Alternative Fuels for Aviation: Progress, Prioritization and Perspectives

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Abstract

The long-term future of aviation will be largely determined by its ability to serve a growing mobility demand, to minimize its impact on climate change and to substitute its fuel from limited fossil resources by sustainable, renewable alternatives with high supply security. To date, no single alternative solution is in sight that presents a promising perspective pertaining to all of the criteria of suitability, sustainability and scalability. Therefore, an objective, reproducible and transparent approach is needed in order to assess and prioritize existing and future jet fuel alternatives. In this work an assessment method is described, which is based on a set of seven criteria: fuel readiness level, drop-in capability, production costs, substitution potential, well-to-wake greenhouse gas emissions, local air-quality emissions and habitat requirements. To each criterion a metric is assigned to translate the fuel information into a characteristic score. A third decision level, independent of the metric, is the weighting of the criteria by a scenario-dependent factor in order to allow context-specific assessments.

1 INTRODUCTION

In the years to come aviation industry will have to face three major challenges. First of all, the depletion of easily accessible fossil resources will impact the supply security of conventional jet fuel as well as leading to increasing jet fuel prices and higher price volatility. Secondly, the estimated growing demand for mobility in general and for air transport in particular and therefore for liquid fuels [1,2]. And finally, the increasing concentration of carbon dioxide (CO_2) in the atmosphere, caused by the combustion of fossil fuels. These urgent challenges combined with the industry's self-imposed emission reduction goals [3] create a strong technological, economical and environmental pull for the development of a variety of "drop-in"-capable renewable jet fuels [4-7].

In the last years several alternatives, from coal derived synthetic kerosene to hydroprocessed esters and fatty acids (HEFA) made from microalgae oil, have been discussed. However, no single fuel alternative was identified that fulfills all the fundamental requirements an alternative has to meet for a large-scale replacement of conventional jet fuel. These fundamental requirements are best expressed by the basic criteria of suitability, sustainability and scalability. In order to compare the huge variety of fuel alternatives with respect to their feedstock types and production pathways and to identify the most suitable alternative fuel options, a transparent and general assessment method is required.

In this paper an assessment method is introduced allowing a semi-quantitative evaluation and prioritization of alternative jet fuels through several independent decision levels.

2 REVIEW OF ALTERNATIVE GAS TURBINE FUEL DEVELOPMENT

In 1999, conventional jet fuel blended with synthetic fuel in a ratio of up to 50% was certified according to the UK Defence Standard 91-91. From that time on, this alternative fuel was authorized to be used in civil aviation. The process was initiated and promoted by the South African company Sasol to supply their Fischer-Tropsch (FT) Synthetic Paraffinic Kerosene (SPK) produced from coal at Johannesburg airport. Meanwhile, also the fully synthetic jet fuel produced from coal by Sasol has been certified for commercial use. This has opened new perspectives for FT-derived drop-in fuel alternatives from a variety of feedstocks to be implemented in civil aviation.

In 2006, Boeing hosted a meeting in Seattle from which the Commercial Aviation Alternative Fuels Initiative (CAAFI) emerged. This initiative, a coalition of aircraft and engine manufacturers, airlines, energy producers and fuel suppliers, researchers and U.S. government agencies, served since then as the nucleus and promoter for the alternative fuel development in civil aviation [8]. Another major partner of CAAFI is the U.S. Air Force (USAF) who strongly supports the large-scale introduction of alternative fuels and intends to certify its complete fleet on 50/50 blends until end of 2011. The ultimate goal is to achieve the procurement of 50% of the fuel needed for flight and ground vehicles from alternative feedstocks from US sources in 2016. The USAF is thereby limited by law to procure only alternative fuels with an equal or better CO_2-emisision balance, based on the product's lifecycle, than conventional crude oil based jet fuel [9].

Since certification of Sasol's synthetic fuels, the first commercial demonstration flight with a new alternative fuel derived from natural gas ("gas-to-liquid", GTL) was performed by Airbus, Rolls-Royce and Qatar Airways with an A380 between Filton and Toulouse, in February 2008 [10]. Less than four weeks later the first in a row of numerous bio-based alternative jet fuel trials all over the world took place when Virgin Atlantic performed a one-hour flight with a 747-400 from London to Amsterdam. One engine was powered by a 20% biofuel blend produced from coconut and babassu nut oil blended with conventional kerosene [11]. Several different airlines followed their example, and more flight test with biofuels from several feedstocks and blending ratios up to 50% in one engine of two- and four-engined aircrafts have been conducted since then.

The efforts of the aviation stakeholder finally lead to the development of the new ASTM standard D 7566 for fuels containing synthetic hydrocarbons and fuel blends containing up to 50% Fischer-Tropsch-derived synthetic paraffinic kerosene (FT-SPK) produced from biomass ("biomass-to-liquid", BTL), coal ("coal-to-liquid", CTL) or natural gas (GTL) were certified for use in commercial aviation in September 2009. In 2011, this was followed by the approval of blends (up to 50%) of hydroprocessed esters and fatty acids (HEFA) [12]. The ultimate target of the certification of generic fully synthetic jet fuel is expected to be achieved in 2012, 100% HEFA certification is expected to follow in 2013.

Recent certification activities also include the approval of hydrocarbons produced from iso-butanol (obtained via fermentation of sugars). When approved, it will be the third pathway for alternative jet fuels besides FT-SPK and HEFA. Eventually, catalytic and pyrolytic pathways to jet fuel are also considered and will follow in the midterm future [13].

3 ASSESSMENT AND PRIORITIZATION FRAMEWORK

To assess and prioritize all alternative fuel options of interest and their respective production pathways, a method is introduced, based on a set of criteria and metrics that are applicable to all relevant fuel options. In order to achieve a high level of transparency and reproducibility in the assessment process, several independent decision levels are implemented.

3.1 Assessment Methods in Literature

In the last years several articles and reports were published discussing alternative fuels and their use for aviation [6,14-18]. In this context, one of the most relevant studies were performed by Hileman et al. [19]. The report describes and assesses various fossil and renewable jet fuel alternatives for commercial use in the next 5 to 10 years with a focus on North America. The basis of their assessment is a set of seven criteria which cover economical, ecological and technological aspects of fuel alternatives with focus on the specific requirements in aviation. All examined fuel options are quantitatively assessed for each criterion applying a "+++/…/0/…/---" score system. The result is a first systematical assessment of the various jet fuel alternatives and their respective pathways.

3.2 The Weighted Decision Matrix

The work of Hileman et al. represents an important first step on the way towards an objective and transparent method for a quantitative assessment and prioritization of fuel alternatives. However, it does not address the problem of different customer benefits, i.e. different questions and preconditions underlying each assessment. In order to tackle this issue, Bauhaus Luftfahrt applied the method of a weighted decision matrix to develop a system for the generally applicable, semi-quantitative and context-specific assessment of alternative aviation fuels.

The idea of this method is based on three distinct decision levels, namely *i*) the selection of the set of assessment criteria C_i, *ii*) the weighting of each criterion through weighting factors W_i, and *iii*) the definition of a metrics conversion relation for each criterion for the translation of an assessed alternative fuel property (primary metrics) with respect to a specific criterion into a score S_i. Consequentially, the evaluation of each alternative can be performed reproducibly without further expert input. Here, we adopt the convention of assigning scores and weights in the range of 0 to 10, which is arbitrary but without loss in generality of the achieved results. Through the metrics conversion relation, the evaluation of primary quantitative metrics such as e.g. particle size distribution results in the primary score S_i which is subsequently multiplied by the respective weighting factor W_i, yielding the weighted score S_{iw}. The sum of weighted scores over all criteria represents the total weighted score S_w of an alternative fuel option. For the sake of better comparability, the total weighted score can be converted according to equation (1) to a normalized rating R_k with values ranging from 0 to 1, usually expressed in per cent.

$$R_k\left(A_k,\{C_i\},\{W_i\}\right)=\frac{\sum_i\left(S_i\left[A_k,C_i\right]\cdot W_i\left[C_i\right]\right)}{S_{\max}\sum_i W_i} \quad (1)$$

A_k represents the k-th alternative fuel option under assessment, $\{C_i\} = \{C_1, C_2, \ldots, C_n\}$ and analogously $\{W_i\}$ the sets of n criteria and weigthing factors, respectively, and $S_{\max}$ the maximum score of 10. As an additional feature, the assessment framework also allows for the subdivision of a criterion C_i into subcriteria C_{ij} with the corresponding weighting factors W_{ij}, thus enabling a further refinement of the assessment (see TAB 2).

The major advantage of the method of the weighted decision matrix is the separation of the primary-metrics-to-score conversion $S_i[A_k, C_i]$ from the weighting $W_i[C_i]$, resulting in the weighted score. A given set of weighting factors reflects a certain customer benefit, a distinctive scenario or different time horizons for a specific assessment. The independent weighting enables an adaption of this scenario according to other customer benefits, while leaving the evaluation, i.e. the primary score, unchanged. In this way, the assessment of a given set of alternatives, criteria, and metrics may result in entirely different prioritizations, depending on the applied set of weighting factors, or in a prioritization robustness analysis showing the stability of results for varying scenarios. In extreme cases, certain criteria can also be weighted as prerequisites, so-called knock-out criteria, or, opposingly, be weighted by $W_i = 0$, i.e. excluded from this specific assessment.

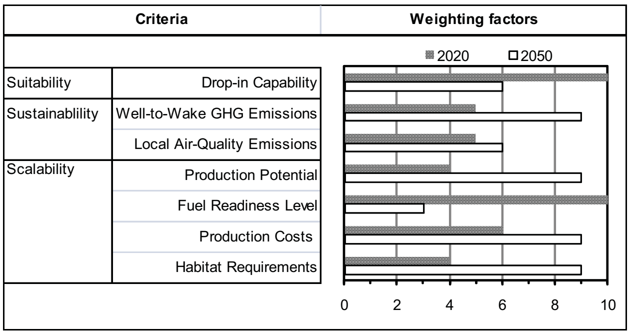
3.3 Selection of Weighting Factors W_i

Each selected set of weighting factors reflects distinctive customer priorities, or scenarios as well as time horizons underlying the respective assessment. For example, the considered time horizon of jet fuel alternatives for the prioritization is represented in the assessment by the weighting of certain criteria: For an introduction of alternative fuels into the market in 2020, the criterion fuel readiness level (FRL) might outweigh the criterion well-to-wake (WtW) greenhouse gas (GHG) emissions, i.e. receive a higher weighting factor, since the immediate availability in large quantities is absolutely vital for such a short-term introduction.

The situation changes in a long-term scenario. In case of a planned market introduction of alternative fuels in 2050, the greenhouse gas reduction potential of a fuel alternative will probably be weighted very high, while the current fuel readiness level is of less importance, as a significant development of the FRL can be expected under such long-term conditions, even for a production path that is still in the state of basic research at the time of assessment.

As another example, the compatibility with the current fuel systems (drop-in capability) is widely considered as a prerequisite for the short-term and medium-term application of alternative fuels in commercial aviation. On the other hand, in a long-term perspective, significant changes in fuel-related systems on ground and on board are conceivable when justified by potentially high benefits like favorable production costs or a large greenhouse gas reduction potential. Consequently, the weighting of this specific criterion will depend strongly on the scenario or time horizon underlying the assessment. Two exemplary sets of weighting factors for the time horizons 2020 and 2050 are given in TAB 1 to illustrate the implications that different customer positions, scenarios or time horizons may have.

TAB 1. Weighting factors W_i exemplarily derived.



3.4 Assessment Criteria C_i and Derivation of Scores S_i from the Respective Metrics

The criteria that will be applied for the assessment are based on previous work by Hileman et al. [19] (section 3.1) and further refined and expanded. They are defined in the following sections, including their respective metrics.

3.4.1 Fuel Readiness Level

The fuel readiness level (FRL) criterion is derived from the Technology Readiness Levels (TRL) defined by NASA [20] and describes the development status of alternative fuel production processes. The NASA-TRL, starting with “TRL 1 - basic principles observed and reported” to “TRL 9 - actual system ’flight proven’ through successful mission operations“ are translated into scores from 1, “FRL 1 - fuel production process is undergoing fundamental research” to 10 “FRL 10 – successful implementation in commercial production”. Each assessed fuel pathway is subjected to the FRL metric and the score is accordingly derived.

3.4.2 Drop-in Capability

The drop-in capability criterion assesses the compatibility of alternative jet fuels and jet fuel blends with the existing aviation system, meaning the ground fueling infrastructure (pipelines and airport tanks) as well as any relevant aircraft and engine systems. Drop-in fuels can per definition be blended with kerosene to any ratio without any safety issues in operation in flight or during ground handling. Any fuel other than conventional jet fuel needs therefore to go through an approval process defined in the ASTM D 4054, to guarantee the properties to be in the range of jet fuel. For instance, the aromatic content of jet fuel as well as for a drop-in replacement needs to be between 8 and 25% volume based. An alternative fuel that does not satisfy the performance characteristics of conventional jet fuel and thus is not drop-in capable can either not be used or would need to offer tremendous benefit to offset the costs for changes in aircraft equipment and infrastructure that would come along with its use. That is why drop-in capability is such an important criterion. The score distribution for the assessment is as follows: Any fuel that cannot be blended at all receives a score of 0. Fuels that can be blended up to 5% (meaning that the resulting fuel blend is drop-in capable) with conventional jet fuel receives a score of 1, for up to 10% a score of 2 and so on until the possible blending ratio reaches 50% and more where a fuel receives a score of 10. The score of 10 for the 50% blending ratio is chosen as 50% is the actual certified blending ratio for SPK produced via FT and HEFA. This metric might be adjusted in the future when blending ratios higher than 50% are certified as drop-in alternatives.

3.4.3 Production Costs

The production costs of any alternative jet fuel are essential in order to compare the economics of fuel alternatives among each other as well as to visualize the competiveness against conventional jet fuel. The production costs of a fuel originate from the several steps between resource procurement and the conversion to jet fuel, as well as the energy consumed, the logistics and all labor and financial costs. Any alternative jet fuel coming on the market has to compete with the actual jet fuel market price in order to have a chance to gain market share. The marginal costs of production of any alternative have therefore at least to be equal or lower compared to the jet fuel price, in order to be economically viable and attractive for airlines and other customers.

For the assessment, the metric is as follows: all fuels with lower production costs than the actual jet fuel price receive the maximum score of 10 as they can be produced and sold on the market without additional funding or subsidies. All fuels with equal production costs compared to the actual jet fuel price receive a score of 5. Fuels with up to 10% higher production costs receive a score of 4, up to 20% a score of 3, up to 30% a score of 2, up to 40% a score of 1 and any fuel with higher production costs of more than 40% compared to the actual jet fuel price receives a score of 0.

3.4.1 Substitution Potential

The substitution potential of any alternative fuel reflects the volume that can be produced and supplied to the aviation sector and therefore possibly substitutes a certain amount of global conventional jet fuel supply. The substitution potential is not a measure of how much alternative fuel will be produced under certain demand and supply assumption but instead it is a measure of the upper limit of the theoretical potential for displacement of conventional kerosene not primarily related to cost or price. The criterion has to be considered under the given time horizon of the assessment. In the near- to medium-term, the production of any alternative fuel will be limited by existing conversion facilities and refinery capacities, e.g. BTL facilities. In a medium- to long-term perspective the production for e.g. biofuels will be ultimately limited by available arable land to cultivate energy crops. The score distribution for the criterion is defined as follows: fuels with no substitution potential receive a score of 0. For up to 5% global jet fuel substitution potential, the allocated score is 1. For more than 5 and up to 10% the score is 2 and so on in 5%-steps. Any fuel with a global substitution potential of more than 45% receives the maximum score of 10.

3.4.2 Well-to-Wake Greenhouse Gas Emissions

The well-to-wake (WtW) greenhouse gas (GHG) emissions criterion represents one of the most fundamental criteria especially with respect to aviations self-imposed emission reduction goals of carbon neutral growth from 2020 on and a 50% CO_2 emission reduction on 2005 levels of the entire aviation sector until 2050 [4]. Therefore all GHG emissions on a life-cycle basis are taken into account and transformed into CO_2 equivalents (CO_{2equ}) to have a common basis for comparison among fuel alternatives and against the benchmark of conventional jet fuel. The conversion to scores for the alternative fuels is defined as follows: All fuel alternatives that match the conventional kerosene WtW GHG emissions receive a score of 5. Fuels with up to 20% lower emissions receive a score of 6, with up to 40% less emission a score of 7 and so on until the fuels have less than 80% of emissions compared to jet fuel where they receive a score of 10. Fuels with higher WtW GHG emissions compared to conventional jet fuel on a life cycle basis receive a score of 4 up to 10%, 3 up to 20%, 2 up to 30%, 1 up to 40% and finally a score of 0 for more than 40% higher emission compared to conventional jet fuel.

3.4.3 Local Air-Quality Emissions

The local air quality emissions criterion assesses the amount of particle emission at airports equal to or smaller than 2.5 µm ($PM_{2.5}$) resulting directly from the fuel combustion or indirectly through SO_x, NO_x and organic compounds emission. $PM_{2.5}$ emissions are directly related to local health and welfare according to Rojo [21]. Alternative fuels show tendencies to reduce $PM_{2.5}$ emissions. For the assessment, conventional jet fuel is the benchmark with a respective score of 5. All fuels with less particle emissions receive a higher score in a 2%-step, meaning that up to 2% less particles emitted the fuel receives a score of 6, up to 4% a score of 7 and up to 8% a score of 10. Fuels with 0-2% higher $PM_{2.5}$ emissions receive a score of 4, with 2-4% a score of 3, with 4-6% a score of 2, with 6-8% a score of 1 and finally with more than 8% a score of 0.

3.4.4 Habitat Requirements

“Habitat requirements” is a criterion that focuses especially on the needs of energy crops with regard to their cultivation. It cannot be applied to fossil fuel alternatives. This criterion is important for the overall assessment as especially the cultivation of energy crops has a major impact on the environmental performance, production costs, as well as substitution potential of the alternative fuel produced from it. For instance, the habitat requirements for any crop define if the crop can be cultivated on marginal land and does therefore not compete with food crops. On the other hand, a crop that has high habitat requirements comes along with high agricultural effort. This could be irrigation as well as high need for fertilization and pest management.

The criterion “habitat requirements” is split into three sub-criteria which are i) the need for water (in 10^6 liter per hectare and year), ii) the nutritional requirements and iii) the vulnerability of the respective crop.

For the sub-criterion the nutritional requirement is chosen instead of the demand for fertilizers, since it is specific for a plant and independent of the soil it is cultivated in. Likewise, the vulnerability of crops is assessed instead of the demand for pesticides. A three step assessment metric is proposed that clusters the energy crops regarding low, average and high need for water, nutrients and their vulnerability resulting in a respective score of 10, 5 and 0.

Regarding the need for water of energy crops, it has to be admitted that a statistical figure for the average need is used, although it is known that depending on the state of the phenology the need for water may differ over the growing period. In order align this sub-criterion with the proposed metric this simplification is taken into account.

3.5 The Ranking R_k of Fuel Alternatives

The evaluation of fuel alternatives is performed for an entire fuel production path for which a combinatorial variety of pathways may exist, e.g. for feedstocks of FT-SPKs, processing options of each kind of biomass, or various land-use options for one kind of biomass. The latter is well known to be important in the context of land-use change and greenhouse gas emissions. Caution has to be applied when various blending ratios of different fuel pathways are considered as a fuel alternative. While some criteria are evaluated with a linear proportional metric, other criteria, such as the FRL, are dominated by one constituent of the blend. Therefore, the application of the metrics to blends is not straightforward and will be discussed in further work.

Once each alternative has been evaluated with respect to the chosen criteria (section 3.3) resulting in individual sets of scores (see TAB 2), the considered alternative fuel pathways can be ranked according to equation (1).

The proposed method provides further insight into the comparison of fuel alternatives apart from the final ranking, expressed by single values R_k for each alternative. The

TAB 2. The weighted decision matrix including criteria C_i and exemplary weighting factors W_i for 2020 (“A”) and 2050 (“B”) [22].

Criteria C_i		Scenarios			Alternative Fuel A_k	
		Weights W_i	"A"	"B"	Score S_i	Weighted Score S_{iW}
C_1	Fuel Readiness Level	W_1	**10**	**3**	S_1	$S_{1W} = W_1 \times S_1$
C_2	Drop-in Capability	W_2	**10**	**6**	S_2	$S_{2W} = W_2 \times S_2$
C_3	Production Cost	W_3	**6**	**9**	S_3	$S_{3W} = W_3 \times S_3$
C_4	Production Potential	W_4	**4**	**9**	...	...
C_5	Well-to-Wake GHG Emissions	W_5	**5**	**9**	...	...
C_6	Local Air Quality Emissions	W_6	**5**	**6**	...	...
C_7	Habitat Requirements	$W_7 = \sum_j W_{7j} / 3$	**4**	**9**	S_7	$S_{7W} = \sum_j (W_{7j} \times S_{1j}) / 3$
$C_{7.1}$	water requirements	$W_{7.1}$	5	10	$S_{7.1}$	$S_{7.1W} = W_{7.1} \times S_{7.1}$
$C_{7.2}$	nutrient requirements	$W_{7.2}$	4	10	$S_{7.2}$	$S_{7.2W} = W_{7.2} \times S_{7.2}$
$C_{7.3}$	vulnerability	$W_{7.3}$	3	7	$S_{7.3}$	$S_{7.3W} = W_{7.3} \times S_{7.3}$
						$S_W(A_k) = \sum_i S_{iW}$
						$R_k(A_k) = S_W(A_k) / [S_{max} \sum_i W_i]$

method also provides traceability throughout the ranking procedure and visualizes the main assets and drawbacks of the assessed fuel alternatives with respect to each criterion in a highly transparent way. It is straightforward to identify the dominating contributions in the individual weighted scores and in the underlying scenario.

Finally, a sensitivity analysis can easily be applied by changing the values of the weighting factors, revealing the determining factors which have the highest impact on the ranking and the potential robustness of results under various scenarios.

4 FUTURE PERSPECTIVES

The proposed method allows a transparent assessment of various jet fuel alternatives. It refines already existing methods in literature by adding a well defined, expert-based metric (primary-metric-to-score conversion, where a quantitative primary metric is available) for each criterion. Furthermore, by introducing another decision level, namely the set of weighting factors, customized prioritizations of the criteria are possible resulting in a rational ranking of alternative fuels.

Future work will apply the assessment method to various alternative fuels, especially in long-term scenarios with a time horizon to 2050 [23]. Additionally, further refinement of the method and of its metric will be performed. Another subject that is of major concern is the development of well-defined scenarios for fuel assessment. Scenarios represent a potential future situation, and therefore, a certain set of weighting factors can be assigned to them improving the reliability of the whole assessment method.

We believe that by realizing these aspects the method presented here will prove a valuable tool for the assessment of jet fuel alternatives, where research progress in metrics and independently in future scenarios can be readily implemented.

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