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# Performance evaluation of jet fuel production by hydrothermal liquefaction in Europe

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**Abstract.** The EU Horizon 2020 project HyFlexFuel successfully demonstrated hydrothermal liquefaction (HTL) fuel production chains from different feedstock types to upgraded kerosene products. Now the question arises which commercial scale HTL system design is associated with the lowest environmental impact and production costs. The contribution addresses this research question by establishing a comprehensive process model for different feedstock types (sewage sludge, straw, miscanthus and microalgae) based on experimental biocrude production and upgrading campaigns in pilot and laboratory scale. This model enables evaluating different process configurations and serves as basis for subsequent system analyses by applying techno-economic and life cycle analyses (TEA and LCA). Upgraded biocrude using sewage sludge, representing a waste stream in wastewater management, can be produced at near-competitive price levels. Compared to conventional jet fuel production, greenhouse gases are reduced significantly. However, sewage sludge is a limited resource and only limited amounts of jet fuel could be substituted. Lignocellulosic feedstock such as straw or miscanthus are available in larger quantities and provide the opportunity to produce large amounts of sustainable aviation fuels at moderate costs.

## 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. 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 decarbonization 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. 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 [1] 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. HTL is a process that converts biomass to highly viscous biocrude at temperatures of 300-420 °C and pressures of 15-35 MPa, which subsequently can be further upgraded to jet fuel, with promising ecological and economic performance [2]. Since a wide range of biomass can be processed as feedstock to produce high-energy content biocrude [3], feedstock versatility is a major advantage of HTL compared to other biomass conversion technologies. The process water is treated by catalytic hydrothermal gasification to recover combustible gases from the admixed organic fraction. Depending on the feedstock, phosphates may be recovered to yield a fertilizer by-product. 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 (microalgae), and sewage sludge (waste) have been chosen to demonstrate the feedstock flexibility of HTL conversion.

This study aims to address the constraints of jet fuel production in Europe and evaluates both the economic and ecological performance, while also taking into account possible improvements including GHG emissions savings, for the overall conversion technology.

## 2. Materials and methods

### *2.1. Biomass and HTL jet fuel availability*

The availability of 11 different feedstock types suitable for HTL and the associated feedstock supply chains in Europe were analyzed in detail during the HyFlexFuel project [4]. In these analyses, one focus was set on the availability of residual urban as well as agricultural feedstocks. The results show that substantial amounts of biofuel could be produced from biogenic residues, with cattle excretion and cereal straw representing the largest shares of all analyzed feedstock categories. Individual values for the minimum and maximum biomass potential of feedstocks can be found in the data publication [4].

### *2.2. Selection of HTL process configurations*

In the LCA and TEA considerations two cases can be distinguished as depicted in Figure 1. The first case comprises feedstocks with high water content, like sewage sludge and microalgae. For this case we assume a feedstock provision on-site and consider a nutrient recovery as part o the process configuration. For these feedstock types an upgraded biocrude production potential of 7.6 kt per year is assumed. The investment cost for an HTL process in this order of magnitude is 23 M€.

The second HTL process category includes the dry lignocellulosic feedstocks straw and miscanthus. In order to reduce process water generation and to improve the process efficiency we assume a recycling of the HTL aqueous phase (AP) of up to 90 %. The AP is a by-product of HTL conversion (see Figure 1). Due to the theoretically higher availability of these feedstocks, we consider larger biocrude production capacities, namely 90 kt per year. These assumptions are associated with investment costs of 122 M€.

For both options it is assumed that process power and heat is provided by using biogas produced by treating the aqueous phase. Hydrogen and additional heat demand is assumed to be covered by natural gas. Detailed mass and energy balances, on which further economic and ecological calculations are based, can be found in [5].

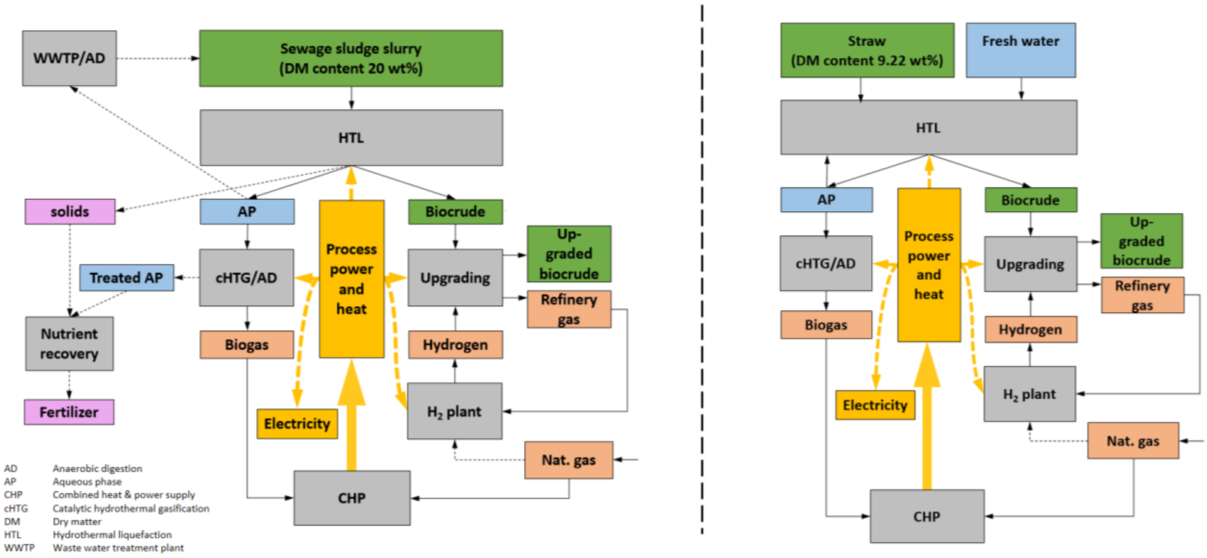


**Figure 1.** Basic building blocks of the HyFlexFuel process chain for the HTL of sewage sludge (left) and cereal straw (right).

## 3. Results

### *3.1. Biomass and HTL jet fuel availability*

The biomass potential provides information on the quantities of HTL fuels that can be produced in Europe. Figure 2 describes a GIS-based study, showing the urban and agricultural biomass hotspots in the EU. The red coloured areas represent areas with high biomass potentials. The map on the left shows that the urban biomass hotspots are mainly distributed over densely populated areas like Western Germany, whereas the map on the right visualizes agricultural preference areas. In these regions agricultural activities are abundant, and therefore the hotspots for agricultural biomass, comprising the north of Italy, the north of Germany and west coast of France are located in these regions. The biomass availability maps also provide an indication of the locations where large quantities of HTL fuels can be produced. Conversion factors, which can be derived from experimental data, can also be used to estimate the fuel potential for the respective feedstock [6]. A fuel potential of 0.86 Mt/year was determined for sewage sludge, 10.9 Mt/year for cereal straw, and 64.7 Mt/year for miscanthus.

According to Eurostat [7], kerosene consumption in the European Union in 2019 increased to 62 million tonnes per year (from 42.8 million tonnes in 2006). From this, almost 100 % was imported from Middle East and Pacific-Asia. With regard to the results of the here presented approach, a considerable amount of Europe's annual kerosene demand could be supplied by HTL derived fuels from the here presented biomass feedstock, assuming an encompassing exploitation of the feedstock.

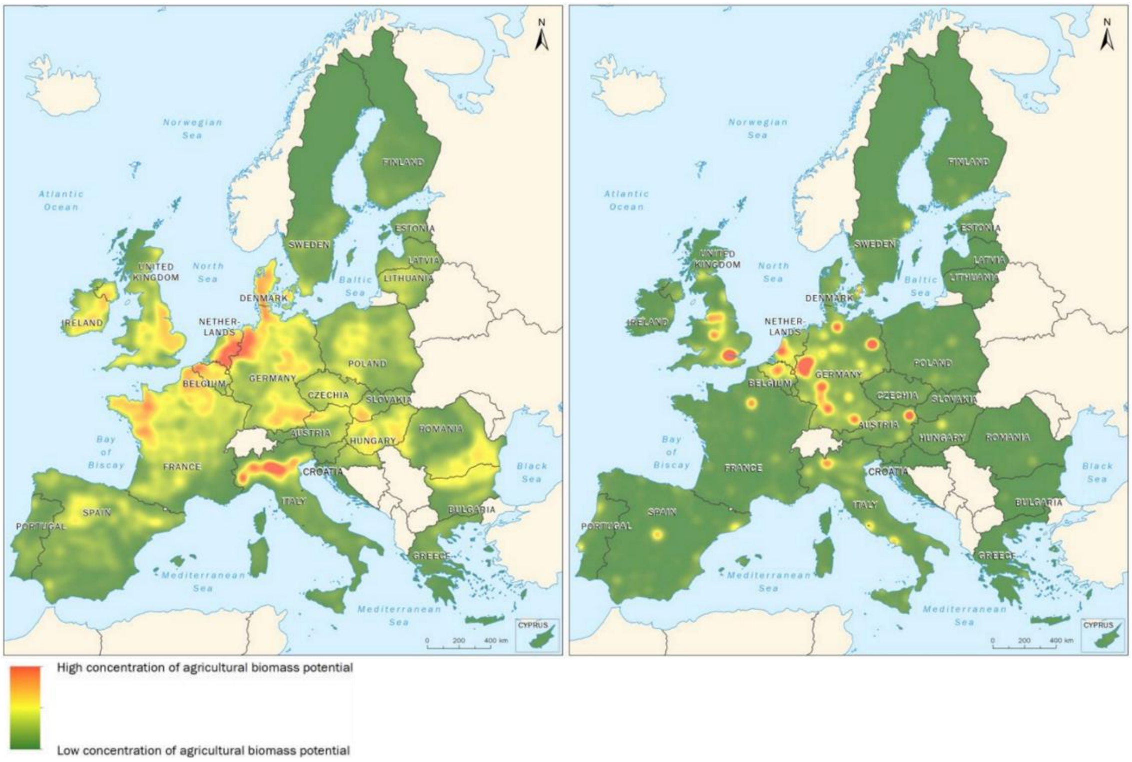


**Figure 2.** Technical biomass potential in Europe (left: urban biomass; right agricultural biomass) [8].

### *3.2. Jet fuel production costs*

In order to identify suitable locations for future HTL projects in Europe, the impact of different site-dependent parameters on the production costs of upgraded biocrude was analysed for HTL performed with the feedstock sewage sludge, miscanthus and straw.

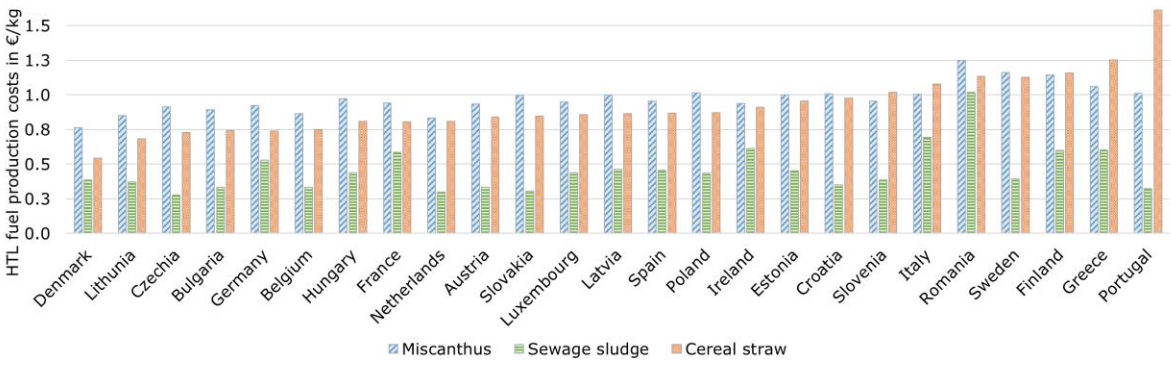


**Figure 3.** Estimated HTL fuel production costs (mixture of hydrocarbon fuels) in EU countries for miscanthus (blue), sewage sludge (green) or cereal straw (orange) as feedstock.

Labor costs, WACC (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 cost savings. Straw and miscanthus costs were considered at country level by taking into account the specific feedstock density for a transportation distance less than 50 km. The production costs of upgraded biocrude in different countries are shown in Figure 3.

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. When using miscanthus, the fuel production costs range from 0.76 € (Denmark) to 0.98 € (Romania) per kg upgraded biocrude. HTL fuels from each of the investigated feedstocks can be produced cost-effectively at different locations. Lowest fuel production costs result for sewage sludge as HTL feedstock, which is mainly related to revenues for sewage sludge treatment. Local feedstock availability and feedstock transport distance play an important role in economy of HTL fuel production. Local investment risk (expressed in WACC) has a major impact on the HTL fuel production cost. The HTL fuel production potential was taken into account to estimate which quantities of fuel can be provided at which costs. Results are illustrated in Figure 4.

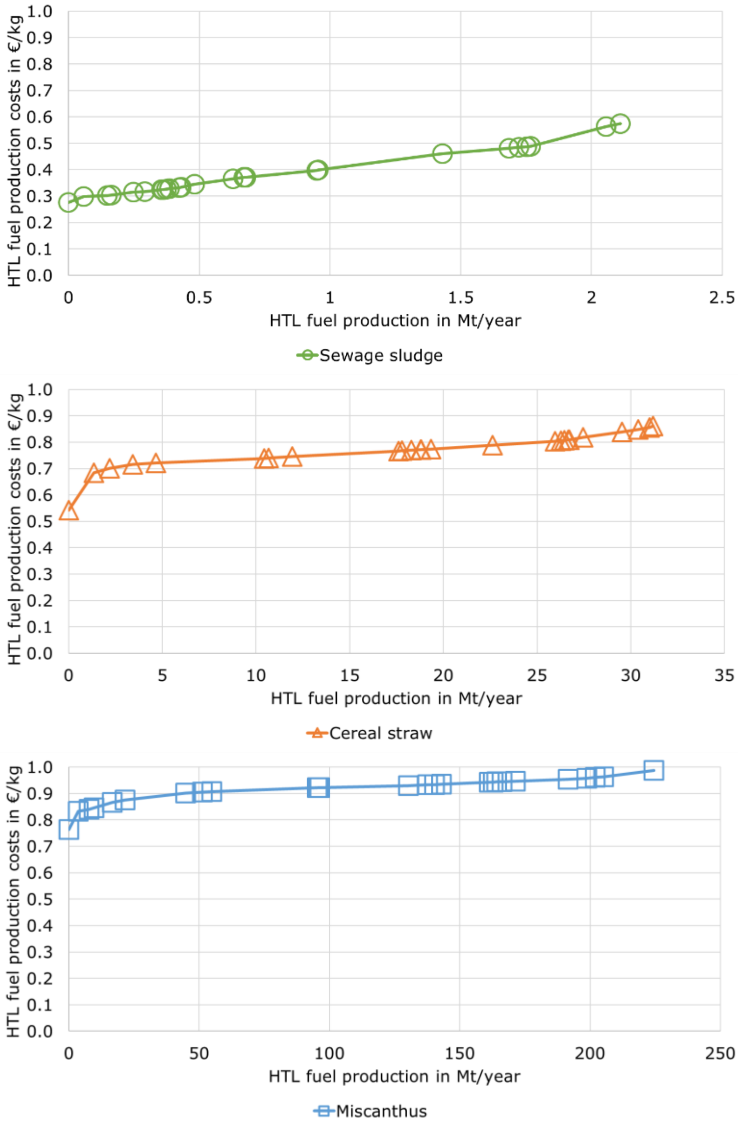


**Figure 4.** Average country specific HTL fuel production costs plotted against aggregated theoretical fuel production potentials for different HTL feedstocks. Depending on the feedstock availability, fuel production costs and potentials vary significantly. The theoretical fuel production potentials disregard competing demand from other sectors.

Sewage sludge as a waste material offers the advantage of being the most cost-effective solution. However, the production potential of this feedstock is limited. Cereal straw and miscanthus, which are associated with slightly higher costs on average, have higher HTL fuel production potential.

### *3.3. Reduction potential for GHG emissions*
For the three feedstock considered, it was shown in a previously published study [2] that greenhouse gas emissions can be reduced significantly by fuel production with different feedstocks.

Life cycle emissions of 0.65 kg $CO_2e$ per kg HTL fuel were evaluated for the conversion of sewage sludge. Comparing this value with the emissions released during the production of conventional kerosene (according to the GREET model 3.6 kg $CO_2e$ per kg jet fuel [9]) results in a saving of 82 %. For the feedstocks cereal straw and miscanthus, the respective savings are 49 % and 50 %.

It should also be mentioned that the modeled HTL process offers further potential for savings. The modeling shows that the GHG emissions result mainly from process heat and hydrogen generation from natural gas. When green hydrogen is used for biocrude upgrading and renewable heat is applied for heat supply, carbon emissions can be strongly reduced. Additionally carbon capturing processes (e. g. carbon capture and storage) offer the potential to realize a carbon negative balance, which makes HTL even more attractive as a sustainable aviation fuel.

### *3.4. Ecological and economical trade-off*
Figure 5 shows a trade-off graph of the HTL fuel production costs, expressed as minimum fuel selling price (MFSP) and GHG emissions for the different investigated HTL scenarios. The lowest MFSP and GHG emissions can be observed for sewage sludge. The reason for these low cost levels is, that 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 effects of a different process configurations like water recycling. Miscanthus shows almost similar GHG emissions as cereal straw, due to the similar process configuration, costs are much higher though, due to higher feedstock costs for miscanthus. Microalgae shows the highest GHG emissions as well as the highest costs, both caused by the feedstock production.

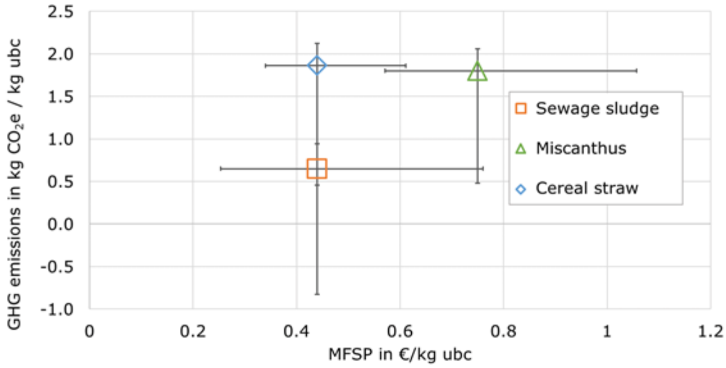


**Figure 5.** Minimum fuel selling price (MFSP) and greenhouse gas emissions for different HTL fuel production routes related to 1 kg upgraded biocrude (ubc).

Even though sewage sludge performs best in this presentation, in a holistic view it should be considered that this feedstock has a lower availability than the other two HTL feedstocks investigated. Taking into account the annual fuel demand of 62 Mt [10] in Europe in 2019, only 1 % of kerosene can be substituted with the available sewage sludge. Including straw into this calculation, 17 % of the demand can be covered. The use of agricultural raw materials such as miscanthus results in a substitution potential of more than 100 %, even with conservative assumptions.

## 4. Discussion

### *4.1. Comparison with literature*
Several techno-economic and lifecycle analysis studies for various HTL process configurations have been carried out in recent years. In the study of Snowden-Swan et al. [11], HTL of sewage sludge in the USA has been investigated. According to the study, the MFSP of upgraded bio crude is determined as 0.58 €, which is around 26 % higher than the calculated MFSP for sewage sludge based HTL in this study.

Since the MFSP is highly dependent on the feedstock availability, transportation prices or local regulations and taxes, this variation might be the result of the location. In another report by Snowden-Swan et al. [12], the emissions of sewage sludge HTL is included and given as 1.55 kg $CO_2e$/kg upgraded biocrude, which is almost 2.5 times higher than the mean data presented in this paper. Indeed, in order to compare the cost and emissions data with different studies, caution is required since the included steps for the analysis can vary significantly. Similarly, in the study of Chen et al. [13], HTL of wet biomass has been assessed, which again can be related with the sewage sludge scenario here, and resulting GHG emission for this process is given as 0.40 kg $CO_2e$/kg upgraded biocrude. These values are lower than the calculated GHG emissions in this study. However, all mentioned data from literature, are in the uncertainty range of our results. Mostly, up to now the TEA studies of HTL fuels, are conducted for woody biomass and sewage sludge.

### *4.2. Estimates of future developments*
Efforts are underway to further develop HTL technology and certify HTL fuels for aviation as well. Each sustainable aviation fuel pathway needs to be approved, in order to guarantee the safe operation of flights with the current engine and aircraft technologies. Until now, all fuels approved biofuels can be blended with conventional jet fuel up to ratios ranging between 10 % to 50 % [14]. Thus, it can be assumed that initially blending ratio for HTL based SAF will also be in this range. It can be further assumed that an initial approval of a HTL jet fuel pathway, e.g. from sewage sludge, could serve as a blueprint for the approval of further waste- and residue-based HTL kerosenes.

## 5. Conclusion
This study showed how significant the production potential of SAFs via HTL is. It was revealed that the use of waste and residual materials can already cover a substantial share of kerosene demand in Europe. By mobilizing further sustainable biomass sources, additional fuel quantities required for aviation can be produced. In addition, the results indicate that sustainable fuels can be produced from different types of biomass at near competitive prices. Various different regions in Europe can be considered as possible HTL locations, depending on the considered feedstock. In order to make HTL fuels available for aviation, investors are needed to advance the technologies already tested on a pilot scale (HTL conversion, biocrude upgrading and aqueous phase treatment) to enable approval of HTL kerosenes as aviation fuel.

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