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Renewable fuel options for aviation – A System-Wide comparison of Drop-In and non Drop-In fuel options

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ABSTRACT

The air transport sector's contribution to anthropogenic climate forcing is estimated at around 4 %. In this respect, alternative fuels are considered as a key measure to reduce greenhouse gas emissions within the air transport system and thus to reduce the contribution of commercial aviation to anthropogenic climate change. Nevertheless, so far the usage-shares of alternative fuels are below 1 %. Thus, the goal of this paper is to analyse a broad selection of aviation fuel options for their greenhouse gas reduction potential based on a set of nine assessment criteria. The fuel options studied are blended synthetic kerosene and neat synthetic kerosene fuels, three alcohols (methanol, ethanol and butanol) and three gases (methane, ammonia and hydrogen). For these fuels a multi-criteria assessment based on a five-step ordinal scale is performed. The assessment results show that the availability of some biogenic feedstock is not sufficient to replace the present overall energy demand of aviation; while the availability of non-biogenic fuels might increase in the near- to mid-term. In general, alternative kerosene-like fuel options are mainly constrained by lacking production capacities, while alcohols and gases considered are constrained by aircraft modifications or development of new aircraft types. All discussed fuel options have the potential to mitigate greenhouse gas emissions of commercial aviation substantially also from a life cycle perspective. Within the next decade, especially alternative kerosene-like options with (intermediate) products experiencing demand from other sectors, such as FT-SPK or AtJ-SPK, show a high development potential. The same holds for hydrogen provided that a hydrogen fueled aircraft will be brought successfully to the market.

1. Introduction

The air transport sector emitted about 1 Gt of CO_2 globally in 2018 corresponding to approximately 2.4 % of the world wide anthropogenic CO_2 emissions [1]. With regards to overall anthropogenic climate forcing, recent studies estimate the air transport sector's contribution at around 4 % by taking non CO_2 effects additionally into consideration [2]. Also, air traffic volumes grew by ca. 4 %/a in the past decades and despite a sharp decrease due to the Covid-19 pandemic in 2020, a return to pre-pandemic levels is expected and based on current developments most likely [3]. In the longer term, the air transport sector will continue to grow – like in the past – with a high probability at average growth rates of approximately 4 %/a [4]. In contrast, technological and operational measures to increase fuel efficiency reduced the passenger-specific fuel consumption of air-travel by about 1.3 %/a [4]. Assuming for the years to come the outlined air traffic growth is constant and the named fuel efficiency improvements can be sustained, aviation's emissions could rise to above 2 Gt of CO_2 in 2050 [4].

In view of these circumstances, the commercial aviation sector is required to lower its climate impact effectively and swiftly. In 2021, the International Air Travel Association (IATA) raised previous GHG reduction emission targets for the air transport sector to a net-carbon neutral GHG emission level in 2050. Also, the International Civil Aviation Organization (ICAO) presently develops a "long-term aspirational

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Abbreviations: **A**, With Aromatics; **ABE**, Acetone, Butanol, Ethanol; **ASTM**, American Society for Testing Materials International; **AtJ**, Alcohol-to-Jet; **BM**, Biomass; **BtL**, Biomass-to-Liquid; **Cat**, Category; **CH**, Catalytic Hydrothermolysis; **CO_2eq**, CO_2 Equivalent Emissions; **FAME**, Fatty-Acid-Methyl-Ester; **FT**, Fischer-Tropsch; **HC**, Hydroprocessed Hydrocarbons; **HEFA**, Hydroprocessed Esters and Fatty Acids; **HFS-SIP**, Hydrofermentet Sugars Synthesized Isoparaffins; **LC**, lignocellulosic; **LPG**, Liquefied Petroleum Gas; **N/A**, Not Applicable; **PtL**, Power-to-Liquid; **Ref**, Reference; **S**, Sugar/Starch; **SK**, Synthesized Kerosene; **SPK**, Synthetic Paraffinic Kerosene; **TRL**, Technology Readiness Level.

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goal" in addition to its present aim of a carbon–neutral growth from 2020 onwards [5,6]. One of the key measures to achieve these goals is the use of "green" aviation fuels (i.e., fuel derived from renewable energy; often-called sustainable aviation fuels (SAF)). This means, currently used aviation fuels almost exclusively produced from fossil crude oil ("fossil kerosene") will have to be gradually replaced by fuels provided from renewable sources. In this respect, primarily kerosene-based fuel alternatives have been pursued so far. These fuels can be summarised as "synthetic" kerosene.[a]

To produce synthetic kerosene, the ASTM D7566 specification is applicable. This specification presently requires the neat synthetic kerosene to be blended with fossil kerosene [8]. After a specification compliant blending procedure, the blend must meet the requirements of ASTM D1655, which is the same specification as for fossil kerosene. This blend can be used within the existing kerosene infrastructure and aircraft without any further technical modifications. Also, the blend can be seamlessly commingled with other kerosene types being in the fuel infrastructure. Therefore, such blends are referred to as "drop-in" aviation fuels [9].

Presently, most of the aviation fuel in use is produced from fossil crude oil. To a minor extent, kerosene is also produced from coal or natural gas (appendix A). Although various synthetic kerosene options of a "green" origin have been extensively discussed and tested for nearly 15 years [10], the usage-share of such synthetic kerosene is globally still at approximately 0.1 % related to the overall kerosene use [11–13]. The statistically recorded production volume of kerosene of renewable origin is at around 200 kt/a compared to around 300 Mt/a of fossil kerosene [13]. Higher production costs of synthetic kerosene compared to fossil kerosene, a lack of production facilities as well as missing regulatory frameworks to foster a synthetic kerosene usage are often stated as major reasons for the missing market ramp-up [14–17].

Additionally, other mobility and industrial sectors claim access to the feedstock needed to produce synthetic kerosene and are possibly willing to pay higher prices compared to the aviation sector. This could limit the availability and cost-effective supply of feedstock for the production of synthetic kerosene options. Simultaneously, the development and use of other fuel options (e.g., hydrogen or methanol), receive increasing interest in other sectors or within the overall energy system [18–20]. Hydrogen, for example, can be produced in relatively few process steps and – in contrast to synthetic kerosene – without the provision of a sustainable carbon source. Therefore, hydrogen has become increasingly relevant recently as a fuel option for aviation applications [21]. Clearly, such fuels are not drop-in capable in contrast to blended synthetic kerosene.

Additionally, the scientific understanding of non-CO_2 related effects (e.g., radiative forcing from aircraft-induced clouds or aerosol emissions) for the assessment of the overall climate impact of aviation is increasing [1,2]. Studies show that using synthetic kerosene can also reduce those effects (but most likely not entirely rule out) [22,23].

In view of this diverse mix of fuel options and an increasing need for climate protection in the air transport sector, the question of how to classify and assess the various "drop-in" options among the "non drop-in" options is becoming increasingly important. Against this background, the goal of this paper is to analyse both drop-in and non drop-in fuel options for their potential use as a fuel for commercial aviation. This assessment uses nine assessment criteria including technological and system-related aspects to compare each fuel option's suitability as an aviation fuel option.

To achieve this goal, the selected fuel options are described in section 2. The assessment methodology and selection of fuel options is presented in section 3, while in section 4 their assessment is conducted. Section 5 contains the results as well as the respective discussion and section 6 provides a brief summary and a final consideration.

2. Background

The distinction between drop-in and non drop-in fuel options is based on whether or not a fuel option complies with the standardized fuel specification. For the majority of the various kerosene options, this specification is defined by the American Society for Testing Materials (ASTM) developing the fuel standards for global civil aviation [24].

- **Drop-in.** The term "drop-in" fuel refers to all specification compliant aviation fuels according to the ASTM D1655 specification. This includes synthetic kerosene produced in accordance with ASTM D7566 and properly blended as well as fuels produced according to ASTM D1655 by a common processing of specific renewable feedstock (e.g., used cooking oil) or specific synthetic crude oils and fossil crude oil in conventional refining processes (Co-Processing). Drop-in fuels can be used within the existing fuelling infrastructure and the commercial aircraft fleet in operation without any technical modifications as a blend with fossil kerosene up to a specific blending limit [25].
- **Non drop-in.** The term "non drop-in" fuel refers to all fuel options, which do not fulfil the ASTM D1655 requirements. Hence, this comprises also synthetic kerosene produced in accordance with ASTM D7566 used above the blending limit or even without any blending procedure [8].

Based on these definitions, below the aviation fuel options selected for the further assessment are presented and described with respect to their main production pathways and future applications.

2.1. Selection

Today, a wide spectrum of different fuels are used for various mobility sectors. Typical examples are diesel and gasoline, methane, liquefied petroleum gas (LPG), bioethanol, fatty-acid-methyl-ester (FAME), or even butanol. Also, e.g., the chemical industry uses several of them as a bulk chemical to be further processed to high-value products. Additionally, hydrogen is also often added as an important future fuel option for the transport sector [20]. From this broad variety, here such fuels are selected, which seemingly have a high potential for a system-wide implementation within the commercial aviation industry. This selection is based on three main criteria.

1. A fuel option is already in use as a renewable fuel option in the air transport system or another specific sector (e.g., bioethanol).
2. A fuel option is considered as an integral part for defossilation of the overall energy system.
3. The potential aviation fuel is liquid or gaseous under standard conditions (i.e., battery-electric aircraft concepts are excluded as well as solid fuels).

Based on these criteria, three alcohol fuel options (methanol, ethanol, butanol, i.e. *n*-butanol and its isomers) as well as three gases (ammonia, methane, hydrogen) are taken into account. For kerosene-based options, blended and neat drop-in synthetic kerosene options are considered. Table 2-1 distinguishes the investigated fuel options as (non) drop-in fuel options. Additionally, the considered production pathways, the present production and the present/the future use possibilities are listed. Table 2-1 can be summarized as follows.

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[a] In some cases this term is used to refer to fuels of non-biogenic renewable origin only or to distinguish among different fuel options within aviation fuel specifications [7]. The use of "synthetic" in this study includes both, options of biogenic and non-biogenic feedstock. Additionally, alternative aviation fuels are often referred to as "sustainable aviation fuel" or "SAF". However, this term will not be used here, as the fuel's renewable origin does not guarantee the fulfilment of other sustainability aspects (e.g., biodiversity or social criteria).

Table 2-1

Drop-in and non drop-in fuel options considered for the assessment (**A** with aromatics; **ABE** Acetone, Butanol, Ethanol; **AtJ** Alcohol-to-Jet; **Cat** Category; **CH** Catalytic Hydrothermolysis; **FT** Fischer-Tropsch; **HC** Hydroprocessed Hydrocarbons; **HEFA** Hydroprocessed Esters and Fatty Acids; **HFS-SIP** Hydrofermented Sugars Synthesized Isoparaffins; **N/A** not applicable; **Ref** Reference; **SK** Synthesized Kerosene; **SPK** Synthetic Paraffinic Kerosene).

Cat		Fuel option	Production pathway considered	Present production (fossil origin renewable origin)	Ref	Present use	Future use
Synthetic Kerosene	Drop-in	Blended Synthetic Kerosene	FT-SPK HEFA-SPK HFS-SIP	0.4 Mt/a[e] < 0.2 Mt/a	[13,26]	aviation fuel	
	Non drop-in	Neat Synthetic Kerosene	FT-SPK/A AtJ-SPK CH-SK HC-HEFA-SPK				
Alcohols		Methanol	Methanol synthesis	90–100 Mt/a < 1 Mt/a	[27]	platform chemical, fuel	
		Ethanol	Fermentation	N/A 100 Mt/a	[28]	fuel (additive), potable alcohol, chemical and pharmaceutical applications	
		Butanol	ABE-fermentation	3.7 Mt/a N/A	[56]	platform chemical	platform chemical, fuel
Gases		Ammonia	Haber-Bosch conversion	180 Mt/a N/A	[29]	fertilizer for agriculture, chemical and pharmaceutical industry	fertilizer for agriculture, chemical and pharmaceutical industry, energy storage and fuel
		Methane	Fermentation Methane synthesis	2,671 Mt/a 0.1 Mt/a	[30]	heat and power generation, production of syngas for chemical industry	heat and power generation, production of syngas for chemical industry, fuel
		Hydrogen	Electrolysis	70 Mt/a N/A	[31]	chemical industry, refineries	chemical industry, refineries, heat and power generation, steel production, fuel, energy storage

This value resembles the global production of FT-fuels (e.g., naphtha, gasoline, kerosene) from coal and gas.

- Methanol and butanol are selected due to their role as platform chemicals [32]. Not only energy provision, but also the defossilation of the chemical industry could be a good reason for their production from feedstock of renewable origin (criterion 2). So far, ethanol is already produced to a significant share from feedstock of renewable origin (criterion 1).
- Ammonia, methane and hydrogen are all considered as options for storage and transport of renewably sourced energy (criterion 2) [30].
- The kerosene-based options take into account all conversion pathways being presently certified by ASTM D7566 (criterion 1). Additionally, an unblended use as neat synthetic kerosene is also discussed.

2.2. Fuel options

Kerosene based fuels. Here, kerosene based fuels are considered either as a specification-compliant blend of a fossil and a synthetic kerosene component or neat synthetic kerosene. Both usually consist of a range of hydrocarbons with a typical chain length of 8 to 16 carbon atoms. The most prominent hydrocarbon types in aviation fuels are n- and isoalkanes, cycloalkanes and aromatics [8]. Seven conversion and two co-processing options are approved for the provision of synthetic kerosene by ASTM D7566 and ASTM D1655. From these options only the production pathways considered in the assessment are discussed here [15,33–36] (additional information is in the appendix A).

Conversion pathways based on Fischer-Tropsch synthesis (FT-SPK) thermo-catalytically convert a synthesis gas ("syngas") into long-chain hydrocarbons ("syncrude"). Syngas can be provided from lignocellulosic biomass (e.g., forestry or agricultural residues) or non-biogenic feedstock[b] (i.e., electricity from renewable energy, water and sustainable CO_2). If syngas is produced exclusively based on "green" electricity, these fuels are often referred to as "power-to-liquid" (PtL) fuel [35,37,38]. The "Hydro-processed Esters and Fatty Acids" (HEFA-SPK) pathway or catalytic hydrothermolysis (CH-SK) are suitable conversion processes for lipid feedstock. Both utilize a thermochemical conversion of lipids into long-chain hydrocarbons. Another conversion pathway is the Alcohol-to-Jet (AtJ-SPK) process; here, alcohols are converted into long-chain hydrocarbons including the jet fuel range. Suitable feedstock for this pathway are sugar and starch and potentially also lignocelluloses. Presently ethanol and isobutanol are certified for the production of AtJ-SPK [7]. This pathway shows a promising potential for two reasons: Ethanol is already being produced from renewable feedstock at large scale (s. Table 2-1) and in contrast to their direct use, the conversion of alcohols to AtJ-SPK does not require modifications at the infrastructure or aircraft technology (s. 4.3). Methanol as intermediate for AtJ-SPK is not yet certified but announcements indicate the start of the certification process for the begin of 2023 [39]. Hydroprocessed Fermented Sugars – Synthesized Isoparaffins (HFS-SIP) denotes a conversion pathway, where a sugary solution is converted via biocatalysts into hydrocarbons. As co-processing pathways contain a large share of feedstock of fossil origin, they are not considered here.

Due to a (slightly) different chemical composition of neat synthetic kerosene (depending on the specific conversion pathway), compliance with ASTM D1655 requires additional adaptations, e.g. the addition of aromatics. Several production pathways do not yield aromatics (e.g., HEFA- or FT-SPK) or show a different distillation curve gradient (e.g., HFS-SIP) [24]. Theoretically, the same production pathways as described for synthetic kerosene blends can be used for neat synthetic kerosene production. To which extent all conversion pathways allow an unblended use has not yet been determined.

Alcohols (Methanol, Ethanol, Butanol). Methanol is also produced from syngas (above and appendix A) [40]. The origin of methanol (i.e., fossil or renewable) is thus primarily determined by the used syngas. The majority of the present methanol production utilizes fossil-based syngas. Compared to that, the major production pathway for ethanol is an

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[b] A production of syngas based on fossil feedstock (e.g., via coal gasification or methane reforming) is also possible. Due to the fossil origin of the feedstock, this pathway is not included here.

anaerobic fermentation of a sugar solution produced from naturally available sugar or converted from starch. Ethanol is basically the only alcohol that is currently produced from renewable feedstock at industrial scale [41,42].

“Green” butanol is produced via the Acetone, Butanol, Ethanol (ABE-) fermentation realised by bacteria. As different products (acetone, butanol, ethanol) are provided, there is a need to separate this product spectrum afterwards [41,43]. In principal, the products of the ABE-fermentation could be used as a blend. However, this option is excluded from this study to limit the number of fuel options, as other combinations of fuel options might also appear advantageous (e.g. blending a small amount of ethanol with fossil kerosene). Other production pathways for butanol do exist, such as the acetaldehyde pathway or fermentation utilizing genetically engineered biocatalysts. In contrast to ABE fermentation, these technologies are at a relatively low degree of technological maturity and thus not included in this study [44–46].

Gases (Ammonia, Methane, Hydrogen). The current ammonia production is based on the Haber-Bosch process converting hydrogen and nitrogen into ammonia. Before that, nitrogen is extracted from ambient air by an air separation processes. Currently, hydrogen for such an ammonia production is provided from natural gas via steam methane reforming. This provision pathway could be replaced by hydrogen provided by water electrolysis using “green” electricity [47].

To produce “green” methane, biomass-based as well as electricity-based supply pathways are possible [30,41,48]. These provision pathways either consist of biomass degradation by anaerobic digestion or methane synthesis [40].

Hydrogen of renewable origin can be produced by water electrolysis. If the electricity for such a water electrolysis is provided exclusively from sustainable, renewable sources (e.g., from photovoltaic and/or wind power plants), “green” hydrogen can be provided [19,20,49]. At standard conditions, gases have a comparatively low volumetric energy density, which can substantially be increased by liquefaction. However, this comes at the cost of energy requirements and higher losses (“boil-off”) [50]. Therefore, the present study assumes that the large scale infrastructure for fuel distribution uses compressed gases, liquefaction takes place at the airport and subsequently aircraft are being fuelled by liquefied gas.

3. Methodology

This assessment (Fig. 3-1) considers nine criteria covering various aspects across the entire fuel value chain. The following section first describes the methodological approach of the assessment performed and then specifies the selection of assessment criteria.

For the considered fuel options, the requirements and implications as aviation fuels are ranked according to a set of nine assessment criteria. A five-stage uniform ordinal ranking is applied for each assessment criterion, as considerable uncertainties exist for several of the criteria. For every assessment criterion, each fuel option is ranked from 1 (“very disadvantageous”) to 5 (“very advantageous”). The decision of the respective ranking is based on an extensive assessment of literature data and other public available information. All values mentioned reflect present-day (2022) techno-economic parameters based on a global view. Additionally, the trend most likely becoming visible within the next decade is discussed based on the expected developments.

The different criteria are not weighted against each other as they fall into very different categories. Thus, they can only be compared with each other to a very limited extent in a robust, fair, and consistent manner. Additionally, the rankings are not aggregated into a single value as this assessment rather aims at illustrating the complex interplay of implications for the use of a fuel option as an alternative aviation fuel instead of finding one “ideal fuel option”.

Table 3-1 lists the assessment criteria to compare the different fuel options. They are grouped into three categories across an aviation fuels

Table 3-1
Assessment criteria considered for the fuel option assessment.

#	Assessment criterion	Definition
1	Feedstock potential	Availability of a particular feedstock
2	Fuel conversion efficiency	Energy (feedstock) required to produce a defined amount of energy per mass unit of a respective fuel option
3	Production capacities	Extent to which production capacities are available or other production infrastructure could be utilized
4	Logistics infrastructure	Extent to which transport infrastructure is available or other transport infrastructure could be used to deliver the fuel from production to the airport
5	Airport infrastructure	Extent to which airport infrastructure is available for fuel storage and handling
6	Fuel properties	Chemical fuel properties and their implication for aviation use
7	Aircraft modifications	Required technological changes and their technology readiness level (TRL) to facilitate the use of non drop-in fuels
8	Lifecycle CO_2 emissions	CO_2-related climate impact of using the respective fuel option
9	Fuel cost	Production costs bandwidth of a respective fuel option

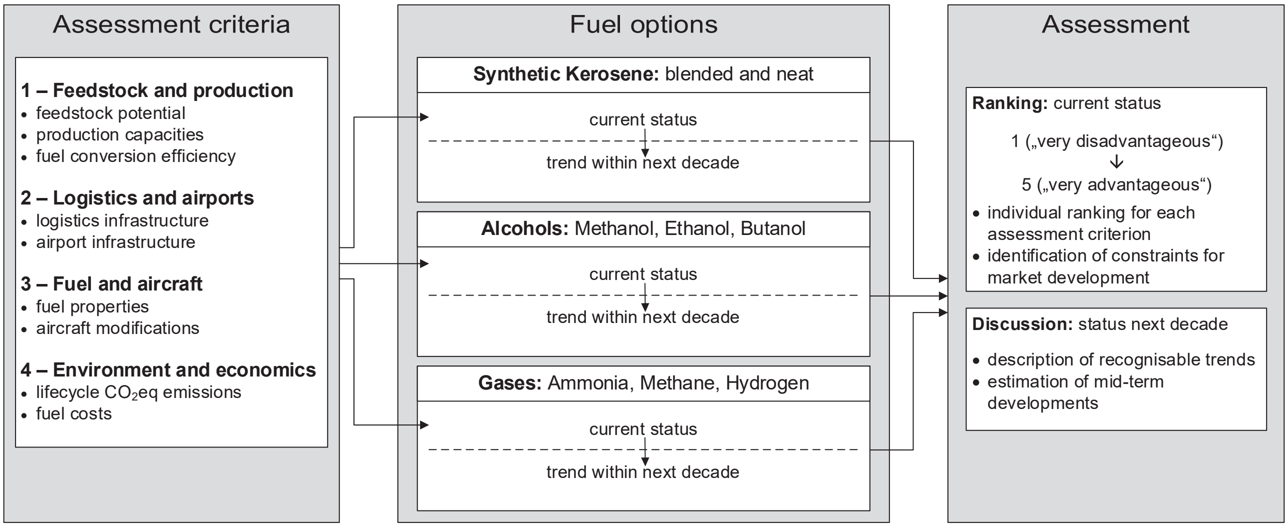

Fig. 3-1. Methodological approach.

physical value chain and one related to overarching aspects.

- The first category comprises three criteria: feedstock potential, production capacities, and fuel conversion efficiency.
- Logistics and airports are evaluated by an assessment of logistics, infrastructure, as well as fuelling and storing capabilities at airports.
- Fuel and aircraft technology is studied by investigating operational fuel properties and aircraft modifications.
- The overarching category, environment and economics is discussed using the criteria life cycle greenhouse gas emissions and fuel costs.

Following this assessment criteria-based analysis, potential constraints for a market development at commercial scale are discussed. Such constraints often depend on exogenous influences, such as the development of a global production system for hydrogen of renewable origin. Hence, the constraints outlined below rather serve as an indication for existing bottlenecks from a time perspective than as a reliable quantitative estimate.

Such a procedure shows clear limitations. One limiting factor is the always incomplete data availability related to one assessment time period; additionally, most of the assessment criteria involve parameter difficult to convert or transform to the same system boundaries. The varying degrees of technological maturity of various processes induce further uncertainties about key process parameter (e.g., conversion efficiency, fuel costs). Beside this, the future trajectory of the fuel options' potential largely depends on the further progress of the entire energy system and thus the further development of the global energy system. One example is the development of hydrogen as a possible energy carrier for a large-scale defossilation of various industrial sectors. Thus, interdependencies with and developments of other sectors significantly effects the air transport system's energy provision as well as the respective economic development. Also, costs and efforts for the deployment of infrastructure are critical factors for the likelihood of the market introduction of alcohols and gases as aviation fuels; a clearly uncertain setting of the political frame conditions add up to this. Nevertheless, based on such an assessment robust conclusions can be drawn.

3.1. *Category 1 – Feedstock and production*

Feedstock potential. A limited feedstock availability limits production possibilities of a fuel option. This is underlined by the fact that primary (renewable) energy sources as well as (sustainable) raw materials are demanded by various sectors being part of our overall economy – and not only by commercial aviation. Within the five-stage ordinal ranking, a feedstock potential being at least two orders of magnitude greater than aviation's energy demand is rated as "very advantageous" (5), a feedstock potential comparable to aviation's energy demand is seen "neutral" (3) and a substantially lower feedstock potential is rated as "very disadvantageous" (1) (Table 3-2).

Production capacities. As the duration to ramp up production capacities can significantly delay the deployment and large-scale use of a corresponding fuel option, this criterion describes the current (2022) availability of existing fuel production capacities. The usability of an existing production infrastructure is rated as "very advantageous" (5), first industrial plants as "neutral" (3) and the complete lack of a corresponding production infrastructure as "very disadvantageous" (1) (Table 3-2). Additionally, the technology readiness level (TRL) [51] is discussed in this section.

Fuel conversion efficiency. Due to a (still) limited availability of "green" energy as well as the respective other (sustainable) resources, a specific conversion route to provide a certain fuel is particularly favourable based on high conversion efficiencies. This criterion is defined as the ratio of energy content of produced jet fuel to the required secondary renewable energy to produce the same mass of fuel (Fig. 3-2).

The values for the ranking are based on the median of estimates of present (2022) technology. Fig. 3-2 shows the system boundaries used for this assessment. The energy content of other by-products is not taken into account. The kerosene yield can be altered significantly by thermochemical post-conversion processes such as hydroprocessing, thus the final kerosene fraction is not necessarily a characteristic of a particular conversion pathway. Therefore a 70 % kerosene fraction is assumed for all synthetic kerosene conversion pathways, to ensure comparability. A median lower than 20 % is ranked as "very disadvantageous" (1), between 40 % and 60 % as "neutral" (3) and above 80 % as "very advantageous" (5) (Table 3-2).

3.2. *Category 2 – Logistics and airports*

Logistics infrastructure. The extent to which logistics and transport infrastructures are currently available for the respective fuels determines the practicability for a global deployment of these fuel options. If an existing logistics infrastructure is available for fuel transportation to airports, this ranks "very advantageous" (5). The possibility to modify infrastructure ranks "neutral" (3) and no existing usable infrastructure is considered "very disadvantageous" (1) (Table 3-2).

Airport infrastructure. Safety and operational implications create considerable differences between fuel logistics to and at the airport. This criterion assesses, to which extent storage and fueling infrastructure at airports would need to be modified/adapted/newly developed for the use of the fuel options discussed. Similar as for logistics infrastructure, if existing storage and fueling infrastructure can be used for a particular fuel option, this ranks "very advantageous" (5). The need for modifications of infrastructure ranks "neutral" (3) and no existing usable infrastructure is considered "very disadvantageous" (1) (Table 3-2).

3.3. *Category 3 – Fuel and aircraft*

Operational fuel properties. Fuel properties might have significant effects on the flight performance and flight profiles of an aircraft. Thus, this criterion evaluates chemical-physical properties of fuel options (e.g., energy and storage density). Favourable operational range improvements (storage density $>$ 5 % above fossil kerosene average of 43.25 MJ/kg [9]) are considered as "very advantageous" (5), small range improvements/losses (storage density $\pm$ 1 % 43.25 MJ/kg [9]) as "neutral" (3) and a significant reduction in aircraft range (storage density $>$ 50 % below 43.25 MJ/kg [9]) as "very disadvantageous" (1) (Table 3-2).

Aircraft design/modifications. Due to high technological and regulatory safety requirements in aviation, the design of a new aircraft as well as aircraft modifications due to another fuel can be associated with high technological efforts, economic risks and considerable time requirements [52]. This criterion compares technological modification requirements of currently certified aircraft technology to enable the use of an alternative fuel option. A "new" fuel option is rated as "very advantageous" (5) if there is no need for modification compared to today's overall aircraft configuration. Minor modifications are rated "neutral" (3) and a need for a new aircraft design and associated certification is ranked as "very disadvantageous" (1) (Table 3-2).

3.4. *Category 4 – Environment and economics*

Lifecycle CO_2eq emissions. This criterion evaluates the life cycle greenhouse gas emissions of the fuel options. CO_2eq emissions below 25 g CO_2eq/MJ are considered to be "very advantageous" (5), 50 to 75 g CO_2eq/MJ as being "neutral" (3) and CO_2-emissions in a similar range compared to fossil kerosene (at or above 95 g CO_2eq/MJ [53]) as "very disadvantageous" (1) (Table 3-2). All emission estimates consider the present state of technology.

But, a significant part of aviation's climate effect does not linearly depend on fuel burn [1]. As hardly any data exists describing the magnitude of such non-CO_2-effects for non-kerosene fuel types (e.g.,

Table 3-2
Ranges for the ranking of each assessment criterion.

#	Assessment criterion	1	2	3	4	5
1	Feedstock potential	Feedstock potential significantly below energy demand of aviation	Feedstock potential below aviation energy demand	Feedstock potential up to one order of magnitude greater than aviation energy demand	Feedstock potential more than one order of magnitude greater than aviation energy demand	Feedstock potential more than two orders of magnitude greater than aviation energy demand
2	Production capacities	No existing production infrastructure	< 5 plants at demonstration scale	First industrial plants	Current renewable production amounts to < 5 % of 2019 global aviation energy demand	Current renewable production amounts to > 5 % of 2019 aviation energy demand
3	Fuel conversion efficiency	< 20 %	20–40 %	40–60 %	60–80 %	> 80 %
4	Logistics infrastructure	No existing logistics infrastructure	Major modifications of existing infrastructure required or regionally limited infrastructure	Existing logistics infrastructure can be modified	Minor modifications of existing infrastructure or widespread infrastructure	Usable logistics infrastructure exists for long-range transport
5	Airport infrastructure	No existing airport infrastructure	Major modifications of existing infrastructure required	Modifications of airport infrastructure necessary	Minor modifications of existing infrastructure	Usable airport infrastructure exists
6	Fuel properties	Significant reduction in aircraft range (storage density > 50 % below 43.25 MJ/kg)	Noticeable reduction in aircraft range (storage density < 50 % but > 1 % below 43.25 MJ/kg)	Negligible reduction in aircraft range (storage density ± 1 % of 43.25 MJ/kg)	No effect on range (storage density < 5 % but > 1 % above 43.25 MJ/kg)	Range improvements (storage density > 5 % above 43.25 MJ/kg)
7	Aircraft modifications	New design and certification required	Major modifications required	Minor modifications required	Modification of only a few components	No need for modifications
8	Life cycle greenhouse gas emissions	≥95 gCO$_2$eq/MJ (reference value for fossil kerosene)	<95 gCO$_2$eq/MJ and ≥75 gCO$_2$eq/MJ	<75 gCO$_2$eq/MJ and ≥50 gCO$_2$eq/MJ	<50 gCO$_2$eq/MJ and ≥25 gCO$_2$eq/MJ	<25 gCO$_2$eq/MJ
9	Fuel cost	>80 €/GJ	60–80 €/GJ	40–60 €/GJ	20–40 €/GJ	<20 €/GJ

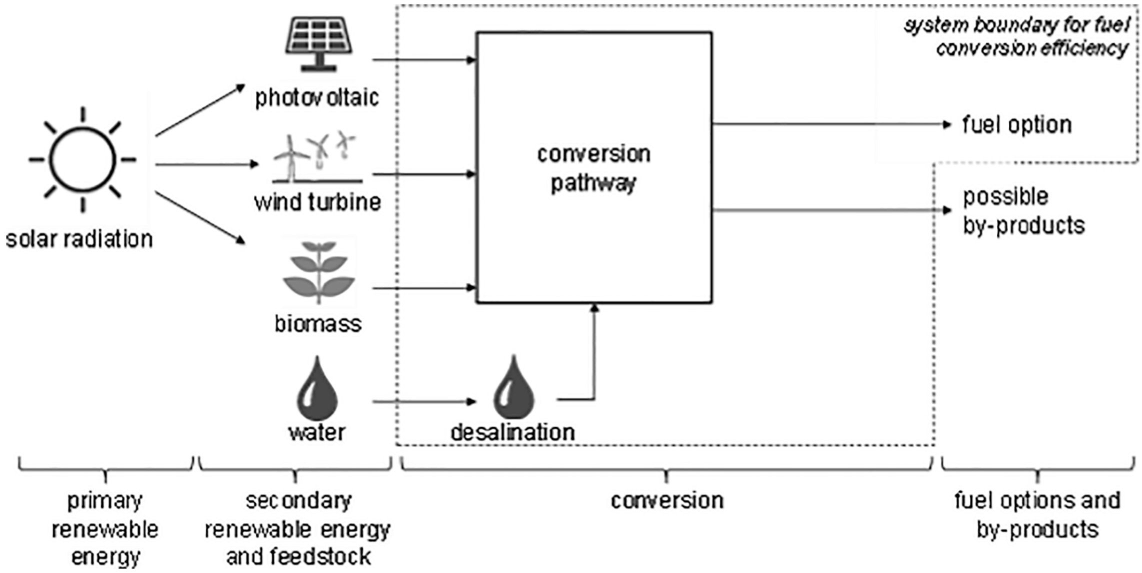

Fig. 3-2. System boundaries for the selection of literature values estimating aviation fuel conversion efficiency.

ethanol or ammonia), these effects are not included in the ranking [1,54].

Fuel cost. The provision costs of each fuel option are a key determinant of airline economic performance[c] [57]. The median of published values from techno-economic analyses of different fuel conversion technologies is used to rank the various fuel options. All cost estimates use real, present day (ca. 2020/22) costs. Costs below 20 €/GJ are considered "very advantageous" (5), between 40 and 60 €/GJ are ranked "neutral" (3) and costs above 80 €/GJ "very disadvantageous" (1) (Table 3-2).

4. Assessment of aviation fuel options

This section covers the assessment of each fuel option along the value chain of an aviation fuel according to the criteria defined above. The main characteristics related to each assessment criterion are given and the assessment results are presented.

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[c] The use of several of the considered fuel options would require the design of a new aircraft. This is usually associated with high development cost for such an aircraft and engine manufacturer and high investment cost for airlines. However, results of existing design studies differ significantly with regard to the magnitude of these cost [55],[56]. Therefore, they are not taken into account in the ranking.

4.1. Feedstock and production

Feedstock Potential. Feedstock of renewable origin can be clustered into feedstock of biogenic (i.e., various types of biomass) and non-biogenic origin (i.e., electricity from renewable origin together with sustainably provided carbon/CO_2) [41]. A renewable provision of non-biogenic carbon/CO_2 can be achieved in principle by capturing atmospheric CO_2 being theoretically available in abundance. But the present technology shows high energy requirements and significant material (and space) demands [58]. Water for electrolysis can be provided basically unlimited by sea water desalination; here the main limitation is its energy requirement [59]. Accordingly, the potential for non-biogenic feedstock is ultimately determined predominantly by the availability of "green" electricity. Therefore, for the availability estimation of non-biogenic feedstock, the assessment is based on its availability instead of the availability of water or atmospheric CO_2. The use of carbon point sources, e.g. from industrial food processing, is not taken into account by assuming that there are abundant carbon resources from this sector to cover the demand for commercial aviation. Fig. 4-1 summarizes the ranking.

Biomass feedstock can be distinguished by four main categories: lipid, sugar, starch and lignocelluloses [41]. Sugar and starch from biomass is not considered for this assessment, as present legal definitions for sustainable aviation fuels increasingly exclude feedstock being in competition with the food and fodder market [60,61]. Remaining and eligible biomass feedstock are mainly non-edible crops and/or organic waste, residues and/or by-products (e.g., sawmill residues, sewage sludge, used cooking oil (UCO)).

The potential for lipid containing, non-edible biomass and waste lipids is estimated to be around 125 to 330 Mt/a corresponding to roughly 4.6 to 12.2 EJ/a [13,14,62] excluding edible vegetable oils (e.g., palm oil). The potential of lignocelluloses-biomass (non-edible), organic waste, residues and by-products is estimated to 2,660 Mt/a corresponding to approximately 46.5 EJ/a [13]. Other estimations state a potential of 125 EJ/a for lignocelluloses-biomass [62]. For comparison, the final energy consumption of aviation fuel in global commercial air transport was about 290 Mt/a fossil kerosene or 12.4 EJ/a in 2019 [63].

These figures clearly illustrate the limited availability of lipids and thus their limited ability as the only feedstock option to provide synthetic kerosene. This is especially true since conversion losses or an extra-sectoral demand is not taken into account in Fig. 4-1 ("disadvantageous", 2). Some conversion pathways based on lignocelluloses do not utilize syngas ("neutral", 3). As syngas can be provided based on lignocelluloses-biomass or renewably sourced electricity and/or a combination of both, pathways based on syngas show an even higher feedstock potential ("very advantageous", 5). AtJ-SPK and Methane cannot only be produced via syngas but also directly from lignocellulose ("very advantageous", 5). The potential for the utilization of renewably sourced electricity is very high ("very advantageous", 5). However, it is currently limited by capacities to convert e.g. solar energy to electricity. Even though a strong ramp-up of "green" electricity is most likely in many regions of the world, the present use does by far not match its potential [64]. For this assessment criterion, limitations by lacking production capacities are not taken into account as the availability of production capacities is discussed in the following section.

Trend within next decade. Due to their characteristic as waste and/or residue, the availability of lipid-based feedstock keeps most likely constant in the decade to come. Substituting lipid-based fuels in road transport by battery-powered vehicles might improve their availability for aviation.

Similarly, the availability of lignocelluloses waste and residues will

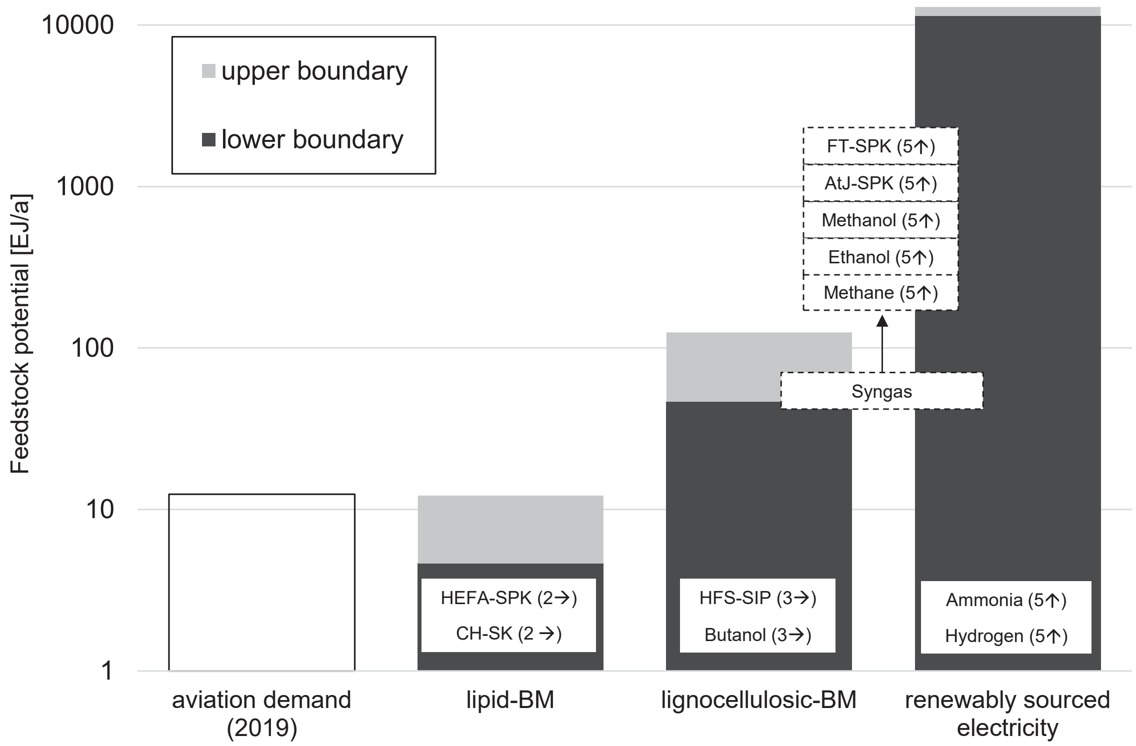

Fig. 4-1. Comparison of potential energy provided by each feedstock category for the corresponding conversion pathways (numbers in brackets indicate each fuel option's ranking) (**AtJ** Alcohol-to-Jet; **BM** Biomass; **CH** Catalytic Hydrothermolysis; **FT** Fischer-Tropsch; **HEFA** Hydroprocessed Esters and Fatty Acids; **HFS-SIP** Hydrofermented Sugars Synthesized Isoparaffins; **SK** Synthesized Kerosene; **SPK** Synthetic Paraffinic Kerosene; ranking: 1 – "very disadvantageous"; 2 – "disadvantageous"; 3 – "neutral"; 4 – "advantageous; 5 – "very advantageous"; trend: ↑– improvement; ↓– deterioration; →– no change;? – unclear ar).

not change substantially. An extension of the feedstock bases may be realized if lignocelluloses-biomass is cultivated with agricultural methods and/or the existing potentials are more extensively used. Assuming that non-biogenic renewable energy sources are utilized more intensively, their availability can increase drastically. Bearing in mind increasing global ambitions to fulfil the legally defined greenhouse gas reduction goals, such a development appears at least possible [65]. However, it remains uncertain, to which extent increasing demand from other sectors outbalances the increased availability of non-biogenic feedstock.

Production Capacities. As shown in Table 4-1, there are hardly any production capacities for the synthetic kerosene options assessed (<0.3 Mt/a, ca. 0.013 EJ/a) [66]. For FT-SPK based on renewable feedstock presently only demonstration facilities exist (TRL 7) [15,67]. However, the fact that large commercial FT-plants for fossil feedstock exist in South Africa (coal), Qatar (natural gas) and Malaysia (coal) [68], might potentially ease the transition of renewable FT-SPK from TRL towards commercial scale. A few commercial plants produce HEFA-SPK (“neutral”, 3); but most of them focus on the production of renewable diesel. This is also the pathway with the highest TRL (8 to 9) [15,37]. For AtJ-SPK and HFS-SIP the conversion of sugar/starch is more developed (TRL 7 to 8) compared to the feedstock lignocelluloses (TRL 5 to 6) [15]. CH-SK is still in the demonstration stage (TRL 3 to 4) [15,37].

Almost the entire global methanol production (90 to 100 Mt/a, ca. 2 EJ/a) is based on (fossil-based) syngas. But the provision of syngas from renewable resources is still not implemented [46]. Similar to FT-SPK, these (fossil-based) production capacities might ease the transition of methanol from renewably sourced syngas towards commercial scale. For “direct” “green” methanol synthesis only a few, small-scale plants are under operation (“neutral”, 3; TRL 8) [27,40,48].

Most of the global ethanol production (100 Mt/a, ca. 3 EJ/a) is currently renewably sourced (“very advantageous”, 5), but mostly based on sugar and/or starch (TRL 9) [28]. As these types of feedstock are increasingly excluded for fuel production due to legal sustainability criteria, lignocelluloses-biomass would need to be converted to ensure long-term compliance (TRL 6) [42,60,61,69]. To provide sugar for fermentation from lignocelluloses-biomass pretreatment steps for saccharification are additionally required, such as comminuting and subsequent hydrolysis or steam explosion [41]. Globally, 3.7 Mt/a (ca. 0.1 EJ/a) of fossil-fuel based butanol is produced being clearly less compared to methanol or ethanol [70,71,72]. Production capacities for renewably sourced butanol are hardly available so far, because existing ABE-fermentation capacities have been shut down due to economic reasons in recent years (TRL 6 to 7) [43]. Currently, no production capacities for “green” butanol greater than a demonstration scale exist (“disadvantageous”, 2) [73].

Ammonia production exists at industrial, global scale (180 Mt/a, ca. 3 EJ/a) [29]. If renewably sourced hydrogen and “green” electricity would be used, these capacities could produce “renewable” ammonia. However, this is currently not realised at scales larger than demonstration scale (“disadvantageous”, 2; TRL 8 to 9) [29].

The major share of the current methane use originates from the consumption of natural gas [30]. Only a few methane production plants (biogas plants) based on biomass exist (<0.2 EJ/a). Even though this production of so-called “biomethane” is technologically well-developed (TRL 9), it seems unrealistic for them to fulfil aviation’s energy demands (“neutral”, 3). For electricity based methane no industrial scale plants exist (TRL 6) [30,48].

Annually, about 70 Mt/a of hydrogen are produced worldwide, but only a minor share via electrolysis of water (approximately 0.1 %, ca. 0.01 EJ/a; “disadvantageous”, 2) [74]. However, the technology to produce hydrogen via electrolysis is well-developed (TRL 8) [20,49]. Additionally, a significant increase in renewably sourced hydrogen production is politically envisioned.

Trend within next decade. The demand for aviation fuel is small compared to other sectors such as road transport or the chemical industry. Therefore, the development of production capacities for synthetic kerosene is strongly influenced by the further development of liquid fuel/bulk chemical production capacities for the overall energy system/for the industrial sector. Here an increasing demand seems particularly likely for applications, where electrification is technologically difficult (e.g., shipping) and/or where industry needs hydrocarbons for the respective production process [65]. Particularly synthetic kerosene options including (intermediate) products/side products with specific application fields outside the “classical” aviation sector would benefit (FT-SPK or AtJ-SPK).

Similar to synthetic kerosene, increasing demand for “green” methanol from other sectors being significantly larger than the demand from aviation (e.g., chemical industry) would support the ramp-up of production capacities on a global scale. This is likely due to the prominent role of methanol as bulk chemical used already within the chemical industry globally. As most ethanol is produced based on renewable resources already today, a steep increase in production capacities is unlikely due to existing limitations in fertile land. However, current land/

Table 4-1

Existing production capacities and resulting ranking (**AtJ** Alcohol-to-Jet; **BM** Biomass; **BtL** Biomass-to-Liquid; **CH** Catalytic Hydrothermolysis; **FT** Fischer-Tropsch; **HEFA** Hydroprocessed Esters and Fatty Acids; **HFS-SIP** Hydrofermented Sugars Synthesized Isoparaffins; **LC** Lignocellulosic; **S** Sugar/Starch; **SK** Synthesized Kerosene; **SPK** Synthetic Paraffinic Kerosene; **PtL** Power-to-Liquid; ranking: 1 – “very disadvantageous”; 2 – “disadvantageous”; 3 – “neutral”; 4 – “advantageous; 5 – “very advantageous”; trend: ↑– improvement; ↓– deterioration; →– no change;? – unclear).

#	Fuel option		Production capacities	Ranking	Trend	TRL
1	Blended Synthetic Kerosene and	FT-SPK (BtL)	First industrial plants	3	→	7
		FT-SPK (PtL)				7
2	Neat Synthetic Kerosene	HEFA-SPK			↑	8–9
		AtJ-SPK			→	7–8
		HFS-SIP			↑	7–8
		CH-SK			→	3–4
					→	
3	Methanol		First industrial plants	3	↑	8
4	Ethanol		Current renewable production > 5 %	5	→	9 (S-BM)
			of global aviation demand			6 (LC-BM)
5	Butanol		< 5 plants at	2	→	6–7
			demonstration scale			
6	Ammonia		< 5 plants at	2	?	8–9
			demonstration scale			
7	Methane		First industrial plants	3	?	8–9
8	Hydrogen		First industrial plants	3	↑	8

road transport can be substituted to a certain extent by electric vehicles and thus existing bioethanol production could shift towards aviation and/or other sectors. Increasing interest from the chemical industry for bioethanol as a "green" bulk chemical would most likely further stimulate demand. As butanol is of minor importance compared to methanol or ethanol, a mid-term increase in "green" butanol production capacities seems rather unlikely.

"Green" ammonia could be used in the mid-term future for fertilizer production and as a potential energy (or hydrogen) carrier, which might cause a significant ramp-up of renewable production capacities. If "green" methane takes a central role as energy carrier in the future, production capacities would increase substantially (similar to synthetic kerosene and methanol). But, a fast development of hydrogen production capacities receives significantly greater interest and investment compared to biomethane production [65]. Taking the ramp-up of renewably sourced electricity into account, increasing production capacities for hydrogen seem to be most likely, while the development of a possible ramp-up of "green" methane or "green" ammonia remains unclear for the time being.

Fuel Conversion Efficiency. Fig. 4-2 compares fuel conversion efficiencies and Table 4-2 summarizes the corresponding references and ranking. Here it becomes obvious that the variation of the conversion efficiency estimates can largely be attributed to the feedstock energy content and the energy demand for feedstock provision. In general, high feedstock energy densities and/or low energy requirements for the conversion positively affect the fuel conversion efficiency. Simultaneously, large uncertainties exist as to the differing technological maturity of the conversion pathways.

FT-SPK shows significant variation in the conversion efficiencies justified by different types of feedstock. Typically, FT-SPK (BtL) conversion efficiencies increase with the feedstock energy content (e.g., higher values for black liquor). For FT-SPK (PtL), low conversion efficiencies result from the high-energy requirements of atmospheric CO_2 capture. HEFA-SPK is the technologically most mature pathway and its feedstock (lipids) is characterized naturally by a relative high energy density. Thus, its conversion efficiency with a median of 0.62 is clearly the highest among the synthetic kerosene options assessed here. The conversion efficiencies for AtJ-SPK include the conversion of biomass to alcohols, resulting in similar feedstock energy densities for all pathways using sugar as intermediate feedstock. Low values of AtJ-SPK conversion efficiencies relate to the conversion of lignocelluloses and higher values to converting sugar or starch. As no study for AtJ-SPK provision based on butanol from ABE-fermentation was available, the lower end of AtJ-SPK does only take into account the conversion of ethanol. If AtJ-SPK were to be provided by butanol from ABE-fermentation, even lower conversion efficiencies would be possible. Other butanol production pathways might yield higher conversion efficiencies (s. below). The median of HFS-SIP is considerably lower than the median of CH-SK (0.32 compared to 0.42).

Values for methanol relate to different syngas feedstock. For syngas based on biogenic feedstock, the conversion efficiency increases with increasing energy content of the feedstock. For non-biogenic feedstock, the used carbon source and the associated energy requirements influence the pathway's conversion efficiency clearly. The conversion pathway to ethanol indicates a lower median in comparison to methanol (0.31 and 0.41) as well as low variations. Lower conversion efficiencies occur for ethanol production from lignocelluloses, while higher efficiencies are given for sugar or starch. The conversion efficiency estimates for butanol are considerably lower than for the other alcohols due to the limited butanol yield of the ABE-fermentation [43,45]. This can be attributed to the fact that only the butanol (and not ethanol or acetone) from this process is taken into account. Additionally, other pathways such as fermentation by genetically engineered biocatalysts, might yield higher efficiencies but were excluded a priori due to their low technological maturity (s. 2.2).

For the gaseous fuel options, energy requirements for liquefaction are not taken into account. This is due to large uncertainties regarding boil off losses during handling and fueling of cryogenic fuels. As presently aircraft are not fueled with cryogenic fuels, their magnitude is difficult to estimate, even though they might be significant especially for hydrogen [56]. Hydrogen conversion efficiencies are the highest (median of 0.66) among the gaseous fuel options. This is ultimately limited by the electrolyser technology considered and potential energy requirements from liquefaction [40,50].

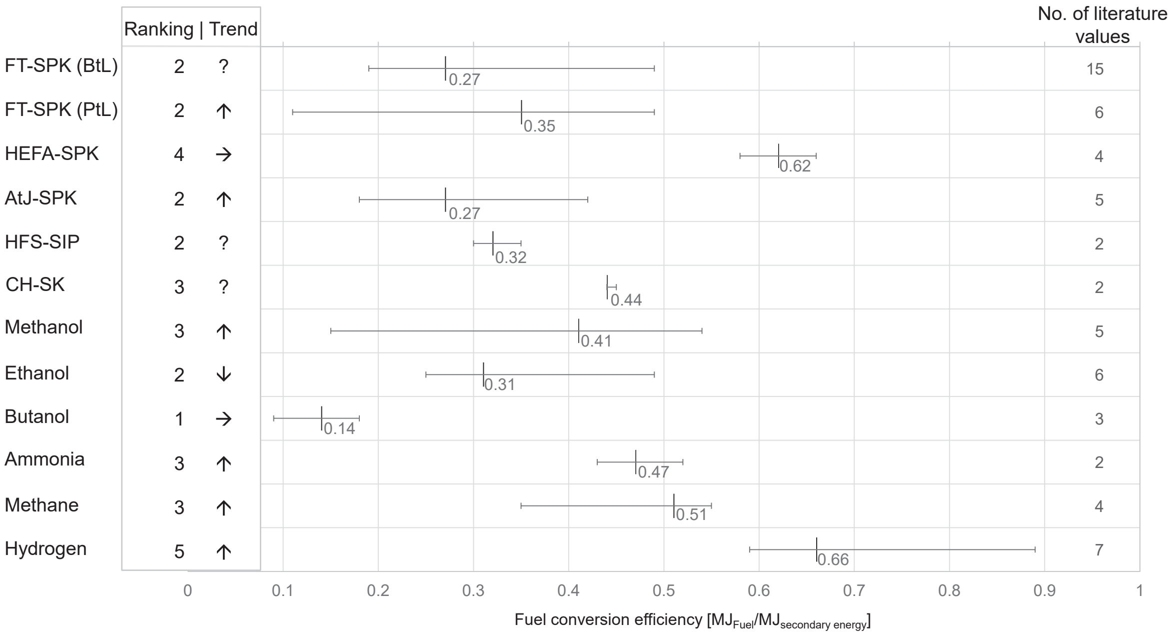

Fig. 4-2. Median and range of aviation fuel conversion efficiencies; error bars indicate the lowest/highest values considered (**AtJ** Alcohol-to-Jet; **BtL** Biomass-to-Liquid; **CH** Catalytic Hydrothermolysis; **FT** Fischer-Tropsch; **HEFA** Hydroprocessed Esters and Fatty Acids; **HFS-SIP** Hydrofermented Sugars Synthesized Iso-paraffins; **SK** Synthesized Kerosene; **SPK** Synthetic Paraffinic Kerosene; **PtL** Power-to-Liquid; ranking: 1 – "very disadvantageous"; 2 – "disadvantageous"; 3 – "neutral"; 4 – "advantageous"; 5 – "very advantageous"; trend: ↑– improvement; ↓– deterioration; →– no change;? – unclear).

Table 4-2
Fuel conversion efficiency and resulting ranking (**AtJ** Alcohol-to-Jet; **BtL** Biomass-to-Liquid; **CH** Catalytic Hydrothermolysis; **FT** Fischer-Tropsch; **HEFA** Hydroprocessed Esters and Fatty Acids; **HFS-SIP** Hydrofermented Sugars Synthesized Isoparaffins; **SK** Synthesized Kerosene; **SPK** Synthetic Paraffinic Kerosene; **PtL** Power-to-Liquid; ranking: 1 – "very disadvantageous"; 2 – "disadvantageous"; 3 – "neutral"; 4 – "advantageous; 5 – "very advantageous"; trend: ↑– improvement; ↓– deterioration; →– no change;? – unclear).

#	Fuel option		Conversion efficiency $[MJ_{fuel}/MJ_{secondary\ energy}]$			Ranking	Trend
			Median	Min-Max	References		
1	Blended	FT-SPK (BtL)	0.27	0.19–0.49	[37,40,75–81]	2	?
		FT-SPK (PtL)	0.35	0.11–0.49		2	↑
	Synthetic Kerosene and	HEFA-SPK	0.62	0.58–0.66		4	→
	Neat	AtJ-SPK	0.27	0.18–0.42		2	↑
2	Synthetic Kerosene	HFS-SIP	0.32	0.30–0.35		2	?
		CH-SK	0.44	0.44–0.45		3	?
3	Methanol		0.41	0.15–0.54	[40,77]	3	↑
4	Ethanol		0.31	0.25–0.49	[80,82,83]	2	↓
5	Butanol		0.14	0.9–0.18	[45]	1	↑
6	Ammonia		0.47	0.43–0.52	[29]	3	↑
7	Methane		0.51	0.35–0.55	[40,42,77]	3	↑ (except Biomethane)
8	Hydrogen		0.66	0.59–0.89	[29,40,77,84]	5	↑

For methane, values based on fermentation are mostly higher (above 0.5) than for a thermo-chemical synthesis. Methane provided from hydrogen and CO_2 as well as ammonia using hydrogen as an intermediate product show necessarily lower conversion efficiencies than hydrogen used as a pure substance (approximately 0.5 compared to 0.7). As methane and ammonia have higher boiling points than hydrogen, their energy requirements for liquefaction and losses by handling and fueling are potentially lower than for hydrogen.

Trend within next decade. For synthetic kerosene based on non-biogenic feedstock (e.g., FT-SPK (PtL)), ongoing improvements for hydrogen and carbon provision (electrolyser technology, direct air capture) might increase overall fuel conversion efficiencies. In contrast, the conversion efficiency of HEFA-SPK has already reached industrial scale at high conversion efficiencies and is thus unlikely to yield further substantial improvements. The inclusion of further feedstock, e.g. methanol, for AtJ-SPK might result in higher jet fuel yields and resulting higher conversion efficiencies.

Methanol based on synthesis of non-biogenic feedstock would also benefit from improvements in non-biogenic hydrogen and carbon provision. Nevertheless, the saccharification step required for the use of lignocelluloses as a feedstock for ethanol will incur necessarily lower conversion efficiencies compared to using sugar/starch. The conversion efficiency of butanol is likely to improve provided that in the mid- to long-term other pathways than ABE-fermentation reach commercial scale.

In the light of globally increasing hydrogen production, conversion efficiencies for all gases considered might improve. A particularly high potential is the development of clearly more efficient electrolysis systems. As the provision of biomethane from fermentation already has a high conversion efficiency (even from less promising organic feedstock) and technological maturity, further improvements seem unlikely.

4.2. *Logistics and airports*

Below, the assessment of infrastructure for fuel logistics and airport infrastructure is conducted. The first of the two criteria ("logistics") covers transportation from the place of production to airports in general, while the second criterion ("airports") discusses peculiarities of handling the fuel options at an airport. Both criteria are summarized in Table 4-3.

Logistics Infrastructure. Due to their drop-in characteristic, the existing infrastructure used to supply fossil kerosene can be used without any modifications for specification compliant blends containing synthetic kerosene. Basically, all major modes of transport can be applied (e.g., pipelines, tanker ships, tank wagons) depending on the overall fuel demand at a particular airport ("very advantageous", 5) [85]. Regulatory requirements to account for the use of synthetic kerosene may require separate logistics [25]. From a technological point of view, also neat synthetic kerosene can be transported within the existing infrastructure. But, as long as they are specified as non drop-in options, they would need to be physically separated from fossil kerosene due to legal reasons ("advantageous", 4).

For all alcohols considered here, infrastructures at global scale exist, even though they usually lack connection to airports. But, the existing logistics infrastructure could be easily extended for the supply of airports because the technology is basically there ("advantageous", 4).

For ammonia and methane, logistics infrastructures exist at a global scale (in particular ships and pipelines, respectively). For the transport

Table 4-3
Available infrastructure for logistics to and at airports and the resulting ranking (ranking: 1 – "very disadvantageous"; 2 – "disadvantageous"; 3 – "neutral"; 4 – "advantageous; 5 – "very advantageous"; trend: ↑– improvement; ↓– deterioration; →– no change;? – unclear).

#	Fuel option	Logistics	Ranking	Trend	Airports	Ranking	Trend
1	Blended Synthetic Kerosene	Usable logistics infrastructure exists	5	→	Usable logistics infrastructure exists	5	→
2	Neat Synthetic Kerosene	Minor modifications of infrastructure required	4	↑	Minor modifications of infrastructure required	4	↑
3	Methanol	Existing logistics infrastructure can be modified	3	?	Modifications of airport infrastructure necessary	3	→
4	Ethanol						
5	Butanol						
6	Ammonia	Minor modifications of existing infrastructure or widespread infrastructure	4	?	Major modifications of airport infrastructure necessary	1	→
7	Methane			↑			
8	Hydrogen	No existing logistics infrastructure	1	↑	Major modifications of airport infrastructure necessary	1	↑

of compressed methane, the natural gas pipeline system could be utilized (“advantageous”, 4) [29,48]. Ammonia transportation via ship is being performed at industrial scale already but the use of existing pipeline systems might require additional efforts due to the toxicity of ammonia (“advantageous”, 4) [29]. Still, most of the airports would need a connection to the existing infrastructure. For hydrogen, a global distribution infrastructure is not in place yet and due to it’s chemical properties (e.g. the lower volumetric energy density compared to methane) it appears unlikely that an existing system such as the natural gas pipeline system could be modified (“very disadvantageous, 1) [18,86].

Trend within next decade. For synthetic kerosene blends, no changes in logistics infrastructure are required in the years to come. The use of neat synthetic kerosene is presently investigated and will most likely be possible by the end of this decade as hardly any technical changes are necessary [24]. If “green” alcohols will be used at a large scale, also their transport infrastructure might grow. To which extent this development materializes, remains questionable due to the limited importance of these fuels for the time being. The same is true for ammonia. Logistics infrastructures for “green” methane do already exist, while the envisioned ramp-up for hydrogen could incentivize the development of transport infrastructure at large scale.

Airport Infrastructure. Again, the drop-in characteristic of synthetic kerosene blends allows for a seamless integration into the existing storage and fuelling infrastructure at airports (“very advantageous”, 5). However, for neat synthetic kerosene regulatory requirements or other reasons might (partially) require separate infrastructure at the airport (“advantageous”, 4). This requirement might be eased in the mid-term [24].

The use of methanol, ethanol or butanol as aviation fuel would require at least significant modifications of aircraft, if not an entirely new design. This, in turn would raise the need for a separate fuel handling system at airports [85,87]. If the existing airport infrastructure is to be used (e.g., aboveground storage tanks), this would most likely require a rededication to the use of alcohols and further modifications. An alternating use of infrastructure for alcohols and kerosene is practically unfeasible. For example, fuel storage would need to be modified to take into account e.g. the greater risk of corrosion and the water adsorption (“neutral”, 3) [88]. As long as no clear indication is visible to use alcohols as an aviation fuels, a change of this situation is highly unlikely.

For ammonia, methane, and hydrogen fuel storage and handling at the airport would require entirely new (different) storage and refuelling systems. Foremost, facilities to liquefy the fuels would be required. The storage of cryogenic hydrogen is particularly technologically challenging [31]. Boil-off losses during storage and handling need to be minimized while managing/distributing such gases at very low temperatures within a liquid state. Based on the higher condensation temperature of ammonia, it ranks somewhat better than methane and hydrogen (“disadvantageous”, 2 compared to “very disadvantageous”, 1) (with the disadvantage of being toxic). As for alcohols, strong changes in the airport infrastructure would be realized only if a clear trend towards using these fuels is apparent.

Trend within next decade. At airports for synthetic kerosene blends no changes in infrastructure are required and the use of neat synthetic kerosene will most likely be possible by the end of this decade [24]. Due to high investment costs and interdependencies with fuel supply at other airports, the provision of non drop-in fuel will be constrained to an option with broad industry consensus for its use. Presently, this is only – if at all – recognizable for hydrogen.

4.3. *Fuel and aircraft*

Fuel Properties. A variety of fuel properties have been defined to be

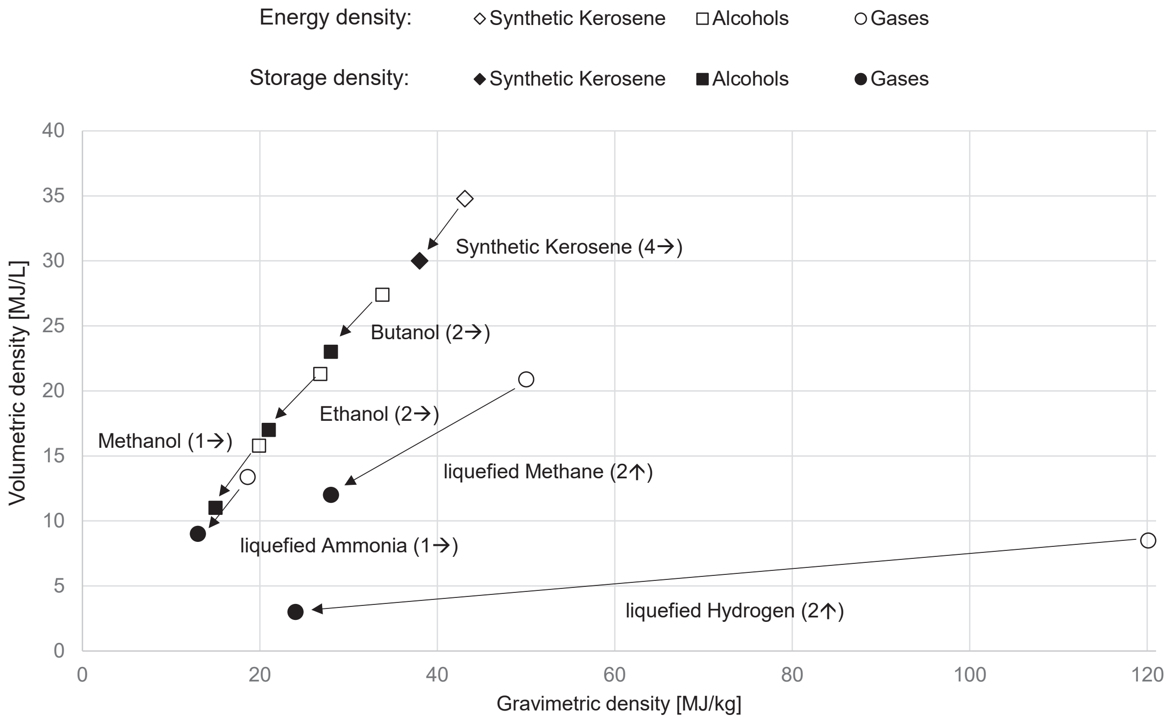

Fig. 4-3. Gravimetric vs volumetric energy and estimated storage densities (based on lower heating value) for the fuel options considered; arrows indicate the relation between storage (full symbols) and energy density (empty symbols); (ranking: 1 – “very disadvantageous”; 2 – “disadvantageous”; 3 – “neutral”; 4 – “advantageous; 5 – “very advantageous”; trend: ↑– improvement; ↓– deterioration; →– no change;? – unclear) [18,32,90–94].

relevant for a fuel to be used for commercial aviation purposes. These are for example the energy and storage density as determinants of range, the freezing point as the lower limit for the fuel temperature within the aircraft fuel tanks and the flash point as an important safety measure [8,89]. Here, energy and storage density are chosen due to their significant influence on aircraft design and flight envelope [32].

Fig. 4-3 shows the energy densities (volumetric vs gravimetric) and estimated storage densities for the fuel options considered [18,32,90–94]. While the energy density only takes the energy of a certain volume/mass of the fuel option into account, the storage density includes an estimate for volume and mass requirements by the overall fuel system (e.g., insulation for cryogenic storage).

The higher the storage density of a fuel option, the less mass/volume is required for fuel storage on board of an aircraft (i.e., the higher the fuel's storage density, the more payload can be carried for a given aircraft design). Fig. 4-3 clearly underlines the advantage of synthetic kerosene options due to their high gravimetric storage density, which is not only higher compared to alcohols but also ca. 2 % higher than fossil kerosene ("advantageous", 4) [9,95]. Butanol, ethanol and methanol show lower gravimetric storage densities (Butanol and ethanol (73 % and 55 % of fossil kerosene average) "disadvantageous", 2 and methanol (39 % of fossil kerosene average) "very disadvantageous", 1). To achieve the same range with a similar aircraft design, a reduction in payload has to be accepted. The storage systems incur a moderate loss.

A similar situation can be observed for ammonia (34 % of fossil kerosene average, "very disadvantageous", 1) and methane (73 % of fossil kerosene average, "disadvantageous", 2). Ammonia has a lower storage density (volumetric and gravimetric) than methane, but both are lower than synthetic kerosene. Losses due to the storage of liquid fuels are moderate for ammonia, but more significant for methane, due to its lower freezing point and the corresponding insulation and cooling requirements. Liquid hydrogen has a lower volumetric storage density but a significantly greater gravimetric storage density than synthetic kerosene. In principle, the same amount of energy carried in form of liquid hydrogen instead of synthetic kerosene would require a greater volume, but less weight. This effect is substantially reduced by the large toll of the storage system for hydrogen in a liquid state at −253 °C (63 % of fossil kerosene average, "disadvantageous", 2). The increased volume requirement might be constrained by aircraft design limitations, which would in turn incur range limitations of hydrogen fuelled aircraft [86]. Table 4-4 summarizes the associated ranking.

Trend within next decade. For all liquid fuel options and ammonia, the difference between energy and storage density is rather low. In case of methane and hydrogen, their large scale implementation is likely to positively affect storage technology which again yield improvements for their storage on board of an aircraft [18,86].

Table 4-4
Operational fuel properties and the resulting ranking (ranking: 1 – "very disadvantageous"; 2 – "disadvantageous"; 3 – "neutral"; 4 – "advantageous; 5 – "very advantageous"; trend: ↑– improvement; ↓– deterioration; →– no change;? – unclear).

#	Fuel option	Operational fuel properties	Ranking	Trend
1	Blended Synthetic Kerosene	No effect on range	4	→
2	Neat Synthetic Kerosene	No effect on range	4	→
3	Methanol	Significant reduction in aircraft range	1	→
4	Ethanol	Noticeable reduction in aircraft range	2	→
5	Butanol	Noticeable reduction in aircraft range	2	→
6	Ammonia	Significant reduction in aircraft range	1	→
7	Methane	Noticeable reduction in aircraft range	2	↑
8	Hydrogen	Noticeable reduction in aircraft range	2	↑

Aircraft Modifications. The use of fuel options with an energy density lower than kerosene in existing aircraft designs would result in a significant loss in flight range. From an airline's perspective this incurs significant disadvantages as some destinations might be out of range [52,96]. Such a range reduction also decreases the degree of flexibility on which routes the aircraft can be used. As airline operations largely depend on the ability to shift aircraft according to demand fluctuations and other operational factors, such a loss in flexibility would be disadvantageous [52]. The associated ranking is summarized in Table 4-5.

Neat and blended synthetic kerosene have similar energy densities and storage properties as fossil kerosene. The energy density of neat synthetic kerosene is slightly higher than for blended synthetic kerosene [95]. Thus, no technical adjustment would be required to maintain similar, if not even improved payload-range properties. However, besides energy densities, other chemical properties of neat synthetic kerosene types may vary to a considerable extent amongst different synthetic kerosene options and compared to fossil kerosene; this might require modifications for the use of unblended synthetic kerosene [9]. For example, most production processes for synthetic kerosene provide a fuel being virtually free of aromatics and of higher energy density compared to fossil keroesen [9]. However, minimum and maximum levels for aromatics are specified for drop-in kerosene with synthetic components [9]. The lower limit (defined within ASTM D7566, does not apply for fossil kerosene) aims to ensure the tightness of sealing components and the upper limit (ASTM D1655) to constrain soot emissions [8,23]. From an environmental perspective, it would be desirable to reduce the fuel's aromatics content as far as technically possible. Modern aircraft use elastomers being less sensitive to the fuel aromatics content (i.e., fluorocarbons and fluorosilicone) [24]. For some legacy aircraft, a replacement of the sealing components might be a prerequisite to allow for the use of neat synthetic kerosene ("advantageous", 4), but not for blended synthetic kerosene ("very advantageous", 5). An exchange of the concerned fuel system components seems comparatively simple compared to implications resulting from the use of e.g. neat alcohols.

The lower energy density (and the resulting storage density) of the alcohols considered, implies a loss in range. Various components of the fueling system (e.g., pumps, heat exchangers) would need to exchanged..Preventive measures need to be taken to avoid corrosion, microbial contamination or freezing of water dissolved in the alcohols [88]. Injectors and heat exchangers need to be replaced to facilitate the different volume flows and chemical properties (e.g. surface tension). Similar requirements apply to the combustion chamber design. Therefore, at least the fueling system and engines of an alcohol-fueled aircraft would need a new design and a time-consuming certification process ("disadvantageous", 2). The loss in range could be avoided by designing a new aircraft at the expense of even longer development times [52,57]..

Table 4-5
Aircraft modifications and the resulting ranking (ranking: 1 – "very disadvantageous"; 2 – "disadvantageous"; 3 – "neutral"; 4 – "advantageous; 5 – "very advantageous"; trend: ↑– improvement; ↓– deterioration; →– no change;? – unclear).

#	Fuel option	Aircraft Modifications	Ranking	Trend
1	Blended Synthetic Kerosene	No need for modifications	5	→
2	Neat Synthetic Kerosene	Modification of only a few components	4	↑
3	Methanol	Minor modifications required	2	→
4	Ethanol	Minor modifications required	2	→
5	Butanol	Major modifications required	2	→
6	Ammonia	Major modifications required	1	→
7	Methane	Major modifications required	1	→
8	Hydrogen	New design and certification required	1	?

Among the gaseous fuel options, the implications from cryogenic storage and reduced storage densities would require an entirely new design and certification (“very disadvantageous”, 1). Aircraft designs utilizing hydrogen as fuel are discussed in a variety of studies [18,56,86,91,97]. Cryogenic hydrogen storage is usually preferred due to increased energy density. This requires significant technological developments for lightweight storage and fuelling systems [91]. All gaseous fuel options considered would also require the design of a gas turbine specifically designed for the combustion of the respective gaseous fuel [98]. A modification of existing aircraft designs does not seem feasible for any of the discussed gaseous fuels. Accordingly, aircraft using one of the considered gases would rather be available in the long-term.

Trend within next decade. Due to its relative simplicity compared with e.g., hydrogen, using neat synthetic kerosene in existing aircraft seems feasible within the decade to come. Again, the use of any of the alcohols and gases is strictly constrained by the required industry consensus for the corresponding option. For the time being, this appears only realistic for hydrogen characterized simultaneously by the highest technological barriers. Whether or not a hydrogen fuelled commercial aircraft will be available in the mid- or long-term is still an open question.

4.4. *Environment and economics*

Life cycle greenhouse gas emissions. Combusting 1 kg of fossil kerosene emits approximately 3.16 kg CO_2, 1.2 kg water vapour, 1.5 g (0.0015 kg) NO_x, 1.2 g (0.0012 kg) sulphur (SO_2) and 0.03 g (0.00003 kg) soot. All of these affect the earth’s radiative balance through a cascade of interrelationships and influence the air quality around airports. Related to climate-effects, a distinction is commonly made between CO_2 and non-CO_2 related climate effects [1].

Fig. 4-4 illustrates the broad range of potential life-cycle CO_2eq emissions for many of the examined fuel options.

The feedstock used and the provision of energy needed for feedstock conversion influence the resulting greenhouse gas emissions substantially. In terms of the synthetic kerosene options, FT-SPK shows the lowest median (“very advantageous”, 5). Values below zero refer to a partial removal of the carbon captured into waste streams. High emission cases for FT-SPK conversion processes often relate to either energy intensive processing of biomass conversion (e.g., due to (indirect) land-use change) or indirect emissions caused by the provision of renewably sourced energy (e.g., manufacturing processes). The medians of greenhouse gas emission values for HEFA-SPK, AtJ-SPK and HFS-SIP (all “advantageous”, 4) are slightly higher compared to FT-SPK. These processes are generally based on biomass; especially the extraction of lipids from biomass or the saccharification of lignocelluloses for AtJ-SPK or HFS-SIP is energy intensive. The narrow bandwidth of emission estimates for CH-SK (“very advantageous”, 5) is most likely related to a low amount of accessible data. However, for synthetic kerosene blends a maximum emission reduction of 50 % compared to neat synthetic kerosene is possible due to the legal blending requirement of maximum 50 vol-%. The development of a certification for neat synthetic kerosene is ongoing [24], accordingly the limit to lifecycle CO_2 reduction by blended synthetic kerosene might diminish in the near future.

Methanol shows the greatest variety in lifecycle greenhouse gas emissions for all fuel options considered. As this process is based on the use of syngas, again the type of feedstock is a central determinant of the respective life cycle emissions. Low emissions can be attributed to lignocelluloses waste streams, while higher emissions stem from the use of electricity provided by photovoltaics (“advantageous”, 4). For ethanol, only fermentation of biogenic feedstock is considered; in this case, the use of lignocelluloses is associated with higher life cycle emissions compared to sugar-rich biomass (“advantageous”, 4). As ABE-fermentation is presently not used at an industrial scale, a limited amount of data is available. Among these, the extent to which emissions from production are allocated to the various products of such an ABE-fermentation (acetone, ethanol) influences clearly the lifecycle emissions attributed to butanol (“disadvantageous”, 2).

In general, the median lifecycle emissions of the gases considered are lower compared to the liquid fuel options (“very advantageous”, 5), mostly influenced by the type of energy provision for water electrolysis. In the case of ammonia, the broad range of different data result from the technology to retrieve nitrogen from ambient air (e.g., cryogenic distillation, pressure-swing adsorption) and the hydrogen provision process (low or high temperature electrolysis). For the greenhouse gas emissions by methane provision either via synthesis or fermentation, no

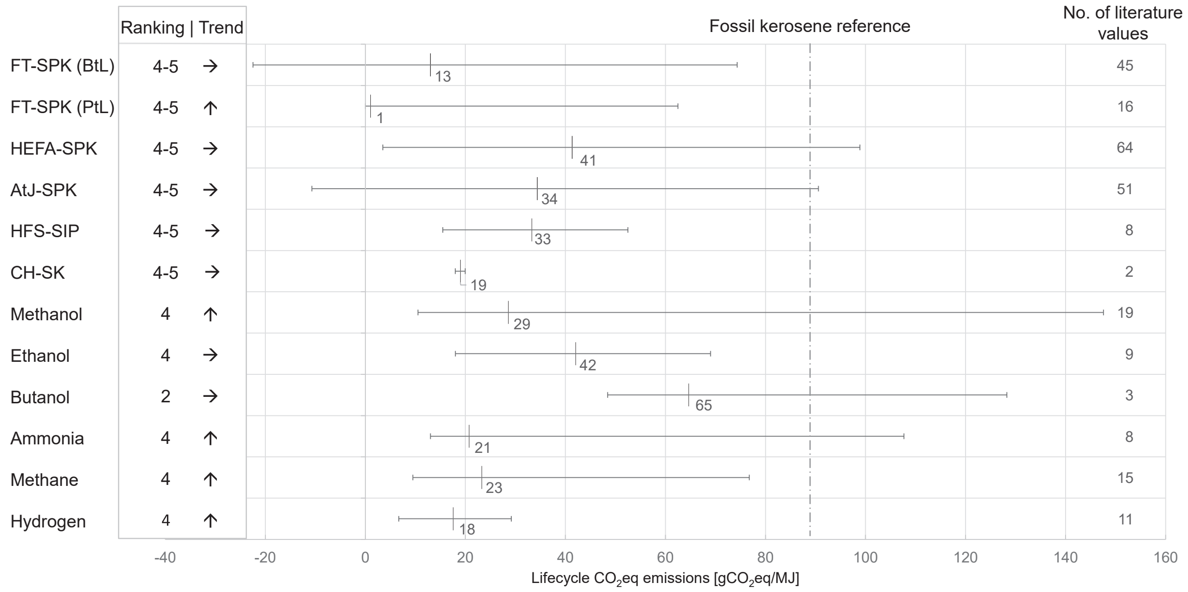

Fig. 4-4. Median and range of values for each fuel options life-cycle CO_2eq emissions. Error bars indicate the lowest/highest values considered (**AtJ** Alcohol-to-Jet; **BtL** Biomass-to-Liquid; **CH** Catalytic Hydrothermolysis; **FT** Fischer-Tropsch; **HEFA** Hydroprocessed Esters and Fatty Acids; **HFS-SIP** Hydrofermented Sugars Synthesized Isoparaffins; **SK** Synthesized Kerosene; **SPK** Synthetic Paraffinic Kerosene; **PtL** Power-to-Liquid; ranking: 1 – “very disadvantageous”; 2 – “disadvantageous”; 3 – “neutral”; 4 – “advantageous; 5 – “very advantageous”; trend: ↑– improvement; ↓– deterioration; →– no change;? – unclear).

clear distinction can be made. In case of synthesis, the choice of renewable electricity provision (wind on–/offshore, photovoltaics) shows a substantial influence and for biomass-based fermentation the type of feedstock (organic waste or cash crops) largely explains the variation.

Concluding, life cycle greenhouse gas emissions of biomass-based fuels are clearly influenced by the chosen feedstock. Additionally, for fuel options based on "green" electricity, indirect emissions of energy provision have a substantial effect. The potential of "negative" life cycle emissions seems rather limited. Table 4-6 depicts a summary of the resulting ranking.

Trend within next decade. For synthetic kerosene options, the improvements will mostly be the approval to use neat synthetic kerosene. For non-biogenic feedstock, increasing shares in renewable electricity and increasing hydrogen provision will further lower lifecycle emissions. For fuels based on biogenic feedstock, the influence of feedstock choice will remain the most significant aspect and thus improvements seem unlikely. Advancing technology for methanol provision based on non-biogenic feedstock can reduce corresponding lifecycle greenhouse gas emissions. For ethanol and butanol, no change can be expected, as the increased use of lignocelluloses as preferred feedstock for ethanol and butanol lowers conversion efficiency and raises material and energy demands. Increasing production of "green" hydrogen and corresponding improvements in electrolyser technology do not only lower lifecycle greenhouse gas emissions of hydrogen but also of ammonia and methane.

Fuel Cost. The production costs of each fuel option outlined below are related to their specific energy content (based on the lower heating value), in order to take into account differences in energy density. In general, all investigated fuel options show higher production costs compared to average market prices for fossil kerosene. The majority of the cost variations presented in Fig. 4-5 can be attributed to the influence of costs for the feedstock, the needed energy, as well as the effort needed for the conversion. Table 4-7 indicates the corresponding ranking.

Among the synthetic kerosene options, costs for FT-SPK based on "Power-to-liquid" feedstock are considerably higher ("disadvantageous", 2) than those for biogenic feedstock ("advantageous", 4). This is caused by high demands for renewable electricity for the earlier [113]. The lower values for HEFA-SPK ("advantageous", 4) correspond to relatively low-cost feedstock (e.g., waste animal fat), while higher values relate to the cultivation of non-edible oils (e.g., Jatropha plants) [35,80]. The cost estimates for AtJ-SPK show a slightly higher median ("advantageous", 4). Lower values are based on studies considering sugar/starch (corn grain, maize) for ethanol production [112], while higher costs are associated with lignocelluloses [80]. The analysis for the HFS-SIP process considers lignocelluloses-based feedstock with saccharification. The process' relatively low degree of technological maturity might explain its high cost estimates. CH-SK is associated with the lowest cost estimates ("advantageous", 4) due to the specific low-cost feedstock options usually considered for CH-SK analyses (e.g., sewage sludge, manure). However, a relatively low technological maturity of this process yields uncertainties in comparison with other processes.

Despite significantly different conversion processes, the estimates for alcohols are in a similar range (all "advantageous", 4). On an energy-specific basis, they show costs comparable to HEFA-SPK or FT-SPK based on biogenic feedstock. Again, most of the variations can be explained by varying assumptions for feedstock costs. Similar to the kerosene-based options, cost improvements could mostly be expected for feedstock types requiring further technological developments, such as lignocelluloses for fermentation or non-biogenic feedstock for methanol synthesis.

Values for ammonia and methane (both "advantageous", 4) are slightly higher than for hydrogen ("advantageous", 4), since both options can be produced within pathways with hydrogen as a key component. Production pathways for methane based on fermentation of biomass residues show very low cost estimates (ca. 14 to 25 €/GJ) indicating a low-cost option. The variability in cost estimates for hydrogen can largely be attributed to different methods of renewably sourced electricity provision [20,32,40].

Trend within next decade. The costs of synthetic kerosene based on non-biogenic feedstock is mostly influenced by the costs of renewably sourced electricity. Whether or not the development of electricity from renewable sources outpaces increasing demand and thus lowers prices is uncertain. Cost for biogenic waste as feedstock for synthetic kerosene are likely to rise with increasing demand as supply is limited (section 4.1). This also applies to ethanol and butanol, as their production is also based on biogenic feedstock. The cost development for methanol is uncertain for non-biogenic feedstock and – like biogenic synthetic kerosene – will most likely increase for biogenic feedstock. Cost for all gases are driven by hydrogen provision costs (except biomethane). Thus, low cost renewable electricity and substantial improvements in electrolysis technology are necessary. The latter seems likely due to industry-wide interest in electrolyser technology.

4.5. Market development

Based on the previous assessment of the value chains for the different fuel options, in this section key constraints are discussed when and to which extent the various fuel options could be available for aviation. The fuel's value chain is subdivided into four stages: production,

Table 4-6

Life-cycle CO_2eq emissions and resulting ranking (**AtJ** Alcohol-to-Jet; **BtL** Biomass-to-Liquid; **CH** Catalytic Hydrothermolysis; **FT** Fischer-Tropsch; **HEFA** Hydroprocessed Esters and Fatty Acids; **HFS-SIP** Hydrofermented Sugars Synthesized Isoparaffins; **SK** Synthesized Kerosene; **SPK** Synthetic Paraffinic Kerosene; **PtL** Power-to-Liquid; ranking: 1 – "very disadvantageous"; 2 – "disadvantageous"; 3 – "neutral"; 4 – "advantageous"; 5 – "very advantageous"; trend: ↑– improvement; ↓– deterioration; →– no change;? – unclear).

#	Fuel option		Lifecycle CO_2eq [g CO_2eq/MJ]			Ranking	Trend
			Median	Min-Max	References		
	Fossil kerosene reference		89	N/A	[99]	N/A	N/A
1	Blended Synthetic Kerosene and	FT-SPK (BtL)	13	–22–74	[34,35,60,97,100–107]	5	→
		FT-SPK (PtL)	1	0–62		5	
2	Neat Synthetic Kerosene	HEFA-SPK	41	3–99		4	(biogenic)
		AtJ-SPK	34	−11–91		4	↑
		HFS-SIP	33	15–52		4	
		CH-SK	19	18–20		5	(non-biogenic)
3	Methanol		29	11–148	[40]	4	↑
4	Ethanol		42	18–69	[108]	4	→
5	Butanol		65	48–128	[109]	2	→
6	Ammonia		21	13–108	[110]	5	↑
7	Methane		23	10–77	[40]	5	↑
8	Hydrogen		18	7–29	[40,111,112]	5	↑

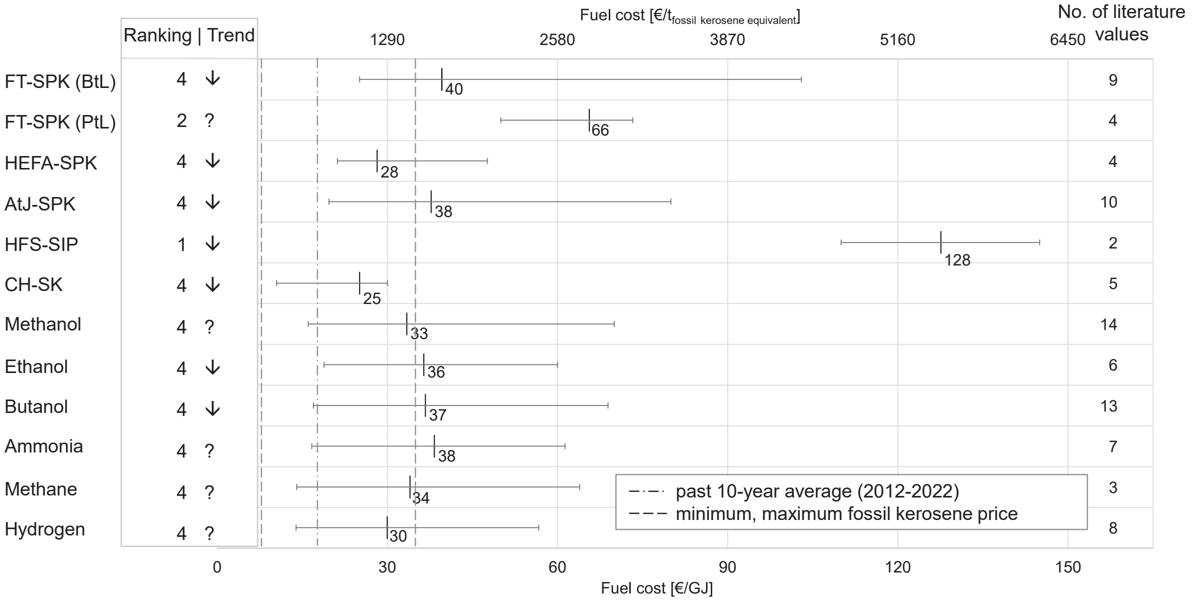

Fig. 4-5. Present fuel costs of the considered fuel options, error bars indicate the lowest/highest values taken into account. The solid line depicts the average price of fossil kerosene, the dashed lines the corresponding lowest/highest price of the past 10 years as of July 2022 (**AtJ** Alcohol-to-Jet; **BtL** Biomass-to-Liquid; **CH** Catalytic Hydrothermolysis; **FT** Fischer-Tropsch; **HEFA** Hydroprocessed Esters and Fatty Acids; **HFS-SIP** Hydrofermented Sugars Synthesized Isoparaffins; **SK** Synthesized Kerosene; **SPK** Synthetic Paraffinic Kerosene; **PtL** Power-to-Liquid; ranking: 1 – "very disadvantageous"; 2 – "disadvantageous"; 3 – "neutral"; 4 – "advantageous; 5 – "very advantageous"; trend: ↑– improvement; ↓– deterioration; →– no change;? – unclear).

Table 4-7
Fuel costs and resulting ranking. Fossil kerosene is shown for comparison (**AtJ** Alcohol-to-Jet; **BtL** Biomass-to-Liquid; **CH** Catalytic Hydrothermolysis; **FT** Fischer-Tropsch; **HEFA** Hydroprocessed Esters and Fatty Acids; **HFS-SIP** Hydrofermented Sugars Synthesized Isoparaffins; **N/A** not applicable; **SIP** Hydrofermented Sugars Synthesized Isoparaffins; **SK** Synthesized Kerosene; **SPK** Synthetic Paraffinic Kerosene; **PtL** Power-to-Liquid; ranking: 1 – "very disadvantageous"; 2 – "disadvantageous"; 3 – "neutral"; 4 – "advantageous; 5 – "very advantageous"; trend: ↑– improvement; ↓– deterioration; →– no change;? – unclear).

#	Fuel option		Cost range [€/GJ]			Ranking	Trend
			Median	Min-Max	References		
	Fossil Kerosene		12.9	3.9–20.9	[114]	N/A	N/A
1	Blended Synthetic Kerosene and	FT-SPK (BtL)	39.5	25.1–103.0	[13,35,40,80,112,113,115]	4	?
		FT-SPK (PtL)	65.5	50.0–73.3		2	
	Neat Synthetic Kerosene	HEFA-SPK	28.1	21.2–47.6		4	
2		AtJ-SPK	37.6	19.7–80.0		4	↓
		HFS-SIP	127.5	110.0–145.0		1	
		CH-SK	25.0	10.5–30.0		4	
3	Methanol		33.3	16.0–70.0	[27,32,40,113,116]	4	?
4	Ethanol		36.3	18.8–60.0	[113,115,116]	4	↓
5	Butanol		36.6	17.0–68.9	[45,73,113]	4	↓
6	Ammonia		38.2	16.7–61.3	[20,32,117,118]	4	?
7	Methane		33.9	14.0–63.9	[20,32,40,117]	4	?
8	Hydrogen		29.9	13.9–56.7	[20,32,40,84,117]	4	?

logistics, airport and aircraft. Table 4-8 summarizes the constraints along each of them.

The development of production capacities poses a significant constraint for synthetic kerosene fuel options. Several processes are technologically mature (e.g., HEFA-SPK), but for commercial reasons existing production capacities are scarce (section 4.1). Due to their drop-in characteristic, transportation, storage and fueling would not require any changes of the existing system. The introduction of neat synthetic kerosene is further constrained by the necessity to accommodate a greater variety in fuel properties. This might imply minor modifications of the respective aircraft. In small amounts, synthetic kerosene is available today.

The only alcohol presently produced at large scale from renewable resources is ethanol. The provision of methanol via synthesis would require the provision of a renewably sourced syngas. For butanol production, ABE-fermentation (or another fermentation process) at large scale would be required. In principle, the existing logistics and airport infrastructure is capable of transporting liquids. Still, due to high investment cost and network interdependencies among airports, broad consensus for a particular non drop-in fuel option would be required. Additionally, infrastructure modifications might become necessary to facilitate larger volumes due to the alcohol's lower energy densities, to ensure material compatibility and/or to prevent microbial contamination. For all alcohols, present aircraft would at least need to be modified to accommodate different volume flows (e.g., fuel pumps, heat exchangers) and to be equipped with newly developed jet engines suitable for alcohol combustion [64]. For both, infrastructures and aircraft, the compatibility of materials presently in use with the respective alcohols will need to be evaluated and components might need to be replaced. The time to develop and develop a jet engine for alcohol combustion appears to be the strictest constraint.

For gaseous fuel options all value chain elements need further

Table 4-8
Key constraints for the market development of the investigated fuel options.

#	Fuel option	Production	Logistics	Airport	Aircraft
1	Blended Synthetic Kerosene	Development of production capacities	None	none	none
2	Neat Synthetic Kerosene			Potentially minor modifications due to different chemical properties	Potentially modifications of components due to different chemical properties
3	Methanol	Switch to renewably sourced syngas	None	Modification of storage and fuelling infrastructure necessary	Modification of existing aircraft necessary
4	Ethanol	none			
5	Butanol	Development of plants, e.g. for ABE-fermentation			
6	Ammonia	Provision of renewably sourced hydrogen and electricity	None	Development and construction of storage and fuelling infrastructure required	Development and certification of new aircraft design
7	Methane	Provision of renewably sourced hydrogen, carbon and electricity			
8	Hydrogen	Provision of renewably sourced electricity	Development of large-scale transport systems (e.g., pipelines, ships)		

technological developments and – similar to alcohols – consensus for a particular option due to the high effort to establish the necessary fuel provision infrastructure. Capacities for a production from renewable resources are technologically available but not installed at industrial scale so far. For methane, it seems likely that the existing network to transport natural gas could be re-used. To which extent this is feasible for ammonia and hydrogen is questionable so far. Additionally, a new fueling infrastructure (trucks, hydrant systems) needs to be built at airports. However, the most prominent barrier is the development and certification of new aircraft and engine types [52].

Hence, for synthetic kerosene options the central temporal constraint is the development of production capacities and technologies. The use of the considered alcohols as aviation fuel is predominantly limited by aircraft modifications and certification as well as by the required development of production capacities (except for ethanol). The greatest temporal barriers exist for the gaseous fuel options. With a development of production capacities, transport and airport infrastructure, and the development of entirely new aircraft designs, each element of the value chain is substantially affected. Concluding, synthetic kerosene seems like a short-term feasible option, while the other investigated fuel options could only become available in a mid- to long-term timeframe.

5. Overall results

Current status. A summarised comparison of all assessment criteria and fuel options shows Table 5-1. Synthetic kerosene options achieve the most advantageous rankings for logistic and airport infrastructure, fuel properties and aircraft modifications.

Compared to the amount of other sectors (e.g., road transport, industrial production), the feedstock demand to cover overall aviation fuel demand is relatively small. It appears unlikely that the demand for aviation fuel alone is sufficient to incentivize the use of a particular

Table 5-1
Overall assessment results (**AtJ** Alcohol-to-Jet; **BtL** Biomass-to-Liquid; **CH** Catalytic Hydrothermolysis; **SK** Synthesized Kerosene; **FT** Fischer-Tropsch; **HEFA** Hydroprocessed Esters and Fatty Acids; **HFS-SIP** Hydrofermented Sugars Synthesized Isoparaffins; **SK** Synthesized Kerosene; **SPK** Synthetic Paraffinic Kerosene; **PtL** Power-to-Liquid).

#	Fuel option	Feedstock and production			Logistics and airports		Fuel and aircraft		Economics and environment	
		Feedstock potential	Production capacities	Fuel conversion efficiency	Logistics infrastructure	Airport infrastructure	Fuel properties	Aircraft modifica-tions	Lifecycle CO₂eq	Fuel costs
1	Blended Synthetic Kerosene	2→ (HEFA-SPK, CH-SK) 3→ (HFS-SIP)	3↑ (FT-SPK, AtJ-SPK) 3→ (other)	2? (FT-SPK (BtL), HFS-SIP) 2↑ (AtJ-SPK, FT-SPK (PtL)) 3? (CH-SK)	5→	5→	4→	5→	4→ (HEFA-SPK, biogenic AtJ-SPK, HFS-SIP) 4↑ (non-biogenic AtJ-SPK)	1↓ (HFS-SIP) 2? (FT-SPK (PtL))
2	Neat Synthetic Kerosene	5↑ (FT-SPK, AtJ-SPK)		4→ (HEFA-SPK)	4↑	4↑	4→	4↑	5→ (CH-SK, FT-SPK (BtL)) 5↑ (FT-SPK (PtL))	4↓ (AtJ-SPK, HEFA-SPK, FT-SPK (BtL), CH-SK)
3	Methanol	5↑	3↑	3↑	3?	3→	1→	2→	4↑	4?
4	Ethanol	5↑	5→	2↓			1→	2→	4→	4↓
5	Butanol	3→	2→	1→			2↑	2→	2→	4↓
6	Ammonia	5↑	2?	3↑	4?	1→	1→	1→	4↑	4?
7	Methane	5↑	3?	3↑ (except Biomethane)	4↑		2↑	1→	4↑	4?
8	Hydrogen	5↑	3↑	5↑	1↑	1↑	2↑	1?	4↑	4?

Ranking:	1 “very disadvantageous”	2 “disadvantageous”	3 “neutral”	4 “advantageous”	5 “very advantageous”
Trend:	↑ improvement	↓ deterioration	→ no change	? unclear	-

feedstock and/or conversion process. Rather, pathways for (intermediate) products seem more likely to develop at an industrial scale, if they can defossilize several industrial sectors and/or can cover a higher demand. This is for example the case for FT-SPK or AtJ-SPK with syncrude or methanol/ethanol/butanol respectively as intermediate feedstock.

Even though neat synthetic kerosene options are not drop-in fuels by present specification/legal constraints, enabling their use in existing infrastructure and aircraft requires substantially less technological adaptations than for other non drop-in fuel options. Conversion efficiency and costs of the synthetic kerosene options varies significantly due to different production processes and various types of feedstock. Overall, while post-production value chain steps of the synthetic kerosene options appear advantageous, the lack of production capacities is disadvantageous.

For alcohols, feedstock potentials and in case of ethanol also production capacities rank highest. If edible feedstock which compete with food and fodder purposes are to be avoided for fuel production (e.g., by using lignocelluloses) further developments of feedstock conversion technologies are required. All alcohols considered are already used as bulk chemicals, especially methanol and ethanol in large amounts. If these are converted to AtJ-SPK, they can become available comparatively soon without any further technological constraints after production. The business model of airlines currently relies to a great extent on the ability to schedule aircraft flexibly in order to adapt to demand fluctuations, (un-)scheduled maintenance events and other factors [52]. Additionally, airport infrastructure is used by a variety of stakeholders more or less simultaneously. If various, incompatible fuels would be offered at different airports, these advantages would not exist anymore. Consensus of the air transport industry for using a particular fuel is a prerequisite to introduce any non drop-in fuel option and to avoid the aforementioned loss of flexibility. As of now, such an industry-wide consensus is not recognizable. Hence, the need for aircraft modifications and/or a new aircraft design and production poses a significant barrier for their use as aviation fuel.

The gaseous fuel options appear particularly advantageous in the area of feedstock and production. Fuel conversion efficiency is highest for hydrogen among the gases considered. Most of the conversion pathways currently under discussion are technologically more or less mature. Yet, the requirements to adopt logistics and airport infrastructures as well as fuel system and aircraft in general are clearly higher than those for alcohols. For this group of fuel options, the development of new aircraft designs will be necessary and an even greater barrier than for alcohols. The development of logistics infrastructures is in particular necessary for hydrogen. The existing natural gas logistics might be used by "green" methane or potentially ammonia, at least from a technological perspective. The gaseous fuel options – especially hydrogen – will be required for the defossilation of several industrial sectors, e.g., the chemical industry. This might incentivize increasing production capacities and supply.

Overall, the global potential for feedstock with a rather high energy content (i.e., lipid biomass/waste) is significantly restricted. Fuels from non-biogenic feedstock have a greater overall availability, but less production capacities are established for their conversion and provision yet and the conversion technology is less mature. Key determinants for fuel conversion efficiency are the feedstock's energy content and the technological maturity of the conversion process or the respective conversion concept. The need for technological modification on both the fuel infrastructure and aircraft side to use gaseous fuels (and also alcohols) can prevent their timely market introduction. The key determinants for fuel costs are feedstock and energy costs.

Drop-in options are constrained by provision steps of the value chain, such as production capacities and (partial) technological maturity of the respective conversion processes. In contrast, most of the non drop-in options are constrained by post-production steps, i.e. the development/design of aircraft certified to use non drop-in fuels and the implementation of infrastructure to provide them.

A reduction of greenhouse gas emissions can be achieved by all fuel options, assuming a favourable combination of feedstock and energy provision. The certification of neat synthetic kerosene would allow for greater greenhouse gas emission reductions of these fuel options at rather low post-production efforts compared with e.g., the gaseous fuel options considered.

Status next decade. Table 5-1 also indicates the trends for the next decade. For synthetic kerosene options, the availability of lipid-biomass and lignocelluloses-biomass will remain restricted. The ranking of production capacities for FT-SPK and AtJ-SPK from non-biogenic feedstock might improve within the next decade, specifically by a potential certification of methanol for AtJ-SPK and in general due to interest from several sectors for their (intermediate) products. Enabling the use of neat synthetic kerosene will reduce logistical efforts to and at airports and – most importantly – lower life-cycle greenhouse gas emissions. To which extent the ramp-up of energy from renewable sources and increasing fuel production capacities can yield price reductions remains uncertain. This is due to the strong influence of extra-sectoral demand for "green" energy. Even though most pathways based on non-biogenic feedstock are currently not available at industrial scale, in the mid-term they might replace substantially greater amounts of fossil kerosene than feedstock constrained fuel options (e.g., fuels based on lipid-biomass).

Also for the alcohols considered the increasing importance of non-biogenic feedstock based conversion pathways is apparent. Increasing availability of "green" methanol and ethanol is more likely than for butanol, as "green" butanol production capacities are of lower importance compared to the others. In contrast to ethanol, conversion efficiency for methanol and butanol can potentially improve. A decrease in costs appears rather unlikely, as for methanol not only feedstock availability but also demand is likely to increase. For ethanol and butanol (mostly from biogenic feedstock) the feedstock availability is additionally limited.

Among the gaseous fuel options, the ranking of hydrogen can change drastically within the next decade. With increasing industry wide demand for hydrogen from renewable sources, the presently (very disadvantageous) criteria for logistics infrastructure can improve substantially. At airports, however, the effects of industry-wide interest are less pronounced and the need for infrastructure modification/development is substantially greater. Thus, a non drop-in fuel option will only become available, if broad industry consensus for its use is reached. Only if the weight toll to store liquid hydrogen is drastically reduced, its high gravimetric energy density would pay off. Increased availability of liquid hydrogen at airports and improved fuel storage in airports are prerequisites for a market introduction of an aircraft using liquid hydrogen directly. These prerequisites can be achieved within this decade, whereas a hydrogen fuelled aircraft would rather be available in the decade thereafter, if at all.

The wide-spread and large-scale use of renewable aviation fuels can potentially be expected in the mid-term (e.g., from 2030 onwards). Comparing the current and next decade status reveals that those options with an advantageous ranking for today's application (drop-in fuels in general, HEFA-SPK in particular) are not necessarily the most advantageous options in the long-term. For example, at the end of the next decade, FT-SPK and AtJ-SPK (for drop-in options) and hydrogen as non drop-in option could be seen far more advantageous as they are today.

6. Conclusion

Alternative fuels are considered as a key measure to reduce greenhouse gas emission in the air transport system and thus lower its contribution to anthropogenic climate change. But, current usage-shares are below 1 %. Among seven conversion pathways certified by ASTM only one (HEFA-SPK) is produced by several companies at an industrial scale. Against this background, this paper investigates blended synthetic kerosene as drop-in aviation fuel and neat synthetic kerosene fuels, three alcohols (methanol, ethanol and butanol) and three gases (methane, ammonia and hydrogen) as non drop-in aviation fuel options. These fuel options are selected because they are discussed as alternative aviation fuels (e.g., synthetic kerosene), are already produced from renewable resources (e.g., ethanol), or considered to play a central role in the defossilation of the global energy system (e.g., hydrogen). Therefore, a set of nine technological and system-related assessment criteria is used to cover the central elements of the entire fuel value chain. A multi-criteria assessment based on a five-step ordinal scale is performed, taking into account the criteria feedstock potential and extra-sectoral demand, aviation fuel conversion efficiency, conversion technology readiness level (TRL), production capacities, logistics and airports, fuel properties, aircraft modifications, fuel costs and environment. The studies' main results can be summed up as follows.

The availability of some biogenic feedstock is not sufficient to replace the present overall energy demand of aviation. Either the feedstock's limited physical availability (e.g., lipid wastes) or potential conflicts with the food and fodder sector are constraining factors. Additionally, lacking capacities for the provision of renewably sourced energy limit the availability of fuels of non-biogenic origin.

Synthetic kerosene options are mainly constrained by a clear lack of production capacities. Nevertheless, the integration of these fuels into the existing air transport system seems easily feasible from a technological point of view. In contrast, the use of alcohols would at least require modifications of aircraft and engines. Additionally, using such fuels results in a loss of range due to their lower energy density. In contrast, significant capacities to produce renewably sourced methanol and ethanol exist. The use of gaseous fuels (e.g., hydrogen) would require the development of new aircraft, with resulting delays for the fuel's market introduction, significant economic risks for aircraft manufacturers and operational constraints for airlines.

All of the discussed fuel options have the potential to mitigate most of the life cycle greenhouse gas emissions of aviation fuels. A prerequisite for a highly efficient greenhouse gas reduction is a favorable combination of feedstock and renewably sourced energy provision. Large uncertainties exist with regard to the non-CO_2 related climate effects of non drop-in fuel options.

Long-term price parity with fossil kerosene is highly unlikely for any of the fuel options studied. Cost of the renewable fuel options considered are mainly driven by feedstock and energy costs.

For the next decade the following conclusions can be drawn.

The further development of fuel provision for aviation cannot be seen independently from the development within the ongoing developments within the overall energy system. If hydrogen develops as currently expected to become the main molecular energy carrier by the mid of this century, most likely hydrogen-based solutions will become market mature also for the aviation sector.

Some fuel options appear more likely to reach significant market shares than others. On the one hand, these are synthetic kerosene options with (intermediate) products experiencing demand from other sectors (e.g., FT-SPK, AtJ-SPK). On the other, the broad interest in ramping up the production of hydrogen from renewable energy sources might induce a fast increase in its availability and decreasing costs. This might provide a mid- to long-term option for carbon-free aviation, assuming that a hydrogen fueled aircraft will be brought successfully to the market.

Within the next decade it is most unlikely that gaseous fuels or non drop-in fuels will gain a significant market importance due to numerous reasons. Thus, if greenhouse gas emission reductions are politically enforced also within the aviation sector, the use of biomass-based drop-in fuels (HEFA-SPK) need to be promoted. Non-biogenic FT-SPK might gain importance in the early/mid thirties if the respective technological and market development is strongly supported. If this materializes, their outlook as commercial aviation fuel can improve clearly, as non-biogenic FT-SPK fuels show large development potentials for several of the assessment criteria.

The most relevant uncertainties are the implications resulting from the potential introduction of a second fuel type next to kerosene in the air transport system for the years to come. Not only the aircraft itself would need to be modified/developed, but also a separate/additional infrastructure would need to be provided at airports and in case of hydrogen also on a global scale. Network interdependencies among airports would require broad consensus for one fuel-option, as economic operation of an aircraft between two (or few) airports seems unlikely. Taking also the high safety and resulting certification standards within commercial aviation into account, these implications are non-negligible and difficult to estimate a priori.

Most of the present climate change mitigation strategies in aviation focus on the reduction of greenhouse gas emissions. However, scientific understanding of the non-CO_2 related climate effects of aviation has improved significantly. A better understanding of these effects for non drop-in fuels would help to understand each of the fuel options' potential to mitigate the entire climate effects of aviation and not only CO_2 related climate effects.

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CRediT authorship contribution statement

Gunnar Quante: Conceptualization, Methodology, Data curation, Formal analysis, Writing – original draft. **Nils Bullerdiek:** Conceptualization, Data curation, Writing – review & editing. **Stefan Bube:** Conceptualization, Methodology, Writing – review & editing. **Ulf Neuling:** Conceptualization, Methodology, Writing – review & editing, Supervision. **Martin Kaltschmitt:** Conceptualization, Methodology, Writing – review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix

Synthetic Kerosene Blends (C_xH_y)

Here, a synthetic kerosene blend is considered as a specification-compliant blend of a fossil and a synthetic kerosene component. Both usually consist of a range of hydrocarbons with a typical chain length of 8 to 16 carbon atoms. The most prominent hydrocarbon types in aviation fuels are n- and isoalkanes, cycloalkanes and aromatics [8]. Seven conversion and two co-processing options are approved for the provision of synthetic kerosene by ASTM D7566 and ASTM D1655 [15,33–36].

- Synthesis gas (“Syngas”) is an intermediate suitable to produce several fuel options (e.g., FT-SPK) to be produced based on biogenic and/or non-biogenic renewable feedstock[d] [37,38]. For biogenic feedstock, two elementary pathways exist. The first covers the conversion of biomass by an anaerobic digestion (fermentation) into biogas (mainly CH_4 and CO_2) and the subsequent production of syngas via a reforming process. Second, lignocelluloses-rich biomass can be converted to syngas by a thermochemical gasification and a subsequent gas cleaning and conditioning. For non-biogenic feedstock, syngas can be produced using electricity from renewable energy, water and sustainable CO_2. Water is split into hydrogen and oxygen by electrolysis utilizing “green” electricity. Renewably sourced CO_2 provided from biogenic sources (e.g., biogas or bioethanol production) or from atmospheric CO_2 is converted with hydrogen into a syngas by using a reverse-water–gas-shift reaction. If syngas is produced exclusively based on “green” electricity, these fuels are often referred to as “power-to-liquid” (PtL) fuel [35,37,38]. To produce synthetic kerosene, this syngas is fed into a Fischer-Tropsch reactor converting the syngas into a so-called “FT-Crude”. This in turn, can be fractionated into synthetic kerosene and other products based on “classical” refinery processes. FT-SPK/A denotes the addition of aromatics, which are considered to be relevant for the sealing of fuel system components (section 0) [7].
- The “Hydroprocessed Esters and Fatty Acids” (HEFA) pathway or catalytic hydrothermolysis (CH) are suitable conversion processes for lipid feedstock. The first consists of a combination of a hydrogenation, cracking and subsequent isomerization. Hydrogen is used to saturate the ester and/or double bonds of the lipids. The oxygen naturally present in the oil/fat molecule is separated as water. The product is then fractionated. The catalytic hydrothermolysis, in turn, converts the feedstock into alkenes in a water atmosphere under supercritical conditions (high pressure and temperature). The alkenes are subsequently hydrogenated into alkanes and then separated into individual fuel fractions. Compared with HEFA, the process has a lower hydrogen demand but a greater degree of technological complexity [37]. HC-HEFA-SPK refers to a similar conversion pathway, however at present it is only certified for lipids derived from the Botryococcus braunii algae species [7].
- Fermentation is an option to convert sugar into aviation fuel. This is either performed via the Hydroprocessed-Fermented-Sugars to Synthetic Isoparaffins (HFS-SIP) process, where genetically modified yeast microorganisms produce a long-chain hydrocarbon (farnesene) to be further upgraded by separation and hydrogenation to farnesane [35,37,119]. Alternatively, for the Alcohol-to-Jet (AtJ) process, sugar or starch is fermented to alcohol, subsequently dehydrated (removal of oxygen from the alcohol molecules in the form of water), oligomerized (formation of long-chain olefins) and hydrogenated. Again, “classic” refinery processes separate the individual hydrocarbon product fractions into, among other products, kerosene [37]. Lignocellulosic biomass can potentially be used for the AtJ-SPK or HFS-SIP via saccharification. However, this technology pathway is still in an early phase [15].
- Co-Processing describes the joint refining of e.g. vegetable oils, animal fats or FT-Crude with fossil crude oil [37]. As these pathways contain a large share of feedstock of fossil origin, they are not considered here.

Currently, the global market share of synthetic kerosene blends is far below 1 %, with the majority being produced via the HEFA process [13]. As they are specifically produced for use as aviation fuels, their major future utilisation would be to gradually replace fossil kerosene.

Neat Synthetic Kerosene

Due to a (slightly) different chemical composition of neat synthetic kerosene (depending on the specific conversion pathway), compliance with ASTM D1655 requires additional adaptations. Several production pathways do not yield aromatics (e.g., HEFA- or FT-SPK) or show a different distillation curve gradient (e.g., HFS-SIP) [24]. Theoretically, the same production pathways as described for synthetic kerosene blends can be used for neat synthetic kerosene production. To which extent all conversion pathways allow an unblended use has not yet been determined.

As neat synthetic kerosene is not yet certified for aviation use; i.e. it is not allowed to be used for commercial flights. Nevertheless, selected airplane and engine manufacturer are currently pursuing test flights using neat synthetic kerosene [120–123]. Like synthetic kerosene blends, their major use will be as an aviation fuel. Since they allow for a greater reduction of aviation’s greenhouse gas emissions and potentially also lower aviation’s non-CO_2 related climate forcing [22,23], from an environmental perspective it would be desirable for them to replace synthetic kerosene blends.

Methanol (CH_3OH).

Methanol is a colourless, toxic, water-soluble liquid. Together with oxygen (e.g., from air) it forms highly flammable mixtures [44]. Methanol is also produced from syngas (see above) [40]. The origin of methanol (i.e., fossil or renewable) is thus primarily determined by the used syngas (section 4.1). Presently, global methanol production ranges from 90 to 100 Mt/a (ca. 2 EJ/a). But only$<$1 % of the produced methanol is from renewable sources [46].

Methanol serves as an important bulk chemical for the chemical industry. In some countries (e.g., China), it is also used as a fuel (component) in parts of road transport or as a feedstock for the conversion of other fuel types. Methanol of renewable origin can substitute methanol of fossil origin in its various applications and thus support defossiliation. Methanol could play an increasingly important role for mobility applications (e.g., maritime fuel, use in heavy-duty road-transportation). For aviation, methanol could theoretically either be used directly as a fuel or converted to a synthetic kerosene via the Methanol-to-Jet pathway. So far, this pathway is not introduced in the evaluation process for a potential certification by ASTM [7].

Ethanol (C_2H_5OH).

Ethanol is a colourless, volatile, water-soluble liquid. Like methanol, together with oxygen (e.g., from air) it forms highly flammable mixtures [44]. Presently, the major production pathway for ethanol is an anaerobic fermentation of sugar and starch. Ethanol is basically the only alcohol that is currently produced from renewable feedstock at industrial scale [41,42]; the global production volume is about 100 Mt/a (ca. 3 EJ/a) [28].

During alcoholic fermentation, sugar is converted by biocatalysts (here: yeasts) into ethanol and carbon dioxide (CO_2). Depending on the used biogenic resource, various pretreatment steps are required to provide a sugar solution. After fermentation has been finished, ethanol is separated and purified. While the use of biomass containing sugar and starch is well-developed, saccharification of lignocellulosic biomass is not yet fully implemented at commercial scale [70,124–126].

A provision of ethanol via syngas processing is also technically feasible. But, due to still unsolved technical challenges, this pathway has no importance on the global market yet.

Ethanol has a wide range of applications (e.g., fuel or fuel additive, potable alcohol, bulk chemical for chemical and pharmaceutical applications). Additionally, ethanol of renewable origin serves as a platform chemical within the chemical industry. Also, it can be used as an educt for the Alcohol-to-Jet conversion pathway to produce synthetic kerosene (AtJ-SPK) [15].

Butanol (C_4H_9OH).

Butanol is a colourless, water-soluble, flammable liquid. It is less

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[d] A production of syngas based on fossil feedstock (e. g. via coal gasification or methane reforming) is also possible. Due to the fossil origin of the feedstock, this pathway is not included in the present study.

volatile than ethanol or methanol [44]. “Green” butanol is produced via the ABE-fermentation realised by bacteria (here: clostridia phylum) or other pathways such as fermentation by genetically engineered biocatalysts or from ethanol via the acetaldehyde pathway. Compared to ethanol production, the conversion efficiency is lower and different products are provided; i.e. there is a need to separate the product spectrum afterwards [41,43]. Since the synthesis of butanol from fossil fuel based reactants is more cost-effective than ABE-fermentation, most ABE-fermentation plants have been shut down in the past [43]. Annually around 3.7 Mt/a (ca. 0.1 EJ/a) butanol are produced being clearly less compared to methanol or ethanol production [70,71].

Butanol can be and is used as a bulk chemical within the chemical industry [44]. Additionally, it can be used as a fuel (additive) for road transportation and potentially also for aviation either in direct use or as synthetic kerosene via the AtJ conversion. The use of isobutanol as feedstock for the AtJ-SPK conversion pathway is already certified [7].

Ammonia (NH_3).

Ammonia is a colourless, water-soluble gas with a pungent smell. The current ammonia production is based on the Haber-Bosch process, which synthesises hydrogen and nitrogen to ammonia. Before that, nitrogen is extracted from ambient air by air separation processes. Currently, hydrogen for such an ammonia production is provided from natural gas via steam methane reforming. This provision pathway could be replaced by hydrogen provided by water electrolysis using “green” electricity [47]. The present global ammonia production amounts to approximately 180 Mt/a (ca. 3.3 EJ/a) [127].

Currently, fertilizer for agriculture is the main market for ammonia. Other consumers are the chemical and the pharmaceutical industry. Beyond replacing the fossil-based ammonia of these industries, ammonia of renewable origin is discussed as an option for energy storage and as a maritime fuel [32,127–129].

Methane (CH_4).

Methane is a colour- and odourless gas. It is the main component of natural gas [30]. To produce “green” methane, biomass-based as well as electricity-based supply pathways are possible [30,41,48]. During the biomass-based provision, biomass is degraded by anaerobic digestion via various intermediate steps to methane and carbon dioxide. In subsequent gas purification processes, pure biomethane is provided [40]. For the electricity-based pathway a methane synthesis is used. Therefore, syngas (section 4.1) is converted to methane (CH_4) and water (H_2O). The global methane production amounts to approximately 2,670 Mt/a, of which<0.1 % (<0.2 EJ/a) are produced from renewable sources [30,48].

Methane resp. natural gas is used today mainly for heat and power generation. Compressed methane serves as a fuel for road transport and liquefied methane as a marine fuel or fuel for heavy duty transportation. Furthermore, it is a feedstock for the provision of hydrogen and methanol – so far mainly from natural gas. In addition to replacing existing use of methane from natural gas, methane of renewable could also successively replace other fuels in the transport sector.

Hydrogen (H_2).

Hydrogen is a is a non-toxic, colour- and odourless gas [31]. Most of the global hydrogen production originates from fossil sources based on natural gas and coal. Hydrogen of renewable origin can be produced by water electrolysis. Technically, also biochemical, solar-thermal, and other production pathways are possible being still in an early development stage [31]. If the electricity for the water electrolysis is provided exclusively from sustainable, renewable sources (e.g., from photovoltaic and/or wind power plants), “green” hydrogen can be provided [19,20,49]. Annually, about 70 Mt/a of hydrogen are produced worldwide, but only a minor share via electrolysis of water (approximately 0.1 %, ca. 0.01 EJ/a) [74]; the latter does not necessarily exclude the (partial) use of electricity produced from fossil fuel energy.

Hydrogen is a key intermediate product in the chemical industry, presently mainly produced from natural gas via steam methane reforming. It is a base chemical to produce ammonia and methanol, among others. Hydrogen is also used in refinery processes for processing of feedstock and further intermediate products (e.g., desulfurization or hydrocracking). In aerospace applications, hydrogen is used as a rocket fuel [31]. Hydrogen provided by renewable energy is regarded as a central element of a CO_2-neutral energy system [31,74].

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