HyFlexFuel

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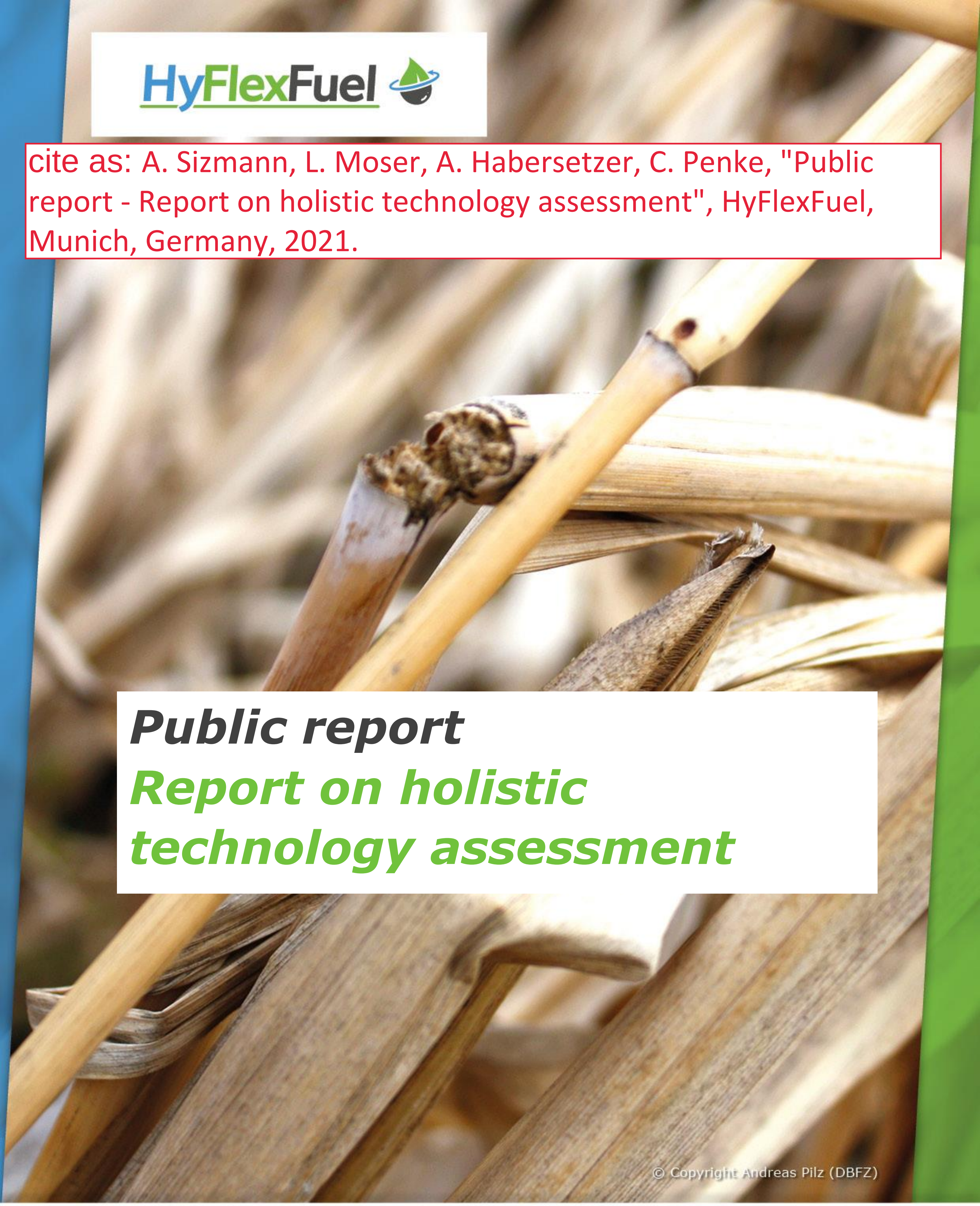

# Public report
# Report on holistic technology assessment



This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No.764734

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# Project Information

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# Public Report – Report on holistic technology 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 and performs system analyses that investigate the performance of the fuel conversion technology with respect to a number of key performance indicators. This public report presents the holistic assessment of alternative production pathways in comparison with hydrothermal liquefaction. A set of key criteria was selected, corresponding to key questions in the context of renewable fuels, taking techno-economic, environmental as well as social criteria into account at the same time in a multiple-criteria framework. The performance with respect to each criterion is evaluated and combined in a common figure of merit. The holistic technology assessment applied to a "sustainable development" and a "rapid deployment" scenario shows that HTL conversion of lignocellulosic residues and sewage sludge achieves high figures of merit in both scenarios, which implies that the priorities in both scenarios are attained at a very high level. In addition, a dual-criteria trade-off representation of techno-economic and GHG emission performance for the selected set of biofuel production pathways showed that HTL fuels can achieve both cost competitiveness with conventional jet fuel and GHG emission reduction by 80%.*

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# *Executive Summary*

Hydrothermal liquefaction (HTL) can convert a broad range of organic feedstock into an intermediate biocrude that can be subsequently upgraded to a transportation fuel product via hydrotreatment. One key advantage is that the hydrothermal processing can handle wet feedstock without excessive drying, another potential advantage is a potentially low capital investment into the conversion systems compared to competing renewable fuel pathways.

This public report presents the holistic assessment of the HTL production pathway within the H2020 project HyFlexFuel. A set of five most relevant criteria was selected, including technical maturity, substitution potential, cost competitiveness, greenhouse gas emission reduction and social benefit of local value creation, which correspond to key questions in the context of decision making in renewable fuels. These criteria take techno-economic, environmental as well as social criteria into account and can be combined in a multiple-criteria assessment (MCA) framework. The performance with respect to each criterion was evaluated as well as combined figures of merit (FOMs) from the MCA framework. The holistic assessment includes a comparison of HTL fuels with other renewable production pathways towards liquid fuels. In total nine alternative fuel pathways were selected from a combination of six feedstock categories and six conversion technologies. Potentials and advantages as well as risks and drawbacks associated with the examined HTL approach are assessed in an integrated, qualitative and quantitative way. The MCA is applied to three distinct scenarios, one in which all criteria are weighted equal ("neutral" scenario with no priorities) and two scenarios with a distinct divergence of priorities, in which the criteria are weighted differently. A *"sustainable development"* scenario assigns a high priority on long-term environmental and socio-economic benefits. A *"rapid deployment"* scenario gives priority to high technical maturity and economic viability for early commercial ramp-up of production.

The resulting figures of merit of HTL- and HEFA-based renewable fuel production tend to be rather stable under both scenarios conditions, showing robust results under the assumptions and database applied for this assessment.

In our multiple-criteria assessment framework HTL conversion of lignocellulosic residues and of sewage sludge as modelled in HyFlexFuel achieve high figures of merit: 75% and 70%, respectively, in the sustainable development scenario and both 90% in the rapid deployment scenario, which implies that the priorities in both scenarios are attained at a very high level.

These results are just a first indication for decision makers in the greater advanced sustainable fuel landscape of technologies. The results not "written in stone", the FOMs will change as science, technology and policy advance.

In addition, a dual-criteria techno-economic and GHG emission trade-off was visualized on the selected set of advanced biofuel production pathways.

While many evaluated options provide substantially reduced specific GHG emissions in comparison to conventional jet fuel, only HTL and BtL seem to offer a substantial emission reduction for the database used in this assessment. The TEA data shows rather high values for BtL and a wide spread of HTL values which depend on the feedstock and the modelling assumptions. No general conclusion can therefore be

formulated for the overall performance of HTL. It has been found that HTL conversion independent of the feedstock penalty contributes only a minor share to cost and emissions and thus has the potential for promising techno-economic (TEA) and life-cycle (LCA) emission performance. HTL fuels can achieve, cost competitiveness with conventional jet fuel and GHG emission reduction by 80%.

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# Glossary

| **Abbreviation Acronym** | **Description** |
|---|---|
| µA | Microalgae |
| AD | Anaerobic digestion |
| AP | Aqueous phase |
| ASTM | American society for testing and materials |
| ATAG | Air transport action group |
| AtJ | Alcohol-to-jet |
| AtJ-SKA | Alcohol-to-jet Synthetic kerosene with aromatics |
| BFSJ | Production of fully synthetic paraffinic jet fuel from wood and other biomass (EU project) |
| BioTFuel | Biomass to Fuel |
| BtL | Biomass-to-liquid |
| CAAFI | Commercial Aviation Alternative Fuels Initiative |
| cHTG | Catalytic hydrothermal gasification |
| CI | Carbon intensity |
| $CO_2$-eq. | $CO_2$ equivalent |
| COVID19 | Corona virus disease 2019 |
| CTRL | Conversion Technology Readiness Level |
| DAC | Direct air capture |
| DM | Dry matter |
| EU | European Union |
| EUR | Euro |
| FOG | Fats, oils and grease |
| FOM | Figure of merit |
| FSRL | Feedstock Readiness Level |
| FT | Fischer-Tropsch |
| FT-SPK | Fischer-Tropsch Synthetic Paraffinic Kerosene |
| GHG | Greenhouse gas |
| HEFA | Hydroprocessed esters and fatty acids |
| HTL | Hydrothermal liquefaction |

| | |
|---|---|
| ILUC | Indirect land-use change |
| JP-8 | Jet Propellant 8 |
| Kg | Kilogram |
| L | Liter |
| LCA | Life cycle assessment |
| LigC | Lignocellulosic |
| MCA | Multiple-criteria assessment |
| MFSP | Minimum Fuel Selling Price |
| MSW | Municipal solid waste |
| Mt | Mega tonne |
| MtG | Methanol-to-gasoline |
| Mtoe | Mega tonne oil equivalent |
| NUTS | Nomenclature des unites territoriales statistiques |
| OPEX | Operational expanses |
| PNNL | Pacific Northwest National Laboratory |
| PtL | Power-to-liquid |
| PV | Photovoltaic |
| RED II | Renewable energy directive |
| RFNBO | Renewable fuels of non-biological origin |
| SAF | Sustainable aviation fuel |
| Sew | Sewage sludge |
| StL | Sunlight-to-liquid |
| TEA | Techno-economic assessment |
| TR score | Technology readiness score |
| TRL | Technology Readiness Level |
| USD | United states dollar |
| Vs. | Versus |
| WtL | Waste-to-liquid |
| WtT | Well-to-tank |
| WtW | Well-to-wake |

# 1. Introduction

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]. To reverse this trend, 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, 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. The current European regulation aims at an increased share of biofuel production from advanced feedstock.

Within the transportation sector, the decarbonisation of aviation of the global fleet and transport aircraft that are currently in production is especially dependent on renewable drop-in kerosene-type turbine fuel[1]. Currently, the biofuels share of jet fuel is well below 1% (in 2020) and is mainly derived from plant oils (incl. used cooking oil) and fats via the HEFA process, for which the availability of sustainable feedstock limited.

Various conversion technologies are under development to convert advanced feedstock such as sewage sludge, municipal solid waste, forest residues, agricultural residues or microalgae into drop-in fuels. Relatively mature conversion technologies that can produce large additional volumes of kerosene range fuels from sustainable feedstock include bio-based Fischer-Tropsch fuels (BtL) and alcohol-to-jet (AtJ) from cellulosic ethanol. The H2020 HyFlexFuel project addresses this challenge and further develops all major process steps of a hydrothermal liquefaction (HTL) process that can convert a broad variety of biomasses into a mixture of hydrocarbon fuels including kerosene and diesel as target products.

In order to compare and rank the HTL fuel production process in comparison to various other fuel production pathways on a wide basis of parameters, a multi-criteria assessment is conducted in this report.

In Chapter 2, a selection of alternative pathways are briefly reviewed together with the properties of the HTL production pathway.

In Chapter 3, a sub-set of a larger collection of relevant criteria was selected for comparative evaluation, in each category of techno-economic, environmental and socio-economic characteristics, corresponding to key questions in the context of renewable fuels. The performance with respect to each selected criterion is evaluated in a multiple-criteria assessment framework yielding figures of merit for each fuel pathway in two different scenarios. The scenario variations are modeled as changes in relative weights of the criteria. Potentials and advantages as well as risks and drawbacks associated with the examined HTL approach and selected alternative fuel pathways are visualized and compared.

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

Chapter 4 shows the performance perspective of the HyFlexFuel approach relative to selected other advanced biofuel pathways in a dual-criteria diagram of life-cycle analysis versus techno-economic analysis data and discusses the results.

Chapter 5 presents a conclusion of the report.

# 2. Overview over selected process chains

## 2.1 Scope

The selection of process chains for the multiple-criteria assessment, including HTL, should cover the following aspects, all with **drop-in capable renewable jet fuel** as a product:

- **Feedstock diversity for advanced biofuels:** sewage sludge, municipal solid waste, forest residues, agricultural residues or microalgae, as well as fats, oils and greases,
- **Conversion technology diversity:** Hydrothermal liquefaction (HTL), Alcohol-to-Jet (AtJ), Fischer-Tropsch Biomass-to-Liquid (BtL), as well as renewable fuels of non-biological origin (RFNBOs) such as Power-to-Liquid (PtL) and Sunlight-to-Liquid (StL) with direct-air-capture (DAC) of $CO_2$ as carbon source,
- **Technical maturity diversity:** HTL is compared to higher TRL biofuel technologies that are proven in the operational environment, such as HEFA (TRL 9), AtJ (TRL 3-7), and BtL (5-6). RFNBOs are represented by PtL (TRL 5-8) and StL (TRL 3-5).

## 2.2 Selected fuel pathways

The selected nine production pathways, consisting of a combination of six advanced feedstock types and six conversion technologies are:

***Table 1:*** *Overview of investigated fuel production pathways*

| Abbreviation | Feedstock | Conversion technology |
|---|---|---|
| AtJ/MSW | Municipal solid waste | Alcohol-to-jet |
| BtL/MSW | Municipal solid waste | Biomass-to-liquid<br>(Gasification and Fischer-Tropsch synthesis) |
| BTL/LigC | Lignocellulosic residues<br>(agricultural and forest residues) | Biomass-to-liquid<br>(Gasification and Fischer-Tropsch synthesis) |
| HEFA/FOG | Fats, oils and grease<br>(including tallow, yellow grease and used cooking oil) | Hydroprocessed esters and fatty acids |
| HTL/µA | Microalgae | Hydrothermal liquefaction |
| HTL/LigC | Lignocellulosic residues<br>(agricultural and forest residues) | Hydrothermal liquefaction |
| HTL/Sew | Sewage sludge | Hydrothermal liquefaction |
| PtL/DAC | Direct air capture $CO_2$, water, renewable electricity from wind and PV | Power-to-liquid<br>(Electrolysis and Fischer-Tropsch synthesis) |
| StL/DAC | Direct air capture $CO_2$, water, concentrated solar energy | Sunlight-to-liquid<br>(Solar thermochemistry and Fischer-Tropsch) |

### 2.2.1 Alcohol-to-jet (AtJ) fuel from municipal solid waste

The pathway alcohol-to-jet (AtJ) essentially consists of two independent processes, namely the production of alcohols and the subsequent conversion of alcohols (the actual AtJ step) into hydrocarbons, *e.g.* jet fuel.

An unconventional, yet advanced type of feedstock for alcohol production is municipal solid waste. The organic fraction of municipal solid waste shows a high potential for ethanol production through simultaneous saccharification and fermentation [2].

Commercialization of AtJ production on other feedstock is driven most prominently by companies like Swedish Biofuels, Gevo, and LanzaTech. Gevo's AtJ production has reached demonstration scale. Swedish Biofuels developed its AtJ technology towards industrial-scale production in the course of the EU-funded project BFSJ, in collaboration with LanzaTech and other partners [3]. Therefore, the current technological maturity of AtJ production is estimated as TRL 7 since 2019 upon completion of the BFSJ project.

AtJ-SPK produced by Gevo based on isobutanol has been tested in a 50/50 blend with JP-8 in a military aircraft without any problems [4] and is ASTM qualified since April 2016 (ASTM D7566-21, Annex 5 [5]) for use in civil aviation with a maximum blending ratio of 50%. While AtJ-SPK from ethanol is also ASTM approved, AtJ fuels from other C2 to C5 alcohols are pending. Furthermore, AtJ-SKA, i.e. Synthesized Kerosene with Aromatics, is in the approval process (Phase 1 testing) [6].

### 2.2.2 Biomass-to-liquid fuel (BtL)

Here we consider two advanced feedstock types, municipal solid waste and lignocellulosic residues. For the lignocellulosic residues, we consider forestry as well as agricultural residues, but no dedicated energy crops or other cultivated biomass.

BtL usually refers to the gasification of a broad range of (lignocellulosic) feedstock, yielding synthesis gas, and subsequent liquefaction. In this report, only Fischer-Tropsch (FT) synthesis is considered for the liquefaction step. Alternative routes, such as the Methanol-to-Gasoline (MtG) process or the methanol-to-jet pathway, for producing liquid hydrocarbon products from synthesis gas, exist as well. However, in particular for the production of middle distillate fuels, such as jet fuel, FT synthesis is by far the most examined and applied technology.

For municipal solid waste (MSW) as feedstock, the process is often labelled Waste-to-Liquid (WtL). WtL is not considered as separate conversion technology here. However, if analyzed at the level of integrated pathways, i.e., feedstock production and supply, conversion and refining, WtL fuels can differ substantially from lignocellulosic BtL fuels in terms of economic and environmental performance. This is taken into account in the assessment of integrated supply chains.

The BtL process follows three basic steps: First, thermal gasification of the feedstock, yielding synthesis gas (syngas; a mixture of carbon monoxide and hydrogen). In contrast to pyrolysis, the presence of sub-stoichiometric quantities of oxygen and/or steam are required in the gasification step. After gasification, the raw gas stream has to be purified and conditioned[2]. Second, Fischer-Tropsch synthesis, converting syngas mainly into hydrocarbons (FT crude), and third, the step of refining/upgrading of FT crude into a broad range of hydrocarbon products is performed. For the production of middle distillate fuels, such as diesel and jet fuel, also hydroprocessing (hydrotreament, hydrocracking and hydroisomerization) is required.

In the French project BioTFuel, two BtL production plants are constructed, one of which (located in Dunkirk, France) is projected to reach a production capacity of 200,000 tons of diesel and jet fuel per year, based on a feedstock input of about one million tons of biomass by 2020.

For the current technological maturity of the BtL conversion process, TRL 6 is estimated after completion of the BioTFuel project by 2017.

FT synthesis generally produces fuels of high quality and was the first fuel production pathway to successfully pass the approval procedure according to the standard ASTM D7566 as *Fischer-Tropsch Hydroprocessed Synthesized Paraffinic Kerosene* (FT-SPK) in 2009.

### 2.2.3 HEFA fuel from fats, oils and grease (FOG)

Hydroprocessed esters and fatty acids (HEFA) is currently the only production process of renewable bio-jet fuel that is industrialized at substantial scale, and consequently HEFA-SPK is the only renewable jet fuel commercially available in relevant quantities at the moment. The targeted product in current production facilities is mainly diesel, while jet fuel is usually produced only on demand and in limited quantities.

Since 2011, Hydroprocessed Esters and Fatty Acids (HEFA or HEFA-SPK) are approved according to the standard ASTM D7566 [5] for use in civil aviation. As the HEFA process exclusively yields paraffinic compounds (i.e. no aromatics), utilization is limited to blends with conventional jet fuel containing up to 50% HEFA components. HEFA is a technology already proven in the operational environment, i.e. in airplanes. The main bottleneck of the HEFA pathways is the availability of sustainably feedstock, consequently the substitution potential, is low.

### 2.2.4 Power-to-liquid (PtL)

Due to the increasing amounts of produced renewable electricity, the power-to-liquid pathway has seen increasing interest during the last decade. Similar to the BtL pathway, the PtL pathway also consist of three main process steps:

- Hydrogen production via water electrolysis using (renewable) electricity
- Conversion of hydrogen with $CO_2$ from direct air capture (DAC) to synthesis gas
- Fischer-Tropsch synthesis and subsequent upgrading of liquid hydrocarbons to refined fuels

[2] Purification includes removal of unwanted volatile components, e.g., ash, and potential catalyst poisons, such as compounds containing sulfur or phosphorous. Conditioning includes adjustment of the $H_2$/CO ratio via Water-gas Shift Reaction (WSR): $CO + H_2O \leftrightarrow CO_2 + H_2$

In general, there are two different conversion pathways, the Fischer-Tropsch pathway and the methanol pathway. Using the aforementioned definition of approval of *Fischer-Tropsch Hydroprocessed Synthesized Paraffinic Kerosene* (FT-SPK) [5], PtL jet fuel would be approved, as long as iron or cobalt catalysts are used. The methanol pathway has not yet been approved yet, however, the good and promising physicochemical properties hint on a timely approval of this pathway. For the comparison in this framework, we assume DAC as carbon source. PtL fuels can also be produced from $CO_2$ from industrial point sources. In this case, the specific $CO_2$ source becomes a decisive factor for the evaluation of key performance indicators, in order to reduce complexity only DAC is considered.

### 2.2.5 Sunlight-to-liquid (StL)

Concentrated sunlight can drive chemical reactions at extremely high temperatures, which is at the core of solar-thermochemical fuel production. Water and carbon dioxide can be split to produce syngas to be used as an input for further fuel synthesis. The StL production pathway is based on a scientific breakthrough in redox thermochemistry using concentrated solar radiation [7]. Solar-driven fuel production for the global supply of clean liquid fuels offers important economic, environmental and social prospects [8–10]. With the aid of metal oxides as reactants, which are not consumed in the process, the oxygen is separated out in a 2-step process. Thus, this process can be performed in a safe manner and at lower temperature than the binding energy of oxygen in $H_2O$ and $CO_2$ implies.

As an example, the EU-FP7 SOLAR-JET project demonstrated this technology at TRL 3 in 2014. The EU-H2020 SUN-to-LIQUID project further advanced it to TRL 4-5 by 2019 [11]. The latter demonstrated solar fuel production in an integrated plant using an advanced high-flux ultra-modular solar heliostat field, a 50-kW solar reactor, and optimized redox materials. Next steps on the roadmap are scaling in 2023 to 1 $MW_{thermal}$ (2,000 $m^2$, 10,000 L/a), and further by 2032 into the 500 $MW_{thermal}$ regime (1 Mio. $m^2$, 30 Mio. L/a at 1.15-1.95 €/L; [9]) using an array of solar reactor modules while enhancing its efficiency with advanced thermal management towards 20%.

The replication potential of StL fuel plants, analogous to PtL, is practically unlimited as the fuel is mainly produced from air and sunlight: the direct air capture (DAC) of $CO_2$ also supplies clean water for fuel production even in arid climates. Future global fuel demand can be met by utilizing less than 1% of the global arid land. Limited to Europe, the sustainable production potential from suitable areas is approximately 100 Mt/a.[12], which greatly exceeds the current (2019: 49 Mtoe/a, [13]) and projected (2050: 38-65 Mtoe/a, [13,14]) jet fuel demand in Europe.

### 2.2.6 Hydrothermal Liquefaction (HTL)

Besides the HTL fuel production process chain configurations, which are described below, HTL literature values were also investigated with lignocellulosic residues as feedstock. More specifically, in this case, lignocellulosic residues include forest as well as agricultural residues. The process configuration of the HyFlexFuel concept is shown in Figure 1 and described in the following. 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 [15]-. The 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 gasses from the admixed organic fraction. Depending on feedstock, phosphates may be recovered to yield a fertilized by-product. The main process steps of hydrothermal liquefaction, catalytic upgrading and energetic use of the aqueous phase are present in most other literature studies as well.

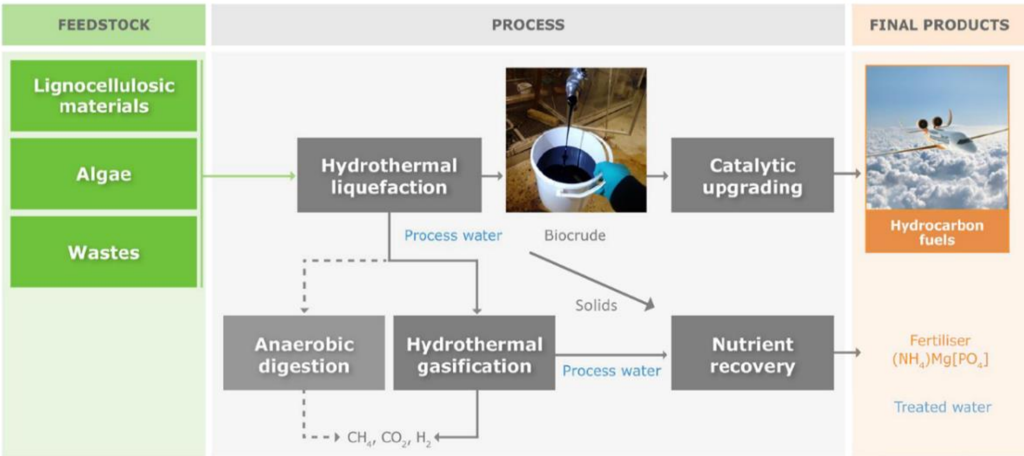


***Figure 1:*** *Basic building blocks of the HyFlexFuel process chain.*

## HyFlexFuel process chain configurations

In the HyFlexFuel project studies, basically, two different scenarios (wet and dry feedstock) with two different feedstock each, namely sewage sludge, cereal straw, miscanthus and microalgae were investigated. The two different process chain configurations are discussed briefly in the following with respect to some key methodological assumptions for the assessment of their economic behavior and ecological footprint. Detailed information on the process chain configurations can be found in another public deliverable report on techno-economic and environmental assessment [16].

## Sewage sludge

Sewage sludge is an attractive HTL feedstock from a cost perspective. 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 [17]. However, there are also other studies [18] that do not give a credit for sewage sludge as feedstock, but rather consider sewage sludge to be neutral in cost. This assumption has a high impact on the subsequently calculated MFSP, as was also found in the HyFlexFuel project [15], where the feedstock credit accounted for more than 50% of the revenues. In the HyFlexFuel project study, the entire sewage sludge from a wastewater treatment plant in Germany is converted to fuels via HTL. In addition to the above mentioned process chain, a hydrogen production cycle is included in the process in order to guarantee sufficient supply of hydrogen for the upgrading process.

### Cereal straw

Straw is an agricultural by-product that makes up a majority of the yield of cereal crops. In the HyFlexFuel project study, a production site in Romania is considered. By recycling the aqueous phase for the preparation of the feed slurry for HTL conversion, the carbon dissolved in the aqueous phase is partially recovered in the fuel product. Since cereal straw is a dry feedstock, recycling of the aqueous phase is assumed in contrast to the aforementioned sewage sludge process chain. Due to the low amount of phosphorous in cereal straw, no nutrient recovery is considered.

### Miscanthus

The configuration and size of the miscanthus HTL process chain is treated along the lines of the process of HTL of cereal straw described above. Northern France was chosen as the location for this process due to favorable conditions for miscanthus cultivation.

### Microalgae

Southern Spain was chosen as the site considered for the cultivation of microalgae due to favorable climatic conditions. 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. Multiple-criteria assessment

The methodology and criteria selection is largely consistent with the considerations and definitions presented in an earlier report to the EU [19], with a few exceptions. The purpose of being largely consistent with the earlier established methodology is to make the results comparable to earlier multiple-criteria analysis (MCA) with different fuel pathways. Deviations are however necessary. We added the socio-economic dimension with the local value chain criterion. Also, the reference chosen for cost competitiveness is based on the current 10/2021 spot market price of kerosene [20], and the reference value chosen for calculating the substitution potential from the production potential is the EU 2019 fuel demand.

## 3.1 Criteria selection

A set of key criteria was selected for a holistic comparative evaluation that covers all three essential categories of techno-economic, environmental and socio-economic characteristics, corresponding to key questions for decision making in the context of renewable fuels. The five key criteria are:

- **Technical maturity** of the entire production chain, including feedstock production and conversion technology at pilot plant scale at state of the art,
- **Substitution potential**, i.e. the production potential compared to the pre-COVID19 European demand, evaluated for the European prediction potential and demand,
- **Cost competitiveness** as expressed by the relative difference of the minimum fuel selling price from a future commercial-scale plant in relation to the selling price of the fuel on the market,
- **Greenhous gas emission reduction** compared to the fossil fuel reference, i.e. the relative difference carbon-equivalent emission
- **Social benefit of local value creation**, i.e. the estimated probability of value created at the community or region around the location the fuel plant

The key criteria are defined based on their relevance in relation to a larger set of performance criteria that characterizes the fuel production pathways. A larger set also contains criteria such as process energy efficiency, process carbon efficiency, EROI, drop-in capability, area-specific yield and land requirement, production potential, water consumption, direct and indirect effects on gross domestic product (GDP) and employment, skill and know-how development and social acceptance.

The selection of five key criteria and their dimensionless formulation by relating them to benchmark or reference values, is motivated by the following consideration: First, in a multiple-criteria assessment (MCA) framework, the criteria should largely *independently evaluate all aspects* of a “value function”, i.e. the overall score. Second, the five key criteria have been defined to support decision making in *all aspects representing a potential pre-decision conflict* [21] in such diverse categories as energy supply, environment, economic viability and social benefit with a focus on five key questions:

- What is the current state of development? (Technology readiness level as an indicator of the development effort and risks that are still ahead)
- How much of the current or future demand can potentially be produced by this technology? (Substitution potential as an indicator of future fuel supply independence)
- How much would it cost to transform the energy supply to 100% renewable and would it work with functioning market mechanisms? (Cost competitiveness as an indicator of economic viability and burden, required policy and financial measures to achieve economic competitiveness)
- What is the potential environmental impact, particularly in terms of greenhouse gas emissions? (Greenhous gas emission reduction relative to the fossil fuel benchmark shows the fraction of emission savings achieved by substitution of the conventional fuel by renewable fuel)
- What is the potential socio-economic benefit? (The propensity of local added-value creation is an indicator of a potentially positive impact on region-specific creation of prosperity)

For example, indicators such as process efficiency, area-specific yield and production potential are important in a detailed deployment analysis but are only indirectly related to the key questions listed above. Process efficiency will enter the TEA and LCA and will be captured by cost competitiveness and emission reduction. Area-specific yield will be dependent on process efficiency and will, together with land requirement and land availability enter the calculation of production potential, such that these criteria will be strongly related in a MCA framework. Production potential is a good indicator, and taking the ratio over the benchmark of fuel demand yields a dimensionless indicator for substitution potential that relates the production potential to the size of the challenge, i.e. to meet the fuel demand.

These examples show that the definitions of the five key indicators cover the key questions largely independently and that their dimensionless (i.e. without units) definition puts them in relation to important reference values (European fuel demand, fossil fuel GHG emissions, fossil fuel market price) which represent the context for multiple-criteria decision making.

## 3.2 Definition of metrics and scores

The key criteria, their metrics and scores are summarized as shown in Table 2.

***Table 2:** Key criteria, metrics and scores*

| Criterion | Metric | | | Score ($0 \leq S \leq 5$) min. (S=0) | Score ($0 \leq S \leq 5$) max. (S=5) |
|---|---|---|---|---|---|
| **Technical maturity** | Technology Readiness Level | TRL (1-9) | TRL = Min[FSRL,CTRL] | TRL = 1 | TRL ≥ 6 |
| Feedstock production maturity | Feedstock Readiness Level | FSRL (1-9) | FSRL (adapted CAAFI def.) | | |
| Conversion technology maturity | Conversion Technology Readiness Level | CTRL (1-9) | CTRL (TRL def. H2020, Annex G) | | |
| **Substitution potential (EU)** | EU production potential relative to EU demand in 2019 (49 Mtoe) | $\sigma$ [%] | $\sigma(\text{Fuel}) = \frac{\dot{M}(\text{Fuel})}{\dot{M}_{\text{Ref}}}$ | $\sigma \leq 0.3\%$ | $\sigma \geq 100\%$ |
| **Cost competitiveness** | Relative difference in minimum fuel selling price, rel. to current fuel spot price (0.67 €/kg, 15.10.2021) | $\gamma$ [%] | $\gamma(\text{Fuel}) = \frac{C(\text{Fuel}) - C_{\text{Ref}}}{C_{\text{Ref}}}$ | $\gamma \geq 275\%$ | $\gamma \leq 0\%$ |
| **GHG emission reduction** | Relative difference in life-cycle GHG emission, rel. to conventional fuel emission (89 $gCO_{2eq}$/MJ) | $\varepsilon$ [%] | $\varepsilon(\text{Fuel}) = \frac{\text{CI}(\text{Fuel}) - \text{CI}_{\text{Ref}}}{\text{CI}_{\text{Ref}}}$ | $\varepsilon \geq 0\%$ | $\varepsilon \leq -90\%$ |
| **Regional socio-economic impact** | Probability of local value generation | Probability: None/low/ medium/high | • Freedom of location choice<br>• Proximity of feedstock sourcing<br>• Share of OPEX in total production cost | None | High |

techical | techno-economic | environmental | socio-economic criterion

The following sub-sections present the detailed definitions of the key criteria, their metrics (or quality levels) and functional translation to a unified score.

### 3.2.1 Technical maturity

The technical maturity criterion addresses the state of the art of the entire integrated production path, that is the "integrated" Technology Readiness Level (TRL).

The integrated TRL is interpreted as metric for the readiness level of a system of all integrated sub-system technologies and therefore reflects the level of development effort to commercialization and uncertainty of success for this integrated system, i.e. the feedstock and fuel production pathway.

**Metric:** For the *integrated TRL* we combine the readiness levels of feedstock and conversion technology, i.e. the Feedstock Readiness Level (FSRL) and the Conversion Technology Readiness Level (CTRL), respectively.

The (integrated) TRL of the entire production chain is given by the lower of the two complementary readiness levels FSRL and CTRL, i.e.

$$\text{TRL} = \text{Min}[\text{FSRL}, \text{CTRL}],$$

which is analogous to the picture that the weakest link defines the strength of the entire chain.

**Scoring:** We use the classical TRLs as defined in the Annex of the Horizon 2020-Work Programme [22] and assign a Technology Readiness Score as shown in Table 3.

***Table 3:*** *Definition of the integrated Technology Readiness Level (TRL) and Technology Readiness Score (TR score).*

| TR score | TRL | Short description |
|---|---|---|
| 0 | 1 | Basic principle observed |
| 1 | 2 | Technology concept formulated |
| 2 | 3 | Experimental proof of concept |
| 3 | 4 | Technology validated in lab |
| 4 | 5 | Technology validated in relevant environment („from lab to pilot scale“) |
| 5 | 6 | Technology demonstrated in relevant environment („from pilot to demonstration scale”) |
| 5 | 7 | System prototype demonstration in operational environment |
| 5 | 8 | System complete and qualified |
| 5 | 9 | Actual system proven in operational environment |

For consistency, we assume here that for any conversion technology at demonstration level, i.e. with an actual TRL 6, no major *technical* obstacles remain on its way to market readiness. Therefore, the maturity of such a technology towards the achievement of relevant goals can be considered as already achieved from the *technical* point of view. With respect to the assessment scale, this means that the maximum score (5 points) is associated with TRL 6 (and higher).

The conversion technology levels are defined in the same way as the TRL in the table above. No score needs to be assigned to the CTRL.

In order to evaluate the FSRL in this context, the tool *Feedstock Readiness Level* (FSRL) [23,24] was introduced by CAAFI in 2011 the as complementary tool for the evaluation of *feedstock production* technologies with respect to their technological maturity. There, the FSRL is defined through a complicated scheme of “components” and “toll gates” which we replace here by a simpler scheme. Following the same argumentation as in case of CTRL, the Feedstock Readiness Levels are defined as in the table below. No score needs to be assigned to the FSRL.

***Table 4:*** *Definition of Feedstock Readiness Levels (FSRL).*

| FSRL | Short description |
|---|---|
| 1 | Basic principles observed (identification of potential feedstock for specific conversion technology) |
| 2 | Production concept formulated (identification of production system and environment etc.) |
| 3 | Proof of concept (initial studies on feedstock potential at lab/experimental scale, e.g. screening genetic resources for yield, requirements etc.) |
| 4 | Validation of concept (preliminary technical evaluation) |
| 5 | Validation of production system in relevant environment (e.g. biomass on-farm, field-scale production trials, assessment of resource requirements, identification of production uncertainties, etc.) ("from lab to pilot scale") |
| 6 | Demonstration of feedstock production, full-scale production initiation (scale-up production) ("from pilot to demonstration scale") |
| 7 | First feedstock production and management in operational environment (small commercial scale) |
| 8 | System complete and qualified, commercialization on-going |
| 9 | Full-scale commercial feedstock production in operational environment (sustainable feedstock production capacity established) |

**Evaluation:** The ranges of technology readiness levels are shown in the following table. In the final assessment, the typical value is chosen according to what best represents the state of the art.

| Fuel pathway | FSRL | CTRL | TRL | References |
|---|---|---|---|---|
| AtJ/MSW | 7-9 | 3-7 | 3-7 | [25,26] |
| BtL/MSW | 7-9 | 5-6 | 5-6 | [25,27] |
| BtL/LigC | 5-8 | 5-6 | 5-6 | [25,27] |
| HEFA/FOG | 9 | 9 | 9 | [27] |
| HTL/µA | 4-6 | 4-5 | 4-5 | [25] |
| HTL/LigC | 5-8 | 4-5 | 4-5 | [25] |
| HTL/Sew | 9 | 4-5 | 4-5 | [25] |
| PtL/DAC | 5-9 | 5-8 | 5-8 | [26,27] |
| StL/DAC | 5-9 | 3-5 | 3-5 | [28] |

### 3.2.2 Substitution potential

The criterion of substitution potential relates the scalability of the fuel production to the volume of the demand. Its specific property is the quantity of jet fuel that can be produced per year in Europe in relation to Europe's annual jet fuel demand. As a reference we use the pre-COVID19 European use of kerosene-type jet fuel in 2019 of 49.0 Mtoe, of which 41.7 Mtoe were used for international flights and 7.3 Mtoe for national flights [13]. This demand of 49 Mtoe matches the projected fuel demand in 2050 in the study of Destination 2050 [29].

The production potential of a fuel pathway can be calculated from its areal productivity and the size of the available, suitable land area under sustainable conditions. For fuel production only those biomass potentials are considered that are "advanced" in that they are not in conflict with food production or protected areas.

The primary focus of the assessment lies on the *European* substitution potential, according to the objective of "increasing energy production in the European Union" as one of the eight key pillars of the European Energy Security Strategy [30].

**Metric**: The *substitution potential is measured by the EU production potential relative to EU demand in 2019.* This relative metric is denoted as $\sigma$, is without units and is defined as

$$\sigma(\text{Fuel}) = \frac{\dot{M}(\text{Fuel})}{\dot{M}_{\text{Ref}}} \ ,$$

where $\dot{M}$ is the annual European production potential of the fuel under assessment and $\dot{M}_{\text{Ref}}$ is the reference value, i.e. the future European annual demand of jet fuel.

**Scoring**: The values for production potential are expected to scale exponentially over time in their initial growth phase and level off when market saturation or feedstock depletion are approached. Therefore, a nonlinear logarithmic function of the production potential will be linearly dependent on time and growth factors. For a production potential at a given time in the future it seems natural to use a logarithmic scale. Based on the simple exponential growth paradigm we assign the following scores:

- $S(\sigma) = 0$ for $\sigma \leq 0.3\%$,
- $S(\sigma) = 5 \cdot \frac{\log(\sigma) - \log(0.003)}{\log(1.0) - \log(0.003)}$ for $0.3\% < \sigma < 100\%$,
- $S(\sigma) = 5$ for $\sigma \geq 100\%$

such that interval delimiters for the metric are 0.3% and 100% for minimum and maximum scores, respectively. The scores for various substitution potentials are shown in the table below.

***Table 5:*** *EU substitution potential in 2019 and related scores based on the logarithmic transfer function given above*

| Score | $\sigma$ | Short description |
|---|---|---|
| 0 | ≤ 0.3% | Insignificant substitution potential |
| 1.0 | 1% | Very low substitution potential |
| 2.0 | 3% | Low substitution potential |
| 3.0 | 10% | Medium substitution potential |
| 4.0 | 30% | High substitution potential |
| 5.0 | ≥ 100% | Very high substitution potential |

**Evaluation:** The production potentials in Europe and derived substitution potentials are shown in the following table.

| Fuel pathway | Production potential $\dot{M}$(Fuel) in Mt/a | Substitution potential $\sigma$ | References |
|---|---|---|---|
| AtJ/MSW | 0.85-1.84 | 1.7-3.8% | [2,31–33] |
| BtL/MSW | 2.8-5.8 | 5.7-11.9% | [31,33,34] |
| BtL/LigC | 1.1-3.6 [a]<br>23.0-61.6 [b] | 49.2-133% | [31,33–35] |
| HEFA/FOG | 1.2-1.7 [c] | 2.4-3.5% | [33,36] |
| HTL/µA | 4.9 | 10.0% | [37] |
| HTL/LigC | 0.7-1.7 [a]<br>15.5-29 [b] | 16.2-62.7% | [31,33,35] |
| HTL/Sew | 2.88 | 5.9% | [31] |
| PtL/DAC | > 50 | > 100% | [38] |
| StL/DAC | > 50 | > 100% | [12] |

[a] from forest residues;
[b] from agricultural residues
[c] from waste fats, oils and grease, including used cooking oil

### 3.2.3 Cost competitiveness

The economic competitiveness of a fuel production pathway is determined by the minimum fuel selling price (MFSP) or the cost of production per unit output in comparison to the cost of production of the same unit of the established fuel product on the market. Therefore, the relative values are important.

In case of carbon credits or fossil energy penalties, the relative cost metric should subtract or add, respectively, the off-set to the relevant cost item. Here we do not take any off-set into account.

As a reference, the spot price of 774.75 \$/t for jet fuel in Europe, reported on 15 Oct. 2021, is used [20]. As a basis for the comparison of the various estimates from literature, the currency USD (\$) is converted to EUR (€) at an exchange rate of 0.8600 EUR/USD. Whenever an original document did not contain distinct information about the time needed to calculate the inflation of the currency, the year of publication was used instead.

**Metric:** For the current assessment we use the *relative difference in production cost, relative to the spot price of conventional jet fuel*. The symbol is $\gamma$, and the relative metric is without units defined as

$$\gamma(\text{Fuel}) = \frac{C(\text{Fuel}) - C_{\text{Ref}}}{C_{\text{Ref}}} \ ,$$

where $C$ is the WTT production cost and $C_{\text{Ref}}$ the spot price of the reference jet fuel, i.e. of conventional jet fuel.

**Scoring**: For scoring fuels on relative cost for economic competitiveness we assume that any MFSP at or below the conventional fuel reference value for ($\gamma \leq 0$) obtains the maximum score of 5. Considering that the spot price is recovering from a low value and is rapidly increasing, we set the upper MFSP limit at a level of 2.0 €/L (2.5 €/kg, equal to $\gamma$ = 275%). Therefore, at this or higher fuel production cost a score of zero is assigned with a linear function in between. In short, we define:

- $S(\gamma) = 0$ for $\gamma \geq 275\%$,
- $S(\gamma) = (2.75 - \gamma)/0.55$ for $0\% < \gamma < 275\%$,
- $S(\gamma) = 5$ for $\gamma \leq 0\%$

The scores for various relative cost values are shown in the table below.

This relative cost metric is adaptable to future scenarios. Policies and economic measures like emission trading give added value to renewable fuels with a favourable greenhouse balance, so that we may adjust the MFSP $C(\text{Fuel})$ of renewable fuels with carbon cost benefits. And by adjusting the reference value $C_{\text{Ref}}$, the defined metric $\gamma$ may take into account that prices for hydrocarbon fuels on the market may rise in the long term, for several reasons, such as increasing fossil oil prices or a carbon tax.

***Table 6:*** *Relative difference in production cost and related scores based on the linear transfer function given above.*

| Score | $\gamma$ | Short description |
|---|---|---|
| 0 | ≥ 275% | Insignificant competitiveness |
| 1 | 220% | Very low competitiveness |
| 2 | 165% | Low competitiveness |
| 3 | 110% | Medium competitiveness |
| 4 | 55% | High competitiveness |
| 5 | ≤ 0% | Very high competitiveness |

**Evaluation:** Techno-economic data were compiled only from those references that present combined TEA and LCA results. Therefore, the relative difference in production cost are listed together with the GHG emission reduction in Table 8 below.

### 3.2.4 Greenhouse gas emission reduction

Lifecycle greenhouse gas (GHG) emissions are also called "well-to-wake" (WtW) emissions and include the fuel combustion. The main difference in fossil and renewable drop-in fuels originates from the source of carbon and other GHG emissions for the well-to-tank contribution, whereas the tank-to-wake emissions differ only slightly. More specifically, the GHG contribution in some biofuel production paths is dominated by the specifics of biomass production and may vary largely for identical fuel products.

For an assessment we have to clearly define the scope of the "GHG emission reduction". A specific renewable fuel technology that has potentially a strong positive impact on emission reduction of the global aviation fleet needs to excel in three categories. It requires:

- a low well-to-wake emission of the unblended fuel,
- a high maximum blending ratio and
- a large production potential.

Here we evaluate only the *specific GHG emission reduction of the unblended fuel relative to conventional jet fuel*, i.e. the first category.

Besides a strong contribution from carbon dioxide ($CO_2$), the fuel production process may also release other greenhouse gases like methane ($CH_4$) or nitrous oxide ($N_2O$) into the atmosphere. The primary metric is the carbon dioxide equivalent ($CO_2$-eq.) emission that takes the equivalent global warming potential of gases into account. For example, methane is considered to have 26 times the global warming potential of carbon dioxide, thus 1 g of methane is expressed as 26 g ($CO_2$-eq.).

**Metric:** For the current assessment we use the relative difference in "carbon-equivalent intensity", i.e. the *relative difference in GHG emission, relative to the GHG emission of conventional jet fuel*, i.e. the percent reduction potential by substitution of the same amount conventional jet fuel. This relative metric is denoted as $\varepsilon$, is without units and is defined as

$$\varepsilon(\text{Fuel}) = \frac{\text{CI}(\text{Fuel}) - \text{CI}_{\text{Ref}}}{\text{CI}_{\text{Ref}}} \ ,$$

where CI is the equivalent carbon intensity of the fuel under assessment and $\text{CI}_{\text{Ref}}$ is the equivalent carbon intensity of the reference fuel, i.e. conventional jet fuel. We obtain
$\varepsilon$(conv. jet) = 0. Negative values of (-100%) < $\varepsilon$ < 0% show GHG reduction potential relative to conventional jet fuel. In some cases even lower values $\varepsilon$ < -100% are possible where net *negative emission* budgets ($\text{CI}(\text{Fuel}) < 0$ ) are found.

For the current assessment the cumulative greenhouse gas emissions CI of a certain fuel production pathway and combustion are determined and expressed as carbon dioxide equivalents per unit mass of jet fuel (g ($CO_2$-eq.)/kg (fuel)).

**Scoring**: For scoring emission reduction we define:

- $S(\varepsilon) = 5$ for $\varepsilon$ ≤ -90%,
- $S(\varepsilon) = 5 \cdot \left(-\frac{\varepsilon}{0{,}90}\right)$ for -90% < $\varepsilon$ < 0%,
- $S(\varepsilon) = 0$ for $\varepsilon$ ≥ 0%

The scores for various emission reductions are shown in Table 7.

***Table 7:*** *Greenhouse gas emission reduction potential and related scores based on the linear transfer function given above*

| Score | $\varepsilon$ | Short description |
|---|---|---|
| 0 | ≥ 0% | Insignificant emission reduction |
| 1,0 | -18% | Very low emission reduction |
| 2,0 | -36% | Low emission reduction |
| 3,0 | -54% | Medium emission reduction |
| 4,0 | -72% | High emission reduction |
| 5,0 | ≤ -90% | Very high emission reduction |

The definition of delimiting values may easily be changed if new insights suggest to do so. The maximum score is assigned for reduction potential at or below -90% because such lifecycle performance is sufficient to reach the ATAG goals in 2050 if significant substitution is achieved. The minimum score value of $\varepsilon$ is set to be equivalent to GHG emissions of conventional jet fuel ($\varepsilon$ = 0%), because the reduction potential vanishes at that point.

**Evaluation:** The relative difference GHG emission is listed together with the relative difference in production cost in Table 8.

***Table 8:*** *Techno-economic and life-cycle emission data for the selected fuel production pathways*

| **Fuel pathway** | **Minimum fuel selling price (MFSP)** $C$ in €/kg | **Relative difference in MFSP** $\gamma$ | **GHG emission** CI in $g_{CO2eq}/MJ$ | **Relative difference in GHG emission** $\varepsilon$ | **References** |
|---|---|---|---|---|---|
| AtJ/MSW | 0.72-1.86 | 8-179% | 26-79 | (-70)-(-11)% | [39] |
| BtL/MSW | 1.06 | 60% | 33 | -63% | [39] |
| BtL/LigC | 2.27-7.28 | 241-993% | 6-39 | (-93)-(-57)% | [40,41] |
| HEFA/FOG | 1.81-2.98 | 171-347% | 19-44 | (-79)-(-51)% | [42] |
| HTL/µA | 0.27-1.77[a]<br>7.70-9.50[b]<br>8.26[c] | (-59)-165%[a]<br>1056-1326%[b]<br>1140%[c] | 16-32[a]<br>70-184[b]<br>124[c] | (-82)-(-64)%[a]<br>(-21)-107%[b]<br>40%[c] | [a][43]<br>[b][44]<br>[c][16] |
| HTL/LigC | 1.27-2.49[d]<br>0.44[e] | 90-274%[d]<br>-34%[e] | 1-33[d]<br>43[e] | (-99)-(-63)%[d]<br>-51%[e] | [d][39]<br>[e][16] |
| HTL/Sew | 2.80-3.70[f]<br>0.44[g] | 320-455%[f]<br>-34%[g] | 23-42[f]<br>15[g] | (-74)-(-53)%[f]<br>-83%[g] | [f][18]<br>[g][16] |
| PtL/DAC[h] | 1.70-3.25 | 155-388% | 2-6 | (-98)-(-93)% | [45,46] |
| StL/DAC[h] | 2.46 | 270% | 18 | -80% | [9] |

[a] Results do not include the cost and cultivation penalties of algae feedstock (see Fig. 2 and Fig. 3 in [43])
[b] The system boundary of the analysis includes all aspects from cultivation through to the delivery of fuels
[c] Feedstock *Spirulina* and HyFlexFuel process model
[d] Feedstock variety of agricultural and forest residues
[e] Feedstock cereal straw and HyFlexFuel process model
[f] No credit for feedstock
[g] Feedstock sewage sludge (negative cost) and HyFlexFuel process model
[h] Renewable electricity (in StL for auxiliary power) and direct air capture as carbon source

## 3.2.5 Social benefit by local added value creation

When it comes to the regional socio-economic impact of different sustainable fuel pathways, the propensity of local added-value creation is certainly one of the most important aspects. Consequently, we qualitatively evaluate to what extent different production pathways show differences in the probability of increasing local added-value and of creating jobs in the local economy. In other words, we discuss how strongly different production processes are rooted locally, which is a good indicator for the propensity of local value creation. Note that the probability of local value creation is understood here as an "average" probability for local value creation for all European regions[3]. In other words, we are interested to better understand whether many European regions might be able to profit from a potential future SAF

[3] „Regional" here is loosely comparable to the NUTS2 level.

production, or if the benefits would likely be concentrated in a few regions, or even outside of the European Union.

In order to approach this complex topic, we define three characteristics of SAF pathways, which are important when discussing the propensity of local added-value creation:

- **Freedom of location choice**: This aspect covers the question, to what extent SAF production plants are limited in their location choice. In other words, locations are relatively exclusive if SAF pathways are dependent on specific characteristics, which can only be found in particular places, and relatively free in their location choice if SAF production plants could be placed in many locations. Thus, the probability of local value creation for an average European region decreases if the location choice for specific production plants is highly exclusive.
- **Proximity of feedstock sourcing:** Here, we specify to what extent feedstock need to be sourced in proximity of the production site, or if feedstock can be transported over large distances. The lower the necessity to source feedstock locally, the less likely it is that value added (from feedstock generation, collection, upgrading, etc.) is concentrated in proximity of the production site.
- **Share of operational cost in comparison to total cost:** In essence, we specify here whether, for individual SAF pathways, investment cost outweigh operational cost, or vice-versa. Simply put, operational cost (such as feedstock cost, regular maintenance, building services, utilities expenditures, etc.) show a higher propensity to flow to local companies. Further, as operational cost also comprise salaries to plant workers, it is likely that those salaries will be spent in the region where workers live. On the other hand, investment cost (costs related to setting up the plant for production), are less likely to remain in the region of the plant location, as specialized machinery and equipment, as well as specialized services are less likely to be located in the region where the production plant is located. In this logic, a high share of operational cost is likely to increase local value-added creation, while a low share is likely to lead to the opposite outcome.

**Metric and scoring**: We assign an overall score, based the evaluation of these three qualitative characteristics of SAF pathways, which characterize the propensity of local added-value creation:

***Table 9:*** *Probability of local value generation and related scores.*

| Score | Short description |
|---|---|
| 0 | No local value creation |
| 1 | Low probability of local value creation |
| 2 | Low to medium probability of local value creation |
| 3 | Medium probability of local value creation |
| 4 | Medium to high probability of local value creation |
| 5 | High probability of local value creation |

The results of the qualitative analysis are shown in Table 10. First, we discuss the freedom of location choice, which gives an indication if production plants could be located in a large share of regions, or if only a few regions with particular characteristics are likely to profit. Overall, the freedom location choice for the majority of production pathways can be characterized as rather low, meaning that many regions in Europe might not be suited for SAF production of specific pathways. Mainly, this is due to those feedstocks, which accumulate in regions with high population density [47]. Consequently, rural regions, and partly also periurban regions would not be suited for production pathways based on municipal solid waste and sewage sludge. Since microalgae need specific climate conditions for a cost-effective production (not to warm or cold, but at the same time high solar irradiation, combined with an abundance of fresh water), HTL production from this feedstock is characterized by a low freedom of location choice. The situation is similar for StL where high direct solar irradiation must be present for a cost-competitive fuel production. Since PtL production can rely on all types of renewable electricity generation the freedom of location choice can be considered as moderate. Finally, the freedom of location for HEFA from FOG can be considered as high, as no specific location requirements exist and as FOG is a commodity, which can be transported easily. HTL and BtL from agricultural and forestry residues also shows a high freedom of location choice, as agricultural and forestry activities, are well spread over Europe [48], so that most regions could provide a certain amount of feedstock for HTL production.

When it comes to the proximity of feedstock sourcing (the possibility to transport feedstock over larger distances), most production pathways are characterized as moderately local. This means that feedstock can be transported for certain distance, so that value creation related to feedstock generation, collection, treatment, and upgrading will likely take place in the same country where the plant is located. There is also a good chance that a substantial share of value creation will take place in the region itself, but this would need to be analysed more thoroughly for specific cases. HTL pathways show a clear advantage (especially from sewage sludge and microalgae, and to a lesser extent also from agricultural and forestry residues) here in comparison to HEFA fuels, and to some extent in comparison with PtL and StL. BtL and AtJ fuels should have the same, moderate probability of value creation when it comes to the proximity of feedstock sourcing, as municipal solid waste and agricultural and forestry residues can be transported of moderate distances.

**Evaluation**: The following table shows the evaluated characteristics and the resulting score

***Table 10:*** *Characteristics for estimating the probability of local value creation of alternative fuels, and the resulting overall score*

| Process | Feedstock | Freedom of location choice | Proximity of feedstock sourcing | Share of operational cost in comp. to total cost | Overall probability score |
|---|---|---|---|---|---|
| HTL | Sewage sludge | low (high population density required) | Highly local | Moderate | Medium |
| | Agricultural and forestry residues | High (abundance of feedstock in many regions) | Moderately local | High | Medium to high |
| | Microalgae | Low (specific climate conditions and water availability) | Highly local | High | Medium to high |
| HEFA | FOG | High (no particular requirement of location) | Hardly local | Moderate | Medium |
| AtJ | Municipal solid waste | Low (high population density) | Moderately local | Moderate | Low to medium |
| BtL | Municipal solid waste | low (high population density) | Moderately local | Low | Low to medium |
| | Agricultural and forestry residues | High (abundance of feedstock in many regions) | Moderately local | Moderate | Medium to high |
| PtL | Renewable electricity, DAC | Moderate (high wind speeds and/or solar irradiation) | Moderately local (CO2 highly local, electricity produced regionally) | Low | Low to medium |
| StL | DAC | Low (high direct solar irradiation) | Highly local | Low | Low to medium |

Finally, we discuss the share of operational cost in comparison to the total cost. In essence, the share of OPEX is relatively low for those pathways where the production plant is composed of costly components and machinery, and where recurring costs (such as salaries, feedstock cost, electricity, gas, etc.) are high. This applies especially to PtL (where we allocate electricity generation cost to investment cost) and StL, but also to BtL from municipal solid waste (as we assume that MSW can be sourced at almost no cost). Further, the share of operational cost is moderate (meaning that operational and investment cost are roughly of the same magnitude) for those pathways where the plants are not characterized by particularly high investment cost, and where feedstock cost represent a relatively important cost element. This applies to HTL from sewage sludge, BtL from agricultural and forestry residues, AtJ from municipal solid waste, as well as for HEFA from FOG. Finally, the share of operational costs is relatively high for HTL from agricultural residues and microalgae, as HTL plants are characterized by relatively low investment cost, and as those two feedstocks a characterized relatively high cost.

Based on the discussion of those three characteristics, we set an overall score for the probability of local value creation from SAF production activities. HTL plants from agricultural and forestry residues as well as from microalgae show the highest score for the probability of local value creation, together with BtL from agricultural and forestry residues. HTL production from sewage sludge is in the upper range with a medium score, as well as HEFA production from FOG. At the lower end of the spectrum are ATJ and BtL from municipal solid waste, as well as fuels of non-biological origin.

## 3.3 Evaluation of alternative fuel production pathways

In this section the selected ten production pathways (Seven advanced biofuel pathways, PtL, StL and as a reference conventional jet fuel) are evaluated with respect to the set of criteria and metrics described in the previous section.

### 3.3.1 Evaluation based on metrics and related scores

In a first evaluation step, data is extracted, converted to common units and compiled from the referenced sources of information. Next to numerous scientific publications, also meta-studies, public databases and other sources were used, complemented with own estimations where necessary. The literature data for LCA and TEA were extracted only from those selected publications that present *combined* results for both LCA and TEA in one paper for consistency of modeling assumptions therein for both GHG emissions and production cost. The collected data are associated with variation (e.g. due to variations in feedstock costs in different EU member states) and uncertainties. In the 50-element multiple-criteria assessment (MCA) matrix of criteria and pathways (each a combination of feedstock and conversion technology), we present the “typical” values without specifying confidence intervals or range of variation in the matrix. Therefore, in a second step, we derived “typical” values by averaging selected results for each of the 10 x 5 matrix elements in the MCA matrix. Variances were shown in e.g. Table 8, however these were not propagated through the MCA matrix. The typical values are shown in Table 11.

In a third step, the fuel technologies are scored according to their performance in each criterion (see Table 12). These scores will then be used as a “unified metric” for an additive value function, as will be shown in Section 3.3.3.

***Table 11:*** *Results of the evaluation of the database with respect to production pathways and the selected criteria. Listed numbers represent "typical" values.*

| Criterion | Metric | | AtJ / MSW | BtL / MSW | BtL / LigC | HEFA / FOG | HTL / µA | HTL / LigC[a] | HTL / LigC[b] | HTL / Sew[c] | HTL / Sew[d] | PtL / DAC | StL / DAC | Ref.: Jet A-1 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Technical maturity** | Technology Readiness Level | TRL (1-9) | 7 | 6 | 6 | 9 | 5 | 5 | 5 | 5 | 5 | 8 | 5 | 9 |
| **Substitution potential (EU)** | EU production potential relative to EU demand in 2019 (49 Mtoe) | $\sigma$ [%] | 2,7% | 8,5% | 91% | 2,9% | 10% | 39% | 39% | 5,9% | 5,9% | 100% | 100% | 0% |
| **Cost competitiveness** | Relative difference in minimum fuel selling price, rel. to current fuel spot price (0.67 €/kg, 15.10.2021) | $\gamma$ [%] | 93% | 60% | 347% | 261% | 1165% | 179% | -34% | 388% | -34% | 276% | 270% | 0% |
| **GHG emission reduction** | Relative difference in life-cycle GHG emission, rel. to conventional fuel emission (89 $gCO_{2eq}/MJ$) | $\varepsilon$ [%] | -41% | -63% | -83% | -66% | 41% | -86% | -51% | -63% | -83% | -94% | -80% | 0% |
| **Regional socio-economic impact** | Probability of local value generation | (None/low/ medium/high) | low - medium | low - medium | medium - high | medium | medium - high | medium - high | medium - high | medium | medium | low - medium | low - medium | none* |

[a] Feedstock variety of agricultural and forest residues
[b] Feedstock cereal straw and HyFlexFuel process model
[c] No credit for feedstock
[d] Feedstock sewage sludge (negative cost) and HyFlexFuel process model
* 96.8% of crude oil used in the EU is imported (Eurostat, Crude oil import 2019). For conventional jet fuel the probability of local value generation is however larger than crude oil production in the EU due to refining. For the sustainable development, no value generation is assumed from non-sustainable fossil resources.

***Table 12:*** *Scoring of the fuel production pathways based on the values shown in the previous table. The scores are derived from the continuous transfer functions or, for "technical maturity" and "regional socio-economic impact", from the look-up tables presented in Section 3.2.*

| Criteria scores (0 – 1.0 – 2.0 – 3.0 – 4.0 – 5.0) | AtJ / MSW | BtL / MSW | BtL / LigC | HEFA / FOG | HTL / µA | HTL / LigC[a] | HTL / LigC[b] | HTL / Sew[c] | HTL / Sew[d] | PtL / DAC | StL / DAC | Ref.: Jet A-1 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Technical maturity score | 5,0 | 5,0 | 5,0 | 5,0 | 4,0 | 4,0 | 4,0 | 4,0 | 4,0 | 5,0 | 4,0 | 5,0 |
| Substitution potential (EU) score | 1,9 | 2,9 | 4,9 | 2,0 | 3,0 | 4,2 | 4,2 | 2,6 | 2,6 | 5,0 | 5,0 | 0,0 |
| Cost competitiveness score | 3,3 | 3,9 | 0,0 | 0,3 | 0,0 | 3,7 | 5,0 | 0,0 | 5,0 | 0,0 | 0,1 | 5,0 |
| GHG emission reduction score | 2,3 | 3,5 | 4,6 | 3,7 | 0,0 | 4,8 | 2,8 | 3,5 | 4,6 | 5,0 | 4,4 | 0,0 |
| Regional socio-economic impact score | 2,0 | 2,0 | 4,0 | 3,0 | 4,0 | 4,0 | 4,0 | 3,0 | 3,0 | 2,0 | 2,0 | 0,0 |

[a] Feedstock variety of agricultural and forest residues
[b] Feedstock cereal straw and HyFlexFuel process model
[c] No credit for feedstock
[d] Feedstock sewage sludge (negative cost) and HyFlexFuel process model

As a first observation from the MCA matrix Table 11 and Table 12:

- The technical maturity of all selected fuel paths is generally high (TRL 5 – 9). For all selected production paths there has been at least at one instance of validation in relevant environment („from lab to pilot scale").
- Cost competitiveness remains a challenge for many production pathways. A detailed assessment of cost-saving potentials and of various potential economic measures is therefore recommended. The "typical" values shown here for e.g. HTL of sewage sludge do not represent the more attractive results derived from the special assumption of negative feedstock cost. In the latter case, HTL achieves cost competitiveness, as has been reported earlier [16].

For a holistic assessment, one would review the targets and strategies that guide the decision making in alternative fuels. Then, the weighting of criteria according to policy targets and strategic priorities ("scenario") allows a scenario-specific ranking of fuel production pathways.

### 3.3.2 Scenario-based weighting of criteria

In the next step, different scenarios are defined. By changing the weighting according to different strategic priorities, the sensitivity and potential "robustness" of results in different scenarios is obtained.

In addition to a "neutral" case, two scenarios with different strategic priorities are used for the holistic MCA:

- **Neutral:** all five criteria have the same weight of 20%. This uniform neutral case is agnostic of preferences. It represents the case of even weight distribution in the absence of further information [21].
- **Sustainable development:** the preference for long-term environmental and sustainable social benefits of alternative fuels gives a high weight of 30% to each of the three criteria of GHG emission reduction and regional socio-economic benefits, and the substitution potential. Cost competitiveness and current technical maturity remain of low priority in this long-term scenario.
- **Rapid deployment:** the preference for early introduction and ramp-up of alternative fuels gives a high weight of 50% to each of the two criteria of "economic competitiveness" and to "technical maturity" as this enables early commercialization.

The weight distribution is shown in Table 13 and is visualized in Figure 2.[4] The radar chart is a useful way to display the distinct difference of the two scenarios. While rapid deployment requires early technical and economic success, the more long-term oriented sustainable development plan has to give high priority to the transition to 100% renewable energy by low carbon-equivalent GHG intensity and high substitution potential, in combination with social benefits by local value generation.

[4] It is important to note that the selection of weighting factors is always a subjective choice that requires reasonable assumptions. During evaluation, a slight variation of the weighting factors from different weighting scenarios is performed and the stability of rankings of fuel technologies is observed – this gives confidence in the result.

***Table 13:*** *Weighting schemes for the two scenarios of sustainable development or rapid deployment and for a baseline case of no priorities (neutral)*

| Criterion | Neutral | Sustainable development | Rapid deployment |
|---|---|---|---|
| Technical maturity | 20% | 5% | 50% |
| Substitution potential (EU) | 20% | 30% | 0% |
| Cost competitiveness | 20% | 5% | 50% |
| GHG emission reduction | 20% | 30% | 0% |
| Regional socio-economic impact | 20% | 30% | 0% |

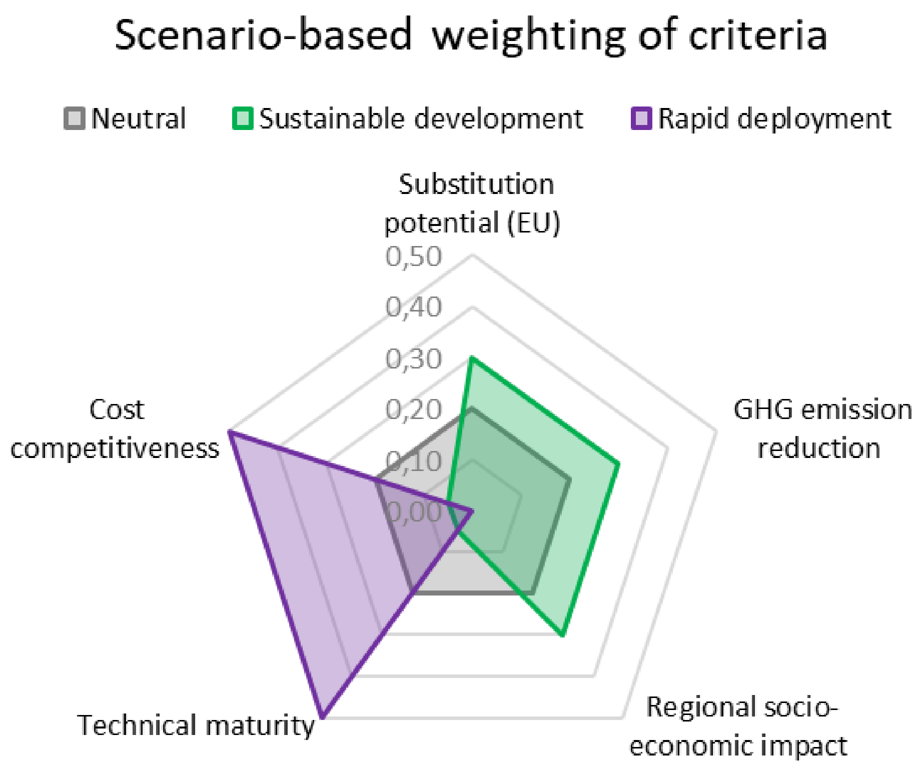


***Figure 2:*** *Graphical representation of the weighting schemes. The two scenarios of sustainable development (green) and rapid deployment (purple) show little overlap in their chosen priorities, thus representing two distinct strategies for the holistic assessment.*

### 3.3.3 Amalgamation using an additive value function

In a final step, the normalized additive value function yields a figure of merit for each fuel technology based on the MCA framework. In short, the overall normalized average score $s$ ($0 \leq s \leq 1$) of each fuel path is given by

$$s(\mathrm{Fuel}) = \frac{\langle S(\mathrm{Fuel})\rangle_{\mathrm{criteria}}}{S_{\mathrm{max}}} = \frac{1}{S_{\mathrm{max}}}\sum_{i=1}^{5} W_i S_i(C_i) \ ,$$

where the performance of the five weighted criteria ($C_{i=1...5}$) of each fuel technology is scored to yield five scores $S_i$. These scores are shown in Table 12. The weights are given in Table 13. The weighted ($W_i$) average score is then normalized to the maximum achievable overall score $S_{\mathrm{max}}$.

As a result, each fuel path shows a figure of merit (the overall normalized average score) between 0 and 100% which is presented in the following sections.

### 3.3.4 MCA results and discussion

The results of MCA are shown in Table 14. In each scenario there is a subset of high-scoring fuel pathways (numbers in bold).

A significant result is that HTL from advanced lingo-cellulosic feedstock (agricultural and forest residues), labelled "HTL/LigC", and the "HTL/Sew[d]" path analysed in HyFlexFuel with negative feedstock cost seem to be attractive fuel pathways in all three scenarios. It is therefore interesting to compare the fuel pathways in these two scenarios of sustainable development and rapid deployment.

***Table 14:*** *Result of MCA. Figures of merit (overall normalized average scores) of the selected fuel production pathways in the three scenarios.*

| | AtJ / MSW | BtL / MSW | BtL / LigC | HEFA / FOG | HTL / µA | HTL / LigC[a] | HTL / LigC[b] | HTL / Sew[c] | HTL / Sew[d] | PtL / DAC | StL / DAC | Ref.: Jet A-1 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Neutral scenario | 58% | 69% | **74%** | 55% | 44% | **83%** | **80%** | 52% | **77%** | 68% | 62% | 40% |
| Sustainable development scenario | 45% | 59% | **86%** | 57% | 46% | **86%** | **75%** | 58% | **70%** | **77%** | **73%** | 10% |
| Rapid deployment scenario | **83%** | **89%** | 50% | 53% | 40% | **77%** | **90%** | 40% | **90%** | 50% | 41% | 100% |

[a] Feedstock variety of agricultural and forest residues
[b] Feedstock cereal straw and HyFlexFuel process model
[c] No credit for feedstock
[d] Feedstock sewage sludge (negative cost) and HyFlexFuel process model

The performance of the alternative fuel paths (the conventional jet fuel reference is not needed here) in the two scenarios with distinct priorities are better understood when visualized in a two-dimensional diagram, as shown in Figure 3.

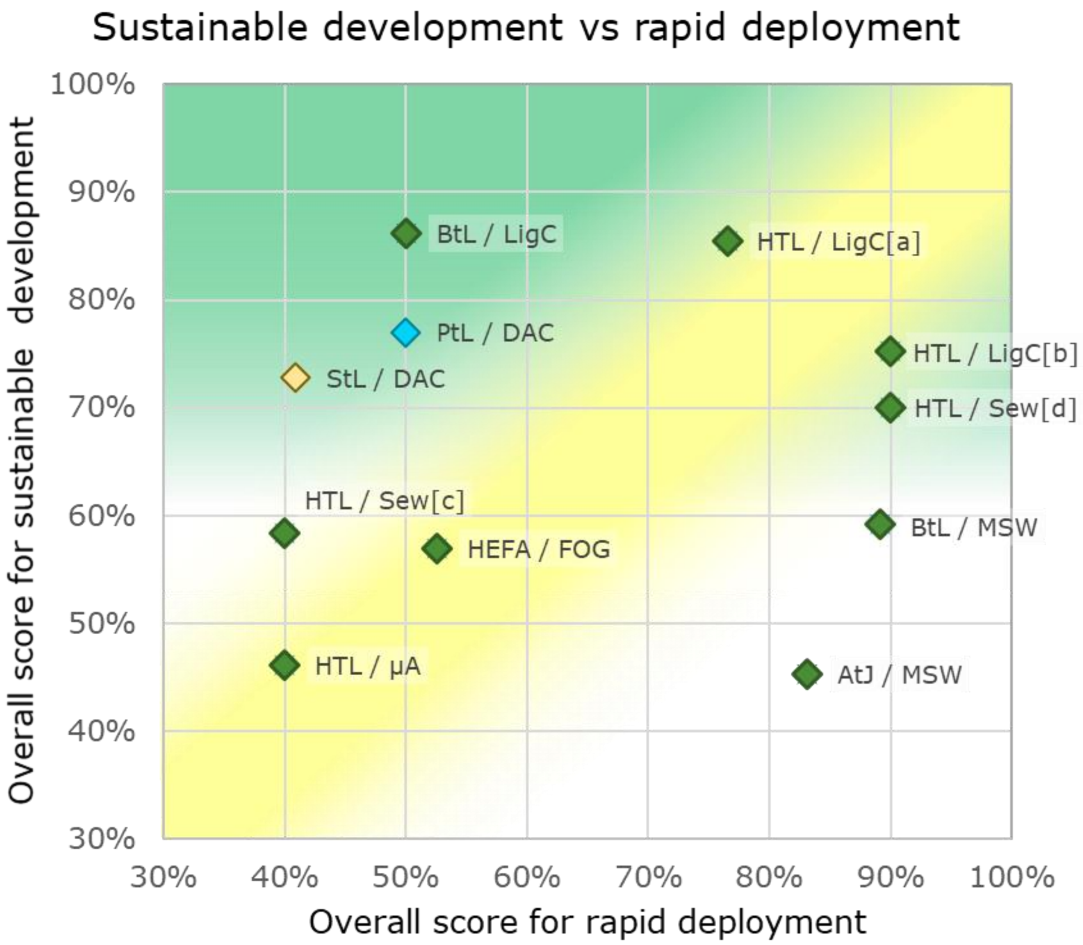


***Figure 3:*** *Result of MCA. Figures of merit (overall normalized average scores) of the selected fuel production pathways in the two distinct scenarios. The yellow diagonal area of "robust solutions" shows which fuel pathways perform equally well on both scenarios. The green highlighted area shows which fuel pathways are particularly attractive for sustainable development.*

Significant results and insights from Figure 3 are:

1. **On-diagonal regime of robust solutions:**
   a. **HTL and HEFA** fuel pathways lie in or near the "diagonal" regime (highlighted in yellow), i.e. they perform in both scenarios almost equally well or bad, depending on the feedstock.
   b. **HTL/LigC** from advanced lingo-cellulosic feedstock (agricultural and forest residues) and **HTL/Sew**[d] show up as attractive fuel pathways in both scenarios as already observed in Table 14.
   c. **HTL/µA** from cultivated microalgae "typically" suffers from high cost and high GHG emission values of the feedstock although these can vary between different assumptions for cultivation and extraction processes. The feedstock penalties then affect the LCA and TEA performance of the entire pathway, see also Table 8.

2. **Strong off-diagonal sustainable development solutions:**
    a. **StL/DAC, PtL/DAC and BtL/LigC are scoring 70% and higher in sustainable development (green regime)** but in contrast to HTL/LigC[b] and HTL/Sew[d] do not offer themselves for rapid deployment. With off-diagonal solutions there is a challenge to understand the technology potentials and gaps. These should be addressed with further research and development to bring these fuel production solutions to higher TRL and economic viability. The latter may also be addressed by financial measures to accelerate deployment.
    b. **Municipal solid waste (MSW) conversion via AtJ or BtL scores 80% and higher in rapid deployment but does not seem to offer itself for long-term sustainable development.** Here is an investment risk and the solution needs to be further studied in detail: will these technologies have the potential to support sustainable development in the future and will future policies support or penalize these investments? The management of municipal solid waste in a circular economy seems to be an important part of a sustainable future scenario. It is therefore recommended to also look into other conversion technologies such as HTL of MWS.

These results are based on “typical” data from the selected referenced literature and do not show the variabilities and confidence intervals in the MCA figures of merit. Future MCAs may apply Monte Carlo methods to propagate the input uncertainties through the analysis steps shown in this report. However, we can visualize the performance of LCA and TEA without the need for weighting and scoring by using the metrics of GHG emission reduction and cost competitiveness directly, as is shown below.

# 4. Dual-criteria assessment: LCA and TEA

Focusing on only two criteria at a time is another approach to a comparative alternative fuel assessment. A useful trade-off relation between criteria is the greenhouse gas emission reduction vs. the cost competitiveness, i.e. the LCA-vs-TEA representation. These are also two key criteria for sustainable development and rapid deployment.

In the selected literature, data for LCA and TEA were extracted only from those selected publications that present *combined* results for both LCA and TEA in one paper. By visualizing the performance based on the original metrics, no scoring is needed and the full variability of results can be observed.

The results are shown in Figure 4, together with three specific LCA and TEA results from the HyFlexFuel bottom-up system modelling reported earlier by C. Penke et al. [16].

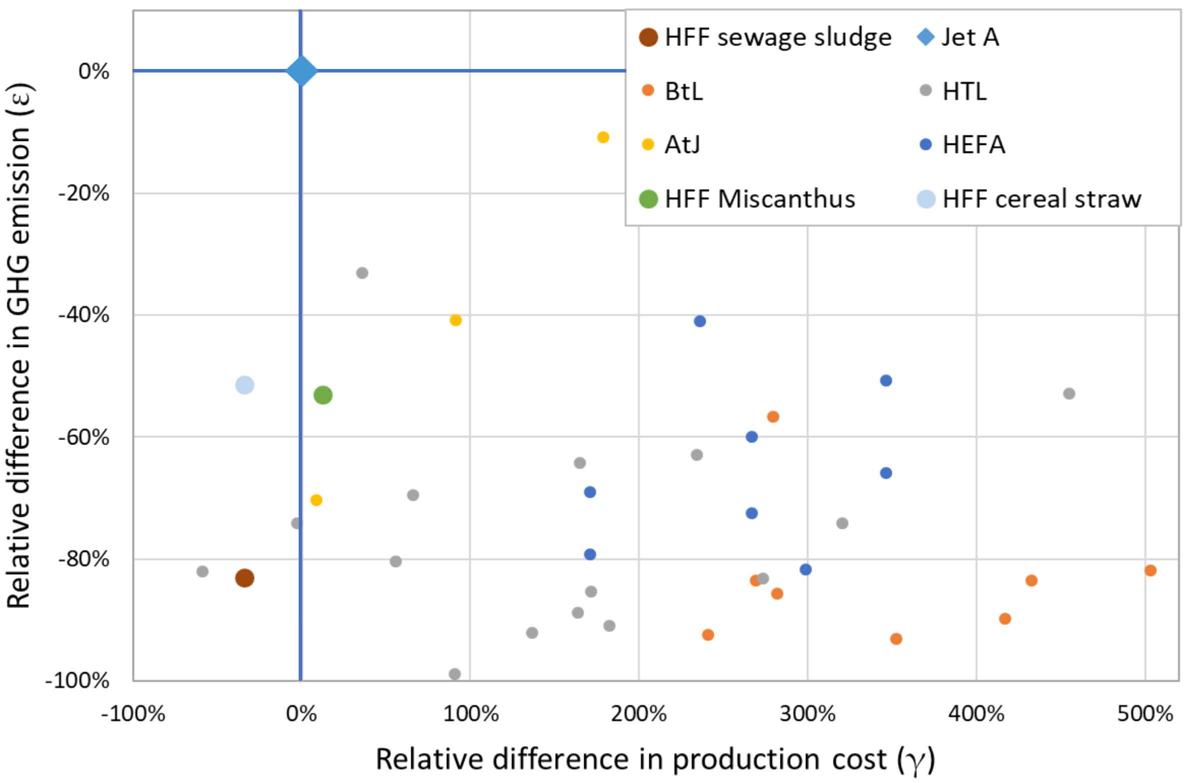


***Figure 4:*** *HyFlexFuel (HFF) results compared to results from other combined TEA & LCA studies of alternative fuel production pathways*

As can be seen from the figure above, the collected data cover a broad range of values. The performance of a conversion technology, when applied to a variety of feedstock types, leads to considerable spreading in the overall performance. In addition to the feedstock variety, some variations originate from differences in the underlying assumptions, methodologies, system boundaries etc. For example, on our modeling of HTL of sewage sludge ($HTL/Sew^d$ = HFF sewage sludge in Figure 4: 0.44 €/kg), negative feedstock cost were assumed based on public data for waste management cost. Other studies on the same type of feedstock with HTL conversion, such as the study by LJ Snowden-Swan et al. [18] (HTL/Sew[c] in Figure 3), do not take this cost advantage into account. It is interesting to see (e.g. HTL/Sew[f] in Table 8: 2.8-3.7 €/kg) that this has indeed a strong effect on the cost competitiveness of HTL of sewage sludge, as was also found in another context in the HFF project [15]. Furthermore, it can be observed that there are opportunities for advanced biofuels to start a potentially competitive early commercial introduction with promising GHG emission reduction, especially in the case of wet waste streams.

The evaluation yielded key findings summarized in the following.

- Many evaluated options provide substantially reduced specific GHG emissions in comparison to conventional jet fuel. However, in the literature base used for this assessment, only HTL and BtL seem to offer an emission reduction beyond 80%. HEFA and AtJ show higher emission values.
- The TEA data shows rather high values for BtL and a wide spread of HTL values which on the feedstock and the modelling assumptions. Therefore each case has to be studied individually and no general conclusion can be formulated.
- The HyFlexFuel study of LCA and TEA of HTL fuel from sewage sludge, with negative feedstock cost perform very well on both criteria. Miscanthus and cereal straw show cost competitiveness but do not exhibit a strong GHG emission reduction per unit volume or mass
- The performance of HTL algae fuel strongly depends on the source of algae. The HTL conversion independent of the feedstock penalty contributes only a minor share to cost and emissions: Chen et al. (2021) [43] show values as low as 0.27 €/kg MFSP ($\gamma$ = -59%) and 16 $gCO_{2eq.}$/kg GHG emissions ($\varepsilon$ = -82%) (HTL/µA[a] in Table 8).

Most alternative fuel options shown in Figure 4 are still expected to be considerably more costly in comparison to current conventional jet fuel prizes. Consequently, a price gap between conventional jet fuel and renewable alternatives is likely to remain at least in the medium-term future. Appropriate regulatory and/or economic measures will be needed to provide a market environment where renewable fuels can be competitive.

# 5. Conclusions

This public report presents the holistic assessment of fuel production via hydrothermal liquefaction in comparison with alternative fuel production pathways based on five key criteria corresponding to technical maturity, substitution potential, cost competitiveness, GHG emission reduction regional socio-economic impact. In a multiple-criteria assessment framework, nine alternative fuel paths were evaluated with respect to these criteria in two different scenarios, representing distinctly different priorities for “sustainable development” and “rapid deployment”.

The resulting figures of merit of HTL- and HEFA-based renewable fuel production tend to be rather stable under both scenarios conditions, showing robust results under the assumptions and database applied for this assessment.

In our multiple-criteria assessment framework HTL conversion of lignocellulosic residues and of sewage sludge as modelled in HyFlexFuel achieve high figures of merit: 75% and 70%, respectively, in the sustainable development scenario and both 90% in the rapid deployment scenario, which implies that the priorities in both scenarios are attained at a very high level.

In addition, a dual-criteria techno-economic and GHG emission trade-off was visualized on the selected set of advanced biofuel production pathways.

While many evaluated options provide substantially reduced specific GHG emissions in comparison to conventional jet fuel, only HTL and BtL seem to offer a substantial emission reduction for the database used in this assessment. The TEA data shows rather high values for BtL and a wide spread of HTL values which depend on the feedstock and the modelling assumptions. No general conclusion can therefore be formulated for the overall performance of HTL. It has been found that HTL conversion independent of the feedstock penalty contributes only a minor share to cost and emissions and thus has the potential for promising techno-economic (TEA) and life-cycle (LCA) emission performance. HTL fuels can achieve, cost competitiveness with conventional jet fuel and GHG emission reduction by 80%.

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HyFlexFuel
Public Report: Report on holistic technology assessment

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