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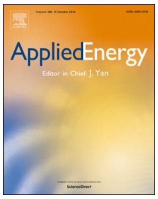

Techno-economic assessment of a renewable bio-jet-fuel production using power-to-gas

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HIGHLIGHTS

- Large number of scenarios (10) shows impact of various practical variations.
- Broad bandwidth of production cost; choice of vegetable oil being the most decisive.
- Power-to-gas adds 26–34% to costs compared to conventional hydrogen provision.
- High cracking rate for jet leads to high production of low-value hydrocarbons.
- Diesel-mode is 30% cheaper than jet-mode.

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ABSTRACT

A techno-economic assessment of a novel biorefinery concept is carried out. It combines the hydrotreatment of vegetable oils (HEFA) with a power-to-gas (PTG) unit that provides the required hydrogen. Several scenarios are examined: the electricity supply for the PTG unit is varied from a grid-based supply to a renewable island solution; the hydrogen supply is varied from a PTG unit to conventional steam reforming; the utilised vegetable oil is varied from jatropha to rapeseed, palm and used cooking oil; the main product is varied from jet fuel to diesel.

The HEFA-plant is assumed to process 500 kt of vegetable oil annually. In the reference scenario, jatropha oil is used as feedstock producing 227 kt a^{-1} of jet fuel. Per ton of processed oil, 1910 kWh_{el} are used to produce 35.7 kg of hydrogen required for its treatment. By using different vegetable oils, both hydrogen demand and fuel output vary in a range of about ± 10%. The overall energetic efficiency towards jet fuel is 41.6%.

With a bandwidth between 1295 and 1800 EUR t^{-1} of jet fuel, the specific production costs are three to four times higher than the market price for fossil jet fuel. Operating the refinery in diesel-mode could lower the production costs by ca. 30%. More high-value, long-chained fuels are produced this way due to a lower cracking rate compared to the jet-mode.

Investments of around 132 million EUR are required for the HEFA-plant in all scenarios. Investments for the PTG-plant lie around 82 million EUR if there is a constant electricity supply from the grid. They reach 246 million EUR if electricity is supplied in an island-solution based on fluctuating renewables demanding much higher hydrogen production and storage capacities. Total investments in the biorefinery reach 378 million EUR in this case. Despite high capital costs, the largest cost item is vegetable oil – similarly to a conventional HEFA plant. Supporting policy instruments such as subsidies or quotas for renewable jet fuel seem indispensable for an introduction of the PTG-HEFA technology in the short to medium term.

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1. Introduction

Limiting global warming to 1.5–2.0 °C above pre-industrial levels is the aim of the Paris Agreement signed in 2015. Since this demands a wide-ranging decarbonization of the economy, it is imperative to minimize the use of fossil fuels. Apart from electrification, the use of biofuels is an option to displace fossil fuels and mitigate greenhouse gases (GHG) in the transportation sector.

The fulfillment of national climate protection targets and the international voluntary commitment to reduce GHG emissions are a huge challenge for the continuously growing aviation sector. 2% of the total anthropogenic carbon dioxide emissions are caused by aviation – a sector estimated to double within the next 20 years [1]. Therefore, the use of sustainable renewable drop-in jet fuels with high specific GHG mitigation potential is key. One short-term option is bio jet fuel based on the HEFA-technology (hydroprocessed esters and fatty acids) [2]. HEFA jet fuel is ASTM standardized and can be blended up to 50% (v/v) with fossil jet fuel. Despite worldwide annual HVO (Hydrotreated Vegetable Oils – a subset of HEFA) production capacities of about 4 million tons (about 2.3 million tons in the European Union), there have only been project-based HEFA jet fuel productions for special use in aviation; an established market does not yet exist [3].

The GHG balance of HEFA can be improved by using renewable (surplus) electricity for the production of the required hydrogen and methane. By integrating power-to-gas (PTG) and HEFA technologies, this hybrid biorefinery concept makes use of substantial technical synergies. Furthermore, such a setup helps to link the electricity and fuel sectors and hence potentially avoid investments in the electricity grids. Fluctuating electricity can be leveled to some degree by a dynamic uptake in the PTG part of the hybrid biorefinery.

The demand for renewable jet fuel in Germany depends on its specific GHG mitigation and is expected to lie between 167 kt a^{-1} and 322 kt a^{-1} by 2020 [4]. In order to fulfill that demand, the PTG-HEFA biorefinery in the assessed scenarios is dimensioned to process 500 kt a^{-1} of vegetable oil.

In the HEFA process, vegetable oils undergo a preconditioning and are then treated with hydrogen to remove oxygen, double bonds, and glycerine. After thermal fractionation, HEFA fuels are obtained that are very similar to their fossil counterparts jet fuel, diesel, and naphtha.

In existing HEFA plants, large amounts of hydrogen are required and usually produced via steam-reforming of natural gas or using co-products like naphtha. The novel plant setup assessed herein sources hydrogen via electrolysis though. This reduces the use of natural gas or biomass and likely increases GHG mitigation – especially if renewable electricity is used for the electrolysis. Biofuel production would be dramatically increased if electricity were used for hydrogen provision instead of a part of the biomass input. These advantages of using electrolysis-based hydrogen for biofuel conditioning was already discussed in Albrecht et al. [5].

In the following, possible advantages of using electrolysis-based hydrogen in a HEFA plant are assessed based on several scenarios with variations of important assumptions. These include three different ways of electricity provision for the electrolysis (constantly from grid, price-optimised from grid, or fully renewable island solution), the hydrogen provision principle (electrolysis or steam reforming using either natural gas, biomethane, or naphtha), the type of used vegetable oil (jatropha, rapeseed, palm, or used cooking oil), and an alternative main product (jet-mode or diesel-mode).

Such a comprehensive comparison of scenarios using uniform methodologies and assumptions is a novelty. Another unique part is the very detailed analysis of the HEFA process that takes the chemical composition of different vegetable oils towards their chain lengths, number of double bonds, and content of free fatty acids, mono-, di-, or triglycerides into account and calculates the exact hydrogen demand to form and crack alkenes.

Other authors have analysed individual settings of HEFA plants considering only a few raw materials and usually one particular system for hydrogen provision (e.g. [6–17]). An assessment of water electrolysis using bioelectricity (from sugarcane) to generate hydrogen for a HEFA plant using different raw materials is made in Klein et al. [8]. These outcomes can only selectively serve as a comparison.

2. Materials and methods

The examined scenarios, methods of the technical and economic assessments, as well as the respective assumptions are described hereafter. All scenarios are assessed under German frame conditions.

2.1. Reference scenario and variations for PTG-HEFA plant setup

2.1.1. Scenario 1: Reference

In the reference scenario, the HEFA plant uses hydrogen produced on-site via electrolysis. Pressurised alkaline electrolyzers are chosen for their high efficiency and low specific investment. An underground hydrogen pipe storage bridges maintenance shutdowns of the electrolysis. Relatively small capacities are assumed for both electrolysis and hydrogen storage since electricity is constantly supplied by the national grid. Hence, both the HEFA and PTG plants operate for 8000 h per year. The PTG-plant needs an input capacity of 121 MW_{el} to produce the required hydrogen (cf. 2.2.2).

Jatropha oil is assumed as the reference oil because it is a promising feedstock for energetic usage. It is not edible, can be grown on marginal lands, and hence hardly competes with food or feed production. Its cultivation can increase soil carbon and therefore serve as a carbon sink. Jatropha is cultivated worldwide with a focus on Asia, Africa, and South America, and is assumed to be transported to the PTG-HEFA biorefinery via ship [18].

The oil is pretreated and refined before it enters the two-stage HEFA plant consisting of a hydrotreating and a combined hydrocracking and isomerization unit. The resulting mix of hydrocarbons is then thermally separated into the different fuel fractions. Parts of the fuel gas are used to generate process steam for the pretreatment and separation units. A basic flow diagram is given in Fig. 1, while the process is described in greater detail in chapter 2.2.

2.1.2. Scenarios 2 and 3: Alternative electricity supply for electrolysis

Instead of using electricity from the grid for 8000 h a^{-1} as in the reference scenario, scenario 2 assumes the best cost-effectivity whilst using electricity from the grid. Scenario 3 assumes a completely renewable and grid-independent electricity provision.

Scenario 2 makes use of spot market prices of the day-ahead auction at EPEX SPOT SE which vary each hour. By running the electrolyzers for only 4000 h a^{-1}, it is possible to buy electricity only when it is cheap. In 2015, the average spot market price of all 8640 h a^{-1} at EPEX SPOT SE was 31.63 EUR MWh^{-1}, whereas the average price of the 4000 cheapest hours was just 21.38 EUR MWh^{-1} (32% less). At the beginning of a year it is not clear which prices would be amongst the 4000 cheapest; but based on the experience of the preceding years, e.g. that prices decrease at night and in times of high renewable energy production, it is possible to buy only during the cheapest hours on the day-ahead-market. The PTG-plant is then operated on an hourly basis with short lead times. It needs an increased input capacity of 244 MW_{el} to produce the required hydrogen (cf. 2.2.2) due to the fewer full load hours.

Scenario 3 assumes a stand-alone power system based on fluctuating renewable energies, i. e. solar and wind energy. Both onshore wind and photovoltaic energy may be produced near the electrolyzer and be directly connected by cable. A completely renewable energy provision is guaranteed this way and a location near the coast in Northern Germany is assumed.

The transmission system operators in Germany publish their profiles of the feed-in of solar and wind energy within their grid region as well