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Research article

Techno-economic and environmental analysis of aviation biofuels

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ABSTRACT

The global awareness to reduce greenhouse gas (GHG) emissions from aviation and thereby make the overall aviation sector more environmentally friendly has increased in recent years. In this context one main driver is seen in the development of advanced biofuels for aviation, which have already been used for some regular flights by various air carrier. Within this context this paper compares four different production processes for biokerosene located in northern Germany using two different types of biomass feedstock each. These conversion processes are then assessed in terms of technical, economic and environmental criteria based on data retrieved from an extensive process simulation. Main outcome of this analysis are mass and energy balances, kerosene production costs and GHG emissions for the investigated conversion routes. The results of the investigated criteria are scattering significantly; i.e. no "silver bulled" can be seen based on these findings. Nevertheless, the significant influence of the provision of the biomass feedstock becomes obvious. Generally spoken the more environmentally sound and economic viable the feedstock provision can be realized, the more promising is the resulting biokerosene related to the economic and environmental criteria assessed here. This result is more or less independent from the respective conversion route.

1. Background

Today the aviation industry is emitting about 820 t_{CO_2}/a representing a total share of 2.5% of the global CO_2 emissions [1]. These emissions are most likely to increase in the years to come, since the ascending living standards in emerging countries like China, India and Brazil (and thus the accelerating travel activities) as well as the strongly rising world trade flows will induce even more and longer flight operations per year. With regard to this development the international aviation industry has developed a challenging self-commitment related to the further development of global CO_2 emissions from civil aviation. This includes a carbon neutral growth starting from the year 2020 leading to CO_2 emission reductions by 50% in 2050 related to the year 2005. These ambitious goals are based on more efficient aircrafts, on optimized flight operations (e.g. single European sky) and on aviation biofuels with a significantly reduced carbon footprint. According to these planning the largest CO_2 emission reduction is expected to be realized based on the market introduction of advanced biofuels for aviation.

Today civil aviation depends basically fully on Jet A-1 (kerosene) produced from crude oil. While for land transportation various alternative options are possible and partly already market mature from a technical point of view (e.g. biofuels, electro mobility, hydrogen and fuel cells, switch to rail roads and/or water ways) this is not the case for aviation (in a large scale) yet. Here research has just recently started to develop alternatives. These activities focus mainly on the development of the provision of alternative aviation fuels with low GHG emissions fulfilling the Jet A-1 specifications (i.e. "drop-in" fuel) or – with a much lower intensity and with a very long term perspective – a fuel similar to Jet A-1 (near "drop-in" fuel). So far most of these activities are strongly dedicated to fuels based on biogenic feedstock; but some early activities are carried out to use CO_2 (e.g. extracted from air) and electricity from renewable sources of energy for the provision of a synthetic kerosene (power to liquid, PtL). The reason for this is that civil airplanes in commercial use today are usually operated with Jet A-1 kerosene and that the average technical lifetime of an airplane is approximately 25 years and longer. Additionally, fuels used within airplanes should have a high energy density to minimize the necessary volume needed to operate a long-haulflight and a good combustion quality to allow for a highly efficient use. Beside this they should be characterized by a widespread or even global availability, fulfill numerous safety requirements, and have to be transported, stored and pumped easily. Kerosene resp. Jet A-1 fulfills all these requirements. Thus it is most likely that this fuel will stay in place also in the years to come especially due to the fact that the fuel characteristics of kerosene are well adapted to the demands of an airplane turbine as well as the harsh conditions during a long distance flight roughly 10,000 m above ground.

So far, numerous options to produce kerosene from organic matter

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(i.e. biomass) have been and still are under investigation globally. Among these various options no silver bullet has been identified for the time being. Against this background, this paper gives an overview of important conversion routes for the production of kerosene (Jet A-1) based on biogenic feedstock currently under discussion. To get a better understanding of the various conversion processes, four conversion routes are selected and presented in more detail. Afterwards they are analyzed related to technical, economic and environmental criteria. Therefore a detailed process modelling simulation of these various processes is realized. Based on these results an overall economic assessment following the annuity method as well as a life cycle assessment (LCA) will be conducted. The results, i.e. mainly the kerosene production costs and the GHG emissions within the overall life cycle, are then compared to each other and to a fossil reference to draw some final conclusions.

Techno-economic as well as environmental assessments of aviation biofuels are widely available. Atsonios et al. focused on the techno-economic assessment of aviation biofuels via alcohol synthesis or fermentation with subsequent upgrading and compared those fuels with fuels produced via Fischer-Tropsch synthesis. They found out that the production of alcohols via fermentation is more economically viable than the production via mixed-alcohol synthesis, whereas the Fischer-Tropsch base case showed minimum fuel selling prices between these technologies [2]. De Jong et al. conducted a comprehensive techno-economic comparison of different production routes for renewable jet fuels and their short-term feasibility. They used technology specific mass balances from different studies and used their own methodology to harmonize the assumptions for a comprehensive cost analysis. None of the processes they assessed was found to reach price parity with jet fuels derived from fossil energies [3]. Another extensive review on biojet fuel conversion technologies was conducted by the National Renewable Energy Laboratory. They basically analyzed and compared four different routes based on the conversion of alcohol, oil, gas or sugars into jet fuels regarding economic and environmental aspects. Therefore they conducted a vast meta study on recent research regarding the fuel production costs, mass balances and GHG emissions of the different production routes [4]. In a more recent study Pereira et al. conducted a financial analysis of biojet fuel production technologies. Therefore they analyzed six different production routes with two different feedstocks for each pathway. By using existing research results on the conversion efficiencies for the different production routes they calculated the internal rate of return for each process and investigated uncertainties with a Monte Carlo analysis. By doing so, they found out that the HEFA process was the economically most promising pathway [5].

Additionally studies more focused on the GHG emissions and other environmental aspects of biokerosene production have been conducted in recent years. In this context Han et al. conducted a study on the lifecycle analysis of biojet fuels, mainly focusing on hydroprocessed renewable jet fuel, as well as pyrolysis and biomass-to-liquids fuels. They found, that GHG emission reductions between 30 and 89% compared to fossil jet fuel can be achieved [6]. Staples et al. published their results on the lifecycle GHG footprint and minimum selling price of renewable jet fuels produced via different fermentation pathways. They also used a harmonizing methodology to conduct their analysis based on a meta study on technical parameters and conversion efficiencies of the different production pathways. By doing so they found out, that a large bandwidth of GHG footprints ranging from − 27.0 up to 117.5 $g_{CO_2}eq/MJ_{fuel}$ and a also a large variety of minimum fuel selling prices can be achieved [7]. Another extensive meta study on the overall sustainability of biokerosene production pathways was conducted by Buchspies et al. They analyzed environmental as well as socio-economic aspects of sustainability in the context of biokerosene and also found out, that the provision of environmental friendly biokerosene is possible, but strongly depends on a sustainable feedstock provision [8].

However most of these studies on the one hand side focus on a detailed assessment of one or two conversion pathways if the processes are modelled and simulated or on the other hand side analyze the economic or environmental aspects based on a meta study regarding the conversion processes. Since the results of such studies strongly depend on assumptions used for the process modelling, economic assumptions, geographical locations and the investigated timeframe those results are not always easily comparable. Therefore the need for a comparative study focusing on techno-economic and environmental aspects based on the same system boundaries and assumptions for different biokerosene production pathways to allow for a fair comparison of the result exists. Additionally the gas-to-liquids (GtL) process is usually assessed when fueled with natural gas as feedstock, whereas biomethane was used in this study to realize a bio-GtL process. This conversion pathway, which has not been assessed and compared to other biokerosene production pathways in depth is a significant contribution to the existing research body.

This is why the present paper focuses on the analysis of all those aspects related to four different, ASTM certified, production routes for biokerosene. In this context the technical efficiency, the production costs as well as the greenhouse gas emissions for the processes are analyzed based on the same methodological framework. Since the assumed plant location is Germany, the four processes are chosen based on German experiences in such conversion technologies. The investigated feedstocks were also selected as representative feedstocks for German agriculture as well as feedstocks with an established logistic infrastructure related to Germany. In this context two different feedstocks have been investigated for each process, representing a broad bandwidth of differing biomass properties.

2. Biokerosene production processes

Under the pressure to make flying more environmentally friendly different pathways for the production of aviation biofuels (so called biokerosene) have been developed in recent years. In a nutshell, all of these options aim to modify the molecules of the organic raw material (e.g. vegetable oil, sugar, lignocelluloses) to fulfill the given fuel specifications for synthetic kerosene. Such changes within the molecular structure of the biomass material might be chemically (mostly via chemical reactions controlled by adapted catalysts at elevated temperatures and/or pressures) and/or biologically (via biocatalysts at moderate temperatures).

An overview of the most important conversion routes for the production of biokerosene is given in Fig. 1. Following the process chain from top to bottom, first different pretreatment steps depending on the utilized biomass are necessary to provide the desired feedstock (i.e. vegetable oil, starch, sugar) for further processing. For most process routes this feedstock is then converted into intermediate products (e.g. alcohol, synthesis gas, bio-crude oil) via a first conversion step. These intermediates are then further processed into a middle distillate like fuel (i.e. biokerosene) via a second conversion step.

In accordance to the ASTM certification scheme developed especially for synthetic fuels (e.g. biokerosene) these fuels are classified into

- synthesized paraffinic kerosene (SPK),
- synthesized paraffinic kerosene plus aromatics (SKP/A) or
- synthesized iso-paraffins (SIP)

depending on the conversion route and/or the characteristics of the respective fuel. Until today fuels produced via the Alcohol-to-Jet (AtJ), the Biomass-to-Liquids (BtL), the Gas-to-Liquids (GtL), the Hydroprocessed Esters and Fatty Acids (HEFA) and the Direct Sugars to Hydrocarbons (DSHC) processes are certified by the ASTM (status: March 2017). Following ASTM D7566 standard synthetic fuels produced via these routes are only allowed to be used as blendstock together with fossil Jet A-1 within the following margins [9]: