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A stakeholders' participatory approach to multi-criteria assessment of sustainable aviation fuels production pathways☆

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ABSTRACT

Sustainable aviation fuels (SAF) provide a viable option to decarbonise global aviation. Unlike conventional jet-fuel, SAFs can be produced in several production pathways making their selection a complex multi-criteria decision making (MCDM) problem with conflicting objectives. In this paper, we propose a multicriteria based framework for evaluating SAF production pathways, which is a sequential decision-making process with feedback adjustment mechanisms. Given the early stage of SAF technologies' development and the scarcity of data on such technologies, in this research, we involved a variety of aviation industry stakeholders to assist with data and preference gathering. Our MCDM framework is designed to be generic to provide flexibilities to potential users in choosing the appropriate implementation decisions for the relevant stakeholders. The strength of the proposed framework lays in its flexibility to accommodate various stakeholders' subjective judgements, choice of ranking method, and robustness of results. We used our MCDM framework within a stakeholders' participatory approach to rank order 11 SAF production pathways against 24 criteria grouped under social, environmental, economic, and technical impact categories. Our analysis revealed that the environmental and the economic impact categories are the most important ones followed by the technical and the social criteria; the gasification/Fischer-Tropsch (F-T) based production processes are preferred over fermentation and oil-based ones; and waste gases are the preferred feedstock along with wood-residue. These findings provide decision-makers with guidelines on the selection of SAF production pathways.

1. Introduction

Commercial aviation has brought global connectivity and prosperity. Governments are expected to gain U.S. $129 billion in tax revenues and 70 million global supply chain jobs in 2019 (IATA, 2019a). Despite economic and social benefits, there are several shortfalls to commercial aviation, particularly the adverse effects on the environment in the form of greenhouse gas emissions (GHG). Although GHG are not limited to carbon dioxide (CO_2), it is the relative contribution of CO_2 (~53%) to the GHG effect that makes it important. Though this emission level merely corresponds to 2%–2.6% share of annual global CO_2 emissions (ICAO, 2016), it is significantly worse than other emission sources as they are emitted at a higher altitude making for a far greater adverse environmental impact (Kivits et al., 2010). The International Air Transport Association (IATA), a global airline trade association, estimates global air passenger numbers to double by 2035 compared to 2016 (O'Connell et al., 2019) with an overall aviation industry growth to be around 4.5–4.8% annually (Deane and Pye, 2018). As a result, the aviation industry's contribution to global fossil fuel CO_2 emissions are expected to reach 4.6–20.2% by 2050 (Staples et al., 2018).

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Technological innovations and operational improvements can be instrumental in decarbonising the sector (IRENA, 2017). Particularly, innovation in aircraft structural design and improved propulsion systems has the potential to improve technological efficiency (Müller et al., 2018). Electrification is considered to be a viable option with research currently assessing the potential of long-distance flights (Schäfer et al., 2019). However, electric aircraft may not be commercially available until well after 2050 (IRENA, 2017). Other options for decarbonising aviation include planning optimised flight paths (Niklaβ et al., 2016), and the use of SAF (Klein et al., 2018; Michailos, 2018; O'Connell et al., 2019). Liquid fuels will continue to play a significant role in aviation due to a lack of technological readiness in alternatives. Hence, the use of SAF is considered as a medium-term solution for combating emissions as well as reducing fossil fuel dependency (The Royal Society, 2019).

Despite its potential for decarbonizing the aviation sector, SAF production pathways face significant sustainability challenges (Wang et al., 2019). These challenges arise from technical uncertainty (IATA, 2019b), social perception (Filimonau and Högström, 2017; Filimonau et al., 2018), the environmental impact of production and distribution (Michailos, 2018) and economic considerations (Bann et al., 2017). Therefore, the decision-making landscape becomes more complex amid a high level of uncertainty in the sector. Most studies tend to measure the effectiveness of SAF pathways via techno-economic analysis (TEA) (see for example, Klein et al., 2018; Li et al., 2018; Neuling and Kaltschmitt, 2018). Although traditional cost-benefit analysis and net present value may be useful, the complexity of the problem warrants multi-criteria decision making (MCDM) problem to be considered to support decision-making in the presence of multiple and often conflicting criteria. Our survey of the literature on MCDM applications in sustainable aviation fuel production points to the scarcity of MCDM studies on SAF production technologies[1] and is further supported by a latest review done by Dožić (2019).

Our paper aims at filling this gap by proposing a stakeholders' participatory approach based on the MCDM framework which integrates aviation industry experts' perspectives on low carbon jet fuel production pathways. The innovative contributions of this paper are summarised as follows. First, we propose a comprehensive framework for assessing SAF production pathways. To operationalise our framework, we identified a set of performance criteria and their measures through both a literature survey and expert opinions. These criteria are synthesised into social, environmental, economic and technical impact categories. Furthermore, through a workshop, we collected, from experts, information on the relative importance of the criteria under consideration as well as ratings of each alternative or SAF production pathway on each criterion. This information is used to model the preference system of experts and to rank SAF production pathways. Finally, we compared our multicriteria ranking results using multiple MCDM methods.

The rest of this paper is organized as follows. Section 2 reviews the various production pathways available to date. Section 3 discusses prior studies on SAF related research. Section 4 presents our MCDM framework for ranking SAF production pathways and its implementation decisions. Section 5 presents and discusses numerical results. The sensitivity analysis is presented in section 6 while section 7 summarises and concludes this paper.

2. Sustainable aviation fuel production pathways

SAFs are produced in many ways and each production pathway has its own technical (e.g., fuel composition), economic (e.g., cost), social (e.g., public acceptance) and environmental (e.g., GHG) characteristics. The academic literature generally classifies SAFs production methods into two broad categories: biochemical processes and thermochemical processes. We summarised SAF production pathways in Fig. 1. A brief description of these pathways is provided in the following sub-sections. For a detailed description of these processes, we refer readers to Shahabuddin et al. (2020).

2.1. Hydroprocessed esters and fatty acids (HEFA)

HEFA is a biochemical process that results in the production of long-chain hydrocarbons. In this process, any type of oil, such as, animal fat, waste grease, vegetable oil, or algal (Dayton and Foust, 2020), are hydrogenated and isomerized to produce long-chain hydrocarbons; an additional selective cracking process yields aviation fuel (Neuling and Kaltschmitt, 2018). Hydroprocessed SAF have high energy content, are thermally stable, and have low tailpipe emissions (Gawron et al., 2020). Due to these features, HEFA fuels have been certified by ASTM for a 50% of blend limit with conventional jet fuel (IATA, 2014). Since 2008, several major airlines including, KLM, Lufthansa, Etihad have successfully conducted flight tests using blends of conventional and HEFA jet fuels (Wang and Tao, 2016).

2.2. Advanced fermentation

Two processes, i) Alcohol to Jet (ATJ) and ii) Direct sugars to hydrocarbons (DSHC) are grouped under the advanced fermentation pathway. The premise of this grouping is that both ATJ and DSHC have fermentation as their underlying process (Kandaramath Hari et al., 2015).

The ATJ process converts alcohols (e.g., ethanol, methanol or n-butanol) to form long-chain hydrocarbons that possess similar characteristics to conventional Jet-A1 fuel. The main feedstock, alcohol can be obtained from the fermentation of sugars, catalytic conversion of biomass or direct conversion of sugars to hydrocarbons (Dayton and Foust, 2020; Kandaramath Hari et al., 2015). Irrespective of the source of alcohol, the ATJ process is comprised of four steps. The process starts with dehydration, followed by oligomerization while the last two steps are hydrogenation and distillation to get the desired product (Geleynse et al., 2020; Neuling and Kaltschmitt, 2018; Wang and Tao, 2016). One of the main advantages of this pathway is the technical maturity of the process involved. The ATJ process features higher infrastructure costs than the F-T process (Atsonios et al., 2015; Geleynse et al., 2020). The choice of catalyst used is critical for both the F-T and ATJ process. The DSHC process on the other hand, does not need alcohol production. Concentrated sugars are converted to hydrocarbons through anaerobic fermentation (Huili Zhang et al., 2020). Phase separation is then performed to synthesize jet fuel (Wang and Tao, 2016).

2.3. Gasification/Fischer-Tropsch (F-T) synthesis

In this thermochemical process, carbon-rich biomass is gasified to produce syngas consisting primarily of carbon monoxide (CO) and hydrogen (H2). The syngas is then converted to liquid fuel via catalytic conversion (Shahabuddin et al., 2020). A wide range of biomass including wood waste from forestry and wood industry, short rotation crops like poplar and willow, and agricultural residues like wheat straw and corn stover can be used to produce a carbon-neutral aviation fuel (Dayton and Foust, 2020). However, due to high pressure and temperature, the additional requirement of an F-T catalyst becomes an expensive option to produce SAF (Kandaramath Hari et al., 2015).

2.4. Pyrolysis

After drying, grinding and chopping, the biomass is heated at high temperatures (400–600 °C) in absence of oxygen (O_2) either rapidly or slowly (Shah et al., 2019). This process then yields three products:

[1] MCDM techniques have been widely used for evaluating the sustainability of transportation projects (Awasthi et al., 2010; Curiel-Esparza et al., 2016); and several authors have considered assessing liquid fuels (Baudry et al., 2018a, 2018b; Turcksin et al., 2011; Ubando et al., 2016).

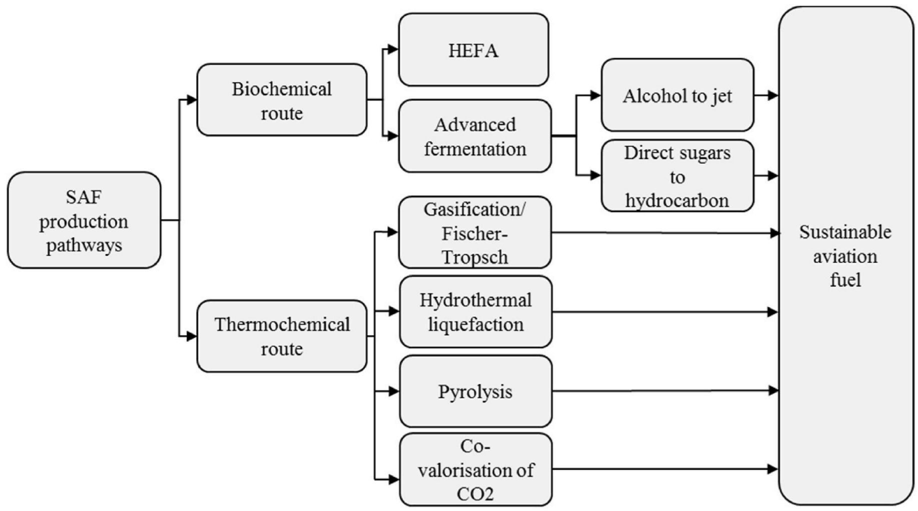

Fig. 1. Classification of process focussed SAF production pathways.

pyrolysis gas, bio-char, and pyrolysis oil (also called bio-oil). The bio-oil is a mixture of organic compounds with carbon ranging from C1 to C21+. Also bio-oil has a high oxygen content which is an unwanted compound in the final fuel. Oxygen molecules are removed by hydrotreating i.e., chemical reactions in the presence of high-pressure hydrogen to remove oxygen. After this cleansing, hydrotreating is then performed in order to produce various hydrocarbons including jet fuel (Chen et al., 2020).

2.5. Hydrothermal liquefaction (HTL)

HTL is a thermochemical process that converts biomass under high temperatures (~250–~375 °C) and pressurised water (4–22Mpa) to liquid fuels (Gollakota et al., 2018). Typical feedstocks used the HTL pathway include algae, manures, sewage sludge and lignocellulosic (e.g., corn stover) biomass (Castello et al., 2019; Tzanetis et al., 2017). A sufficient time is required for the molecule breaking process to occur. The resultant oil is called bio-crude and has a high O_2 content which is removed by a hydrotreating process. The upgraded hydrocarbons are then separated via a distillation process to yield jet fuel, diesel and other co-products.

2.6. Co-valorisation of CO_2 and waste biomass

This pathway makes use of two feedstocks or input to the F-T process: CO rich syngas produced from waste biomass gasification and H_2 rich syngas produced from co-electrolysis of CO_2 along with water as dual feedstocks (Zhang et al., 2020).

3. Literature review

Our literature survey is organised around studies concerned with the social, environmental, economic and technical perspectives. The need for such an approach is to reflect the opinions of different and sometimes conflicting groups of stakeholders (Kim et al., 2019), which together form a strategic part of the energy production matrix, leading to the sustainability of low carbon jet fuels (Neves et al., 2020). Each of the four perspectives within the context of aviation fuels is discussed in this section.

From a social perspective, there are studies that focus on public perceptions and acceptance of sustainable liquid fuels in road transportation (Amin et al., 2017). These studies show that the public are generally aware of environmental and economic benefits of sustainable fuels use; however, the social-environmental impact of fuel production is still not being fully considered. It was also found that the *'food vs fuel'* debate persists in the public shaping their perceptions of sustainable fuels. There are other studies that look into farmers willingness to grow crops towards the promotion of sustainable fuels and agriculture advisers' attitude towards sustainable fuel promotion (Pischke et al., 2018; Yaghoubi et al., 2019). The focal point of these studies was to explore the farmers' willingness to commit land, labour, and resources for the growing energy crops. These studies indicate that the farmers' willingness to grow fuel-crops consists of a complex interaction of economic, social and biophysical dynamics. The Farmers' willingness to grow vary by region, type of crop and its profitability, level of farmers' education, and financial and technical resource available. Other research found media framing and labelling of biofuels as a tool for public acceptance (e.g., Radics et al., 2016).

Less attention has been paid on the aviation sector. Filimonau et al. (2018), for example, explored tourists' opinions about aviation biofuel use in Poland. They measured perceptions of benefits and safety concerns and suggested a need to develop an awareness campaign to highlight sustainable fuel use in aviation. Another exploratory study on environmental concerns of aviation and SAF use was done in the UK by Filimonau and Högström (2017). This study demonstrated a limited public understanding of the environmental benefits of using SAF. Challenges and opportunities for SAF adoption were highlighted by Chiaramonti (2019) while the role of airports in supporting clean aviation was explored by Kivits et al. (2010). More recently, Wang et al. (2019) used a macroeconomic approach of Input-Output analysis to investigate the contribution of aviation fuel production to the Brazilian economy. The analysis revealed net positive socio-economic effects on employment and GDP. In summary, the public plays an important role in developing the sustainable fuel supply chain (Malik et al., 2019), to achieve carbon neutral growth in the aviation sector.

Several studies focused on the environmental effects of SAF production (Kolosz et al., 2020). GHG emission savings and energy efficiency were considered as the two crucial criteria in the most recent Life Cycle Analysis (LCA) study by O'Connell et al. (2019). Their analysis revealed that certain SAF conversion pathways are more energy intensive then others except the ones using waste and residues as a feedstock. A study by Staples et al. (2018) looked into emission savings by SAF production from non-food[2] feedstocks through various conversion

[2] Non-food feedstock include by-products (cereal straw, sugar cane bagasse, wood residues), organic components of municipal solid wastes (MSW), and dedicated feedstocks like purpose-grown grasses and short rotation forests (Sims et al., 2010).

pathways over their entire life cycle. The analysis showed that around 12 billion USD per annum investments are to be required to achieve 50% or less GHG emission by 2050. Besides considering multiple feedstocks and conversion processes there are other studies that investigated a single feedstock and process assessment. An LCA study was performed on a wood-based feedstock by Ganguly et al. (2018) for SAF production. It was found that such a SAF produced can achieve a 78% improvement in global warming impact compared with conventional jet fuel. Similarly, HTL of microalgae feedstock assessment was performed by Fortier et al. (2014) for two different production plant locations. Their analysis suggested that the LCA of SAF produced at a wastewater treatment plant was less GHG intensive than fuels produced at a conventional refinery. Likewise, Seber et al. (2014) implemented LCA to find GHG emission savings and production costs associated with HEFA jet from yellow grease and tallow. It was found that the LCA of SAF from yellow grease produced lower GHG emissions than that from tallow when compared to petroleum-based jet fuel. In addition, yellow grease derived SAF yields a lower Minimum Selling Price (MSP) than SAF from tallow as a feedstock. There seems to be a consensus in LCA studies that SAFs have the potential to reduce GHG emissions in aviation. However, as each study makes its own assumptions regarding the system boundary, the outcome of such studies is not comparable due to the heterogeneity of the environment. Finally, from a policy perspective, a continuous-time simulation approach was used by Sgouridis et al. (2011) to evaluate the impact of long-term policies and strategies on mitigating CO_2 emissions from global air transportation. The study suggested that a combination of using low carbon fuel and a carbon pricing mechanism has the potential to achieve the goal of reducing emissions.

From an economic perspective, Bann et al. (2017) followed a financial approach for finding the best suitable process of producing SAF. They used stochastic modelling for finding the MSP of SAF based on a net present value approach for six different pathways. A comprehensive pioneer plant TEA was performed for six SAF production pathways by de Jong et al. (2015). Based on the assumptions used, none of the pathways assessed was able to reach price parity with fossil-derived jet fuel until 2020 and suggested that co-production of SAF with existing production infrastructures will be the likely strategy to bridge the price gap and bring SAF production to commercial scale. Unlike other TEA, Diederichs et al. (2016) focussed on food-crop[3] and non-food feedstocks for comparing aviation fuel MSP. They consider HEFA, gasification/F-T synthesis, as well as a hybrid gasification and syngas fermentation processes. The MSP from each production pathway resulted in a fuel 2–4 times higher than convention fossil-derived jet fuels. They also discovered that SAF from vegetable oil feedstock is closer in price parity to conventional jet fuel as compared to non-food feedstocks. In term of the production process, gasification/F-T is more financially viable than the hybrid process. Trivedi et al. (2015) performed an Energy Return on Investment (EROI) for F-T, HEFA and advanced fermentation processes using different feedstocks. The F-T process with switchgrass resulted in the best option with an EROI of 9.8%. Neuling and Kaltschmitt (2018) performed another TEA with environmental considerations of SAF production pathways. They used a mass and energy balance approach to analyse such processes. Their results suggested that satisfying technical, economic and environmental criteria simultaneously is not feasible for any single pathway. Further, TEA for SAF from camelina oil via hydro-processing was done by Li et al. (2018). Under the production conditions considered, their analysis found MSP of SAF to range from 0.40 to 01.7 $/L with most sensitivity to feedstock cost than any other criterion. Likewise, the detailed process design and economic valuation of SAF from sugar cane residue (bagasse) were performed by Michailos (2018). It was found that 0.121 kg of SAF can be produced from a kg of dry bagasse yielding a price of 2.78 $/L. Finally, Klein et al. (2018) incorporated an environmental perspective and TEA for setting up a SAF production facility with an existing sugarcane processing industry in Brazil. Their analysis revealed that the HEFA production pathway could yield the highest production capacity whereas gasification/F-T gives the best economic performance, while ATJ is the least desirable pathway due to its low jet fuel yield.

From a technical perspective, fuel viscosity and cloud point temperature of SAFs were compared for compatibility to conventional jet fuel by Chuck and Donnelly (2014). SAFs from oil-based feedstocks were found to be closer to conventional jet fuel compared with other sources of SAFs production. Focusing on the technical characteristics of oil-based feedstocks (macauba palm tree), the operational characteristics of reaction pressure, atmosphere, presence of stirring and catalysts use were studied by Silva et al. (2016). It was found that oil from the macuba palm tree has the potential to be used as a feedstock for SAF. The analysis also indicated a blend of 5% SAF with conventional jet fuel is possible. Similarly, Lokesh et al. (2015) developed a model that looked into SAF hydrocarbon chemistry, thermodynamic behaviour and fuel combustion on engine/aircraft performance. Three SAFs from camelina, jatropha, and microalgae were considered and compared to conventional jet fuel. It was established that SAF performs better than conventional jet fuel on fuel-savings and emissions.

It is worth mentioning that a study undertaken by Hileman and Stratton (2014) provide a comparative analysis based on multiple criteria for assessing the feasibility of various fuel options for the aviation sector has been. They found that fuels derived from F-T and HEFA processes are viable for augmenting current jet fuel supply, whereas hydrogen was found to be infeasible due to the current aircrafts' engine design. Alcohol, biodiesel and bio-kerosene were found to be more suitable for road transportation. Despite the problem rationale of the above-mentioned studies representing a multi-criteria problem, none of these actually use the multi-criteria decision analysis methodological framework which is slowly becoming integrated into the LCA/TEA toolkit as a final endpoint method. Some of these studies are reporting that the criteria under consideration are conflicting which requires consideration of MCDM methodologies. This paper aims at filling this gap by proposing a stakeholders' participatory MCDM based framework which integrates aviation industry experts' perspectives on low carbon jet fuel production pathways.

4. Proposed MCDM framework

In this section, we propose an MCDM based framework to assess the relative performance of SAF production pathways under multiple criteria, and devise a multi-criteria ranking to assist a variety of aviation industry stakeholders to make informed decisions. A graphical summary of the proposed framework is depicted in Fig. 2.

Notice that, by design, our system is flexible and adaptive. To be more specific, the system is flexible in that it has a generic nature which makes it a plug and play framework. On the other hand, it is adaptive as it includes feedback mechanisms that allow one to adjust implementation decisions to specific applications and their contexts. Notice that the proposed framework allows for any group of stakeholders to customise it to their own needs or take on board their inputs with respect to both the choice of ranking method and robustness of its results. In the following sub-sections, we shall discuss the implementation decisions of the framework and describe the methods used at each of its different stages.

4.1. Choice of performance criteria and their measures

The first stage of our framework is concerned with the identification of performance criteria and their measures for evaluating SAF production pathways. Within this MCDM framework, SAF production pathways shall be referred to as alternatives. Our review of the literature revealed that there are currently 15 SAF production pathways which are summarised in appendix A1, where a production pathway is a combination

[3] Food-crop feedstock include cereals, sugar crops and oil seeds (Sims et al., 2010).

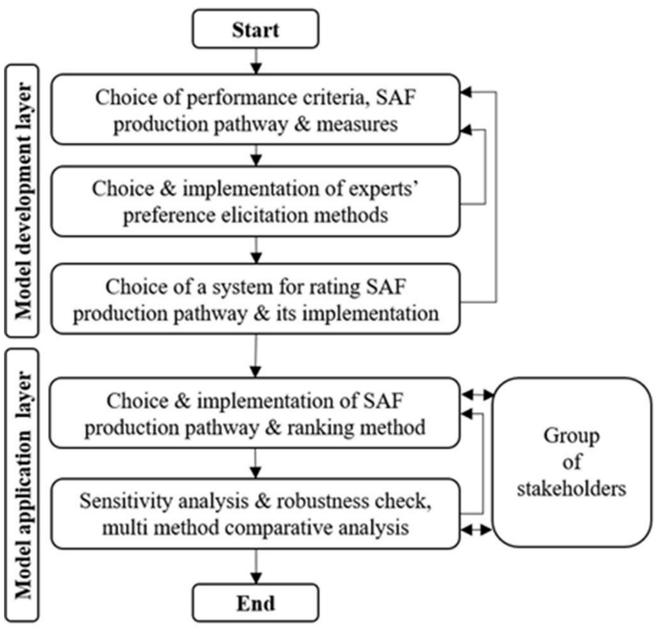

Fig. 2. SAF production pathways multi-criteria assessment framework.

of the production process and its feedstock. Our review of the academic literature on social, environmental, economic and technical aspects of sustainable liquid transportation fuels identified an initial set of 45 performance criteria (see appendix A2). Buchholz et al. (2009) and Markevičius et al. (2010) in their research found that not all criteria are critical for evaluation purposes. Therefore, we narrowed down the initial set of 45 criteria and 15 SAF production pathways to 24 and 11, respectively. To be more specific, we use the methodology proposed by Kassem et al. (2016) implemented by means of an online survey of experts in bio/aviation fuels; namely, a value tree methodology embedded within the Delphi method, which is a structured multi-round technique with feedback mechanisms to achieve higher levels of consensus amongst the participating panellists (i.e., experts and stakeholders) and a stability measure-based stopping criterion. The value trees are refined from one iteration or round to the next using a hybrid penalty-reward approach based on chosen thresholds of aggregate measures; that is, a degree of importance index (DII) and a degree of consensus index (DCI) for each criterion. Recall that DII is fundamentally a weighted sum of respondents' evaluations that takes account of the importance of each criterion using a Likert-scale, whereas DCI cluster respondents' evaluation into three categories representing the agreement level amongst the respondents about the importance rating – see Table 1. For more details, the reader is referred to Kassem et al. (2016).

There is no set threshold level for DII and DCI, however, based on the literature (Kassem et al., 2016), we applied a 50% threshold to narrow down criteria and SAF production pathways. This resulted in a total of 39 criteria and 15 pathways. Furthermore, we discussed each criterion and production pathways during our workshop with experts from bio/aviation fuel producers, airlines, academia, governmental regulators, and aviation sector international bodies. As a result, the final evaluation model consisted of 24 criteria and 11 SAF production pathways. Tables 2 and 3 summarise the performance criteria and SAF

Table 1
Degree of consensus categories.

Category	Description
A	A total number of 'very important' and important' responses
B	A total number of 'Moderate' responses
C	A total number of 'not important' and 'negligible' responses

Table 2
Final assessment criteria descriptions, code and references.

Category	Criterion	Code	Description	Reference
Social	Traceability	Soc1	This criterion is concerned with the transparency of the production pathway from feedstock to the final product.	Lanzini et al. (2016)
	Contribution to economy	Soc2	This refers to the creation of new commerce, industrial districts, rural development and so on.	Li et al. (2015); Wang et al. (2019)
	Food security	Soc3	Impact of feedstock used for SAF production on food security.	Sikarwar et al. (2017)
	Social acceptability	Soc4	The general public's perception of SAF production and use.	Gegg and Wells (2017)
Environmental	Feedstock sustainability	Env1	It represents the continuity of feedstock supply for SAF production.	Chiaramonti (2019)
	GHG emission savings	Env2	Net CO_2 emissions savings compared to jet-A fuel.	Zemanek et al. (2020)
	Land-use change impact	Env3	Both direct and indirect land-use change due to SAF production.	Lanzini et al. (2016)
	Soil and water pollution	Env4	Impact of the use of fertilizer and pesticides for biomass production.	Efroymson et al. (2017)
Economic	Feedstock alternative use	Eco1	Possible uses of feedstock other than for SAF production (e.g., electricity and bio-methane).	Hileman and Stratton (2014), Klein et al. (2018)
	Feedstock profitability	Eco2	Financial benefits in producing a specific feedstock.	Klein et al. (2018)
	Minimum selling price (MSP)	Eco3	The expected minimum selling price of the SAF.	Diederichs et al. (2016), Ribeiro et al. (2017)
	Input energy use	Eco4	Amount of energy consumed during SAF production.	Diederichs et al. (2016)
	Land productivity	Eco5	Inclusion of short rotation crops or intensive farming techniques.	Baudry et al. (2018b), Hileman and Stratton (2014)
	Operations & maintenance cost	Eco6	This relates to the operational and maintenance cost of the SAF production facility.	Li et al. (2018)
	Feedstock cost	Eco7	Expenses incurred in procuring the primary material used for fuel production.	Diederichs et al. (2016)
	Plant capital cost	Eco8	This cost refers to the establishment of production	de Jong et al. (2015)

(*continued on next page*)

Table 2 (*continued*)

Category	Criterion	Code	Description	Reference
			plant and related facilities.	
Technical	Blending limit	Tec1	Percentage of alternative fuel certified for mixing with conventional jet-A fuel.	Moore et al. (2017)
	Conventional jet fuel compatibility	Tec2	Closeness to conventional jet fuel in fuel characteristics including flashpoint, viscosity, density, energetic content, etc.	Cheng and Brewer (2017)
	Domestic technological ability	Tec3	Availability of domestically available production technology.	Expert panel
	Process integration	Tec4	Integration ability of a production pathway with existing jet-fuel refinery infrastructure.	Neuling and Kaltschmitt (2018)
	Process technical maturity	Tec5	Current development status of a production pathway: pilot, demonstration or commercial.	Ahmad et al. (2017); Fiorese et al. (2012)
	Process yield	Tec6	Amount of SAF obtained from a conversion pathway.	Bann et al. (2017)
	Production volume scalability	Tec7	Capacity for later expansion of the SAF processing facility.	Schillo et al. (2017)
	Quality and composition of feedstock	Tec8	SAF batch quality.	Atsonios et al. (2015)

Table 3
SAF production pathways assessed in this study.

Production process	Feedstock	Reference	Code for Pathways
HEFA	Algae/Microalgae	Tao et al. (2017)	A1
	Used Cooking Oil/ Animal fat	Chen et al. (2020)	A2
	Oilseeds	Zemanek et al. (2020)	A3
Gasification/F-T Synthesis	Municipal Solid Wastes (MSW)	Suresh et al. (2018)	A4
	Wood residue/ Agriculture waste	Han et al. (2013), Klein et al. (2018)	A5
Pyrolysis	Algae/Microalgae	Guo et al. (2017)	A6
	Wood residue/ Agriculture waste	Shah et al. (2019)	A7
Hydrothermal liquefaction	Algae/Microalgae	Castello et al. (2019)	A8
	Wood residue/ Agriculture waste	Tzanetis et al. (2017)	A9
Advanced Fermentation	Wood residue/ Agriculture waste	Geleynse et al. (2020)	A10
Co-valorisation of CO_2 and waste biomass	Industrial waste gases CO_2 + Wood residue	Zhang et al. (2020)	A11

production pathways considered for evaluation in section 5.

4.2. Choice and implementation of experts' preferences elicitation method

To model experts' preferences, we organised an industry workshop to gather information on expert's preferences with respect to the relative importance they assign to different criteria. A total of 40 experts from Europe representing different organisations belonging to SAF supply chains participated in our workshop. As there is no consensus about the most valid preference elicitation method (Lienert et al., 2016), we discussed with these experts a practical choice of the elicitation method to use amongst the ones described in Ouenniche et al. (2018). Particular attention has been paid to a direct rating method, a relative rating of Max100, Min100, point allocation method, Simos' cards method, and the Analytic Hierarchy Process. Based on experts' feedback and type of our study we adopted the *point-allocation* method proposed by Doyle et al. (1997). In this method, impact category criteria (social, environmental, economic, and technical) were rated relative to each other by distributing 100 points between them. Such a choice was motivated by its ability to reflect the criteria's relative importance to the objective and experts' desires, as well as its simplicity from a user's perspective (Xu et al., 2016).

4.3. Choice of a system for rating SAF production pathways and its implementation

The ratings of SAF production pathways against each criterion were obtained from aviation industry experts using a simple rating system. Because of the novelty of this application and the scarcity and unavailability of data on the measures of these criteria, we conducted a survey amongst aviation industry experts to collect data and opted for discrete measures for all criteria but one (blending limit) which is measured on a continuous scale. To be more specific, we used a 5-point Likert scale to allow experts to express their ratings for each SAF production pathway and criterion combination. A numeric scale of 1–9 was considered (1 is very bad, 3 being bad, 5 is average, 7 is good and 9 is very good) to enhance the discrimination power of the ranking methods used in section 4.4. On one hand, the choice of the Likert scale was made based on the non-availability of SAF specific data, while reducing expert's cognitive burden, on the other hand.

4.4. Choice and implementation of a ranking method for SAF production pathways

In this paper, our focus is on the use of an outranking PROMETHEE method which was first presented by Brans in 1982 (Brans and Mareschal, 2005); namely, the PROMETHEE II method.[4] The reason of our choice, PROMETHEE II, is its ability to use both quantitative and qualitative data for alternative evaluation; and its ability to handle uncertainty in experts' preferences and rankings based on pairwise comparisons of alternatives.[5]

Conceptually, PROMETHEE II could be seen as a modelling and solution framework for MCDM problems, where the decision problem is modelled as a complete network whose nodes represent alternatives and whose arcs represent preference relationships between pairs of nodes or alternatives (a, b), say $\pi(a, b)$. The strength of a node or alternative a, commonly referred to as the net outranking flow and denoted by $\phi(a)$or $\phi_{net}(a)$, is computed as the difference between the so-called leaving outranking flows, say $\phi^+(a)$, and entering outranking flows, say $\phi^+(a)$; that is, $\phi_{net}(a) = \phi^+(a) - \phi^-(a)$. The solution to the problem of ranking

[4] For a detailed description of PROMETHEE II reader is referred to Brans and Mareschal (2005).

[5] Note that our choice of MCDM ranking method is also verified by an online tool (www.mcda.it) developed by Wątróbski et al. (2019).

a set of alternatives under multiple criteria is then obtained by sorting alternatives in descending order of their strengths as measured by the net outranking flows, ϕs. The detailed steps of the method are outlined below.

Input: Decision matrix and Weighting scheme.

In PROMETHEE II, the information gathered from the decision maker is synthesised into a $m \times n$ matrix, commonly referred to as the decision matrix (DM), as shown in Eq. 1:

$$DM = \begin{bmatrix} c_1(a_1) & \cdots & c_n(a_1) \\ \vdots & \ddots & \vdots \\ c_1(a_m) & \cdots & c_n(a_m) \end{bmatrix} \quad \text{Eq.1}$$

where $A = \{a_1, a_2, \dots a_i \dots a_m\}$ is the set of alternatives and $C = \{c_1, c_2 \dots c_j \dots c_n\}$ is the set of performance criteria under consideration, and $c_j(a_i)$ is the performance of alternative a_i on criterion j; $i = 1, \dots, m$, $j = 1, \dots, n$.

Then, we compute the relative importance weight, w_j, of the n performance criteria under consideration. The vector $w_j = (w_1, w_2, \dots, w_n)$, $j = 1, \dots, n$ comprises of non-negative weights conforming to $\sum_{j=1}^{n} w_j = 1$.

Step 1: For each pair of alternatives (a, b) and each criterion j, we compute the difference in performance on criterion j of alternatives a and b, say $D_j(a, b)$, as shown in Eq. (2):

$$D_j(a,b) = c_j(a) - c_j(b),\ j = 1, \dots, n\ \forall\, a, b \in A \quad \text{Eq. 2}$$

Step 2: For each pair of alternatives (a, b) and each criterion j, compute a local or criterion-dependent preference index or function, say $P_j(a, b)$, which takes account of the difference in performance on criterion j of alternatives a and b computed in step 1. Different preference functions and their details can be found in Brans and Vincke (1985). In our case, we used the type 1, the usual preference function as shown in Eq. (3).

$$P(D) = \begin{cases} 0, & D \le 0 \\ 1, & D > 0 \end{cases} \quad \text{Eq. 3}$$

Step 3: For each pair of alternatives (a, b), we compute a global or aggregate preference index or function, say $\pi(a,b)$, which expresses the degree to which alternative a is preferred over alternative b on all criteria under consideration as shown in Eq. (4); in sum, $\pi(a, b)$ is a weighted average of local performance indexes $P_j(a, b)$.

$$\pi(a,b) = \left[\sum_{j=1}^{n} w_j\, P_j(a,b)\right] \Big/ \sum_{j=1}^{n} w_j \quad \forall\, a, b \in A \quad \text{Eq. 4}$$

Step 4: For each alternative or node a, we compute leaving (ϕ^+) and entering (ϕ^+) outranking flows as shown in Eq. (5) and Eq. (6), respectively.

$$\phi^+(a) = \frac{1}{m-1} \sum_{x \in A}^{m} \pi\,(a, x) \quad \text{Eq. 5}$$

$$\phi^-(a) = \frac{1}{m-1} \sum_{x \in A}^{m} \pi\,(x, a) \quad \text{Eq. 6}$$

The leaving outranking flow expresses the degree to which an alternative a is outranking all the others. Regarded as the power of an alternative, the higher$\phi^+(a)$, the better the alternative. On the other hand, the entering outranking flow expresses the degree to which an alternative a is outranked by all the others. Regarded as the weakness of an alternative, the lower$\phi^-(a)$, the better the alternative.

Step 5: For each alternative a, we compute the net outranking flow or strength as shown in Eq.7.

$$\phi_{net}(a) = \phi^+(a) - \phi^-(a) \quad \text{Eq.7}$$

Output: The final ranking of all alternatives is based on the principle that the higher the $\phi_{net}(.)$, the more attractive that alternative is; in summary, the global ranking is obtained by sorting alternatives from best to worst in descending order of their net outranking flow.

5. Results and discussion

In this section, we present and discuss the outcome of our empirical analysis. To be more specific, we shall first present the multi-criteria weights obtained followed by mono-criterion evaluation of SAF production pathways. Then, we present the broader impact category-wise rankings. Finally, we report the complete or global PROMETHEE II rankings of these pathways.

5.1. Performance criteria weights

During our expert workshop, we obtained experts' preferences as expressed by the relative importance assigned to each criterion or equivalently the criteria weights. To ensure our results have not been affected by the outliers, our analyses are based on using the geometric mean values of all experts' preferences.[6] We find that environmental and economic categories are the most important ones with relative weights of 31% and 28%, respectively. The technical criteria category is the third most important category with a relative weight of 25%, whereas the social criteria category is the least important one with a relative weight of 16%.

Within each impact category, *local weights* define the importance of a single criterion. For example, *food security* gets the highest importance (29.8% out of 100%) over the other three in decreasing order; *social acceptability, contribution to economy* and *traceability*, having weights of 26.9%, 23.3% and 20.0%, respectively within the social impact category. Similarly, within the environmental category, *GHG emission savings* is rated the most important (36.6%) while *soil and water pollution* is least preferred (17.5%). The consensus among the experts is to rate *MSP* as the most important criterion (17.8%). Finally, *conventional jet fuel compatibility* (18.7%) is preferred over other criteria within the technical criteria category with *domestic technological ability* getting the least preference (8.6%).

Next, we compute the global weights of each criterion. This is done by multiplying each criterion local weight with its respective impact category's relative weight. For example, food *security* belongs to the social impact category, its global weight (4.8%) is a product of 0.298 (local weight) and 0.16 (impact category's relative weight). All criterion weights (local and global) are summarised in Fig. 3.

Global criteria ranking analysis reveals that *GHG emission saving* has the highest importance (11.3%) followed by *feedstock sustainability* at 8.5% and *land use change impact* at 5.8%. Notice that the top three global criteria are from the environmental impact category. This importance ranking by experts is understandable as SAFs are presented as an environmentally friendly option for aviation. MSP with a weight of 5% is the most important criterion from the economic impact category. *Food security* and *conventional jet fuel compatibility* are considered important from the social and the technical impact categories with global criterion weights of 4.8% and 4.6%, respectively.

The conflicts, similarities, and independencies among the criteria are explored using the Geometrical Analysis for Interactive Assistance (GAIA) plane. The GAIA plane presents the result of Principal Components Analysis onto a two-dimensional plane such that the longer a criterion vector, the more discriminating this criterion (Lai and Ishizaka, 2020). In our case, a 24-dimensional space of criteria is projected preserving 67.1%[7] of the total information from the experts (Fig. 4). This

[6] Note that out of the total 40 experts who have participated our workshop, we have included 22 experts' preferences and excluded those who has provided us incomplete data.

[7] Brans and Mareschal (2005) suggest information preservation threshold of 60%.

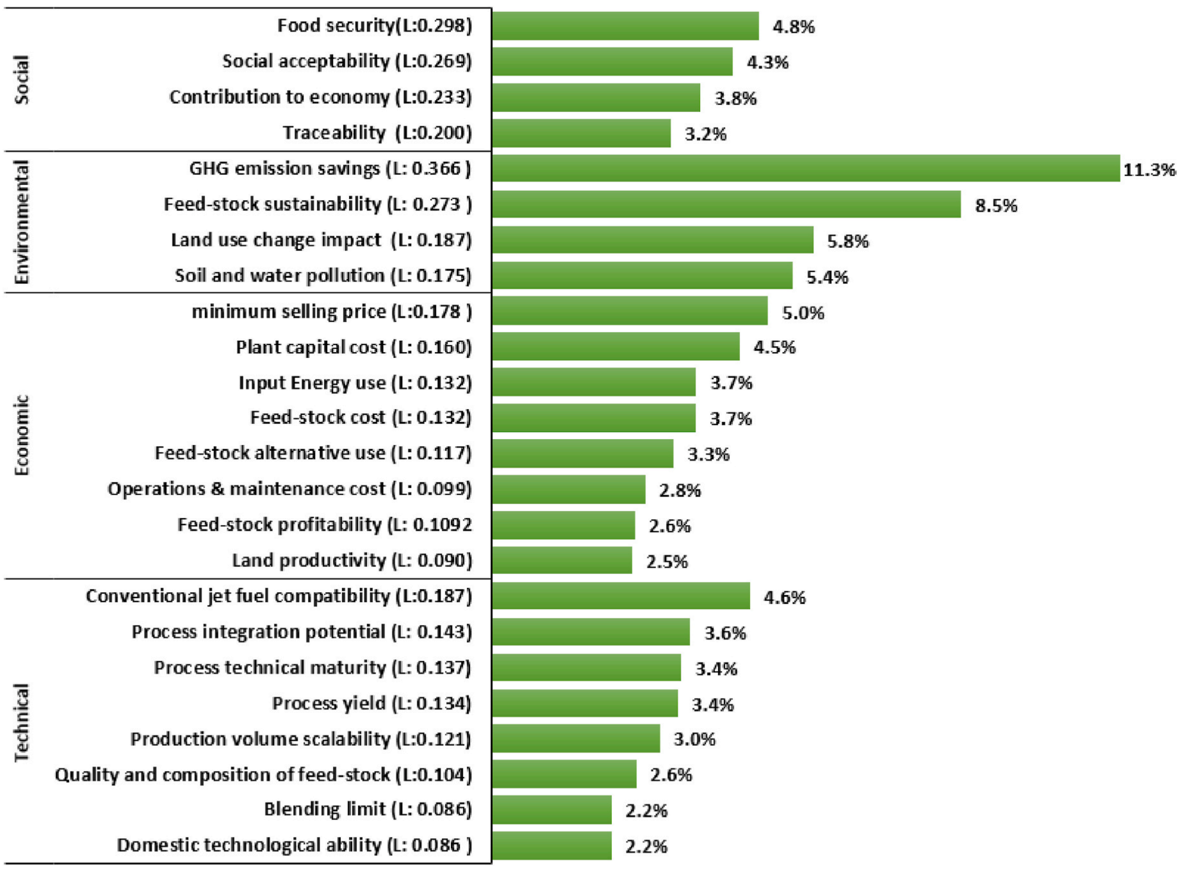

Fig. 3. Global weights of criteria *(L:xxx denotes criterion local weight).*

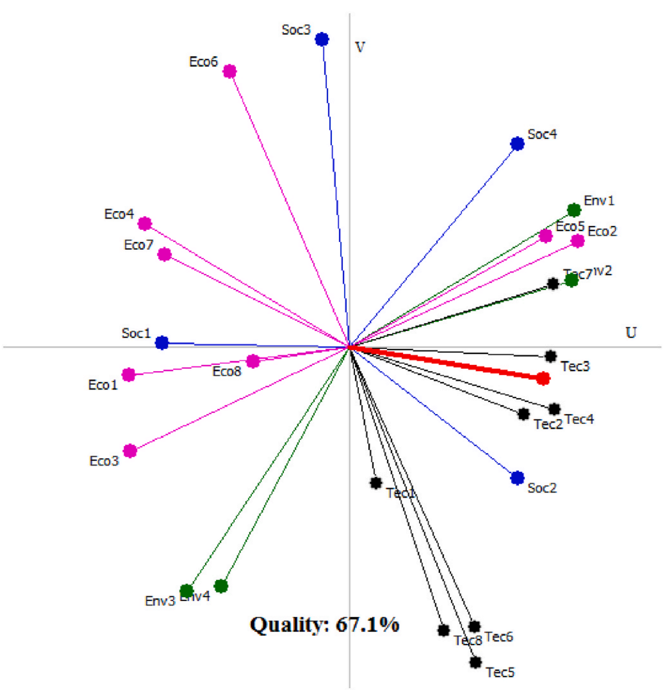

Fig. 4. GAIA-criteria plane.

indicates the reliability of the information provided by the panel of experts.

The GAIA-criteria plane in Fig. 4 shows that there are criteria expressing conflicting preferences. For example, *feedstock profitability* (Eco2) and *land productivity* (Eco5) are conflicting *feedstock alternative use* (Eco1), *MSP* (Eco3) and *plant capital cost* (Eco8). Likewise, criteria expressing similar preferences are represented by vectors oriented in approximately the same direction. *Feedstock sustainability* (Env1) and *GHG emission savings* (Env2) from the environmental impact category while *conventional jet fuel compatibility* (Tec2), *domestic technological ability* (Tech3) and *process integration* (Tech4) exhibit similar preferences. *Food security* (Soc3), *land-use change impact* (Env3), *operations & maintenance cost* (Eco6) and *process technical maturity* (Tec5) are the most discriminating criteria. However, except for Tec5, none of the most discriminating criteria are in the direction of the decision axis (the red colour vector). The decision axis points to the direction of preferred SAF production pathways currently not shown in Fig. 4. Finally, *contribution to economy* (Soc2) and *social acceptability* (Soc4); *GHG emission savings* (Env2) and *land-use change impact* (Env3); *operations & maintenance cost* (Eco6) and *land productivity* (Eco5), and *conventional jet fuel compatibility* (Tech2) and *production volume scalability* (Tech7) exhibit independence within social, environmental, economic and technical impact categories, respectively. The presence of conflicting criteria is an indication that the selection of a good SAF production pathway will be a challenge.

5.2. A mono-criterion evaluation of SAF production pathways

Table 4 summarises the rankings of SAF production pathways from the best to the worst by considering only one criterion at a time. The usefulness of mono-criterion rankings lays in exploring how a SAF production pathway performs on a specific performance criterion. Next, we discuss our findings on the most important performance criterion from each impact category.

Food security is considered as one of most important performance criteria on the social impact category. We find that the SAF production pathway A1 is ranked the best while A3 is considered the worst. Despite

Table 4
Criterion wise ranking of SAF production pathways.

Criterion	Ranking (from best to worst)
Social	
Traceability	A1>A9>A2↔A3>A6↔A11>A7>A8>A5↔A10>A4
Contribution to the economy	A4>A5>A11>A2>A10>A3>A7>A8>A1>A6>A9
Food security	A1>A4↔A9↔A11>A2>A6>A5↔A10>A7↔A8>A3
Social acceptability	A11>A4>A8↔A9>A7>A5↔A10>A6>A2>A1↔A3
Environmental	
Feedstock sustainability	A11>A5>A4>A8>A7>A7>A10>A6↔A9>A1>A2>A3
GHG emission savings	A11>A5>A4>A7>A8↔A10>A2>A1↔A6>A9>A3
Land use change impact	A3>A10>A1>A2↔A8>A9>A7>A6>A5>A11>A4
Soil and water pollution	A9>A11>A5>A6>A7↔A4>A8↔A10> A2↔A1>A3
Economic	
Feedstock alternative use	A3>A1>A6>A9>A10>A2>A4>A7>A8>A11>A5
Feedstock profitability	A11>A4>5>A8>A10>A7>A6>A9>A2>A1>A3
Minimum selling price	A3>A2↔A9>A1↔A6>A7>A8↔A10>A4>A5>A11
Input energy use	A1>A2>A6>A9>A3↔A4>A7↔A10>A11>A8>A5
Land productivity	A5>A11>A8>A4>A7>A2↔A6>A9>A1>A10>A3
Operations & maintenance cost	A1>A6↔A10>A4>A9>A7>A8>A2>A3↔A11>A5
Feedstock cost	A1>A9>A3>A8>A4>A6>A2>A10>A11>A7>A5
Plant capital cost	A2>A1↔A7>A4>A3>A8>A5>A6>A9>A10>A11
Technical	
Blending limit	A1↔A2↔A3↔A4↔A5↔A11>A10>A6↔A7↔A8↔A9
Conventional jet fuel compatibility	A5>A10>A4>A11>A2>A6>A8>A3↔A9>A7>A1
Domestic technological ability	A10>A4>A5↔A11>A7>A8>A6>A2>A3>A9>A1
Process integration	A5>A4↔A11>A8>A7>A3>A6>A2>A10>A9>A1
Process technical maturity	A3↔A10>A5>A11>A4>A2↔A7>A8>A6>A9>A1
Process yield	A11>A2↔A5>A3↔A8>A7↔A10>A9>A6>A4>A1
Production volume scalability	A11>A5>A10>A7>A8>A4>A9>A1>A6>A2>A3
Quality and composition of feedstock	A11>A3>A5>A10>A8>A9> A7↔A6↔A2>A1>A4

Notes: ">" signifies higher rank; "↔" indicates the same rank.

both A1 and A3 have HEFA as the main conversion process, it is the feedstock used that influences their ranking. Production pathway A1 uses algae/microalgae as a feedstock which does not compete with arable land or freshwater rather it can be grown off-shore or utilising city's waste treatment facilities (Daroch et al., 2013; IATA, 2014). In contrast, A3 uses oil-seeds as feedstocks which places them in direct competition with food production (Tenenbaum, 2008), and the use of the cropland (Axelsson et al., 2012). Hence, making this production pathway the least attractive one.

Moving on to the environmental impact category. The highest *GHG emission savings* are achieved by A11, while the least savings can be from SAF produced via the A3 pathway. The reason for this preference is that A11 uses direct CO and CO_2 from waste processes giving it better emission savings as compared to A3 (Zheng et al., 2017). *GHG emission savings* are further enhanced by the use of wood residue which is considered a better feedstock than oil-seeds in terms of life cycle emission savings (O'Connell et al., 2019).

Given that SAF have been found to be 2 to 3 times more expensive than conventional jet A1 (O'Connell et al., 2019), the selling price becomes a major deciding factor. Mono-criterion analysis reveals that production processes A3 and A2 are ranked the best in terms of achieving lowest MSP whereas A11 is ranked the least attractive alternative. HEFA production pathways are generally found to achieve a lower MSP than gasification/F-T synthesis as reported by Diederichs et al. (2016), IATA (2014) and Tao et al. (2017).

Finally, from the technical impact category, *conventional jet fuel compatibility* is found to be best achieved by SAF production process A5, while A1 is the worst SAF production pathway. It is interesting to note that both A1 and A3 are found to produce SAF as substitutes of conventional jet-A, even better in some fuel characteristics (Zhang et al., 2016), yet we see that experts in our panel prefer gasification/F-T synthesis (conversion process used in A1 pathway) over HEFA (conversion process used in A3 pathway). One possible explanation could be again in using different feedstocks that MSW is more suitable than algae/microalgae for producing SAF.

However, one of the main drawbacks of the unidimensional or mono-criterion rankings is conflicting rankings across the criteria. For instance, A11 offers the best pathway on GHG emission savings and it ranked as the worst by being an expensive alternative as depicted by performing worst on MSP criterion, whereas A3 provides least GHG emission savings, and the best option based on MSP as compared to other production pathways. This situation results in a conundrum for decision-makers. They would not be able to make an informed decision as to which SAF production pathway performs best when all criteria are considered simultaneously. In addition, uni-dimensional rankings can result in ties amongst the alternatives (e.g., A1-A2 and A8-A9 rank equal for blending limit criterion and A6-A9 for feedstock sustainability). This finding is not unusual given that many SAF production pathways have similar social, environmental, economic and technical requirements. In order to alleviate mixed performance results and to reduce the number of equal ranks or ties, it is required to consider multiple criteria concurrently within each impact category.

Hereafter, we report and discuss SAF production pathway findings based upon each impact category; namely, social, environmental, economic and technical.

5.3. SAF production pathways evaluation based on impact categories

First, from the perspective of public welfare reflecting socially motivated stakeholders (e.g., government agencies, not-for-profit organisations), we obtained the SAF production pathways ranking (see Fig. 5) using a weight vector of [0.200; 0.233; 0.289; 0.269] for the social impact category of criteria. Focusing on the production process it is found that gasification/F-T synthesis processes, A11 and A4, rank higher than HEFA processes, A1 and A2. In terms of feedstock, wood residue is preferred over algae/microalgae. This is understandable as wood residue and MSW supply chain and market is mature and acceptable to the public (McGuire et al., 2017). However, the lack of information about potential buyers, unfamiliarity with the optimal cultivation methods, among others have been identified as barriers for algae and oil seeds social acceptance (Axelsson et al., 2012; Gegg and Wells, 2017). Surprisingly, A2 is ranked fifth in the social impact category contrary to the fact that the majority of flights around the globe have used or are using HEFA and waste cooking oil/animal fat-based SAF (Kousoulidou and Lonza, 2016). This shows the lack of public engagement from airlines and SAF producers on their initiatives which otherwise would have resulted in more social acceptance of SAFs.

For environmentally motivated stakeholders (e.g., climate advocacy groups, international regulatory agencies, etc.) with the weight vector of [0.273; 0.366; 0.187; 0.175], we obtained the ranking for SAF production pathways as shown in Fig. 5. SAF production pathway A11 performs best due to utilising captured CO_2 followed by A5 and A8 while A3, A6, and A9 are found to have the worst environmental performance Gasification/F-T synthesis based production processes using captured CO_2 and wood residue/agriculture waste show higher environmental savings as compared to oily biomass (Agusdinata et al., 2011; Staples et al., 2018). This is due to the high use of fertilizer and cultivation process emissions for algae/microalgae and oil-seeds production (de Jong et al., 2017). However, this is found to be opposite for A8 and A9 rankings. In fact, A8 and A9 both have HTL as a conversion process but use algae/microalgae and wood residue/agriculture waste as feedstock, respectively. This inclination towards algae/microalgae is due to its faster growth rates resulting in better CO_2 sequestration, higher per land area yield, and non-requirement of fertile soil (Gollakota et al., 2018). Hence, making HTL of algae/microalgae perform better environmentally than HTL of other terrestrial biomass options.

Economic preference represents the commercially motivated

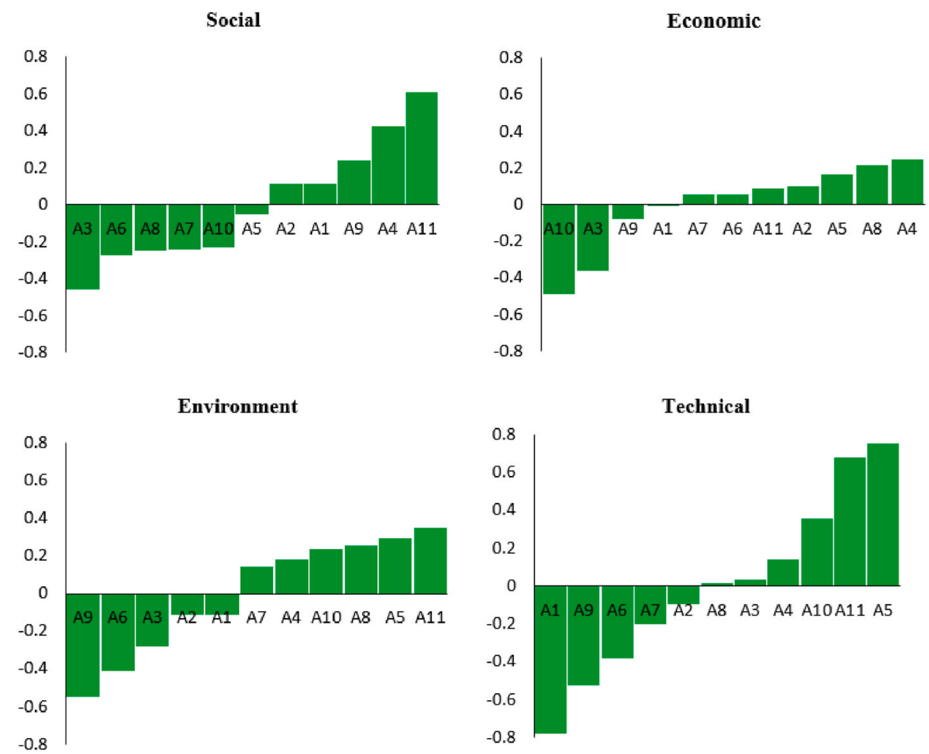

Fig. 5. Impact category wise SAF production pathway ranking.

stakeholders (e.g., SAF producers, airlines, and feedstock providers) perspective. These stakeholders are interested in evaluating financial gains from producing SAF using a particular pathway. Fig. 5 summarises the rankings with the economic criterion weights vector of [0.117; 0.092; 0.178; 0.132; 0.090; 0.098; 0.132; 0.159]. It is found that the top three SAF production pathways show a mix of chemical processes used for the fuel production. However, gasification/F-T based synthesis (A4, A5 and A11) dominate others. This situation indicates a convolution of chemical process and feedstock used. This finding is further confirmed by looking at the relative economic ranking of production pathway A2 and A3; both use the HEFA process but different feedstocks. It is seen that MSW along with wood residue/agriculture waste are preferred due to their relatively negative cost compared to oily biomass (A3). SAF production pathways A6 and A7 are almost equally ranked. Preference of gasification/F-T synthesis over HEFA based processes is in contrast to the most important criterion of MSP within the economic impact category. Bann et al. (2017) estimated the SAF price to be within \$0.66/litre–\$1.24/litre for HEFA using waste oil, \$0.79/litre–\$1.42/litre for HEFA using animal fat, and within the range of \$0.95/litre–\$1.39/litre for gasification/F-T synthesis of MSW. Similar findings have been reported by Chu et al. (2017) and Janić (2018) for HEFA based SAF production pathways that show better economic performance compared to gasification/F-T synthesis based ones. Though Bann et al. (2017) rate HTL based processes as lower in economic performance (based on net present value), our analysis rank A8 over HEFA and gasification/F-T synthesis except production pathway A4. HTL based processes are considered to be a viable option for SAF production in short to medium term (de Jong et al., 2015; Dimitriadis and Bezergianni, 2017).

Finally, from a technical evaluation perspective, the SAF production pathways ranking is performed using a weight vector of [0.086; 0.186; 0.086; 0.143; 0.137; 0.134; 0.121; 0.104]. The ranking of SAF production pathways is presented in Fig. 4. A5, A11, and A10 are the top three ranked SAF production pathways. A5 is gasification/F-T synthesis based production process, which is high SAF yielding, and a mature process as compared to A10 (Suresh et al., 2018), while A11 is still at a lower technology readiness level (The Royal Society, 2019). On the other hand, A1 technically ranks the worst of the SAF production pathways, followed by A9 and A6. A1 and A6 using algae/microalgae possesses lower SAF yield due to high water and oxygen content in bio-crude oil produced (IRENA, 2016). Our analysis ranks A6 higher in giving a better production pathway than A9. This finding is contrary to the previous findings where HTL (A9) is found to be better than pyrolysis (A6) for the majority of biomass feedstock including dry biomass like wood residue (Dimitriadis and Bezergianni, 2017). Further, in terms of the commercial level availability of technology, biomass gasification and pyrolysis systems are commercially available while biomass HTL is at a pilot phase (Sikarwar et al., 2017)

5.4. SAF production process global MCDM ranking

Next, we detail the steps for obtaining the PROMTHEE II global rankings of 11 SAF production processes on 24 criteria. Leaving and entering flows for each production pathway are given in Table 5 while net flows and rankings are shown in Fig. 6. The vertical axis in Fig. 5 represents net outranking flows of each pathway. Note here that we are limiting our discussion to SAF production pathways that have positive outranking flows only. The reason for this focus is that these production

Table 5
Leaving and entering flows in SAF production pathways.

Production pathway	Entering flow	Leaving flow	Net Phi
A1	0.441	0.517	−0.076
A2	0.486	0.464	0.022
A3	0.422	0.533	−0.111
A4	0.582	0.385	0.197
A5	0.551	0.422	0.129
A6	0.374	0.581	−0.207
A7	0.445	0.516	−0.071
A8	0.482	0.463	0.019
A9	0.379	0.583	−0.204
A10	0.508	0.446	0.062
A11	0.604	0.364	0.24

Fig. 6. SAF production pathways MCDM ranking.

pathways make a credible business case for future investments and policy developments.

Looking at the extreme end of the ranking spectrum in Fig. 6, A6 is found to be the least preferred SAF production process with a net outranking flow of −0.207 followed by A9 and A3 with net flows of −0.2045 and −0.111, respectively. SAF production pathway A11 outranks all other processes with a net outranking flow of 0.240. The top three production processes, A11, A4, and A5 comprise of gasification/F-T synthesis processes show that experts agree that these are the most suitable processes for SAF production. Recall that the main constitute of gasification/F-T synthesis, syngas, is derived from relatively cheap feedstock (MSW, wood residue/agriculture waste). This gives gasification/F-T synthesis based production pathways a competitive advantage by balancing out their high capital cost and small scale production over HEFA pathways (Neuling and Kaltschmitt, 2018). Our analysis reveals that A10 (advanced fermentation) is the second best after gasification/F-T synthesis. This is contrary to the literature which presents advanced fermentation (DSHC and ATJ) based pathways as falling short to achieve the commercialisation phase of development (de Jong et al., 2017) and are restrained in terms of feedstock sustainability (Bosch et al., 2017). However, the advanced fermentation production pathway could be difficult to upscale (Neuling and Kaltschmitt, 2018). It can be seen from Fig. 6 that our panel of experts ranked A10 relatively higher due to its better overall environmental and technical characteristics. A2 (HEFA with waste cooking oil/animal fats) is ranked higher to A8 (HTL processes with algae/microalgae) though the potential capacity expansion of this production pathway is limited by the supply of feedstock (Bosch et al., 2017). Finally, A6 and A9 (Pyrolysis and HTL based pathways) are outranked by other alternatives. Our findings are in line with the related study on biofuel production conversion technology by Fiorese et al. (2012). In their expert survey, gasification/F-T synthesis came out to be the most preferred production process followed by oil-based processes; namely, HEFA, Pyrolysis, and HTL.

Focusing on the second part of SAF production pathway, feedstock, it is found that within gasification/F-T synthesis group direct conversion of CO_2 to SAF (pathway A11) is regarded as the best option. This could be because experts perceive capturing CO_2 from industrial processes as a direct approach as compared to using MSW (A4) and wood and agriculture waste (A5). Though converting MSW to SAF avoids GHG emissions that would have otherwise resulted from landfilling and incinerating operations, yet the GHG emission savings are foregone which would have been realised by landfill gas offsetting fossil fuel usage (Suresh et al., 2018). Feedstock analysis shows that algae/microalgae is less preferred over wood residue and agriculture waste. One possible explanation could be unfamiliarity with algae as a reliable feedstock and higher pre- and post-processing needed for algae/microalgae feedstock (IRENA, 2016). Similarly, our analysis reveals that exerts continue to view oil-seeds as an infeasible option and seem to have been caught up in food versus fuel feud.

5.5. SAF production pathways ranking based on PROMETHEE group decision support system (GDSS)

In the previous section, we discussed the aggregate ranking of SAF production pathways. To further the analysis, we compare individual expert's[8] preference to capture any conflict among them. For this purpose, for each expert, we perform an individual PROMETHEE-GAIA analysis to check potential conflicts. Next, we aggregate them to obtain the global ranking and use the GAIA plane to understand different perceptions among the experts.

Fig. 7 reports the different inclinations among the experts on the ranking of SAF production pathways. Note that each expert's preference is represented by a vector labelled 'E' while SAF production pathway as points. The direction of decision axis (the red vector) is towards A11, A4 and A5, which are the best production pathways, and opposite to A6, A9, A3, the worst alternatives. In respect to decision vector, not all production pathways perform well for all the experts. A clustering of preference towards a group of production pathways is evident. SAF production pathways, A1 and A2 forms one such cluster preferred by expert nine experts (E5, E8, E11, E13, E17, E19, E21, E20, E21) while A11, A4, A5 forms the other cluster preferred by the remaining experts. This distinction can be attributed to experts' specific background.

6. Sensitivity analysis

The reliability of the results yielded from the initial model needs to be evaluated to ensure the validity of the selected alternatives. To this end, sensitivity analysis is performed, and the initial ranks of the alternatives are validated. For this aim we adopted two distinct approaches: (1) change the criteria weights and validated the ranking using PROMETHEE, and (2) use two other MCDM methods to validate and compare SAF production pathway ranking.

6.1. Criteria weight experiments

To investigate the influence of the criteria weight's changes on the ranks of alternatives, we divide the experiments into three categories: 1) *pessimistic* (considering the minimum criteria weights across all stakeholders); 2) *likely* (considering the mean criteria weights), and 3) *optimistic* (considering the highest criteria weights obtained during expert consultation). In order to check to what extent, the preference of decision-makers will affect the results reported earlier, we assume that each criterion is equally important; thus, a weight value of 4.2% is used for each of the 24 criteria. This experiment is labelled '*neutral*'.

Fig. 8 presents the results of sensitivity analysis and shows that out of the four experiments, SAF production pathway A11 has the highest score in all four experiments followed by A4 occurring at second rank three times and A5 at rank three thrice. A10 comes at rank four in all four experiments while A2 comes at rank five and six twice each time. (Appendix A3 shows the frequency of SAF production pathway ranking). We find that by altering the weights to an equal weighting scheme, the rankings of the best and worst performing production pathway ranking did not change much. This implies that our findings are robust and do not yield to input criteria weight variations. Thus, giving confidence in the SAF production pathways rankings.

6.2. Comparison with other MCDM methods

To compare our findings on the rank order of SAF production pathways, we employed two widely used MCDM methods: TOPSIS (Hwang and ve Yoon, 1981) and VIKOR (Opricovic, 1998). To incorporate experts' preferences uncertainty, we follow Awasthi et al. (2018, 2010) and Oliveira et al. (2018) in using the fuzzy versions of TOPSIS and

[8] We have used a total of 22 experts' preferences.

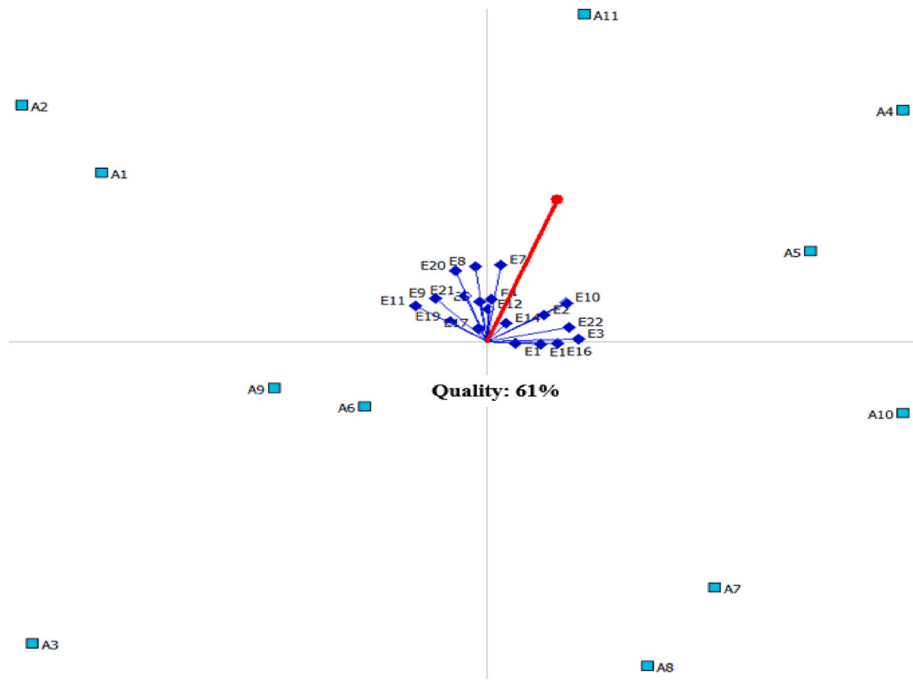

Fig. 7. GAIA plan for the global ranking of SAF production pathways.

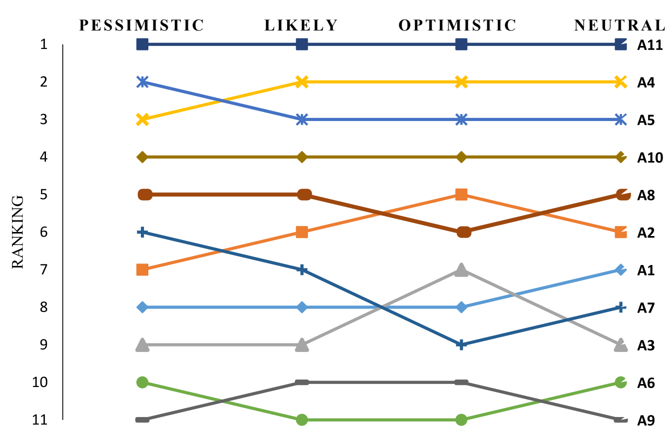

Fig. 8. Sensitivity analysis results.

VIKOR methods, respectively.[9] Our descriptions of fuzzy TOPSIS and fuzzy VIKOR are outlined in Fig. 9 with specific implementation details summarised in Table 6.

Table 7 reports the ranking obtained using fuzzy TOPSIS and fuzzy VIKOR methods. Both methods ranked A4 and A5 amongst their top three options, whereas A6 and A9 are systematically ranked in the bottom three. However, the ranks assigned to A11 and A3 by fuzzy TOPSIS are different from the rank assigned by fuzzy VIKOR, because of the differences in the principles underlying these methods (Opricovic and Tzeng, 2004).

Furthermore, we investigate the relationship among the ranking generated by all three MCDM methods we have considered in this study. By performing the Spearman's rho correlation analysis, we find that the PROMETHEE ranking is hihgly positvely correlated with fuzzy TOPSIS (0.927), while it is slightly less but also signficantly correlated with fuzzy VIKOR (0.673) – see Table 8. In sum, it can be inferred that our rankings are reliable and robust.

[9] Note that, for comparability of the results purpose, we modified the fuzzy VIKOR version proposed by Awasthi et al. (2018) so that the weighted normalised aggregate fuzzy ratings are common input to both TOPSIS and VIKOR.

7. Conclusions

Sustainable aviation fuels have the potential to play an important role in the aviation sector's efforts to combat carbon emissions and to continue the search for an alternative jet-fuel supply. SAF can be produced in several ways thus making the selection of a particular pathway a complex strategic decision. The current literature focuses on evaluating the relative performances of a single or a few pathways using the TEA or LCA studies. There is a lack of comprehensive multiple-criteria evaluation of pathways approved for SAF production based on experts' preferences.

7.1. Theoretical contribution

To address this gap, we followed a stakeholders' participatory approach to develop a holistic framework in collaboration with experts based on social, environmental, economic and technical impact categories. To gather stakeholders' views and preferences, we have developed a questionnaire to help us devise a list of the critical criteria that need to be considered when investing/producing/purchasing/using SAF. Furthermore, we have validated the choice of criteria during our in-depth interviews with industry experts. Another questionnaire was distributed, in a workshop, to industry experts to gather preferences on performance criteria and ratings of each SAF production pathways under consideration. In addition to PROMETHEE, we applied fuzzy TOPSIS and fuzzy VIKOR for validation purposes to minimize experts' judgemental biasedness in evaluating SAF production pathways.

7.2. Practical contribution

Our study found that environmental and economic issues are more important as compared to technical and social ones. The emphasis on these two categories is plausible as SAFs are promoted to have lesser adverse environmental effects than conventional jet-A fuel but are also relatively an expensive option. Furthermore, GHG *emission savings,*

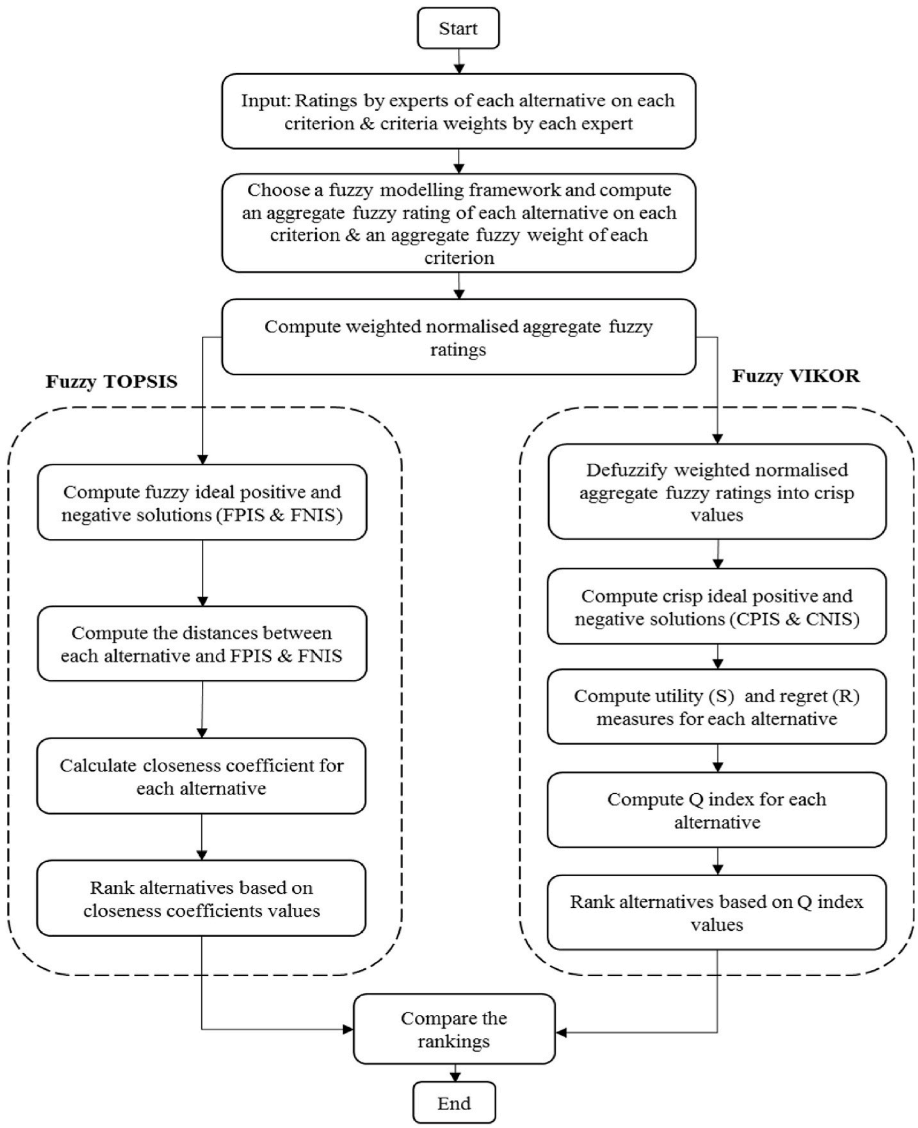

Fig. 9. The flowchart for the fuzzy MCDM methods.

feedstock sustainability, MSP, jet fuel compatibility and SAF *traceability* are found to be the most important performance criteria for ranking SAF production pathways.

Mono-criterion rankings of SAF production pathways reveal that no one production pathway gets the prominence on all 24 criteria considered for evaluation. Furthermore, in mono-criterion rankings, while considering each impact category separately, we see a mix of results as well. However, in the economic impact category, the HEFA based production process outranks other alternatives. We advise caution on this finding as HEFA seems be the best option for the other three impact categories. Complete/Global MCDM rankings reveal that gasification/F-T synthesis is the best conversion process to consider while producing SAFs followed by fermentation and hydrothermal liquefaction-based ones. HEFA based processes, though technically mature and widely in operation at commercial scale, are less attractive options.

In terms of feedstock, this study reveals that captured waste gases and wood residues along with agriculture waste are a better option than algae/microalgae and purposely grown non-edible oil seeds. Animal fat and waste cooking oils are also an attractive option but are not capable of giving higher SAF production due to their limited availability. Hence, based on our findings, we recommend that efforts be made to integrate/design/modify waste gases and residues supply chain towards SAF production.

Our framework for analysing and ranking SAF production pathways are useful for policy development. The choice of SAF production pathways should be focussed on a country's local technological features, feedstock availability, and/or market conditions (Royal Academy of Engineering, 2017). For example, sugarcane has been used to produce SAF in Brazil, while MSW and agriculture waste has been identified as the most suitable feedstock for SAF production in the UK (Department for Transport, 2018). Thus, financial incentives could be provided to feedstock producers to ensure a steady supply of raw material for SAF production (Klein et al., 2018), as optimised feedstock supply chain would help to minimize the uncertainty in SAF production; and ensure businesses sustainability for both feedstock suppliers and the SAF producers. On the technology side, policy frameworks to strengthen specific SAF production pathways and R&D capabilities would manifest in national competitiveness and contribute towards a prosperous bio-economy. These capabilities would then be exported to other regions of the world. Furthermore, as highlighted in our study, SAF production pathway's plant capital cost is a crucial criterion. In this regard, we propose that schemes should be arranged which would make securing debt or equity financing less complicated and underwritten by national governments. This setting will boost private investors' confidence for

Table 6
A summary description of Fuzzy MCDM methods.

Input: The ratings by K experts of m alternatives on n criteria, x_{ij}^k; $i = 1,\ldots,m$, $j = 1,\ldots,n$, $k = 1,\ldots,K$, and the weight of each criterion by each expert, w_j^k; $j = 1,\ldots,n$, $k = 1,\ldots,K$.

Step 1: Choose a fuzzy modelling framework and compute an aggregate fuzzy rating of each alternative on each criterion and an aggregate fuzzy weight for each criterion. Note that there are several fuzzy modelling frameworks to choose from. The simpler and most common one consists of using triangular fuzzy numbers to model the fuzzy nature of the data, which in our case corresponds to the ratings. Under this choice, for each alternative i ($i = 1,\ldots,m$) and each criterion j ($j = 1,\ldots,n$), the ratings by the K experts are aggregated into a single triangular fuzzy rating, say $\widetilde{x}_{ij} = (a_{ij}, b_{ij}, c_{ij})$, as follows:

$$a_{ij} = \min_k\left\{x_{ij}^k\right\};\ b_{ij} = \frac{1}{K}\sum_k x_{ij}^k;\ c_{ij} = \max_k\left\{x_{ij}^k\right\} \quad \text{Eq.8}$$

Similarly, an aggregate fuzzy weight for each criterion j ($j = 1,\ldots,n$), say $\widetilde{w}_j = (w_{j,1}, w_{j,2}, w_{j,3})$, is computed as follows:

$$w_{j,1} = \min_k\left\{w_j^k\right\};\ w_{j,2} = \frac{1}{K}\sum_k w_j^k;\ w_{j,3} = \max_k\left\{w_j^k\right\} \quad \text{Eq.9}$$

Encapsulate aggregate fuzzy ratings into a fuzzy decision matrix & fuzzy weights into a vector of criteria fuzzy weights.

Step 2: Compute weighted normalised aggregate fuzzy ratings, say $\widetilde{n}_{ij}$ ($i = 1,\ldots,m$; $j = 1,\ldots,n$), as follows:

$$\widetilde{n}_{ij} = \widetilde{w}_j \otimes \left(\frac{a_{ij}}{\max_i c_{ij}}, \frac{b_{ij}}{\max_i c_{ij}}, \frac{c_{ij}}{\max_i c_{ij}}\right) = \left(w_{j,1}\frac{a_{ij}}{\max_i c_{ij}}, w_{j,2}\frac{b_{ij}}{\max_i c_{ij}}, w_{j,3}\frac{c_{ij}}{\max_i c_{ij}}\right); i = 1,\ldots,m; j \in C^+ \quad \text{Eq.10}$$

$$\widetilde{n}_{ij} = \widetilde{w}_j \otimes \left(\frac{\min_i a_{ij}}{a_{ij}}, \frac{\min_i a_{ij}}{b_{ij}}, \frac{\min_i a_{ij}}{c_{ij}}\right) = \left(w_{j,1}\frac{\min_i a_{ij}}{a_{ij}}, w_{j,2}\frac{\min_i a_{ij}}{b_{ij}}, w_{j,3}\frac{\min_i a_{ij}}{c_{ij}}\right); i = 1,\ldots,m;\ j \in C^- \quad \text{Eq.11}$$

where C^- (resp. C^+) denote the set of cost criteria (resp. benefit criteria) for which lower (resp. higher) values are better.

FUZZY TOPSIS

Step 3: Compute the fuzzy positive ideal solution (FPIS) and fuzzy negative ideal solution (FNIS), say $\widetilde{n}^+$ and $\widetilde{n}^-$, as follows

$$\widetilde{n}_j^+ = \begin{cases} \min\limits_{i=1,\ldots,m} \widetilde{n}_{ij} IF\ j \in C^- \\ \max\limits_{i=1,\ldots,m} \widetilde{n}_{ij}\ IF\ j \in C^+ \end{cases};\ j = 1,\ldots,n \quad \text{Eq.12}$$

and

$$\widetilde{n}_j^- = \begin{cases} \max\limits_{i=1,\ldots,m} \widetilde{n}_{ij} IF\ j \in C^- \\ \min\limits_{i=1,\ldots,m} \widetilde{n}_{ij}\ IF\ j \in C^+ \end{cases}; j = 1,\ldots,n \quad \text{Eq.13}$$

Step 4: Compute the distances $d(i,\widetilde{n}^+)$ and $d(i,\widetilde{n}^-)$ between each alternative i ($i = 1,\ldots,m$) and FPIS and FNIS, $\widetilde{n}^+$ and $\widetilde{n}^-$ respectively, as follows:

$$d_i^+ = \left\{\frac{1}{n}\sum_j\left(\widetilde{n}_{i,j} - \widetilde{n}_j^+\right)^2\right\}^{\frac{1}{2}} \quad \text{Eq.14}$$

And

$$d_i^- = \left\{\frac{1}{n}\sum_j\left(\widetilde{n}_{i,j} - \widetilde{n}_j^-\right)^2\right\}^{\frac{1}{2}} \quad \text{Eq.15}$$

Step 5: Choose the similarity score – also referred to as the closeness coefficient - for each alternative i ($i = 1,\ldots,m$) as follows:

$$S_i^- = d(i,\widetilde{n}^-) \Big/ \left(d(i,\widetilde{n}^-) + d(i,\widetilde{n}^+)\right) \quad \text{Eq.16}$$

Step 6: Rank alternative in descending order of their similarity scores. Thus, the best alternative is farthest from FNIS and closest to FPIS.

FUZZY VIKOR

Step 3: Defuzzify the weighted normalised aggregate fuzzy ratings, $\widetilde{n}_{ij}$ ($i = 1,\ldots,m$; $j = 1,\ldots,n$), into crisp values, say n_{ij}, as follows

$$n_{ij} = \frac{1}{6}\left(w_{j,1}\frac{a_{ij}}{\max_i c_{ij}} + 4w_{j,2}\frac{b_{ij}}{\max_i c_{ij}} + w_{j,3}\frac{c_{ij}}{\max_i c_{ij}}\right); i = 1,\ldots,m; j \in C^+ \quad \text{Eq.17}$$

and

$$n_{ij} = \frac{1}{6}\left(w_{j,1}\frac{\min_i a_{ij}}{a_{ij}} + 4w_{j,2}\frac{\min_i a_{ij}}{b_{ij}} + w_{j,3}\frac{\min_i a_{ij}}{c_{ij}}\right); i = 1,\ldots,m; j \in C^- \quad \text{Eq.18}$$

Step 4: Compute the crisp positive ideal solution (CPIS), say n^+, using scrip ratings as follows:

$$n_j^+ = \begin{cases} \min\limits_{i=1,\ldots,m} n_{ij} IF\ j \in C^- \\ \max\limits_{i=1,\ldots,m} n_{ij}\ IF\ j \in C^+ \end{cases}; j = 1,\ldots,n \quad \text{Eq.19}$$

Step 5: Compute a performance score, say Q_i, for each alternative i ($i = 1,\ldots,m$) as follows:

$$Q_i = \alpha\left(\frac{S_i - S^+}{S^- - S^+}\right) + (1-\alpha)\left(\frac{R_i - R^+}{R^- - R^+}\right); 0 \le \alpha \le 1 \quad \text{Eq.20}$$

where

$S_i = \sum_{j=1}^m (n_j^+ - n_{ij})$; $R_i = \max_j\{(n_j^+ - n_{ij})\}$

$S^+ = \min_i S_i$; $S^- = \max_i S_i$; $R^+ = \min_i R_i$; $R^- = \max_i R_i$

In our implementation, we have chosen $\alpha = 0.5$.

Step 6: Rank alternative in ascending order of their performance scores. Thus, the best alternative has the smallest Q value.

Table 7
Fuzzy TOPSIS and VIKOR based SAF production pathway ranking.

	Alternate ranking
Fuzzy TOPSIS	A11>A4>A5>A1>A2>A10>A3>A8>A7>A6>A9
Fuzzy VIKOR	A4>A5>A2>A1>A10>A11>A7>A8>A6>A9>A3

Table 8
Correlation coefficients (Spearman's rho) for the raking methods.

	PROMETHEE	Fuzzy TOPSIS	Fuzzy VIKOR
PROMETHEE	1		
Fuzzy TOPSIS	0.927***	1	
Fuzzy VIKOR	0.673***	0.745***	1

***Correlation is significant at the 0.01 level.

not only new investors but also the existing refineries producing sustainable fuel for road transport to include SAF in their business model. Similarly, our analysis may help in devising policy options of setting production/consumption quotas from a specific SAF production pathway, taxing conventional-jet fuel (resulting in a level playing field for a specific SAF production pathway) and subsidising aviation fuels from sustainable production pathways. Moreover, SAF production can be identified as an enabler within wider national climate change policy development, as identified by Larsson et al. (2019).

To conclude, we expect the insights from our study to be considered by decision-makers while making an investment or policy decision regarding SAF production pathways. Our observations suggest for additional research questions that one may consider.[10] For example, it would be interesting to investigate conflicts within each of the social, economic, technical and environmental criteria. Furthermore, we plan to incorporate a range-based approach to explore ranking distributions and include more synthetic pathways for SAF production. We leave these issues for future work.

Appendix

A1
The initial list of SAF production pathways

Production process	Non-food feedstock
HEFA	Algae/Microalgae
	Yellow grease
	Tallow
	Soybean
Gasification/F-T Synthesis	MSW
	Wood residue/Agriculture waste
Pyrolysis	Algae/Microalgae
	Corn stover
	Wood residue/Agriculture waste
Hydrothermal liquefaction	Algae/Microalgae
	Wood residue
ATJ	Wood residue
	Wheat straw
DSHC	Wheat straw
Co-valorisation of CO_2 and waste biomass	Industrial waste gases CO_2 + Wood residue

A2
The initial list of performance criteria

Social	Environmental	Economic	Technical
Contribution to economy	GHG emission savings	Feedstock profitability	Conventional jet fuel compatibility
Food security	Water use	Land productivity	Process technical maturity
Food price	Land use change impact	Minimum selling price	Domestic technological ability
Green branding	Soil and water pollution	Feedstock cost	Production volume scalability
Jobs created	Feedstock sustainability	SAF availability	Energetic content
Social acceptability		Input energy use	Process integration
Technical Partnerships		Operations & maintenance cost	Process yield
Traceability		Plant capital cost	Quality and composition of feedstock
		Feedstock alternative use	Blending limit
		Feedstock transportation and storage cost	Process efficiency
		Long-term off-take agreements	Process flexibility
		Production incentives	SAF yield
		Infrastructure development subsidies	Ease of SAF transportation and storage
		Cost of capital	Combustion Efficiency
			SAF Boiling range
			SAF freezing temperature
			Flash temperature
			SAF Viscosity at −20 °C

A3
Ranking frequency of production processes

	Rank					
Production Process	1	2	3	4	5	6
A2					✓✓	✓✓
A4		✓✓✓	✓			
A5		✓	✓✓✓			
A8					✓✓	
A10					✓✓✓✓	
A11	✓✓✓✓					

[10] We would like to thank one of the anonymous referees suggesting these questions for future research.

References

Agusdinata, D.B., Zhao, F., Ileleji, K., DeLaurentis, D., 2011. LCA of potential biojet fuel production in the United States. Environ. Sci. Technol. 45, 9133–9143.
Ahmad, S., Nadeem, A., Akhanova, G., Houghton, T., Muhammad-Sukki, F., 2017. Multi-criteria evaluation of renewable and nuclear resources for electricity generation in Kazakhstan. Energy 141, 1880–1891.
Amin, L., Hashim, H., Mahadi, Z., Ibrahim, M., Ismail, K., 2017. Determinants of stakeholders' attitudes towards biodiesel. Biotechnol. Biofuels 10, 1–17.
Atsonios, K., Kougioumtzis, M.A., Panopoulos, K.D., Kakaras, E., 2015. Alternative thermochemical routes for aviation biofuels via alcohols synthesis: process modeling, techno-economic assessment and comparison. Appl. Energy 138, 346–366.
Awasthi, A., Chauhan, S.S., Goyal, S.K., 2010. A fuzzy multicriteria approach for evaluating environmental performance of suppliers. Int. J. Prod. Econ. 126, 370–378.
Awasthi, A., Govindan, K., Gold, S., 2018. Multi-tier sustainable global supplier selection using a fuzzy AHP-VIKOR based approach. Int. J. Prod. Econ. 195, 106–117.
Axelsson, L., Franzén, M., Ostwald, M., Berndes, G., Lakshmi, G., Ravindranath, N.H., 2012. Perspective: jatropha cultivation in southern India: assessing farmers' experiences. Biofuels, Bioprod. Biorefining 6, 246–256.
Bann, S.J., Malina, R., Staples, M.D., Suresh, P., Pearlson, M., Tyner, W.E., Hileman, J.I., Barrett, S., 2017. The costs of production of alternative jet fuel: a harmonized stochastic assessment. Bioresour. Technol. 227, 179–187.
Baudry, G., Macharis, C., Vallée, T., 2018a. Range-based Multi-Actor Multi-Criteria Analysis: a combined method of Multi-Actor Multi-Criteria Analysis and Monte Carlo simulation to support participatory decision making under uncertainty. Eur. J. Oper. Res. 264, 257–269.
Baudry, G., Macharis, C., Vallée, T., 2018b. Can microalgae biodiesel contribute to achieve the sustainability objectives in the transport sector in France by 2030? A comparison between first, second and third generation biofuels though a range-based Multi-Actor Multi-Criteria Analysis. Energy 155, 1032–1046.
Bosch, J., de Jong, S., Hoefnagels, R., Slade, R., 2017. Aviation Biofuels: Strategically Important, Technically Achievable, Tough to Deliver.
Brans, J.-P., Mareschal, B., 2005. Promethee methods. Multiple Criteria Decision Analysis: State of the Art Surveys. Springer-Verlag, New York, pp. 163–186.
Brans, J.P., Vincke, P., 1985. A preference ranking organisation method: (the PROMETHEE method for multiple criteria decision-making). Manag. Sci. 31, 647–656.
Buchholz, T., Luzadis, V.A., Volk, T.A., 2009. Sustainability criteria for bioenergy systems: results from an expert survey. J. Clean. Prod. 17, S86–S98.
Castello, D., Haider, M.S., Rosendahl, L.A., 2019. Catalytic upgrading of hydrothermal liquefaction biocrudes: different challenges for different feedstocks. Renew. Energy 141, 420–430.
Chen, Y.K., Lin, C.H., Wang, W.C., 2020. The conversion of biomass into renewable jet fuel. Energy 201, 117655.
Cheng, F., Brewer, C.E., 2017. Producing jet fuel from biomass lignin: potential pathways to alkyl-benzenes and cycloalkanes. Renew. Sustain. Energy Rev. 72, 673–722.
Chiaramonti, D., 2019. Sustainable aviation fuels: the challenge of decarbonization. Energy Procedia 158, 1202–1207.
Chu, P.L., Vanderghem, C., MacLean, H.L., Saville, B.A., 2017. Financial analysis and risk assessment of hydroprocessed renewable jet fuel production from camelina, carinata and used cooking oil. Appl. Energy 198, 401–409.
Chuck, C.J., Donnelly, J., 2014. The compatibility of potential bioderived fuels with Jet A-1 aviation kerosene. Appl. Energy 118, 83–91.
Curiel-Esparza, J., Mazario-Diez, J.L., Canto-Perello, J., Martin-Utrillas, M., 2016. Prioritization by consensus of enhancements for sustainable mobility in urban areas. Environ. Sci. Pol. 55, 248–257.
Daroch, M., Geng, S., Wang, G., 2013. Recent advances in liquid biofuel production from algal feedstocks. Appl. Energy 102, 1371–1381.
Dayton, D.C., Foust, T.D., 2020. Alternative jet fuels. Anal. Methods Biomass Charact. Convers. 147–165.
de Jong, S., Antonissen, K., Hoefnagels, R., Lonza, L., Wang, M., Faaij, A., Junginger, M., 2017. Life-cycle analysis of greenhouse gas emissions from renewable jet fuel production. Biotechnol. Biofuels 10, 1–18.
de Jong, S., Hoefnagels, R., Faaij, A., Slade, R., Mawhood, R., Junginger, M., 2015. The feasibility of short-term production strategies for renewable jet fuels - a comprehensive techno-economic comparison. Biofuels, Bioprod. Biorefining 9, 778–800.
Deane, J.P., Pye, S., 2018. Europe's ambition for biofuels in aviation - a strategic review of challenges and opportunities. Energy Strateg. Rev. 20, 1–5.
Department for Transport, 2018. Aviation 2050 - the Future of UK Aviation.
Diederichs, G.W., Ali Mandegari, M., Farzad, S., Görgens, J.F., 2016. Techno-economic comparison of biojet fuel production from lignocellulose, vegetable oil and sugar cane juice. Bioresour. Technol. 216, 331–339.
Dimitriadis, A., Bezergianni, S., 2017. Hydrothermal liquefaction of various biomass and waste feedstocks for biocrude production: a state of the art review. Renew. Sustain. Energy Rev. 68, 113–125.
Doyle, J.R., Green, R.H., Bottomley, P.A., 1997. Judging relative importance: direct rating and point Allocation are not equivalent. Organ. Behav. Hum. Decis. Process. 70, 65–72.
Dožić, S., 2019. Multi-criteria decision making methods: application in the aviation industry. J. Air Transport. Manag. 79.
Efroymson, R.A., Dale, V.H., Langholtz, M.H., 2017. Socioeconomic indicators for sustainable design and commercial development of algal biofuel systems. GCB Bioenergy 9 (6), 1005–1023.
Filimonau, V., Högström, M., 2017. The attitudes of UK tourists to the use of biofuels in civil aviation: an exploratory study. J. Air Transport. Manag. 63, 84–94.
Filimonau, V., Mika, M., Pawlusiński, R., 2018. Public attitudes to biofuel use in aviation: evidence from an emerging tourist market. J. Clean. Prod. 172, 3102–3110.
Fiorese, G., Catenacci, M., Verdolini, E., Bosetti, V., 2012. Advanced biofuels: future perspectives from an expert elicitation survey. Energy Pol. 56, 293–311.
Fortier, M.O.P., Roberts, G.W., Stagg-Williams, S.M., Sturm, B.S.M., 2014. Life cycle assessment of bio-jet fuel from hydrothermal liquefaction of microalgae. Appl. Energy 122, 73–82.
Ganguly, I., Pierobon, F., Bowers, T.C., Huisenga, M., Johnston, G., Eastin, I.L., 2018. 'Woods-to-Wake' Life Cycle Assessment of residual woody biomass based jet-fuel using mild bisulfite pretreatment. Biomass Bioenergy 108, 207–216.
Gawron, B., Białecki, T., Janicka, A., Suchocki, T., 2020. Combustion and emissions characteristics of the turbine engine fueled with HeFA blends from different feedstocks. Energies 13, 1–12.
Gegg, P., Wells, V., 2017. UK macro-algae biofuels: a strategic management review and future research agenda. J. Mar. Sci. Eng. 5, 32.
Geleynse, S., Jiang, Z., Brandt, K., Garcia-Perez, M., Wolcott, M., Zhang, X., 2020. Pulp mill integration with alcohol-to-jet conversion technology. Fuel Process. Technol. 201, 106338.
Gollakota, A.R.K., Kishore, N., Gu, S., 2018. A review on hydrothermal liquefaction of biomass. Renew. Sustain. Energy Rev. 81, 1378–1392.
Guo, F., Wang, X., Yang, X., 2017. Potential pyrolysis pathway assessment for microalgae-based aviation fuel based on energy conversion efficiency and life cycle. Energy Convers. Manag. 132, 272–280.
Han, J., Elgowainy, A., Cai, H., Wang, M.Q., 2013. Life-cycle analysis of bio-based aviation fuels. Bioresour. Technol. 150, 447–456.
Hileman, J.I., Stratton, R.W., 2014. Alternative jet fuel feasibility. Transport Pol. 34, 52–62.
Hwang, C.-L., ve Yoon, K., 1981. Multiple Attribute Decision Making-Methods and Applications: A State of the Art Survey. Springer, New York.
IATA, 2019a. Economic Performance of the Airline Industry.
IATA, 2019b. Sustainable Aviation Fuels Fact Sheet.
IATA, 2014. Report on Alternative Fuels.
ICAO, 2016. On Board: A Sustainable Future - 2016 Environmental Report.
IRENA, 2017. Biofuels for Aviation: Technology Brief.
IRENA, 2016. Innovation Outlook Advanced Liquid Biofuels.
Janić, M., 2018. An assessment of the potential of alternative fuels for "greening" commercial air transportation. J. Air Transport. Manag. 69, 235–247.
Kandaramath Hari, T., Yaakob, Z., Binitha, N.N., 2015. Aviation biofuel from renewable resources: routes, opportunities and challenges. Renew. Sustain. Energy Rev. 42, 1234–1244.
Kassem, A., Al-Haddad, K., Komljenovic, D., Schiffauerova, A., 2016. A value tree for identification of evaluation criteria for solar thermal power technologies in developing countries. Sustain. Energy Technol. Assessments 16, 18–32.
Kim, Y., Lee, J., Ahn, J., 2019. Innovation towards sustainable technologies: a socio-technical perspective on accelerating transition to aviation biofuel. Technol. Forecast. Soc. Change 145, 317–329.
Kivits, R., Charles, M.B., Ryan, N., 2010. A post-carbon aviation future: airports and the transition to a cleaner aviation sector. Futures 42, 199–211.
Klein, B.C., Chagas, M.F., Junqueira, T.L., Rezende, M.C.A.F., Cardoso, T. de F., Cavalett, O., Bonomi, A., 2018. Techno-economic and environmental assessment of renewable jet fuel production in integrated Brazilian sugarcane biorefineries. Appl. Energy 209, 290–305.
Kolosz, B.W., Luo, Y., Xu, B., Maroto-Valer, M.M., Andresen, J.M., 2020. Life cycle environmental analysis of 'drop in'alternative aviation fuels: a review. Sustain. Energy Fuels 4 (7), 3229–3263.
Kousoulidou, M., Lonza, L., 2016. Biofuels in aviation: fuel demand and CO2emissions evolution in Europe toward 2030. Transport. Res. Transport Environ. 46, 166–181.
Lai, Y.L., Ishizaka, A., 2020. The application of multi-criteria decision analysis methods into talent identification process: a social psychological perspective. J. Bus. Res. 109, 637–647.
Lanzini, P., Testa, F., Iraldo, F., 2016. Factors affecting drivers' willingness to pay for biofuels: the case of Italy. J. Clean. Prod. 112, 2684–2692.
Larsson, J., Elofsson, A., Sterner, T., Åkerman, J., 2019. International and national climate policies for aviation: a review. Clim. Pol. 19, 787–799.
Li, X., Mupondwa, E., Tabil, L., 2018. Technoeconomic analysis of biojet fuel production from camelina at commercial scale: case of Canadian Prairies. Bioresour. Technol. 249, 196–205.
Li, Y., Tseng, C.L., Hu, G., 2015. Is now a good time for Iowa to invest in cellulosic biofuels? A real options approach considering construction lead times. Int. J. Prod. Econ. 167, 97–107.
Lienert, J., Duygan, M., Zheng, J., 2016. Preference stability over time with multiple elicitation methods to support wastewater infrastructure decision-making. Eur. J. Oper. Res. 253, 746–760.

Lokesh, K., Sethi, V., Nikolaidis, T., Goodger, E., Nalianda, D., 2015. Life cycle greenhouse gas analysis of biojet fuels with a technical investigation into their impact onjet engine performance. Biomass Bioenergy 77, 26–44.
Malik, M., Abdallah, S., Orr, S., Chaudhary, U., 2019. The differences in agent effects on sustainable supply chain management: an activity theory construction. Supply Chain Manag. 24, 637–658.
Markevičius, A., Katinas, V., Perednis, E., Tamašauskienė, M., 2010. Trends and sustainability criteria of the production and use of liquid biofuels. Renew. Sustain. Energy Rev. 14, 3226–3231.
McGuire, J.B., Leahy, J.E., Marciano, J.A., Lilieholm, R.J., Teisl, M.F., 2017. Social acceptability of establishing forest-based biorefineries in Maine, United States. Biomass Bioenergy 105, 155–163.
Michailos, S., 2018. Process design, economic evaluation and life cycle assessment of jet fuel production from sugar cane residue. Environ. Prog. Sustain. Energy 37, 1227–1235.
Moore, R.H., Thornhill, K.L., Weinzierl, B., Sauer, D., D'Ascoli, E., Kim, J., Lichtenstern, M., Scheibe, M., Beaton, B., Beyersdorf, A.J., Barrick, J., Bulzan, D., Corr, C.A., Crosbie, E., Jurkat, T., Martin, R., Riddick, D., Shook, M., Slover, G., Voigt, C., White, R., Winstead, E., Yasky, R., Ziemba, L.D., Brown, A., Schlager, H., Anderson, B.E., 2017. Biofuel blending reduces particle emissions from aircraft engines at cruise conditions. Nature 543, 411–415.
Müller, C., Kieckhäfer, K., Spengler, T.S., 2018. The influence of emission thresholds and retrofit options on airline fleet planning: an optimization approach. Energy Pol. 112, 242–257.
Neuling, U., Kaltschmitt, M., 2018. Techno-economic and environmental analysis of aviation biofuels. Fuel Process. Technol. 171, 54–69.
Neves, R.C., Klein, B.C., da Silva, R.J., Rezende, M.C.A.F., Funke, A., Olivarez-Gómez, E., Bonomi, A., Maciel-Filho, R., 2020. A vision on biomass-to-liquids (BTL) thermochemical routes in integrated sugarcane biorefineries for biojet fuel production. Renew. Sustain. Energy Rev. 119.
Niklaß, M., Lührs, B., Grewe, V., Dahlmann, K., Luchkova, T., Linke, F., Gollnick, V., 2016. Potential to reduce the climate impact of aviation by climate restricted airspaces. Transport Pol. 1–9.
O'Connell, A., Kousoulidou, M., Lonza, L., Weindorf, W., 2019. Considerations on GHG emissions and energy balances of promising aviation biofuel pathways. Renew. Sustain. Energy Rev. 101, 504–515.
Oliveira, G.A., Tan, K.H., Guedes, B.T., 2018. Lean and green approach: an evaluation tool for new product development focused on small and medium enterprises. Int. J. Prod. Econ. 205, 62–73.
Opricovic, S., 1998. Multicriteria Optimization of Civil Engineering Systems.
Opricovic, S., Tzeng, G.H., 2004. Compromise solution by MCDM methods: a comparative analysis of VIKOR and TOPSIS. Eur. J. Oper. Res. 156 (2), 445–455.
Ouenniche, J., Xu, B., Pérez-Gladish, B., 2018. A DSS for designing an MCDA study with application in performance evaluation of forecasting models. Financial Decision Aid Using Multiple Criteria. Multiple Criteria Decision Making. Springer, Cham, pp. 19–48.
Pischke, E.C., Rouleau, M.D., Halvorsen, K.E., 2018. Public perceptions towards oil palm cultivation in Tabasco, Mexico. Biomass Bioenergy 112, 1–10.
Radics, R.I., Dasmohapatra, S., Kelley, S.S., 2016. Public perception of bioenergy in North Carolina and Tennessee. Energy. Sustain. Soc. 6.
Ribeiro, L.A., Pereira da Silva, P., Ribeiro, L., Dotti, F.L., 2017. Modelling the impacts of policies on advanced biofuel feedstocks diffusion. J. Clean. Prod. 142, 2471–2479.
Royal Academy of Engineering, 2017. Sustainability of Liquid Biofuels. Royal Academy of Engineering.
Schäfer, A.W., Barrett, S.R.H., Doyme, K., Dray, L.M., Gnadt, A.R., Self, R., O'Sullivan, A., Synodinos, A.P., Torija, A.J., 2019. Technological, economic and environmental prospects of all-electric aircraft. Nat. Energy 4, 160–166.
Schillo, R.S., Isabelle, D.A., Shakiba, A., 2017. Linking advanced biofuels policies with stakeholder interests: a method building on Quality Function Deployment. Energy Pol. 100, 126–137.
Seber, G., Malina, R., Pearlson, M.N., Olcay, H., Hileman, J.I., Barrett, S.R.H., 2014. Environmental and economic assessment of producing hydroprocessed jet and diesel fuel from waste oils and tallow. Biomass Bioenergy 67, 108–118.
Sgouridis, S., Bonnefoy, P.A., Hansman, R.J., 2011. Air transportation in a carbon constrained world: long-term dynamics of policies and strategies for mitigating the carbon footprint of commercial aviation. Transport. Res. Part A Policy Pract. 45, 1077–1091.
Shah, Z., Veses, R.C., Vaghetti, J.C.P., Amorim, V.D.A., Silva, R. da, 2019. Preparation of jet engine range fuel from biomass pyrolysis oil through hydrogenation and its comparison with aviation kerosene. Int. J. Green Energy 16, 350–360.
Shahabuddin, M., Alam, M.T., Krishna, B.B., Bhaskar, T., Perkins, G., 2020. A review on the production of renewable aviation fuels from the gasification of biomass and residual wastes. Bioresour. Technol. 312, 123596.
Sikarwar, V.S., Zhao, M., Fennell, P.S., Shah, N., Anthony, E.J., 2017. Progress in biofuel production from gasification. Prog. Energy Combust. Sci. 61, 189–248.
Silva, L.N., Fortes, I.C.P., De Sousa, F.P., Pasa, V.M.D., 2016. Biokerosene and green diesel from macauba oils via catalytic deoxygenation over Pd/C. Fuel 164, 329–338.
Sims, R.E.H., Mabee, W., Saddler, J.N., Taylor, M., 2010. An overview of second generation biofuel technologies. Bioresour. Technol. 101, 1570–1580.
Staples, M.D., Malina, R., Suresh, P., Hileman, J.I., Barrett, S.R.H., 2018. Aviation CO2emissions reductions from the use of alternative jet fuels. Energy Pol. 114, 342–354.
Suresh, P., Malina, R., Staples, M.D., Lizin, S., Olcay, H., Blazy, D., Pearlson, M.N., Barrett, S.R.H., 2018. Life cycle greenhouse gas emissions and costs of production of diesel and jet fuel from municipal solid waste. Environ. Sci. Technol. 52, 12055–12065.
Tao, L., Milbrandt, A., Zhang, Y., Wang, W.C., 2017. Techno-economic and resource analysis of hydroprocessed renewable jet fuel. Biotechnol. Biofuels 10, 1–16.
Tenenbaum, D.J., 2008. Food vs. fuel diversion of crops could cause more hunger. Environ. Health Perspect. 116, 254–257.
The Royal Society, 2019. Sustainable Synthetic Carbon Based Fuels for transport:Policy Briefing.
Trivedi, P., Olcay, H., Staples, M.D., Withers, M.R., Malina, R., Barrett, S.R.H., 2015. Energy return on investment for alternative jet fuels. Appl. Energy 141, 167–174.
Turcksin, L., Macharis, C., Lebeau, K., Boureima, F., Van Mierlo, J., Bram, S., De Ruyck, J., Mertens, L., Jossart, J.M., Gorissen, L., Pelkmans, L., 2011. A multi-actor multi-criteria framework to assess the stakeholder support for different biofuel options: the case of Belgium. Energy Pol. 39, 200–214.
Tzanetis, K.F., Posada, J.A., Ramirez, A., 2017. Analysis of biomass hydrothermal liquefaction and biocrude-oil upgrading for renewable jet fuel production: the impact of reaction conditions on production costs and GHG emissions performance. Renew. Energy 113, 1388–1398.
Ubando, A.T., Cuello, J.L., El-Halwagi, M.M., Culaba, A.B., Promentilla, M.A.B., Tan, R. R., 2016. Application of stochastic analytic hierarchy process for evaluating algal cultivation systems for sustainable biofuel production. Clean Technol. Environ. Policy 18, 1281–1294.
Wang, W.C., Tao, L., 2016. Bio-jet fuel conversion technologies. Renew. Sustain. Energy Rev. 53, 801–822.
Wang, Z., Pashaei Kamali, F., Osseweijer, P., Posada, J.A., 2019. Socioeconomic effects of aviation biofuel production in Brazil: a scenarios-based Input-Output analysis. J. Clean. Prod. 230, 1036–1050.
Wątróbski, J., Jankowski, J., Ziemba, P., Karczmarczyk, A., Zioło, M., 2019. Generalised framework for multi-criteria method selection. Omega 86, 107–124.
Xu, B., Nayak, A., Gray, D., Ouenniche, J., 2016. Assessing energy business cases implemented in the North Sea Region and strategy recommendations. Appl. Energy 172, 360–371.
Yaghoubi, J., Yazdanpanah, M., Komendantova, N., 2019. Iranian agriculture advisors' perception and intention toward biofuel: green way toward energy security, rural development and climate change mitigation. Renew. Energy 130, 452–459.
Zemanek, D., Champagne, P., Mabee, W., 2020. Review of life-cycle greenhouse-gas emissions assessments of hydroprocessed renewable fuel (HEFA) from oilseeds. Biofuels, Bioprod. Biorefining 1–15.
Zhang, C., Hui, X., Lin, Y., Sung, C.J., 2016. Recent development in studies of alternative jet fuel combustion: progress, challenges, and opportunities. Renew. Sustain. Energy Rev. 54, 120–138.
Zhang, Huili, Fang, Y., Wang, M., Appels, L., Deng, Y., 2020. Prospects and perspectives foster enhanced research on bio-aviation fuels. J. Environ. Manag. 274, 111214.
Zhang, Hanfei, Wang, L., Van herle, J., Maréchal, F., Desideri, U., 2020. Techno-economic evaluation of biomass-to-fuels with solid-oxide electrolyzer. Appl. Energy 270, 115113.
Zheng, Y., Wang, J., Yu, B., Zhang, W., Chen, J., Qiao, J., Zhang, J., 2017. A review of high temperature co-electrolysis of H2O and CO2to produce sustainable fuels using solid oxide electrolysis cells (SOECs): advanced materials and technology. Chem. Soc. Rev. 46, 1427–1463.