Deutscher Luft- und Raumfahrtkongress 2012
DocumentID: 281191

RENEWABLE AVIATION FUELS – ASSESSMENT OF THREE SELECTED FUEL PRODUCTION PATHWAYS

C. Endres, C. Falter, A. Roth, F. Riegel, and A. Sizmann,
Bauhaus Luftfahrt e.V., Lyonel-Feininger-Str. 28, 80807 München, Germany

Abstract

Three selected long-term feedstocks and production pathways for renewable “drop-in” jet fuel are compared in a holistic and transparent assessment. The results show the individual strengths and weaknesses of hydroprocessed oil from microalgae and two Fischer-Tropsch synthetic paraffinic kerosenes, one based on woody biomass (Biomass-to-Liquid, BtL) and the other based on “inverse combustion” in a novel two-step solar-driven thermochemical process (Sunlight-to-Liquid, StL). According to the assessment, that gives a high priority to the criteria *production costs*, *greenhouse gas emissions* and *fresh water consumption*, the thermochemical “inverse combustion” technology represents the most promising option, closely followed by fuel production from woody biomass. Hydrotreated microalgal oil was ranked lowest, mainly because of the enormous production costs of the fuel production pathway.

1. INTRODUCTION

The future growth of air travel depends on the ability of the aviation industry to find solutions for three pressing challenges: the global increase in mobility demand, the aviation’s impact on the environment and climate as well as the dwindling fossil resources for fuel production. Alternative fuels are considered to be a promising option to tackle all of these challenges.

Until now a great number of possible fuel production pathways from various renewable feedstocks have been suggested. In order to determine the most suitable solutions, a transparent and holistic assessment is required. In this study such an assessment is conducted for three selected long-term options for alternative jet fuel, namely synthetic kerosene from lignocellulosic biomass, hydrotreated oil from microalgae and synthetic kerosene from syngas produced in a novel solar-driven thermochemical process.

The assessment shows the strengths and weaknesses of these promising fuel options with respect to technical, economical and ecological criteria. The final ranking of the fuels further illustrates their potential for the aviation industry.

2. SELECTED LONG-TERM FUEL ALTERNATIVES

2.1. Synthetic paraffinic kerosene from lignocellulosic biomass

Synthetic paraffinic kerosene (SPK) produced via gasification of lignocellulosic biomass to syngas (a mixture of carbon monoxide (CO) and hydrogen (H_2)) and subsequent Fischer-Tropsch (FT) synthesis represents a promising alternative to conventional jet fuel. The process is already certified according to the ASTM standard D 7566, and blends with conventional jet fuel containing up to 50% FT-SPK (based on biomass, natural gas or coal) can be readily used as drop-in fuel in commercial aviation. Various types of non-food biomass can serve as feedstock in this process; however, this study is solely focused on woody biomass from short rotation forestry. Typical plants for short rotation forestry are willow, poplar and eucalyptus. These trees/shrubs show high area-specific biomass production rates. Moreover the whole plant can be used as feedstock for the production of liquid fuels, resulting in high fuel yields. This is a major advantage compared to other fuel production pathways that rely only on specific parts of the plant, e.g. seeds.

The woody biomass can be harvested and processed into wood chips using established agricultural processes and commercially available machinery. Subsequently the wood chips are converted into jet fuel using the mentioned techniques. According to Stratton et al. [1] the density of the FT jet fuel product is 0.76 kg/L. This value is also used for the calculations conducted for the present study.

2.2. Hydrotreated plant oil from microalgae

Instead of using terrestrial plants also aquatic biomass can be used as feedstock for fuel production. Microalgae can contain large quantities of oil and have oil production rates that exceed those of traditional energy crops by far [2]. Additionally, microalgae do not require fertile soil and are not limited to the use of freshwater. This allows algae cultivation in areas not suitable for conventional agriculture. The oil of microalgae can be converted into jet fuel by hydrotreatment (hydrotreated fatty acids and esters, HEFA). This process is also certified according to ASTM standard D 7566. The resulting fuel can therefore be used commercially in blends containing a minimum of 50% conventional jet fuel.

In the last decades various algae cultivation systems have been proposed. Among the most popular systems were open raceway ponds, closed tubular and flat panel reactors. For the assessment we concentrate on open raceway ponds since they belong to the best described systems in literature. Raceway ponds are shallow pools typically 0.3 m deep. The culture medium containing the algae is moved in a closed loop which reminds of a raceway track. Agitation and mixing is provided by paddlewheels. For the assessment we assume algae cells with an oil content[1] of 25% and an oil production rate of around 2.5 $L/m^2/a$. The oil is separated from the residual biomass via solvent extraction and further processed through hydrotreatment into jet fuel. For the conversion process from oil to jet fuel a maximum conversion efficiency of 60 wt% is assumed. The physical density of algae oil required for the calculations within this study was adopted from Lundquist et al [3] (0.92 kg/L), while the density of the final HEFA product is adopted from Stratton et al. [1] (0.76 kg/L). In the considered model process the residual biomass left from the extraction process is used in an anaerobic digester for the production of biogas.

2.3. Solar fuels

Solar energy represents the largest renewable energy resource on earth. Therefore, it is desirable to make direct use of this resource without cultivation of biomass as intermediate step. The fuel production concept discussed in this study represents a novel pathway to directly convert sunlight into liquid fuels for aviation.

In the first step of this pathway sunlight is concentrated by mirrors (heliostats) and directed to a receiver, typically designed as a solar tower. Similar demonstration plants were already constructed for the purpose of solarthermal electricity production. However, instead of using the concentrated sunlight for electricity generation the light is guided into the inside of a thermochemical reactor to drive a redox reaction. By using cerium oxide (CeO_2) as reactive material, water (H_2O) and carbon dioxide (CO_2) are converted into syngas [4]. This syngas is processed, analogously to syngas from other feedstocks (coal or biomass), into liquid fuels in a FT reactor.

For the solar pathway we assume that carbon dioxide is captured directly from the atmosphere instead of using flue gas from fossil power plants, because the latter does not represent a renewable resource. Fresh water required for hydrogen production is provided by desalination of sea water using a process called reverse osmosis. Since the FT jet fuel is chemically identical to FT fuel from woody biomass, the same fuel density was assumed for our calculations (0.76 kg/L).

3. FRAMEWORK FOR ASSESSMENT AND PRIORITIZATION

3.1. The weighted decision matrix

The assessment method used in this paper has already been described in detail in an earlier publication by Naundorf et al. [5]. We therefore limit the following discussion to the key aspects relevant for the present work. In particular, the selected assessment criteria and corresponding metrics are described.

The assessment method is based on the principle of a weighted decision matrix. A set of criteria is selected, representing important technological, economical and environmental aspects of alternative aviation fuels (see next section). The weighting factor of a specific criterion represents its importance relative to the other criteria and can range from 0 (neglecting the criterion) to 10 (highly important) (see also section 3.3). Each considered fuel option receives a certain score with respect to each criterion.

For the assessment in the weighted decision matrix this score is multiplied by the weighting factor, assigned to the criterion, resulting in a weighted score. By adding all weighted scores of a fuel production pathway a total score, S_{total}, is calculated

$$S_{\text{total}} = \sum_{i=1} S_i W_i \,, \tag{1}$$

where S_i is the score and W_i the weighting factor for the criterion i.

3.2. Selected assessment criteria

The criteria used for the present assessment are shortly described in the following. Aspects like the technical compatibility with current aircraft systems as well as the impact of fuel combustion on local air quality (particulate matter) are not considered in this study because of the essentially identical chemical composition of the considered fuels, resulting in indistinguishable behavior with respect to these criteria.

The criteria that were actually selected for the present assessment are *fuel readiness level* (FRL), *production potential*, *production costs*, *well-to-wake greenhouse gas emissions*, *water consumption* and *nutrient requirements*.

For each of these criteria a metric is defined, enabling a translation of fuel-specific properties into individual scores ranging from 0 to 10. This dimensionless score allows for a comparison of different criteria on a mutual basis. The metrics of the criteria are defined in two different ways. For the criterion *fuel readiness level* discrete scores are defined, each representing a specific degree of development of a considered production technology (TAB 1).

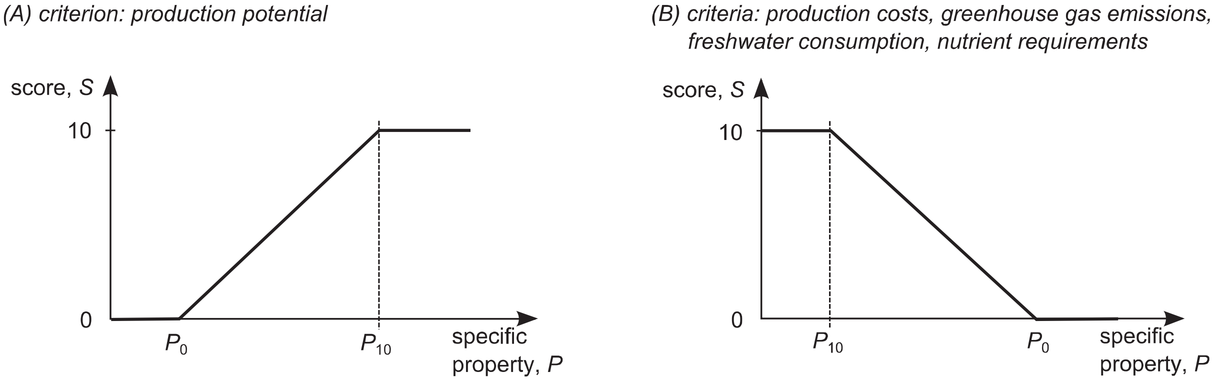
For all other criteria, continuous metrics are defined with a limit for the maximum score of 10 points (P_{10}) and a limit for the minimum score of 0 points (P_0). For example, in the case of *production costs*, 0 points are assigned to costs equal or higher than 2.00 €/L, while 10 points are assigned to production costs equal or lower than 0.60 €/L. The score for values between the interval borders is determined by linear interpolation. This procedure, including the general equations for the linear interpolation, is illustrated in FIG 1. The interval borders for all criteria are listed in TAB 2.

3.2.1. Fuel readiness level

The *fuel readiness level* characterizes the status of development of fuel technologies. Technologies in an early stage of development are considered risky, because

---

[1] In this context oil refers to the chemical group of triacylglycerides (TAG).



(A)

$S = 0$ for $P < P_0$

$$S = 10 \cdot \frac{P - P_0}{P_{10} - P_0} \quad \text{for } P_0 \le P \le P_{10}$$

$S = 10$ for $P > P_{10}$

(B)

$S = 0$ for $P > P_0$

$$S = 10 \cdot \frac{P - P_0}{P_{10} - P_0} \quad \text{for } P_0 \ge P \ge P_{10}$$

$S = 10$ for $P < P_{10}$

FIG 1. General description of the metrics for the assessment criteria *production potential* (case (A)), *production costs*, *greenhouse gas emissions*, *freshwater consumption* and *nutrient requirements* (case (B)). The score with respect to each criterion can be calculated by using the shown equations and interval borders. Values for all upper and lower interval borders are given in TAB 2. In the presented equations, S represents the resulting score, P_{10} and P_0 the upper and lower interval borders and P the specific property of a considered fuel with respect to the metric of an individual criterion.

their performance and economical viability are not proven. A higher development status is therefore considered positive, resulting in higher scores. The following list shows the specific scores attributed to a certain level of maturity. The idea of evaluating alternative fuels according to their FRLs was originally introduced by the US initiative CAAFI[2]. Here we use a simplified system of FRL categories described by Perimenis et al. [6]. (TAB 1)

Fuel readiness level	Score, *S*
Basic concept	0
Laboratory scale	2
Pilot scale	5
Demonstration scale	7
Commercial scale	10

TAB 1. Mertric for the criterion *fuel readiness level*.

3.2.2. Production potential

The criterion *production potential* is used to account for the scalability of fuel production pathways. Its specific property is the amount of jet fuel in liters that can be globally produced per day. The global *production potential* of a fuel pathway can be calculated from its areal productivity and the size of the available, suitable land area. As available for fuel production only areas are considered that are not required for food production and are no environmental protection zones.

The interval borders for the metric are here defined as 0 L/d for P_0 (0 points) and 500 million L/d for P_{10} (10 points), the latter corresponding to approximately 60% of the average global jet fuel demand of the year 2008. [7]

3.2.3. Production costs

In this study the economical viability of fuel production pathways is characterized by the costs to produce one liter of aviation fuel. As mutual basis for the comparison of the various estimates from literature the currency Euro (€) is chosen (2012 value). Where necessary the original information was converted into this unit by using historical inflation and exchange rates. Whenever an original document did not contain distinct information about the time needed to calculate the inflation of the currency, the year of publishing was used instead.

As interval borders we chose 0.60 €/L for P_{10} and 2.00 €/L for P_0. The spot price for jet fuel in the year 2011 was around 0.65 €/L [8]. When comparing production costs of 2.00 €/L with the given spot price, P_0 appears rather high. However, prices for jet fuel will probably rise in the long term due to increasing oil prices. Additionally, renewable fuels with a favorable greenhouse balance might profit from economic measures like emission trading. Therefore, even fuels with production costs as high as 2.00 €/L might be profitable in the long-term perspective.

3.2.4. Well-to-wake greenhouse gas emissions

Lifecycle[3] greenhouse gas balances are taken as a measure for the impact of a production system on the world's climate. The most prominent greenhouse gas is carbon dioxide (CO_2). However, during the fuel production process also other greenhouse gases like methane (CH_4) or nitrous oxide (N_2O) can be released into the atmosphere. To take these gases into account their global

---

[2] Commercial Aviation Alternative Fuels Initiative

[3] For jet fuel the lifecycle is characterized by the term well-to-wake (WtW).

Criterion	Metric (specific property *P*) for minimum score (P_0)	Metric (specific property *P*) for maximum score (P_{10})
Fuel readiness level	Basic concept	Commercial Scale
Production potential	0 L (fuel)/d	500 million L (fuel)/d
Production costs	2.00 $€_{2012}$/L (fuel)	0.60 $€_{2012}$/L (fuel)
WtW greenhouse gas emissions	3500 g (CO_2-eq.)/L (fuel)	0 g (CO_2-eq.)/ L (fuel)
Fresh water consumption	7500 L (water)/L (fuel)	50 L (water)/L (fuel)
Nutrient requirements	40 g (phosphorous)/L (fuel)	0 g (phosphorous)/L (fuel)

TAB 2. Overview of selected assessment criteria and corresponding interval borders (P_0 and P_{10}).

warming potential is determined and emissions are converted into carbon dioxide equivalents (CO_2-eq.). 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.). For the current study the cumulative greenhouse gas emissions of a certain fuel production pathway are determined and expressed as carbon dioxide equivalents. These emissions divided by the amount of produced jet fuel (g (CO_2-eq.)/L (fuel)) are used as metric for the criterion *WtW greenhouse gas emissions*.

We define the interval as 0 g (CO_2-eq.)/L (fuel) for P_{10} and 3500 g (CO_2-eq.)/L (fuel) for P_0. The value for P_0 is based on emission values of conventional jet fuel.

3.2.5. Fresh water consumption

The limited availability of clean fresh water is an increasing problem especially in emerging and developing nations. The large scale production of alternative fuels may add to this problem. In particular the cultivation of biological feedstocks may require large amounts of fresh water for irrigation, potentially leading to shrinking water resources, that are also needed for food production.

Here, we use the amount of fresh water consumed by the processes divided by the amount of produced fuel as metric for the evaluation. The interval borders are defined as 7500 L (water)/L (fuel) for P_0 and 50 L (water)/L (fuel) for P_{10}. The interval border P_0 hereby bases on typical values for energy crops while the value of P_{10} is based on the minimum amount of water needed to provide the hydrogen in the resulting hydrocarbon fuel molecules.

3.2.6. Nutrient requirements

Cultivation of energy crops requires a sufficient supply with various nutrients. The most important nutrients, so-called macronutrients, are nitrogen and phosphorous. When these nutrients are not available in sufficient amounts in soil and water, fertilizers have to be applied. However, the use of artificial fertilizers has several disadvantages. First, the production of artificial fertilizers is expensive and energy consuming. These two issues are already covered by the criteria *production costs* and *WtW greenhouse gas emissions* and are thus not further considered here. Second, the excessive use of fertilizers may lead to the eutrophication of water bodies. This may result in the pollution of drinking water and threaten natural habitats. Third, fertilizers containing phosphorous are produced from phosphorous ore, a limited and non-renewable resource [9], [10]. If more and more biofuels are produced, also the demand for fertilizer is expected to increase. Modern agriculture, however, relies on fertilizers for food production. The exhaustion of natural phosphorous resources will therefore lead to a conflict between fuel and food production and consequently, fuel production pathways requiring no or low input of phosphorous are preferable and receive a higher score in the assessment.

As a metric for the evaluation of *nutrient requirements* we chose the amount of consumed phosphorous in grams per liter of produced fuel. P_0 is set to 40 g (phosphorous)/L (fuel) which is approximately the amount of fertilizers needed to produce one liter of jet fuel from rapeseed. P_{10} corresponds to 0 g (phosphorous)/L (fuel).

3.3. Prioritization

Based on a survey among international experts of alternative aviation fuels conducted earlier by our team, we use the following weighting scheme for the present study (TAB 3).

Criterion	Weight, W_i
Fuel readiness level	2
Production potential	6
Production costs	8
WtW greenhouse gas emissions	10
Fresh water consumption	9
Nutrient requirements	5

TAB 3. Weighting factors used in the present assessment.

As can be seen from the table the *fuel readiness level* receives the lowest weight (weighting factor 2) of the considered criteria. This takes into account that only long-term fuel alternatives are compared. Consequently, the current degree of technological development plays only a minor role in the assessment with respect to long-term implementation. It is further assumed that sustainability aspects like *greenhouse gas emissions* and *fresh water consumption* will be of high importance in the future. Thus high weighting factors are attributed to these criteria. At the moment the diminishing phosphorous resources are not considered as a major threat to our society. However, studies indicate that phosphorous handling and ways to reduce phosphorous consumption will gain weight in the long term [9], [10]. The corresponding weighting factor thus is 5. The *production costs* will remain an important criterion resulting in a weighting factor of 8. For the weighting factor of the *production potential* a moderate value (weighting factor 6) is chosen, taking into account that it is not necessary that a single fuel production technology provides enough fuel to satisfy the complete fuel demand in aviation.

It is important to note that the selection of weighting factors is always a personal and somewhat subjective choice. The weighting factors selected here are based on our experience and interviews with a number of experts from airlines, fuel producers, aircraft manufactures including component suppliers, and research institutes.

4. EVALUATION OF THE FUEL PRODUCTION PATHWAYS

4.1. Synthetic paraffinic kerosene from lignocellulosic biomass

Fuel readiness level: Gasfication and subsequent Fischer-Tropsch synthesis of coal is already a fully commercialized process. Large scale plants exist in South Africa and are operated by the company Sasol. Other large scale plants using natural gas as feedstock are under construction in Qatar (Shell) and Nigeria (Chevron). The conversion of woody biomass into jet fuel, however, has not been commercialized yet. The companies Choren and Rentech built demonstration Fischer-Tropsch plants using biomass as feedstock. The latter plant is still operational and has a capacity of around 10 bpd[4]. We therefore conclude that this fuel pathway is in demonstration scale, resulting in a score of 7 points for the criterion *fuel readiness level*.

Production potential: A high-resolution approach is used to determine the production potential of fuel from woody biomass. The methodology of these calculations is described in detail by Riegel and Steinsdörfer [11]. The land area available for cultivating energy crops is calculated using geographical information systems. In a first step the net area suitable for agriculture is determined. Areas not suitable for agriculture include, for example, urban areas and areas of low soil quality and/or areas that are either too dry or too cold for cultivation. In the second step the area needed for food production is calculated and removed from the net area. Following our calculations, the resulting area available for the cultivation of energy crops is around $1.36 \cdot 10^9$ ha [12]. Assuming a moderate dry biomass yield of 8.0 t/ha/a [13], a total of $1.1 \cdot 10^{10}$ t/a (wood chips) could be produced from this area. According to personal correspondance with a scientist working at a BtL plant, around 1 bbl[5] of liquid fuels can be produced from 1 t dry biomass. If optimized for jet fuel production, a fraction of around 70% of the produced liquid hydrocarbons can be used as alternative to conventional jet fuel. Assuming these conversion efficiencies, around $3.33 \cdot 10^9$ L/d jet fuel could be produced globally. This amount is around 4 times the global jet fuel consumption of 2008, and about equal to the consumption in 2050 assuming a yearly growth of 3%. Therefore, this fuel production pathway receives a maximum score of 10 points for *production potential*.

Production costs: The production costs of SPK from woody biomass are estimated based on the studies of Kreutz et al. [14] and Buchholz and Volk [15]. In their study, Kreutz et al. examined various concepts for FT plants that operate on biomass, coal or a mixture of both. For a BtL plant operated on biomass only with a capacity of 4400 bpd, fuel production costs of 22.49 €/GJ were calculated. A major assumption Kreutz et al. made for their calculation is the feedstock type, herbaceous biomass, and the corresponding price of the biomass, 4.41 €/GJ. When using a different type of feedstock the costs could be substantially reduced. Buchholz and Volk estimated that wood chips from short rotation coppice can be provided at costs of 50.38 € per dry ton or 2.59 € per GJ in the long term. We therefore assume for our study the feedstock costs as estimated by Buchholz and Volk within the cost model for the fuel production plant as developed by Kreutz et al. The fuel production costs are thus 0.61 €/L, resulting in a score of 9.9 points.

WtW greenhouse gas emissions: To our knowledge no study exists that holds information about greenhouse gas (GHG) emissions specifically for jet fuel produced from woody biomass via gasification and FT conversion. Diesel, however, is used in larger quantities. Therefore, greenhouse gas emissions are often reported for diesel in the literature. Diesel and jet fuel are very similar in their chemical structure, and both fuels have nearly identical values with respect to their density and energy content. We therefore use published greenhouse gas emission data for FT diesel as estimation for the unavailable values for FT jet fuel. Jungbluth et al. [16] state in their study that the lifecycle greenhouse gas emissions of Fischer-Tropsch diesel from short rotation coppice are around 69% lower than those of EURO 3 low sulfur petrol. Expressed in absolute values this amounts to lifecycle emissions of 29 g (CO_2-eq.)/MJ. Using a lower heating value of 44.1 MJ/kg and a density of 0.76 kg/L the well-to-wake greenhouse gas emissions of jet fuel are calculated 972 g (CO_2-eq.)/L. This leads to a score of 7.2 points.

Fresh water consumption: Röhricht and Ruscher [17] estimate the water consumption of different species of poplars and willows around 600 L/kg (dry biomass) and 700 L/kg (dry biomass), respectively. For our study we assume an average value for short rotation crops of 650 L/kg (dry biomass). Using the above-mentioned conversion efficiency for dry woody biomass into jet fuel, around 5840 L of fresh water are needed to produce 1 L of jet fuel. This results in a score of 2.2 points.

Nutrient requirements: Following Röhricht et al. [18], in average dry woody biomass contains around 0.11% phosphorous. Assuming the above-mentioned efficiency for the conversion of dry biomass into liquid jet fuel, about 9.9 g phosphorous are needed to produce 1 L of fuel. Studies show that ash residues from gasification hold a lot of phosphorous that can theoretically be recycled and used as fertilizer [19]. Quantifying these amounts, however, appears difficult since the actual phosphorous uptake depends on soil, rainfall, type of ash and type of biomass cultivated on the applied ash. For this study we therefore assume that 50% of the phosphorous can be recycled. This results in a total phosphorous requirement of around 4.9 g/L, resulting in a score of 8.8 points.

4.2. Hydrotreated oil from microalgae

Fuel readiness level: Long-term cultivation of microalgae for fuel production was successfully demonstrated in the

---

[4] bpd = barrels per day (10 bpd = 1590 L/d)

[5] bbl = barrels (1 bbl = 159 L)

Aquatic Species Program of the NREL[6] [20]. Over the course of the program several pilot plants designed as raceway ponds were constructed and operated. The maximum size of these pond systems was 1000 m^2. In the last decades larger cultivation systems were built. For example the company Aurora Algae, Inc. operates a demonstration facility covering an area of 8 ha. Other demonstration facilities are operated by Sapphire Energy, Inc. and Parabel, Inc. Full commercial plants exist for the production of high value products, like food supplements or cosmetics. However, large scale, commercial microalgae cultivation for the purpose of fuel production has not been realized yet. According to the criterion *fuel readiness level*, algae fuel production therefore receives a score of 7 points.

Production potential: As mentioned before, microalgae are highly productive organisms. Assuming, for example, a moderate oil production rate of 2.5 L/m^2/a and a conversion efficiency from oil to jet fuel of 60 wt.%, around 500 million liter of fuel (P_{10})could be produced every day from an area the size of Iceland (100 000 km^2). This fuel production rate would be high enough to cover 60% of the global jet fuel consumption of the year 2008 [7]. Considering further that microalgae can be cultivated in areas that cannot be used for conventional agriculture, we assume for this study that enough jet fuel can be theoretically produced from algae to satisfy the global demand. This assumption is further supported by a report of the Ecofys institute, where it is estimated that 80 EJ/a of algae oil can be produced from open ponds in arid and semiarid regions [21]. This amount could theoretically be converted into around $5.0 \cdot 10^9$ L (fuel)/d, around 8.5 times the amount of jet fuel consumed in 2008 [7]. The fuel production pathway thus receives the maximum score (10 points) for the criterion *production potential*.

Production costs: The production costs of algae oil are estimated based on a report of Lundquist et al. [3]. In this report the economic potential of microalgae cultivated in open raceway ponds is analyzed. Lundquist et al. estimate that for a 400 ha plant with focus on oil production, costs to produce 1 L of oil will be around 1.63 €. Additional costs have to be taken into account to process algae oil into jet fuel. The costs of converting vegetable oil into aviation fuel via hydrotreatment were calculated by Pearlson [22]. Using the given values for a large 6000 bpd biorefinery with focus on jet fuel production, refining costs of 0.22 €/L (HEFA fuel) have to be added to the algae oil production costs. In this context it has to be considered that according to the conversion rates listed by Pearlson around 1.15 L oil are required for the production of 1 L of liquid distillates. The total production costs for HEFA jet fuel from microalgae therefore sum up to 2.09 €/L (fuel). This results in a score of 0.0 for the *production cost* criterion.

WtW greenhouse gas emissions: Values for greenhouse gas emissions were adopted from Stratton et al. [1]. In contrast to other studies, Stratton et al. estimate the emissions specifically for the aviation sector, with jet fuel as final product. The system examined by Stratton et al. is a raceway open pond system. In their study a low emission, a baseline and a high emission scenario are distinguished. For the current assessment we use the results for the baseline scenario since the presumed oil production rates in this scenario are in good accordance with the rates assumed for the model system considered in the present study. The WtW greenhouse gas emissions calculated for the baseline scenario amount to 50.7 g (CO_2-eq.)/MJ [1], corresponding to a volumetric emissions balance of 1700 g (CO_2-eq.)/L (fuel). This value results in a score of 5.1 for *WTW greenhouse gas emissions*.

Fresh water consumption: Water use in algae cultivation systems is a critical aspect. When using open ponds, large quantities of the culture medium may evaporate. To replace the losses and to keep the water level constant, different sources of water may be used. Water sources proposed in the literature include seawater, saline and brackish groundwater, wastewater and freshwater. For every type of water various positive and negative aspects may be named. For example, saline groundwater may not be used as drinking water or for irrigation, however, it is often a fossil, non-renewable resource. Furthermore additional energy input has to be considered if the water is pumped up from great depths. In our study we therefore define freshwater as water source for algae cultivation. The water consumption for the production of 1 L algae oil is around 1735 L [3]. When using the mentioned conversion efficiencies for processing oil to jet fuel, around 2410 L freshwater are required for the production of 1 L of jet fuel. Water losses related to the hydrotreating process itself are neglected in this study, since they are considered small in relation to the water losses occurring during algae cultivation. The score of the microalgae pathway for this criterion therefore is 6.8 points.

Nutrient requirements: Nutrient requirements of microalgae and recycling of nutrients within an algae production process are described by Rösch et al. [23]. In that study three different model species of microalgae with different lipid and TAG contents are considered. After oil extraction the residual biomass can either be used for anaerobic digestion, hydrothermal gasification or as animal feed resulting in different recycling rates for the nutrients. According to that study, the production of 3.7 kg of biomass with a TAG content of 25% requires 28 g of phosphorous. The oil content of the biomass can further be extracted and converted into jet fuel. If the residual biomass is fed into an anaerobic digester for the production of biogas, around 80% of the phosphorous can be recycled. The phosphorous demand therefore amounts to 8.0 g (phosphorous)/L (fuel). This results in a score of 8.0 points for the criterion *nutrient requirements*.

4.3. Solar fuels

Fuel readiness level: Solar thermal power plants exist in demonstration scale in Spain and the US. Analogous to electricity production these plants could also be used to drive the thermochemical reaction of the here considered pathway. Chue et al. [4] demonstrated in a laboratory environment the technical feasibility of thermochemical splitting of water and carbon dioxide into syngas. A similar status of development can be determined for the various techniques of capturing carbon dioxide from the atmosphere [24–26]. In contrast, the final conversion of syngas to FT jet fuel is a well established process (see above).

When considering the *fuel readiness level* of the complete

---

[6] National Renewable Energy Laboratory

fuel production pathway the least developed steps are important. With respect to the low technical maturity of the thermochemical reactor and the carbon capture techniques the fuel readiness level thus is categorized laboratory scale resulting in a score of 2 points.

Production potential: For solar fuels, as well as for biofuels, the primary energy supply is solar irradiation. The supply of solar energy on earth is vast and equals $1.22 \cdot 10^{17}$ W [27] while the global demand of energy on earth was equal to $1.11 \cdot 10^{13}$ W in 2009 [28]. Solar energy incident on earth is therefore around ten thousand times the amount of energy consumed. Taking this into account, even a very low energy conversion efficiency of solar energy to solar fuels would in principle be sufficient to cover the entire aviation fuel demand. The assigned score is therefore 10 points.

Production costs: Cost estimations of not yet fully developed processes generally are a difficult task requiring assumptions concerning the costs for constructing and operating the facility. Especially for technologies that are still in a basic testing and development phase, such as solar fuels, these estimations always display an inherent degree of uncertainty. This has to be considered for the following cost estimation.
The costs for fresh water can be estimated by applying typical costs for the desalination of sea water. Desalination in general is realized by a process called reverse osmosis. The costs to produce one cubic meter of fresh water are around 0.45 € [29], [30]. Carbon dioxide can be derived directly from the atmosphere by different capture technologies such as physical adsorption or chemical absorption. For the latter, several cost estimations exist that reach from about 25.60 €/t (CO_2) [31] to 488.40 €/t (CO_2) [32]. For the present study the intermediate value of 127.75 €/t (CO_2) published in reference [33] is selected. Hydrogen production using concentrated sunlight in a solar tower was examined by Kromer et al. [34]. In their study the costs to produce 1 kg of hydrogen from water were estimated to be 2.14 €. For the solar thermochemical production of carbon monoxide no comparable study was found. However, since the plant layout basically is the same as for hydrogen production we assume that the costs of hydrogen production and carbon monoxide production are identical[7]. The conversion of syngas to fuel is carried out in a FT reactor. Capital expenditures and operating expenditures of this process were adopted from van Bibber et al. [35].
Taking into account the mentioned cost factors the total costs for solar fuels sum up to 1.15 €/L. The resulting score for the criterion *production costs* thus is 6.1 points.

WtW greenhouse gas emissions: Emission of greenhouse gases in the solar thermochemical process are associated with the construction of the facility including the heliostats, the tower and the Fischer-Tropsch plant, and with operation and maintenance, e.g. electricity for sun tracking, provision of heat for the FT-reaction, or catalyst replacement.
In ref. [36], the GHG emissions for a solar tower power plant producing electrical energy are calculated. While the receiver in a thermochemical process is different, the infrastructure for solar concentration remains the same. It is assumed that solar fuel production has the same emissions relative to the energy output. Emissions from the FT-plant are taken to be equal to those of FT-conversion of natural gas as in [37] without ancillary feedstock emissions. As an integrated generic power plant is considered, storage of syngas and transport of gases and liquids are not taken into account.
The emissions sum up to about 1500 g (CO_2-eq.)/L (fuel), which corresponds to a score of 5.7.

Fresh water consumption: Compared to processes that are based on photosynthesis, a solar-driven thermochemical process does not require water input for plant irrigation. It is, however, required to supply fresh water for the production of syngas which is further converted in a Fischer-Tropsch process. The feedstock for the production of liquid hydrocarbons is hydrogen – from the splitting of water – and carbon monoxide – from carbon dioxide. Since fresh water is supplied by the desalination of sea water, natural fresh water reservoirs are not affected. Therefore, in the context of this criterion, no fresh water is consumed during the process. Nevertheless, even when fresh water is used from natural reservoirs only a stoichiometric amount of water would be needed. Taking into account the fraction of hydrogen in the resulting fuel it can be calculated that around 1 L of water is required per liter of jet fuel. Even if taking into account further water losses in the process the water consumption stays well below threshold for the maximum score of the criterion. Thus 10 points are assigned to the solar fuel pathway for the criterion *water consumption*.

Nutrient requirements: As mentioned before, the solar fuels pathway is completely independent of biomass. Consequently no fertilizers are needed for fuel production and nutrient demand, including phosphorous, is assumed to be zero. Solar fuels are thus rated with the maximum score of 10 points for the criterion *nutrient requirements*.

5. FUEL ASSESSMENT AND DISCUSSION

The scores of the three evaluated fuel production pathways with respect to the various assessment criteria are summarized in TAB 4. Using the set of weighting factors defined in section 3.3, a total score is calculated according to Eq. 1 and finally converted into the normalized total score (normalized with respect to the maximum achievable total score), presented in TAB 4. As can be seen, solar fuels are assessed as most suitable fuel alternative (310 points, normalized: 0.78). Ranked second, fuel production from woody biomass via Fischer-Tropsch synthesis (289 points, normalized: 0.72) follows, while fuel production from microalgae oil via hydrotreatment ranks third (226 points, normalized: 0.57).

Solar fuels profit from high scores for the criteria *water consumption* and *nutrient requirements*. As described above, the production of solar fuels does not require biogenic feedstock, thus no nutrients and only minor amounts of fresh water are consumed in the production process. With respect to the other criteria, except for *fuel readiness level*, solar fuels at least achieve average scores. And since the *fuel readiness level* plays only a minor role when considering a long-term perspective and

---

[7] Identical costs were assumed on a molar basis, meaning in our assumption the costs to produce 1 mol of hydrogen (H_2) are the same as the costs to produce 1 mol of carbon monoxide (CO). Due to the difference in molecular weight costs per kilogram are not identical.

Criterion	Weight, W_i	Woody crops	Microalgae	Solar fuels
Fuel readiness level	2	7.0	7.0	2.0
Production potential	6	10.0	10.0	10.0
Production costs	8	9.9	0.0	6.1
WtW greenhouse gas emissions	10	7.2	5.1	5.7
Fresh water consumption	9	2.2	6.8	10.0
Nutrient requirements	5	8.8	8.0	10.0
Total weighted score	-	289	226	310
Total weighted score (normalized)	-	0.72	0.57	0.78

TAB 4. Overview of the scores of the three considered fuel production pathways including the final assessment results.

is consequently attributed a low weight only, the influence of the low score of solar fuels with respect to this criterion on the overall ranking is not substantial.

Ranked second in our study is fuel production from woody biomass via gasification and Fischer-Tropsch synthesis. This production pathway achieves high scores with respect to the *criteria production costs* and also *WtW greenhouse gas emissions*. However, *fresh water consumption* is substantially higher than in case of the other two considered fuel production pathways. Evaluation of *nutrient requirements* resulted in a high score as well, but nevertheless below that of solar fuels, where no nutrients are required at all for the production.

Fuel production from microalgae following the HEFA pathway was assessed to be the least favorable solution. *Water consumption* is lower than that in case of the fuel production from woody biomass. However, still around 2400 L of water are needed to produce 1 L of jet fuel from microalgae oil. The most critical aspect of the pathway was found to be the high production costs resulting from the complex and expensive cultivation of microalgae.

6. CONCLUSIONS

In the present study three production pathways toward alternative, renewable aviation fuels were compared and assessed. All pathways are considered long-term (2030+) solutions and will probably not be commercially available within the next 10 or 15 years. Our assessment shows that especially the direct thermochemical conversion of sunlight into jet fuel represents a very promising future option. The main advantage of this technology lies in its independence of biogenic feedstock, resulting in low water consumption and no need for fertilizers. However, solar-driven thermochemical conversion represents the least technologically mature of the considered options. Future development efforts might therefore reveal additional advantages or problems that have not been accounted for in the present assessment.

The main drawback of the production pathway based on woody biomass was found to be the relatively high water demand in the biomass production step. This demand is even higher than in case of the cultivation of microalgae in the selected model cultivation setup. An additional problem of this production pathway, in contrast to the other two considered options, is that the feedstock production requires valuable fertile land. Nevertheless, from today's point of view, fuel production from woody biomass seems more promising than from microalgal oil, mainly because of the extraordinarily high production costs of the latter option.

It is important to emphasize that the present assessment is based on published data and information that had been compiled through an extensive review of available scientific literature. It has to be kept in mind that the utilization and comparison of data extracted from different sources is only possible to a limited extent as boundary conditions and assumptions usually differ from study to study. The data used in the present assessment were adapted as best as possible in order to increase comparability, but nevertheless an intrinsic uncertainty remains.

Another important issue that needs to be addressed is the fact that the technologies considered here are yet far from being readily developed for commercial implementation. Naturally, technical information on such future technologies is somewhat speculative and based on empiric data from small-scale experiments at best, thus adding to the uncertainties in the assessment. Nevertheless, the presented assessment clearly reveals the advantages and drawbacks of the considered production technologies for alternative aviation fuels based on the currently available information, thus providing a basis for the development of a strategy for systematic improvements.

The methodological refinement of the assessment framework represents an important part of our ongoing work. The focus of the refinement lies on the quantification of the impact of uncertainties on the ranking. As described above, substantial uncertainties are an inherent problem when assessing future technologies. Therefore, the quantification of those uncertainties is of particular interest, especially when the evaluated alternatives receive similar scores, as in case of the thermochemical conversion of sunlight and the fuel production from woody biomass considered in the present work. It is a straight forward task to include uncertainties and to quantify their impact on the final result. This topic will be addressed in future work.

REFERENCES

[1] R. W. Stratton, H. Min Wong, and J. I. Hileman, "Life Cycle Greenhouse Gas Emissions from Alternative Jet Fuels," Cambridge, 2010.

[2] J. Ferrell and V. Sarisky-Reed, "National Algal Biofuels Technology Roadmap," 2010.

[3] T. J. Lundquist, I. C. Woertz, N. W. T. Quinn, and J. R. Benemann, “A Realistic Technology and Engineering Assessment of Algae Biofuel Production,” Berkeley, 2010.

[4] W. C. Chueh, C. Falter, M. Abbott, D. Scipio, P. Furler, S. M. Haile, and A. Steinfeld, “High-Flux Solar-Driven Thermochemical Dissociation of CO_2 and H_2O Using Nonstoichiometric Ceria,” *Science*, vol. 330, no. 6012, pp. 1797-1801, 2010.

[5] S. Naundorf, A. Roth, C. Endres, and A. Sizmann, “Alternative Fuels for Aviation: Progress, Prioritization and Perspectives,” in *Deutscher Luft- und Raumfahrtkongress 2011, Document-ID: 241439*, 2011, pp. 1021-1026.

[6] A. Perimenis, H. Walimwipi, S. Zinoviev, F. Müller-Langer, and S. Miertus, “Development of a decision support tool for the assessment of biofuels,” *Energy Policy*, vol. 39, pp. 1782-1793, 2011.

[7] U.S. Energy Information Administration (EIA), “International Energy Statistics,” 2011. [Online]. Available: http://www.eia.gov/cfapps/ipdbproject/IEDIndex3.cfm. [Accessed: 26-Apr-2011].

[8] U.S. Energy Information Administration (EIA), “Spot Prices for Crude Oil and Petroleum Products,” 2011. [Online]. Available: http://www.eia.doe.gov/dnav/pet/pet_pri_spt_s1_a.htm. [Accessed: 20-May-2011].

[9] D. Cordell, J.-O. Drangert, and S. White, “The story of phosphorus: Global food security and food for thought,” *Global Environmental Change*, vol. 19, no. 2, pp. 292-305, May 2009.

[10] K. Syers et al., “Phosphorus and Food Production,” in *UNEP Year Book - Emerging Issues in our Global Environment*, T. Goverse and S. Bech, Eds. Nairobi: United Nations Environment Programme, 2011, pp. 1-92.

[11] F. Riegel and J. Steinsdörfer, “Bioenergy in Aviation: The Question of Land Availability, Yields and True Sustainability,” in *3rd CEAS Air & Space Conference*, 2011, pp. 675-681.

[12] F. Riegel, *Manuscript in preparation*.

[13] H. Eckel, *Energiepflanzen: Daten für die Planung des Energiepflanzenanbaus*. Darmstadt: Kuratorium für Technik und Bauwesen in der Landwirtschaft e.V., 2006.

[14] T. G. Kreutz, E. D. Larson, G. Liu, and R. H. Williams, “Fischer-Tropsch Fuels from Coal and Biomass,” Pittsburg, 2008.

[15] T. Buchholz and T. A. Volk, “Improving the Profitability of Willow Crops—Identifying Opportunities with a Crop Budget Model,” *BioEnergy Research*, vol. 4, no. 2, pp. 85-95, 2010.

[16] N. Jungbluth, S. Büsse, R. Frischknecht, and M. Tuchschmid, “Ökobilanz von Energieprodukten: Life cycle Assessment of Biomass-to-Liquid Fuels,” Bern, 2008.

[17] C. Röhricht and K. Ruscher, “Anbau schnellwachsender Baumarten im Kurzumtrieb auf landwirtschaftlichen Flächen,” in *6. Mitteldeutscher Bioenergietag “Biofestbrennstoffe aktuell,”* 2009.

[18] C. Röhricht, S. Kiesewalter, and A. Groß-Ophoff, “Acker- und pflanzenbauliche Untersuchungen zum Anbau ein- und mehrjähriger Energiepflanzen im Freistaat Sachsen,” Dresden, 2002.

[19] M. Mozaffari, M. P. Russelle, C. J. Rosen, and E. A. Nater, “Nutrient Supply and Neutralizing Value of Alfalfa Stem Gasification Ash,” *Soil Science Society of America Journal*, vol. 66, no. 1, pp. 171-178, 2002.

[20] J. Sheehan, T. Dunahay, J. Benemann, and R. Paul, “A Look Back at the U. S. Department of Energy’s Aquatic Species Program: Biodiesel from Algae,” Golden, 1998.

[21] A. Florentinus, C. Hamelinck, S. de Lint, and S. van Iersel, “Worldwide Potential of Aquatic Biomass,” Utrecht, 2008.

[22] M. N. Pearlson, “A Techno-Economic and Environmental Assessment of Hydroprocessed Renewable Distillate Fuels,” Massachusetts Institute of Technology (MIT), 2011.

[23] C. Rösch, J. Skarka, and N. Wegerer, “Materials flow modeling of nutrient recycling in biodiesel production from microalgae,” *Bioresource technology*, vol. 107, pp. 191-9, Mar. 2012.

[24] J. K. Stolaroff, “Capturing CO_2 from ambient air: a feasibility assessment,” Ptittsburg Carnegie Mellon University, 2006.

[25] V. Nikulshina and A. Steinfeld, “CO_2 capture from air via CaO-carbonation using a solar-driven fluidized bed reactor—Effect of temperature and water vapor concentration,” *Chemical Engineering Journal*, vol. 155, no. 3, pp. 867-873, Dec. 2009.

[26] J. A. Wurzbacher, C. Gebald, and A. Steinfeld, “Separation of CO_2 from air by temperature-vacuum swing adsorption using diamine-functionalized silica gel,” *Energy & Environmental Science*, vol. 4, no. 9, p. 3584, 2011.

[27] M. Pidwirny, “Energy balance of Earth,” *Encyclopedia of Earth. Eds. Cutler J. Cleveland (Washington, D.C.: Environmental Information Coalition, National Council for Science and the Environment)*, 2012. [Online]. Available: http://www.eoearth.org/article/Energy_balance_of_Earth. [Accessed: 02-Jul-2012].

[28] International Energy Agency (IEA), “Key World Energy Statistics,” Paris, 2011.

[29] Black & Veatch Corporation, “Black & Veatch-Designed Desalination Plant Wins Global Water Distinction,” *edie.net*, 2006. [Online]. Available: http://www.edie.net/news/news_story.asp?id=11402&channel=0. [Accessed: 06-Jul-2012].

[30] European Jewish Press, “EJP News France French-run water plant launched in Israel,” 2005. [Online]. Available: http://www.ejpress.org/article/4873. [Accessed: 06-Jul-2012].

[31] K. S. Lackner, “Capture of carbon dioxide from ambient air,” *The European Physical Journal Special Topics*, vol. 176, no. 1, pp. 93-106, Sep. 2009.

[32] R. Socolow et al., “Direct Air Capture of CO_2 with Chemicals Panel on Public Affairs,” 2011.

[33] D. W. Keith, M. Ha-Duong, and J. K. Stolaroff, “Climate strategy with CO_2 capture from the air,” Calgary, 2005.

[34] M. Kromer, K. Roth, R. Takata, and P. Chin, “Support for Cost Analyses on Solar-Driven High Temperature Thermochemical Water-Splitting Cycles,” Lexington, 2011.

[35] L. van Bibber, E. Shuster, J. Haslbeck, M. Rutkowski, S. Olson, and S. Kraemer, “Baseline Technical and Economic Assessment of a Commercial Scale Fischer-Tropsch Liquids Facility,” 2007.

[36] Committee on U.S.-China Cooperation on Electricity from Renewable Resources; National Research Council; Chinese Academy of Sciences; Chinese Academy of Engineering, “The Power of Renewables: Opportunities and Challenges for China and the United States,” Washington, D.C., Mar. 2010.

[37] J. J. Marano and J. P. Ciferno, “Life-Cycle Greenhouse-Gas Emissions Inventory for Fischer-Tropsch Fuels,” Greenwich, 2001.