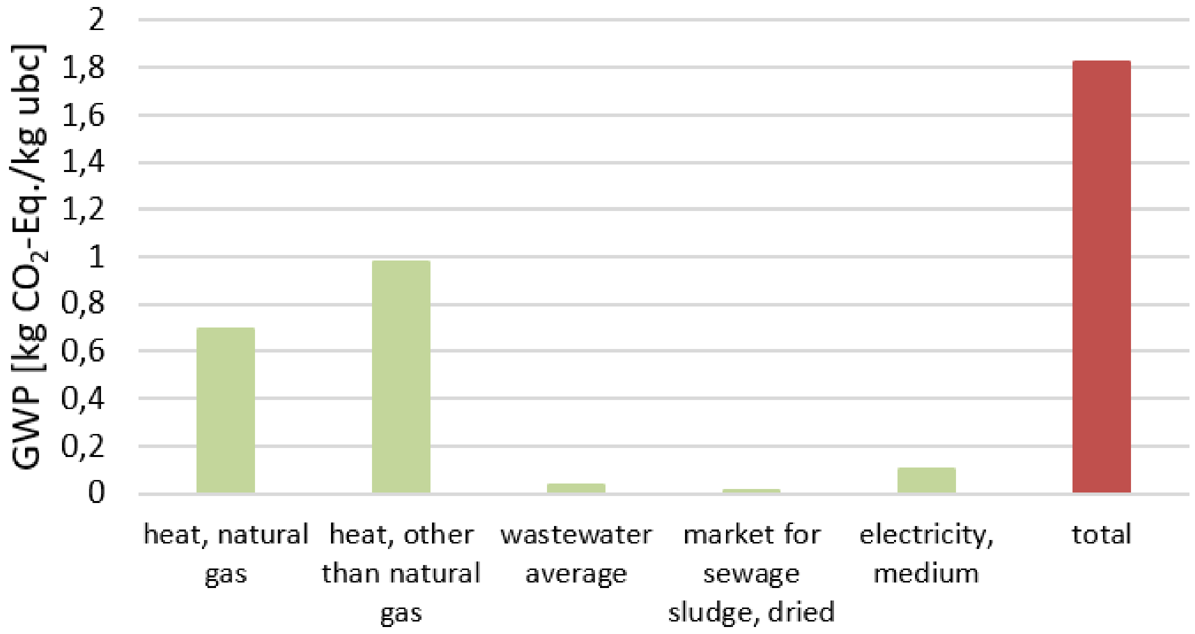

Figure 22: *Contribution of the individual inputs of the reference process "drying of sewage sludge".*

The impact of the reference process drying of sewage sludge is dominated by the high heat demand in order to achieve a DM content of 92 wt%. The sewage sludge itself, the resulting wastewater and electricity demand only have minor contributions.

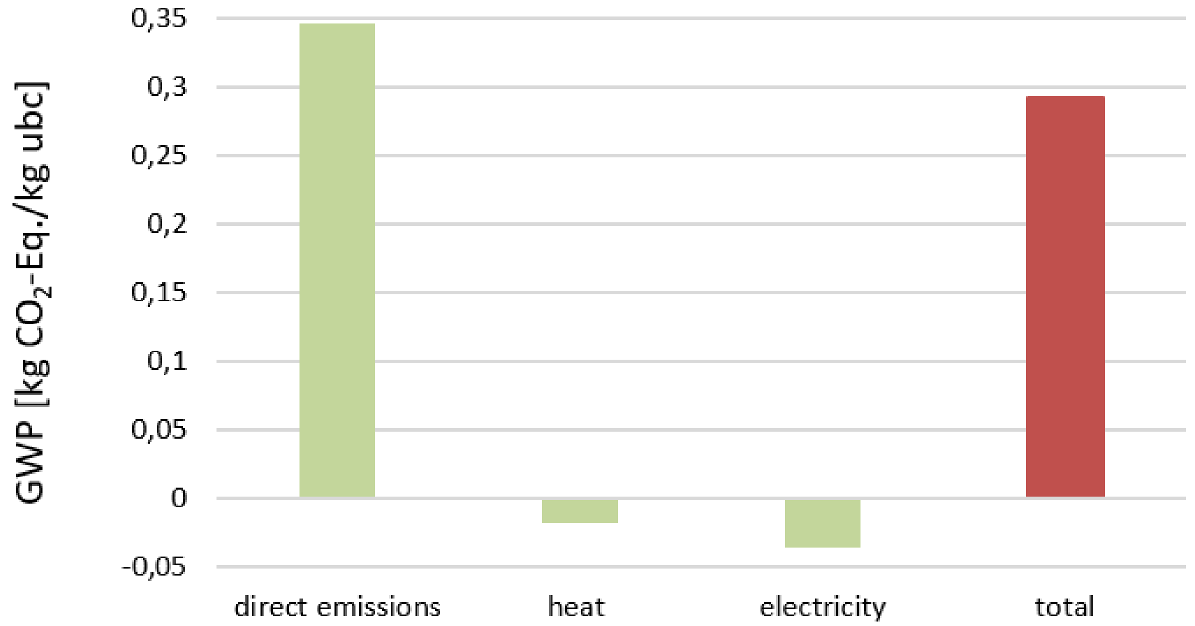

Figure 23: *Contributions of the individual inputs of the reference process "incineration of sewage sludge".*

The impact of the incineration of sewage sludge is mainly driven by the direct emissions of the incineration process, while only minor positive contributions can be attributed to the generated heat and electricity.

As can be seen in *Figure 20*, two sub-processes of the HTL pathway show a significantly higher impact compared to the other sub-processes. These are the cHTG process step and the HTL process step. The high impact can be explained by the fact, that these sub-processes are linked to direct emissions of off-gas, which mainly consists of CO_2 and therefore is modeled as pure CO_2. Minor contributions can be observed for the sub-processes of nutrient recovery and hydrogen plant. In the following, the individual contributions of the four above-mentioned sub-processes with the highest impacts will be shown in more detail.

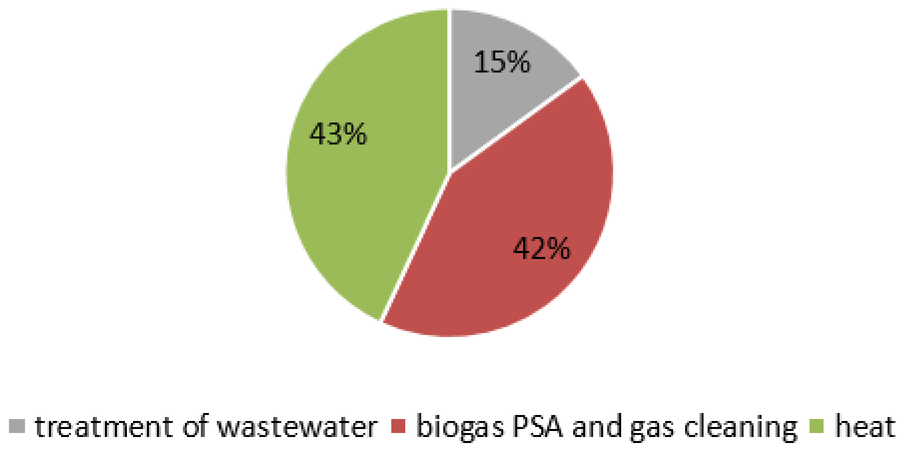

Figure 24: *Different contributions to the emissions of the cHTG sub-process.*

For the cHTG process step (*Figure 24*), it can be observed that the heat demand and the biogas PSA and gas cleaning sub-process dominate the emissions, followed by a smaller contribution of the treatment of watewater.

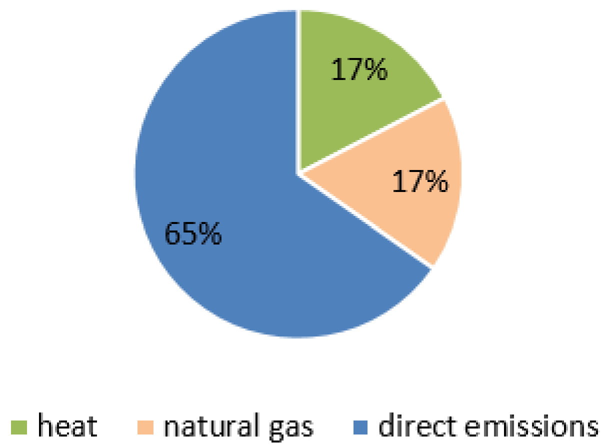

Figure 25: *Different contributions to the emissions of the H2 plant sub-process.*

The sub-process hydrogen plant also consists of three major emission contributors. These are the direct emissions resulting from hydrogen generation from natural gas and the HT off-gas. Furthermore, heat demand and emissions correlated to the supply of natural gas play a role.

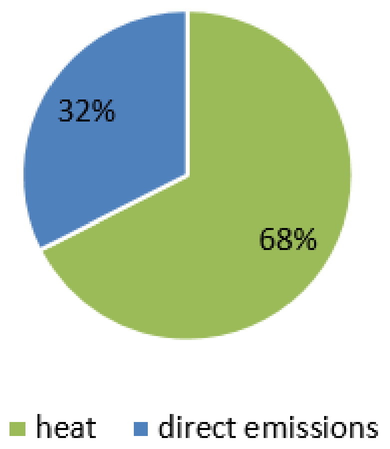

Figure 26: *Different contributions to the emissions of the HTL sub-process.*

The HTL process step is dominated by only two major contributors, which are the heat demand (68%) and the direct emissions through the HTL off-gas.

In *Figure 27*, the impact of the individual contributions of the subprocess "nutrient recovery" are depicted. Although the substituted fertilizer in the nutrient recovery can be seen as an avoided burden (negative emissions), the process step of nutrient recovery shows positive net emissions due to the use of chemicals (NaOH, MgO and H_2SO_4) and the treatment of wastewater (Figure 18).

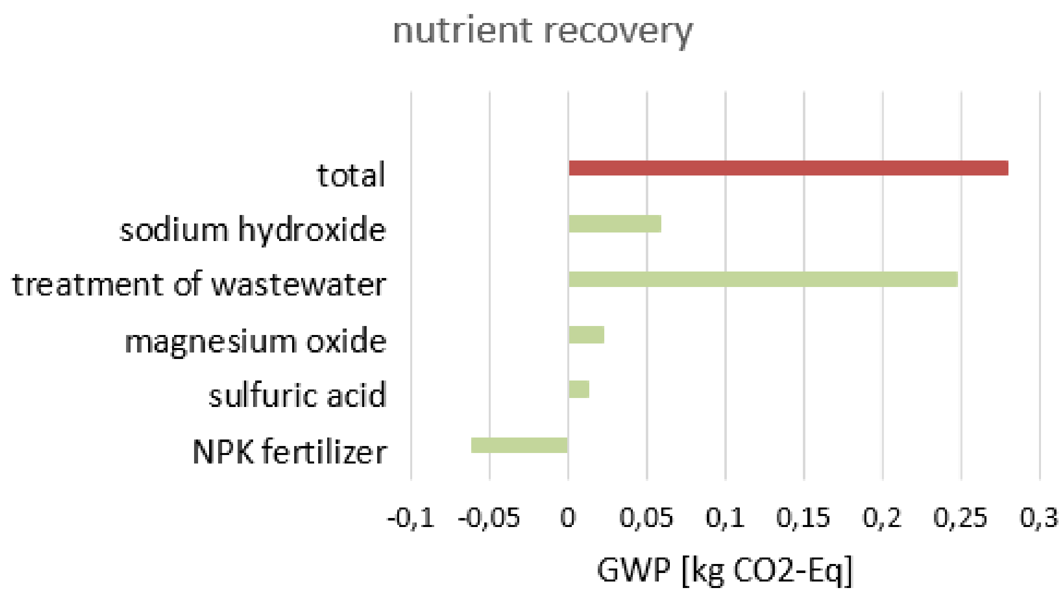

Figure 27: *Impacts of the individual contributions of the sub-process "nutrient recovery".*

Besides the impact category climate change total, also other impact categories, such as freshwater ecotoxicity (FW Ec) and dissipated water (DW) have been looked at. In the following, the results of each impact category will be shown as an overview.

The impact category freshwater ecotoxicity gives a quantitative assessment of the toxicity of processes on the freshwater. Toxicity of different pollutants is converted into so-called comparative toxic unit equivalents (CTU equivalents). This is similar to the calculation of the global warming potential, where the impact of other greenhouse gases is correlated to the standard of CO_2. In the case of dissipated water, the chosen unit is cubic meters and the impact category assesses the amount of water that dissipates during an operation.

Figure 28 shows the results for the impact category freshwater ecotoxicity. The HTL process is clearly dominated by the avoided burden of the sewage sludge supply and the nutrient recovery. Further contributions can be observed for the HTL and cHTG process step as well as for the transport of the “fuel mix”. The total net value of ecotoxicity is 0.39 CTU.

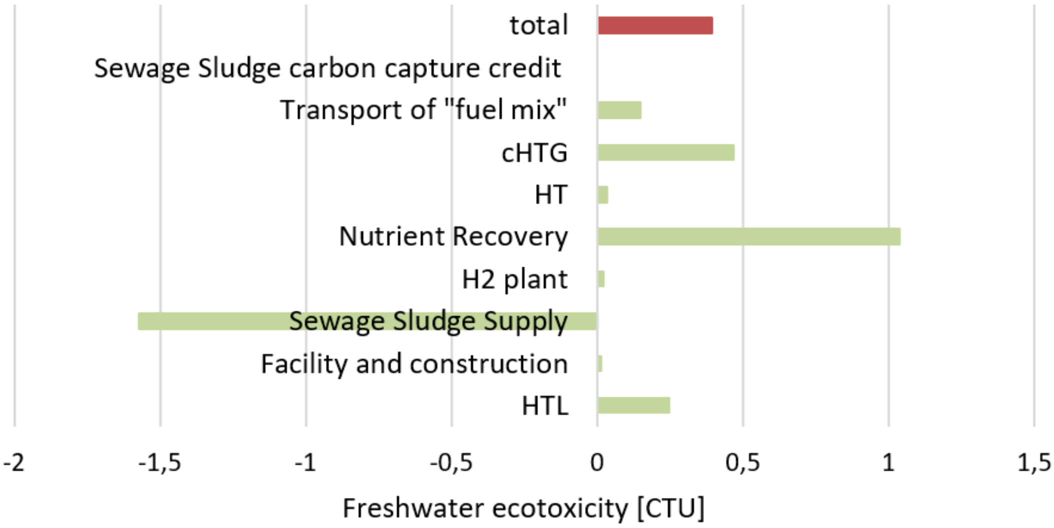

Figure 28: *Contributions of the HTL sub-processes to the impact category freshwater ecotoxicity (CTU: comparative toxic unit).*

Figure 29 shows the impacts for the HTL pathway for the impact category dissipated water. While the whole process is clearly dominated by sewage sludge supply again, nutrient recovery and cHTG do have a noticeable impact as well. The net impact of the process is -0.30 m^3 considering the sewage sludge supply and 0.32 m^3 neglecting the avoided burden of sewage sludge supply.

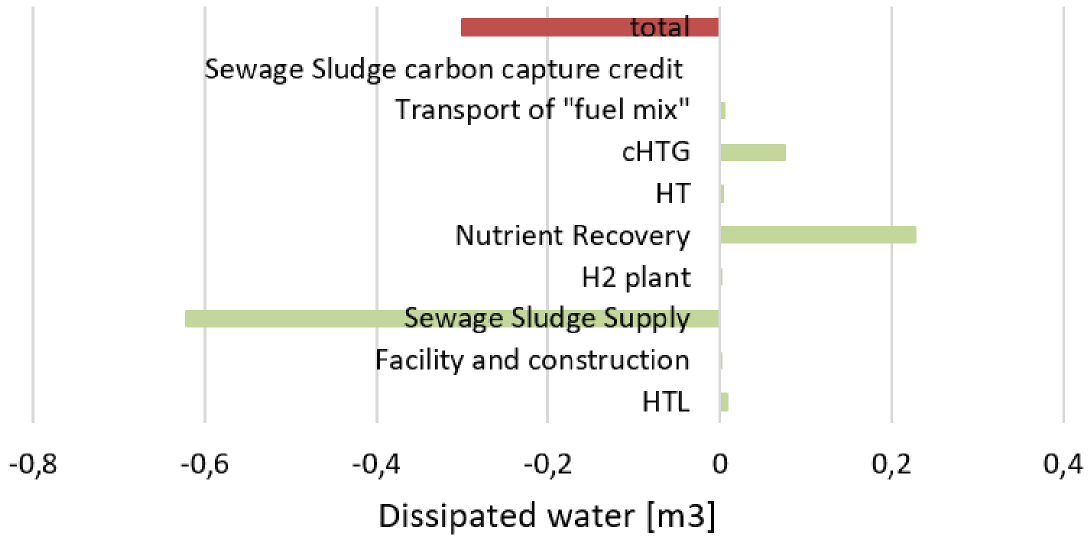

Figure 29: *Contributions of the HTL sub-processes to the impact category dissipated water.*

5.2 HTL of agricultural residues

Agricultural residues, like wheat straw for example, present themselves differently compared to the waste stream sewage sludge. In this case, no avoided burden for the feedstock supply can be calculated, rather positive emissions can be observed for the straw production and the straw pretreatment. Furthermore, one has to consider emissions related to the transportation of wheat straw to the HTL plant. Before discussing the emissions depicted in *Figure 30*, it should be noted that the model on which the LCA is based is considering the recycling of large parts (90%) of the aqueous phase back to the feedstock input. This entails significant differences in the mass balances. Firstly, the amount of aqueous phase treated in the cHTG is reduced, which is why also the internally provided methane content is reduced. Secondly, the higher amount of solvable components is assumed to lead to a higher yield of biocrude, but also to a higher amount of gaseous phase, which almost exclusively consists of CO_2. However, these are just assumptions, since there is still a research gap in this field and the fate of the recycled, aqueously dissolved biomass has to be investigated in the future. The changes in the mass balance lead to different distributions of emissions of the sub-processes and to higher net emissions of the process. As can be seen from *Figure 30*, the emissions are clearly dominated by the carbon capture credit and the fuel combustion. Nevertheless, also the HTL process step plays a key role, due to higher amounts of exhausted CO_2 and a higher share of heat that cannot be covered internally. The emissions of the cHTG however are reduced due to the considerably smaller amount of water that is processed in the cHTG, which leads to a significantly lower heat demand. The total net GWP emissions add up to 1.86 kg CO_2 Eq./kg ubc. The total net impact of the freshwater ecotoxicity is calculated to be 1.28 CTU, while the net water demand amounts to 1.78 m^3 of water. It should be mentioned, that the straw production alone consumes 1.67 m^3 of water.

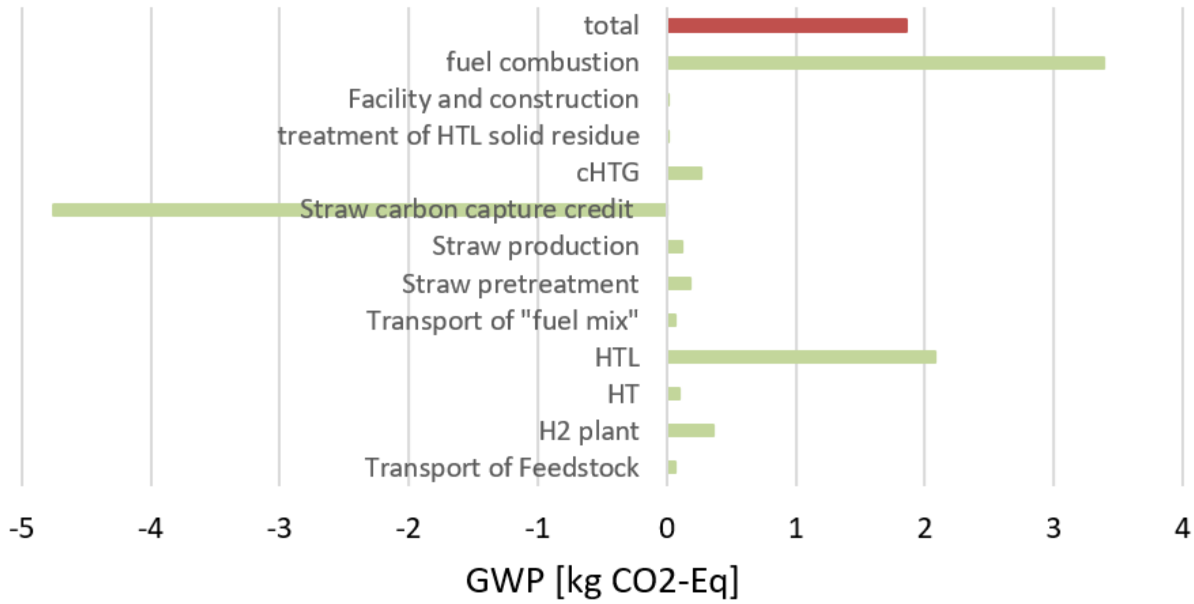

Figure 30: *Global warming potential of different sub-processes of HTL with wheat straw as feedstock.*

5.3 HTL of miscanthus

For miscanthus, aqueous phase recycling was considered again. The main emissions can again be observed for the carbon capture credit and the fuel combustion. As could be observed for wheat straw as feedstock, considerable GWP emissions can be observed for the HTL process step, due to an increased amount of off-gas. The share of emissions from the cHTG is decreased compared to sewage sludge, due to a decreased amount of water and subsequently decreased heat demand. The net GWP emissions add up to 1.80 kg CO_2 Eq./kg ubc. The net impact of freshwater ecotoxicity is calcaluted as -1.48 CTU, whereat the miscanthus production alone has an impact of -2.48 CTU. The impact of dissipated water states a demand of 0.21 m^3 of water for the whole process and a consumption of 0.11 m^3 of water for the miscanthus production.

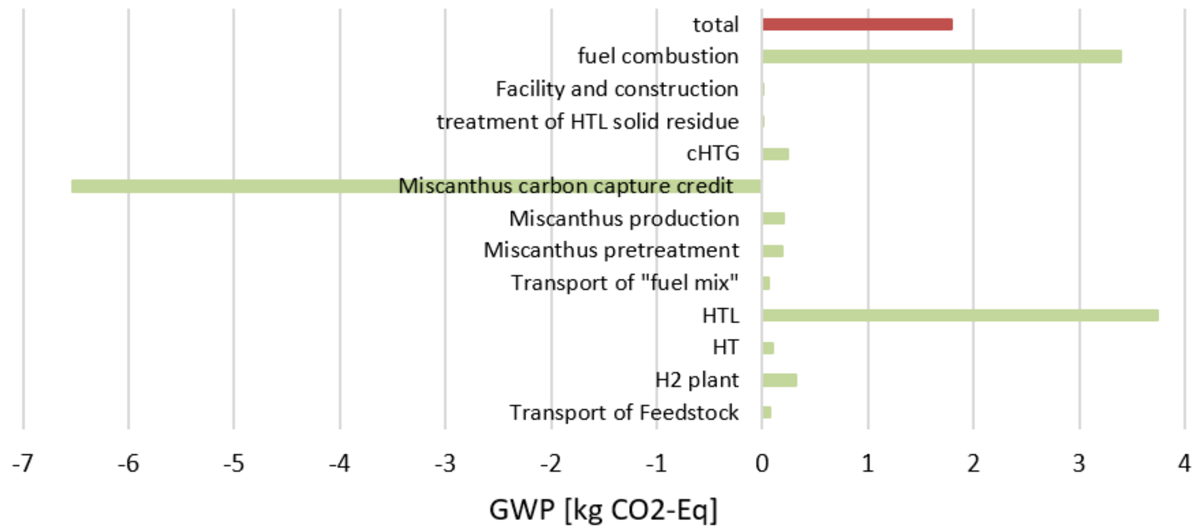

Figure 31: *Global warming potential of different sub-processes of HTL with miscanthus as feedstock.*

5.4 HTL of microalgae

The case of hydrothermal liquefaction of microalgae proves to be different compared to the above discussed cases in the sense that the feedstock production clearly dominates the net emissions of the process. Microalgae production and harvesting emissions have not been modeled, rather a literature value has been used [13]. The emissions of the microalgae production amount to 4.67 kg CO_2 Eq./kg ubc, while the total net emissions are calculated to be 5.34 kg CO_2 Eq./kg ubc. Further major contributions to the net emissions are observed for the HTL and cHTG process steps, due to heat demand and off-gas emissions. For the impact of freshwater ecotoxicity, a value of 1.09 CTU has been calculated. It should be mentioned however, that no literature value for the microalgae production has been found and therefore is not included in the calculation. The net water demand for the whole process was calculated to be 17.14 m^3 of water, which is significantly higher compared to the above discussed results. This can almost exclusively be explained by the high water demand of 17.04 m^3 for the algae production.

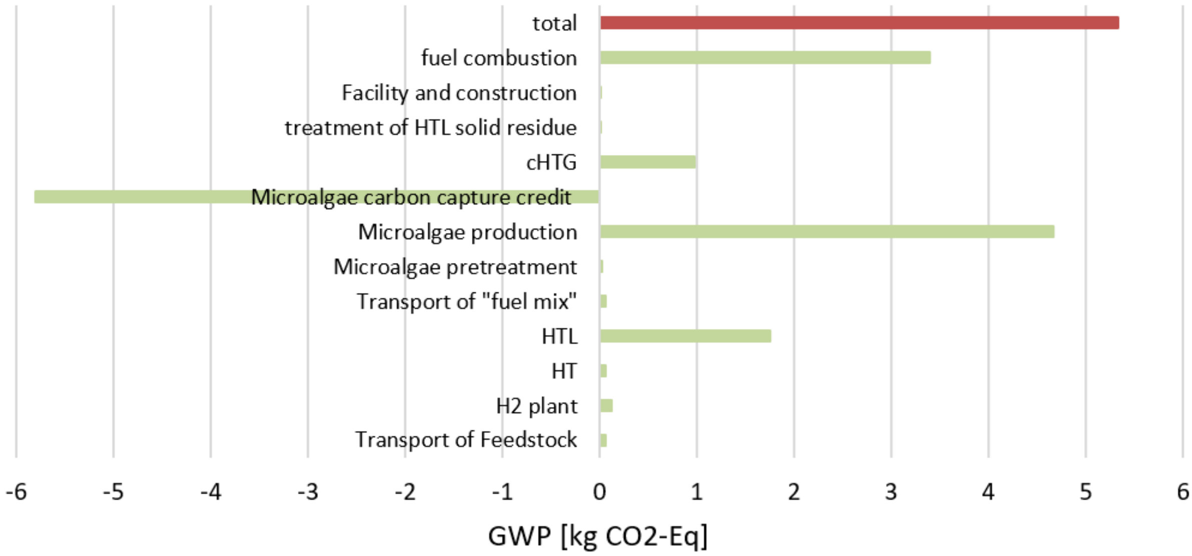

Figure 32: *Global warming potential of different sub-processes of HTL with microalgae as feedstock.*

6. Discussion

6.1 Numerical system model

The numerical process model provides the basis for the techno-economic and life-cycle analyses. In order to indicate reliable values for performance criteria such as fuel production costs and life-cycle emissions, it is important that the process model covers the entire HTL process chain from biomass production or supply to the final fuel product.

For this reason, all system-relevant process steps were modeled on an industrial scale for the use of different feedstock.

Special focus was put on modeling the HTL conversion step, cHTG and biocrude upgrading and validating these with experimental results.

Establishing an extensive reaction network in Aspen Plus® based on proposed reactions from literature for these process steps and also modeling the cHTG and HT reactors with large quantities of reactions has proven to be a successful modeling approach.

The effect of the yield increase modeled with recycling of the aqueous phase (AP) is based only on one experimentally conducted campaign. Only the biocrude and the AP were analyzed. The fact that the solid phase remains unchanged and the yield of HTL gas phase increases is therefore based on assumptions and is subject to inaccuracies. In future studies, several runs with a variation of the recycling rate should be carried out and the gas phase and the solid phase should also be analyzed in order to provide the basis for more reliable modeling.

6.2 TEA

A detailed analysis of the direct and indirect costs associated with HTL fuel production for different feedstock, as well as the profits to be gained by selling the products, was carried out. This was done by referring to a process model based on experimental HTL campaigns and literature research. It should be noted that this model is specific to the processes studied in the HyFlexFuel project (HTL, AP treatment via cHTG and HT). In applications of modified processes, it is possible that the process model may differ. In addition, a variety of econometric assumptions have been incorporated into the TEA. Attempts have been made to include local parameters such as interest rate in terms of WACC, labor costs, or feedstock availability. When it comes to more detailed planning of an implementation of HTL-based fuel production, these parameters should be re-analyzed. Factors such as local emissions and acceptance by the population should also be taken into account.

6.2.1 Assessment of HTL scenarios

The results from the TEA show that sewage sludge is the feedstock associated with the lowest cost (MFSP of 0.44 €/kg ubc). Thus, it is likely that first commercial HTL plants will convert this feedstock type. However, biomass availability of sewage sludge is limited in that a wastewater treatment plant only treats wastewater in a specific catchment area. Greater fuel production potential is offered by lignocellulosic biomasses such as straw or miscanthus. With an appropriately sized plant, as assumed in this study, the effect of scaling up means that fuels can be produced at moderate prices even when using these slightly more expensive feedstocks (MFSP 0.44 - 0.65 €/kg ubc).

With investment costs on the order of several million euros, the magnitude of the local investment risk plays an important role. Therefore, we assume that larger plants will be built first in economically robust countries.

There is only a small difference in the calculated MFSP compared to conventional crude oil, which is traded at prices of about 0.40 €/L. With appropriate political measures such as a CO_2 taxes, we see HTL fuels as an economically competitive fuel in the near future.

6.2.2 Process design options for improved economic performance

In HyFlexFuel, we studied different process configurations that consider fuel production from different feedstocks. The option of on-site H_2 production is reasonable from an economic perspective. A comparison between the options of producing H2 on-site via steam reforming and sourcing H_2 from the market was performed and the results are shown in Figure 33.

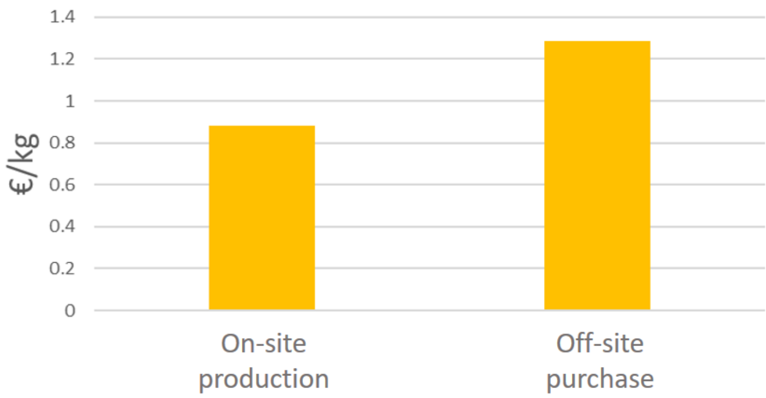

Figure 33: *Comparison of fuel producion costs of on-site hydrogen production and purchasing hydrogen using sewage sludge as feedstock.*

Accordingly, it makes a difference of about 40 ct/kg ubc in our computation for the conversion of sewage sludge. Similar results can be obtained for other feedstocks. On-site hydrogen production in combination with an HTL plant is particularly useful because biocrude upgrading also produces a gas that is rich in hydrogen and methane. To recycle these components and reduce hydrogen demand, a PSA process was modeled. This PSA process, in turn, is part of the hydrogen plant.

This synergy and the fact that a common integrated heat recovery system can be realized result in cost savings for in-process hydrogen production.

It was also investigated from an economic point of view whether it would be worthwhile to obtain electricity from the natural gas purchased in addition to the heat required for the process.

The results show that it is advantageous in terms of production costs to use the natural gas consumed for both heat generation and electricity production (CHP). Although this has the consequence that the efficiency of the heat utilization is lower and the investment costs are higher due to the additional implementation of a CHP process, the revenues generated by the excess electricity produced and fed into the grid nevertheless outweigh the costs. It should be noted, however, that the electricity is merely a byproduct that is put to practical use. Accordingly, the CHP unit should only be sized to generate the necessary process heat.

Our studies have shown that nutrient recovery involves additional costs (about 8 ct/kg ubc, see Figure 34). Thus, although this option is expensive, it makes sense from an ecological point of view to avoid losing valuable nutrients such as phosphorus. Furthermore, in the case of sewage sludge, nutrient recovery may be mandatory if it is to be integrated into existing wastewater treatment processes [23].

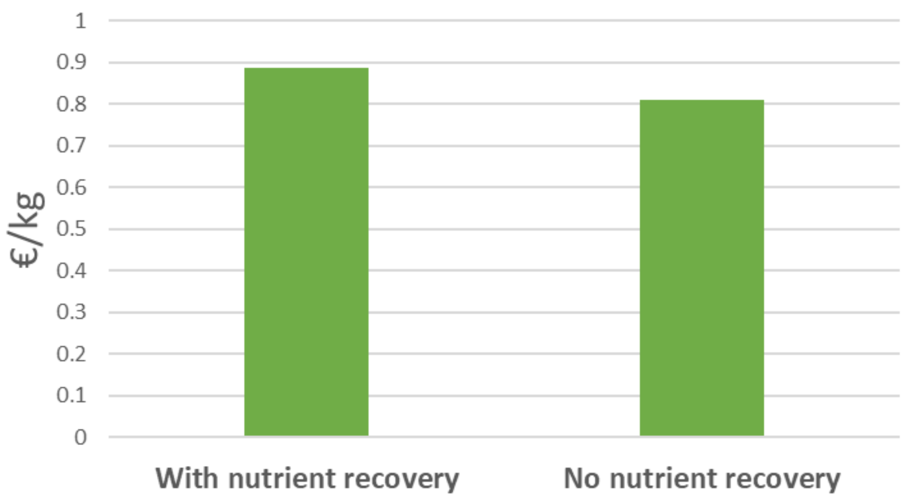

Figure 34: *Production costs (without revenues) for HTL with and without an integration of a nutrient recovery process using sewage sludge as feedstock.*

There are other aspects that were not considered in this study. Since our models are only designed to convert one feedstock type at a time, we did not investigate the economic benefits of mixing multiple feedstocks.

Studies by Madsen et al. and Biller et al. [24,25], in which sewage sludge was mixed with lignocellulosic feedstock, indicate that this is technically possible and that even an increase in biocrude yield can even be achieved.

If a HTL process is designed to co-liquefy different types of feedstock, shortages of certain types of biomas can be compensated and the feedstock storage can be designed in a smaller scale.

6.2.3 Comparison with literature values

There exist several studies in the literature as techno-economic and life-cycle assessment reports, developed for a variety of feedstock and for a variety of conversion technologies of fuel processing. Reports' contents vary significantly, in terms of specific steps included or assumptions made.

PNNL provide a TEA report for fuel produced from HTL of sewage sludge and subsequent upgrading. The considered process includes HTL plant, cHTG for aqueous phase treatment of HTL and the HTL biocrude is transported to a centralized biocrude upgrading plant, where off-gas is processed in a hydrogen plant [26]. When calculated separately, the HTL plant's biocrude production costs are 0.73 €/kg biocrude and upgrading costs are 0.94 €/kg. Therefore, the total upgraded biocrude costs amount to 1.67 €/kg upgraded biocrude. In another PNNL report [27], HTL processing of wet waste to fuels is analyzed. Biocrude from sludge HTL shows production costs 0.45 €/kg, while upgrading process costs are at 0.67 €/kg upgraded biocrude. Results shows that the total process costs amount to 1.12 €/kg biocrude upgraded. Our results for sewage sludge are lower with a value of 0.44 €/kg upgraded biocrude. This can mainly be related to the fact that we are assuming optimistic conditions regarding negative feedstock costs.

Jiang et al., 2019 [28], modelled a biocrude production from microalage and determined the minimum biocrude selling price as 11.35 USD/GGE (corresponding to 2.17 €/kg upgraded biocrude). 90% of this price results from feedstock costs.

It should be mentioned that biocrude upgrading was not considered in this study. Even with optimistic assumptions, our calculations result in higher production costs when using microalgae (more than 8 €/kg).

A study of Tzanetis et al. [29] assesses the impact of different parameters on production costs of HTL with forestry residues as feedstock and biocrude oil upgrading for renewable jet fuel production. The calculated production costs including upgrading correspond to 1.04-1.25 €/kg upgraded biocrude.

In a study of Magdeldin et al. [30], HTL with lignocellulosic residues is assessed. Biocrude production costs of the HTL process are calculated as 0.96 €/kg biocrude.

It should be mentioned however, that the results of TEA studies are highly dependent on the assumed feedstock costs and the scale of the study. Furthermore, different process configurations can make direct comparisons less meaningful and are very difficult to interpret or adapt for results on a unified consistent basis.

6.3 LCA

6.3.1 GHG in literature

Several life-cycle assessment studies have been performed to quantify the GHG emissions of HTL biofuel production. However, LCA results may differ from study to study, due to varying locations, system configurations, used feedstock, assumptions for key process parameters as well as the treatment of by- and/or co-products.

In the study of Nie al. [31], average GHG emissions for three different HTL scenarios using forest residues as feedstock, are calculated to be 0.817 kg CO_2-Eq./kg ubc. Compared to the herein presented results for lignocellulosic feedstock, this equals a reduction of about 50 %, which is probably caused by the different emissions for heat production as well as the differing process configurations.

A techno-economic study by PNNL [26], also includes a short and preliminary LCA, which suggests the GHG emissions of an HTL process treating municipal wastewater to be between 0.99 and 1.81 kg CO_2-Eq./kg ubc, depending on the values of different parameters. The authors identified the consumed natural gas, covering the HTL heat demand, as the key driver for the GHG emissions. This is quite similar to this report, where the heat demand has also been identified as a key driver of GHG emissions. The total GHG emissions are calculated to be slightly higher compared to the emission values in this report, which might be caused by the assumption of a more efficient heat recovery in this report.

In the study of Fortier et al. [32], the GWP of HTL of microalgae is investigated for bio-jet fuel. In the report, two different pathways were analyzed. The first option considers the HTL reactor to be located directly by the upgrading unit, but not at the WWTP, where the algae production is located. The second option considers the HTL reactor to be located at the WWTP, where algae is cultivated. According to the base case calculations, the algae bio-jet fuel pathway that is performed at the WWTP showed GHG emissions of 1.51 kg CO_2-Eq/ kg ubc, while the refinery pathway was calculated to have GHG emissions of 3.72 kg CO_2-Eq./kg ubc. These values are significantly lower compared to the values calculated in this report. However, this can be explained by the different assumptions for the emissions of algae production. In this report, almost 88% of GHG emissions are generated by algae production, while in the paper by Fortier et al., these emissions are negligible.

6.3.2 Land use change

Indirect land use change (ILUC) emissions arise, when grassland and forests are converted to cropland in order to meet the demand for commodities displaced by the production of HTL feedstock. In contrast, direct land use change occurs when a previous land use is converted to bioenergy crop production. In several studies, the effect of ILUC in GHG emissions is included to assess the overall reduction of GHG of biofuels. Fargione et al. [33] published an article claiming that clearing the lands in the scope of biofuel feedstock production created a carbon deficit.

Lignocellulosic feedstock, particularly residual woody biomasses represent the largest availability of low indirect land use change (ILUC) biomass in Europe for advanced biofuels production due to the large amounts produced as forestry and agriculture residues [34]. HTL fuels produced from sewage sludge and microalgae are linked to a lower risk of negative indirect land use change.

6.3.3 Fossil vs. biogenic carbon emissions

One key assumption that was made for all four feedstock is that the carbon contained in the feedstock biomass is considered to be biogenic, which means, that no impacts are associated with emissions coming from the feedstock source. For the global warming potential, this is considered as the carbon capture credit. As compensation for this credit, all the emissions associated with the feedstock biomass are considered. Since the amount of CO_2 bound in the biomass ranges from 4.8 to 6.5 kg per kg of ubc production, this corresponds to significant savings.

6.3.4 Process design options for an improved performance

Looking at the LCA results and in particular at the drivers of the emissions, it becomes clear that there are several options of improving the environmental footprint of a fuel production pathway via HTL. First of all, CO_2 off-gas plays a major role. In the current process scheme, it is assumed that the off-gas is simply vented into the atmosphere, inducing considerable emissions. However, CO_2 can be considered as a valuable feedstock for other fuel production pathways, such as the Power-to-Liquid pathway, including Fischer-Tropsch or methanol-to-jet synthesis routes. Furthermore, the heat demand of process steps including high temperatures and large amounts of water (HTL and cHTG) has a considerable impact. Therefore, a sustainable way of heat generation and an optimal heat integration system are indispensable for further reducing the impact of the HTL fuel production pathway. This could include, for example, heat from a concentrated solar power station. Renewable electricity can also play a role, however, the amounts of electricity are quite small compared to those of the heat demand. Renewable electricity could be used for the generation of hydrogen via electrolysis though, reducing the amount of externally required natural gas. Regarding the topic of net negative emissions, an important role could be played by carbon sequestration in the form of the HTL solids. This topic is not investigated adequately yet from an LCA perspective, which represents an interesting and important research gap. Future work should focus on implementing these alternative design options into the HTL process chain, on the one hand experimentally, and on the other hand on a system analysis basis. Optimizing all mentioned aspects might open the opportunity for a net negative emission pathway.

6.4 Economic and ecological trade-off

Figure 35 shows a trade-off graph of MFSP vs. GHG emissions for the process configurations of sewage sludge, miscanthus and cereal straw. The results for microalgae are not shown, because these are significantly higher for both GHG emissions (5.34 kg CO_2-Eq./kg ubc) as well as MFSP (8.26 €/kg ubc). The best result can be observed for sewage sludge, because feedstock costs can be declared negative, due to the substitution of the current disposal pathway. Costs of cereal straw are equal to those of sewage sludge due to the effects of economy of scale, the GHG emissions are higher though, due to the effects of a different process configuration (water recycling). Miscanthus shows almost similar GHG emissions as cereal straw, due to the same process configuration (water recycling), The costs are much higher, due to higher feedstock costs for miscanthus. The error bars are calculated based on different interest rates in the case of the MFSP and based on different assumptions for the heat provision and heat recovery in the case of GHG emissions, since these parameters were identified as key drivers.

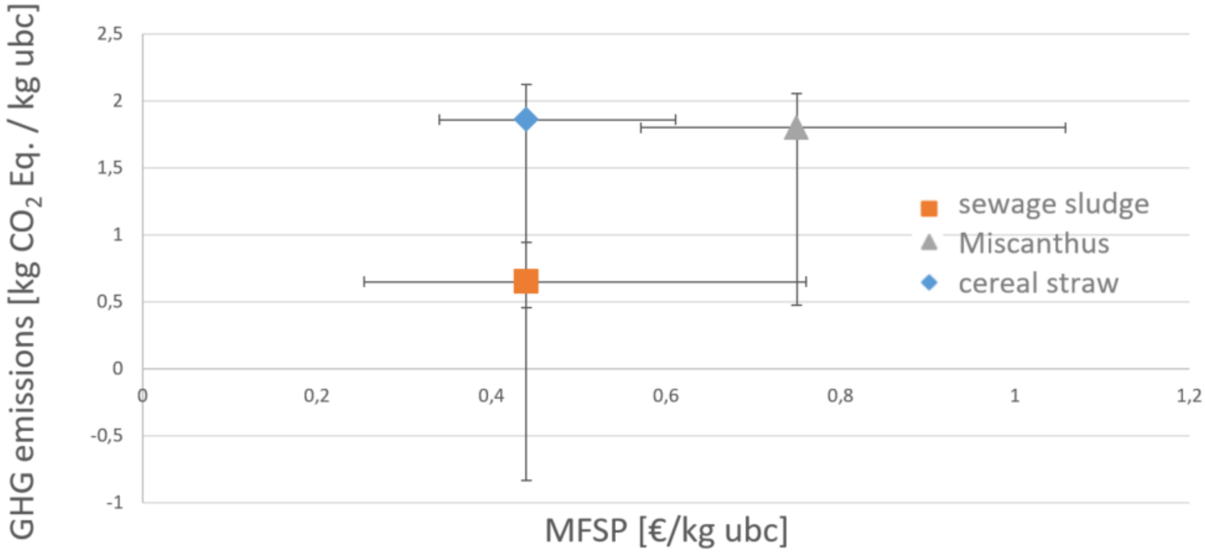

Figure 35: *MFSP vs. GHG emissions for the different HTL cases investigated in this report.*

7. Conclusions

In the following, the main conclusions, both for the TEA and LCA, are described.

Different process configurations have been investigated from an economic perspective and the main results for individual process steps are described herein. First of all, on-site hydrogen production was found to be favorable compared to acquisition of hydrogen from an economic point of view. Furthermore, nutrient recovery is linked with additional costs. However, especially in the case of sewage sludge, nutrient recovery is essential and necessary from an environmental point of view in order to avoid nutrient losses.

It could be observed that fuel production costs (i.e. minimum fuel selling prices, MFSP) are different for different feedstock. Sewage sludge presents itself as suitable for cost-effective fuel production (MFSP = 0.44 €/kg ubc) on a small-scale, however, the feedstock availability for sewage sludge is limited. Higher production potentials can be observed for straw (MFSP = 0.44 €/kg ubc) and miscanthus (MFSP = 0.75 €/kg ubc) and, due to economy of scale effects, costs for the fuel production from these feedstock are also competitive.

Several cost drivers could be identified for operating costs as well as for direct and indirect investment costs. Operating costs include feedstock costs with a major impact, but also loan costs and costs for natural gas demand play a role. Looking at the direct investment costs it becomes clear, that the HTL process (~40%) dominates, but also other sub-processes of the fully integrated plant account for large parts. Indirect investment costs are highly dependent on the location of the HTL site, since interest rates, expressed as weighted average cost of capital (WACC) vary quite significantly.

The main results from the environmental perspective include that GHG emissions are significantly different for different feedstock. HTL with sewage sludge (0.65 kg CO_2 Eq./kg ubc) shows the lowest GWP, while lignocellulosic feedstock are quite similar (1.80 kg CO_2 Eq./kg ubc for miscanthus and 1.86 kg CO_2 Eq./kg ubc for wheat straw). Due to very high emissions stemming from algae production, the total emissions for HTL with microalgae is 5.34 kg CO_2 Eq./kg ubc. The impact of the feedstock does play a major role here, as can be seen for the result for microalgae e.g. The main impacts from the different process steps can be observed for the HTL, the cHTG and the H_2 plant process steps. In the case of sewage sludge, also the nutrient recovery plays a role. These impacts can be explained by the main emission drivers, which are the direct emissions (mainly CO_2) and the heat demand to heat the large amounts of water. These drivers are also the reason why HTL with sewage sludge has a lower GWP compared to lignocellulosic feedstock. Aqueous phase (AP) recycling in the cases of lignocellulosic feedstock lead to an increase in gaseous phase in the HTL and therefore to a higher portion of direct emissions. Furthermore, AP recycling leads to a lower amount of organics that can be converted into biogas in the cHTG, which leads to a lower share of internally usable methane in the CHP (50 % for sewage sludge, ~ 15% for lignocellulosic feedstock). However, the major emission drivers also present possible improvements for future HTL plant process configurations. Future work should include the assessment of using the CO_2 off-gas, covering the heat demand with renewable sources and using electrolysis with renewable electricity for hydrogen production for hydrotreating.

Considering a trade-off of both LCA and TEA results, it becomes obvious that sewage sludge shows the best performance. Both lignocellulosic feedstock straw and mischanthus show a higher GWP, straw however is economically competitive to sewage sludge due to effects for economy of scale. Microalgae shows high GWP and MFSP values due to microalgae production.

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Appendix

Table A1: Description for used commodity codes

Commodity code	*Commodity description*
2807	Sulphuric acid; oleum
2815	Sodium hydroxide (caustic soda); potassium hydroxide (caustic potash) peroxides of sodium or potassium
7304	Tubes, pipes and hollow profiles, seamless, of iron (other than cast iron) or steel
7309	Reservoirs, tanks, vats and similar containers; for any material (excluding compressed or liquefied gas), of iron or steel, capacity exceeding 300l, whether or not lined or heat insulated
7311	Containers for compressed or liquefied gas, of iron or steel
8413	Pumps; for liquids, whether or not fitted with measuring device, liquid elevators
8414	Air or vacuum pumps, air or other gas compressors and fans; ventilating or recycling hoods incorporating a fan whether or not fitted with filters
8416	Furnace burners for liquid fuel, for pulverised solid fuel or for gas; mechanical grates, mechanical ash dischargers and similar appliances
8421	Centrifuges, including centrifugal dryers; filtering or purifying machinery and apparatus for liquids or gases
8460	Machine-tools; for deburring, sharpening, grinding, honing, lapping, polishing or otherwise finishing metal, sintered metal carbides or cermets by means of grinding stones, abrasives or polishing products
8471	Automatic data processing machines and units thereof, magnetic or optical readers, machines for transcribing data onto data media in coded form and machines for processing such data, not elsewhere specified or included
282731	Chlorides; of magnesium
381519	Catalysts, supported; reaction initiators, reaction accelerators and catalytic preparations, with an active substance other than nickel or precious metals or their compounds, n.e.c. or included
840682	Turbines; steam and other vapour turbines, (for other than marine propulsion), of an output not exceeding 40MW
841911	Heaters; instantaneous gas water heaters, for domestic or other purposes
841950	Heat exchange units; not used for domestic purposes
841989	Machinery, plant and laboratory equipment; for treating materials by change of temperature, other than for making hot drinks or cooking or heating food
842119	Centrifuges; n.e.c. in heading no. 8421, including centrifugal dryers (but not clothes-dryers)
842121	Machinery; for filtering or purifying water
842129	Machinery; for filtering or purifying liquids, n.e.c. in item no. 8421.2
847982	Machines; for mixing, kneading, crushing, grinding, screening, sifting, homogenising, emulsifying or stirring

Table A2: Description for used industry codes

Industry code	*Description*
D20T21	Chemical and pharmaceutical products
D25	Fabricated metal products, except machinery and equipment
D26	Computer, electronic and optical products
D28	Machinery and equipment n.e.c.
D35T39	Electricity, gas and water supply; sewerage, waste management and remediation activities
D41T43	Construction
D69T82	Real estate, renting and business activities

Table A3: Installation cost for a HTL plant

Equipment parts	**[Equipment type considered in TEA]**	**Commodity code**	**Industry Code**	**Equipment cost in €**	**Installation costs in €**
		Pretreatment			
Dewatering (for wet feedstock only)	Centrifuges, atmospheric suspended basket	8421	D28	266,474	399,711
Extruder (for dry feedstock only)	Pulverizer	8460	D28	0	0
Feed hopper	Static mixer	847982	D28	796	1,193
additional costs electronics	additional costs electronics	8471	D26	26,727	40,090
additional costs piping	additional costs piping, steel	7304	D25	26,727	40,090
		HTL			
Tank sewage sludge	Tank, floating roof	7309	D25	201,655	302,482
Pump Feed slurry	single stage, centrifugal	8413	D28	1,544	4,633
Pump HEX	single stage, centrifugal	8413	D28	1,426	4,277
HTL reactor and HEX	pipe reactor and pipe in pipe heat exchanger	841989	D25	1,373,145	4,119,436
Hydrocyclone	Centrifuges, atmospheric suspended basket	842119	D28	29,241	58,483
Gravimetric separator	Centrifuges, atmospheric suspended basket	842119	D28	24,836	49,672
Tank biocrude	Tank, floating roof	7309	D25	40,774	61,161
Tank AP	Tank, floating roof	7309	D25	68,650	102,974
Tank Solids	Tank, cone roof	7309	D25	22,374	33,561
additional costs electronics	additional costs electronics	8471	D26	260,013	390,019
additional costs piping	additional costs piping	7304	D25	260,013	390,019
		cHTG			
AP Mebrane concentation	Centrifuges, atmospheric suspended basket	8421	D28	28,599	42,899
Pump AP	single stage, centrifugal	8413	D28	1,787	5,362
Pump HEX	single stage, centrifugal	8413	D28	1,494	4,481
cHTG salt separator	reactor, jacketed, agitated	841989	D25	182,556	547,669

cHTG reactor	reactor, jacketed, agitated	841989	D25	211,857	635,571
HEX	Plate and frame	841950	D28	126,349	379,048
Filter treated water	Plate and frame	842121	D28	52,463	78,694
PSA methane concentration (PSA)	reactor, jacketed, agitated	841989	D25	69,068	207,204
Tank Treated water	Floating roof	7309	D25	68,650	102,974
High pressure gas vessel	vertical, 304 ss	7311	D25	10,064	30,191
additional costs electronics	additional costs electronics	8471	D26	111,479	167,219
additional costs piping	additional costs piping	7304	D25	111,479	167,219
Hydrotreating (onsite)					
Pump biocrude	single stage, centrifugal	8421	D28	1,671	5,014
Reactor 1st stage	jacketed, agitated	841989	D25	21,043	63,129
Reactor 2nd stage	jacketed, agitated	841989	D25	99,638	298,915
HEX	U-tube shell and tube	841950	D28	385,384	1,156,152
Pump HEX	single stage, centrifugal	8421	D28	1,721	5,163
Tank upgraded biocrude	Tank, floating roof	7309	D25	43,152	64,728
High pressure gas vessel	vertical, 304 ss	7309	D25	8,792	26,375
Gas compressor	Centrifugal compressor	8414	D28	176,570	264,856
additional costs electronics	additional costs electronics	8471	D26	104,892	157,338
additional costs piping	additional costs piping	7304	D25	104,892	157,338
Nutrient recovery					
Pump AP	single stage, centrifugal	8421	D28	1,728	5,183
Pump solids	single stage, centrifugal	8421	D28	1,712	5,135
Tank N-Solution	Tank, cone roof	7309	D25	25,924	38,886
Tank H2SO4	Tank, cone roof	7309	D25	5,345	8,017
Tank MgCl2	Tank, cone roof	7309	D25	3,753	5,629
Tank NaOH	Tank, cone roof	7309	D25	3,721	5,581
Reactor 1	jacketed, agitated	841989	D25	21,043	63,129
Reactor 2	jacketed, agitated	841989	D25	17,605	52,816
Reactor 3 (Crystallizer)	jacketed, agitated	841989	D25	41,529	124,587
Struvite separation	Plate and frame filter	842129	D28	50,986	76,479
Tank precipitate	Tank, floating roof	7309	D25	42,472	63,707
Solid filter	Plate and frame	842129	D28	50,986	76,479
additional costs electronics	additional costs electronics	8471	D26	28,020	42,030
additional costs piping	additional costs piping	7304	D25	28,020	42,030
H2 plant					
Pump HEX	single stage, centrifugal	8421	D28	1,657	4,971
HEX	U-tube shell and tube	841950	D28	5,962	17,886
Steam drum	Evaporator, vertical tube	841950	D28	44,834	44,834
Reformer	Reactor jacketed, agitated	841989	D25	36,914	110,743
Desulfirization I	Reactor jacketed, agitated	841989	D25	36,914	110,743

Desulfirization II	Reactor jacketed, agitated	841989	D25	36,914	110,743
Water pump	single stage, centrifugal	8421	D28	1,654	4,962
H2 pump	Condensing steam cycle	8421	D28	8,171	24,512
PSA I	Reactor jacketed, agitated	841989	D25	50,999	152,997
PSA II	Reactor jacketed, agitated	841989	D25	36,914	110,743
PSA III	Reactor jacketed, agitated	841989	D25	35,520	106,560
H2 pressure gas vessel	vertical, 304 ss	7311	D25	10,597	31,792
additional costs electronics	additional costs electronics	8471	D26	45,541	68,312
additional costs piping	additional costs piping	7304	D25	45,541	68,312
		CHP			
Compressor	Centrifugal compressor	8414	D28	184,854	277,281
Steam heater	Evaporator, vertical tube	841911	D28	49,845	49,845
Furnace	Cylidrical	8416	D28	191,000	191,000
Gas turbine	Condensing steam turbine	840682	D28	73,804	110,706
Steam turbine I	Condensing steam turbine	840682	D28	4,787	7,180
Steam turbine II	Condensing steam turbine	840682	D28	2,001	3,001
Pump HEX	single stage, centrifugal	8414	D28	1,731	5,194
HEX	U-tube shell and tube	841950	D28	10,507	31,521
additional costs electronics	additional costs electronics	8471	D26	23,885	7,880
additional costs piping	additional costs piping	7304	D25	23,885	7,880
Total				**5,815,271**	**12,834,629**

Table A4: Operation cost for a HTL plant

Name	Industry code	Commodity code	cost in €/year	Total cost over 20 years in €
Natural gas	D35T39	n. A.	1,359,576	27,191,511
H2SO4	D20T21	2807	131,633	2,632,659
NaOH	D20T21	2815	39,891	797,829
MgCl2	D20T21	282731	170,016	3,400,325
Waste water treatment	D35T39	n. A.	255,827	5,116,546
Catalysts	D20T21	381519	162,693	3,253,869
Workforce	D69T82	n. A.	1,383,084	27,661,672
Total				**70,054,413**

Table A5: LCA data

Activity		amount	amount	amount	amount	
Biogas PSA and gas cleaning		**Sewage sludge**	**Miscanthus**	**Wheat straw**	**Microalgae**	**unit**
product	methane	1	1	1	1	kg
Exchanges						
Carbon dioxide		1.398082	1.398082	1.398082	1.398082	kg
Heat and power co-generation, natural gas	Power	0.00048	0.00048	0.00048	0.00048	kWh
Heat and power co-generation, natural gas	Heat	2.036238	2.036238	2.036238	2.036238	MJ
Facility and construction		**Sewage sludge**	**Miscanthus**	**Wheat straw**	**Microalgae**	
product	Facility	1	1	1	1	unit
Exchanges						
CHP construction		1	1	1	1	unit
Chemical factory construction, organics		0.01	0.01	0.01	0.01	unit
Feedstock drying		**Sewage sludge**	**Miscanthus**	**Wheat straw**	**Microalgae**	
product	20 wt% raw sewage sludge	1	-	-	-	kg
Exchanges						
Chemical factory construction		3.41e-07	-	-	-	Kg
Market for electricity, medium voltage		0.005908	-	-	-	kWh
Feedstock transport		**Sewage sludge**	**Miscanthus**	**Wheat straw**	**Microalgae**	
Product	Feedstock transport with specific radius	1	1	1	1	
Exchanges						
Market for lorry, 40 metric ton		0	1	1	1	unit
H2 plant		**Sewage sludge**	**Miscanthus**	**Wheat straw**	**Microalgae**	
Product	hydrogen	1	1	1	1	kg
Exchanges						

Carbon dioxide, fossil		0.499878	0.586752	0.615006	0.294894	kg
H2 plant catalyst		8.64e-07	4.02e-07	4.02e-07	4.02e-07	kg
Heat and power co-generation, natural gas	Power	0.000758	0.000824	0.000733	0.000661	kWh
Heat and power co-generation, natural gas	Heat	1.552804	1.513059	1.226738	2.71646	MJ
Market for natural gas, high pressure		0.25148	0.333283	0.369596	0.17463	m³
Market for water, deionised		0.206281	0.218229	0.222115	0.178089	kg
H2 plant catalyst		**Sewage sludge**	**Miscanthus**	**Wheat straw**	**Microalgae**	
Product	H2 plant catalyst	1	1	1	1	kg
Exchanges						
Market for aluminium oxide, non-metallurgical		0.18	0.18	0.18	0.18	kg
market for copper oxide		0.52	0.52	0.52	0.52	Kg
market for electricity, medium voltage		0.608016	0.608016	0.608016	0.608016	kWh
market for natural gas, high pressure		0.19476	0.19476	0.19476	0.19476	m³
market for steam, in chemical industry		0.118439	0.118439	0.118439	0.118439	Kg
market for water, deionised		9.9e-07	9.9e-07	9.9e-07	9.9e-07	Kg
market for water, ultrapure		0.573722	0.573722	0.573722	0.573722	Kg
market for zinc oxide		0.3	0.3	0.3	0.3	kg
Hydrotreating		**Sewage sludge**	**Miscanthus**	**Wheat straw**	**Microalgae**	
Product	Upgraded biocrude	1	1	1	1	kg
Exchanges						
Mo catalyst		0.000145	0.000142	0.000142	0.000142	kg
NiMo catalyst		0.000145	0.000142	0.000142	0.000142	kg
Heat and power co-generation, natural gas		0.000318	0.000403	0.000343	0.000262	kWh
Heat and power co-generation, natural gas		0.8064	0.999094	0.999094	0.695958	MJ
Treatment of wastewater from vegetable oil refinery		-0.00018	-0.00028	-0.00028	-6.8e-05	m³
HTL		**Sewage sludge**	**Miscanthus**	**Wheat straw**	**Microalgae**	
Product	biocrude	1	1	1	1	kg
Exchanges						

Carbon dioxide		0.291904	1.690888	0.722548	0.871251	kg
Heat and power co-generation, natural gas	Power	0.007332	0.007741	0.009867	0.007996	kWh
Heat and power co-generation, natural gas	Heat	7.102582	8.221632	10.84751	6.971888	MJ
Incineration SeSl		**Sewage sludge**	**Miscanthus**	**Wheat straw**	**Microalgae**	
Product	92 wt% raw sewage sludge	1	-	-	-	
Exchanges						
treatment of raw sewage sludge, municipal incineration with fly ash extraction	Electricity	0.074	-	-	-	kWh
treatment of raw sewage sludge, municipal incineration with fly ash extraction	Heat	0.722	-	-	-	MJ
treatment of raw sewage sludge, municipal incineration with fly ash extraction	92 wt% raw sewage sludge	1	-	-	-	kg
Mo catalyst		**Sewage sludge**	**Miscanthus**	**Wheat straw**	**Microalgae**	
Product	Mo catalyst	1	1	1	**1**	kg
Exchanges						
market for aluminium oxide, non-metallurgical		0.83	0.83	0.83	0.83	kg
market for electricity, medium voltage		0.608015	0.608015	0.608015	0.608015	kWh
market for molybdenum		0.17	0.17	0.17	0.17	kg
market for natural gas, high pressure		0.0021	0.0021	0.0021	0.0021	M^3
market for steam, in chemical industry		1.18439	1.18439	1.18439	1.18439	kg
market for water, deionised		0.990075	0.990075	0.990075	0.990075	kg
market for water, ultrapure		0.573722	0.573722	0.573722	0.573722	kg

NiMo catalyst		Sewage sludge	Miscanthus	Wheat straw	Microalgae	
Product	NiMo catalyst	1	1	1	1	kg
Exchanges						
market for aluminium oxide, non-metallurgical		0.83	0.83	0.83	0.83	kg
market for electricity, medium voltage		0.608015	0.608015	0.608015	0.608015	kWh
market for molybdenum		0.13	0.13	0.13	0.13	kg
market for natural gas, high pressure		0.0021	0.0021	0.0021	0.0021	m^3
market for nickel, class 1		0.04	0.04	0.04	0.04	kg
market for steam, in chemical industry		1.18439	1.18439	1.18439	1.18439	kg
market for water, deionised		0.990075	0.990075	0.990075	0.990075	kg
market for water, ultrapure		0.573722	0.573722	0.573722	0.573722	kg
Nutrient Recovery		**Sewage sludge**	**Miscanthus**	**Wheat straw**	**Microalgae**	
Product	struvite	-	-	-	-	
Exchanges						
Heat and power co-generation, natural gas		0.040485	-	-	-	kWh
market for NPK (15-15-15) fertiliser		-1	-	-	-	kg
market for magnesium oxide		0.332903	-	-	-	kg
market for sodium hydroxide, without water, in 50% solution state		0.769187	-	-	-	kg
market for sulfuric acid		1.760297	-	-	-	kg
treatment of HTL solids residue		0.862249	-	-	-	kg
treatment of wastewater from vegetable oil refinery		-0.20056	-	-	-	m^3
Sewage Sludge Supply		**Sewage sludge**	**Miscanthus**	**Wheat straw**	**Microalgae**	
Product	Feedstock	1	1	1	1	kg
Exchanges						
Feedstock drying		5	-	-	-	kg

Incineration SeSl		1.086957	-	-	-	kg
Drying, sewage sludge		20	-	-	-	kg
carbon capture credit		**Sewage sludge**	**Miscanthus**	**Wheat straw**	**Microalgae**	
Product	feedstock	1	1	1	1	kg
Exchanges						
Carbon dioxide, fossil		-1.44	-1.72	-1.80	-1.72	kg
Transport of fuel mix						
Product	Transport of fuel mix	1	1	1	1	t km
Exchanges						
market for transport, freight, lorry 7.5-16 metric ton, EURO6		1	1	1	1	t km
cHTG		**Sewage sludge**	**Miscanthus**	**Wheat straw**	**Microalgae**	
Product	methane	1	**1**	**1**	**1**	
Exchanges						
Biogas PSA and gas cleaning		1	1	**1**	**1**	kg
cHTG catalyst		0.000156	2.87e-06	2.87e-06	2.87e-06	kg
cHTG sulfur trap catalyst		0.000156	2.87e-06	2.87e-06	2.87e-06	kg
Heat and power co-generation, natural gas		0.008997	0.007587	0.006562	0.011046	kWh
Heat and power co-generation, natural gas		18.87833	15.92094	13.77027	23.17886	MJ
Treatment of wastewater from vegetable oil refinery		-0.02665	-0.03794	-0.03281	-0.03738	m³
cHTG catalyst		**Sewage sludge**	**Miscanthus**	**Wheat straw**	**Microalgae**	
Product	Ru/C catalyst	1	1	1	1	kg
Exchanges						
market for activated carbon, granular		0.95	0.95	0.95	0.95	kg
market for electricity, medium voltage		0.608015	0.608015	0.608015	0.608015	kWh
market for natural gas, high pressure		0.0021	0.0021	0.0021	0.0021	m³
market for steam, in chemical industry		1.18439	1.18439	1.18439	1.18439	kg
market for water, deionised		0.990075	0.990075	0.990075	0.990075	kg
market for water, ultrapure		0.573722	0.573722	0.573722	0.573722	kg

platinum group metal, extraction and refinery operations		0.0088	0.0088	0.0088	0.0088	kg
cHTG sulfur trap catalyst		**Sewage sludge**	**Miscanthus**	**Wheat straw**	**Microalgae**	
Product	cHTG sulfur trap catalyst	1	1	1	1	kg
Exchanges						
market for aluminium oxide, non-metallurgical		0.1	0.1	0.1	0.1	kg
market for electricity, medium voltage		0.608015	0.608015	0.608015	0.608015	kWh
market for natural gas, high pressure		0.0021	0.0021	0.0021	0.0021	m³
market for steam, in chemical industry		1.18439	1.18439	1.18439	1.18439	kg
market for water, deionised		0.990075	0.990075	0.990075	0.990075	kg
market for water, ultrapure		0.573722	0.573722	0.573722	0.573722	kg
market for zinc oxide		0.9	0.9	0.9	0.9	kg
Drying, sewage sludge		**Sewage sludge**	**Miscanthus**	**Wheat straw**	**Microalgae**	
Product	5 wt% raw sewage sludge	-1	-	-	-	kg
Exchanges						
Market for electricity, medium voltage		0.00225	-	-	-	kWh
market for heat, district or industrial, natural gas		0.173364	-	-	-	MJ
market for heat, district or industrial, other than natural gas		0.173364	-	-	-	MJ
market for sewage sludge, dried		-0.05435	-	-	-	kg
Market for wastewater, average		-0.00095	-	-	-	m³
Treatment of HTL solid residue		**Sewage sludge**	**Miscanthus**	**Wheat straw**	**Microalgae**	

Product	HTL solids, landfilled	-1	-1	**-1**	**-1**	kg
Exchanges						
The HTL solids are modeled with different ecoinvent landfilling activities for the different feedstock.						
Pretreatment		**Sewage sludge**	**Miscanthus**	**Wheat straw**	**Microalgae**	
Product	Feedstock	1	**1**	**1**	**1**	kg
Exchanges						
Heat and power co-generation, natural gas		-	0.031189	0.039827	0.029539	
Market for potassium hydroxide		-	0.014752	0.01849	**-**	
Market for water, decarbonised		-	0.053682	0.41293	3.863009	
Feedstock production		**Sewage sludge**	**Miscanthus**	**Wheat straw**	**Microalgae**	
Product	Feedstock	1	1	1	1	kg
Exchanges						
Miscanthus production		-	1	-	-	kg
Straw production		-	-	1	-	
Microalgae production		-	-	-	1	
Transport of feedstock		**Sewage sludge**	**Miscanthus**	**Wheat straw**	**Microalgae**	
Product	Transport of feedstock	1	1	1	1	t km
Exchanges						
market for transport, freight, lorry 16-32 metric ton, EURO6		1	1	1	1	t km

Table A6: LCA reference flows

Reference flow	Amount	Unit	Product	Activity
		Sewage sludge		
1	1.3795	kg	Biocrude	HTL
2	1.9458e-09	unit	Facility	Facility and construction
3	3.8711	kg	Feedstock	Sewage sludge supply
4	0.2905	kg	Hydrogen	H2 plant
5	0.058076	kg	Struvite	Nutrient recovery
6	1	kg	Upgraded biocrude	HT
7	0.27906	kg	methane	cHTG
8	0.3	t km	Transport of fuel mix	Transport of fuel mix

9	3.8711	kg	Sewage sludge	carbon capture credit
		Miscanthus		
1	0.42891	t km	Transport of feedstock	Transport of feedstock
2	0.36392	kg	Hydrogen	H2 plant
3	1	kg	Upgraded biocrude	HT
4	1.5613	kg	Biocrude	HTL
5	0.3	t km	Transport of fuel mix	Transport of fuel mix
6	3.7955	kg	Miscanthus pretreated	Miscanthus pretreatment
7	3.7955	kg	Miscanthus	Micanthus production
8	3.7955	kg	Miscanthus	carbon capture credit
		Wheat straw		
1	0.36485	t km	Transport of feedstock	Transport of feedstock
2	0.39651	kg	Hydrogen	H2 plant
3	1	kg	Upgraded biocrude	HT
4	1.2567	kg	Biocrude	HTL
5	0.3	t km	Transport of fuel mix	Transport of fuel mix
6	2.931	kg	Straw pretreated	Straw pretreatment
7	2.931	kg	Straw	Straw production
8	2.931	kg	Straw	Carbon capture credit
9	0.077685	kg	Methane	cHTG
10	0.088972	kg	HTL solids, landfilled	Treatment of HTL solid residue
11	8.2146e-10	unit	Facility	Facility and construction
		Microalgae		
1	0.38084	t km	Transport of feedstock	Transport of feedstock
2	0.19681	kg	Hydrogen	H2 plant
3	1	kg	Upgraded biocrude	HT
4	1.1909	kg	Biocrude	HTL
5	0.3	t km	Transport of fuel mix	Transport of fuel mix
6	3.3701	kg	Microalgae	Microalgae pretreatment
7	3.3701	kg	Microalgae	Microalgae production
8	3.3701	kg	Microalgae	Carbon capture credit
9	0.22404	kg	Methane	cHTG
10	0.17872	kg	HTL solids, landfilled	Treatment of HTL solid residue
11	1.9456e-09	unit	Facility	Faclity and construction

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