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Performance Evaluation of Alternative Jet Fuels using a hybrid MCDA method

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Abstract

We design a hybrid multi-criteria decision-making analysis (MCDA)-based framework to evaluate competing alternative jet fuels (AJFs). Our analysis on AJFs is based on a wide range of criteria with different forms of data and relations and reflect stakeholders' view and opinions. This contrast with conventional cost-benefit analysis which typically focuses on the economic benefits at the expense of environmental, technological and social aspects. Our work adds value to understand developing technologies to date, technical barriers to commercialization, other development drivers such as the availability and willingness of financial institutions to finance, businesses to invest in AJFs productions and its supply chains in the UK, policy support and regulation, and likely commercialization and scale-up potentials. By focusing on motives, attitudes and stakeholders rather than merely the technical and economic aspects of AJFs, our paper makes an important contribution to the field.

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Keywords: Alternative jet fuels; multi-criteria decision-making analysis; stakeholder analysis; Gasification and FT Synthesis; Analytical Hierarchy Process; PROMETHEE II

Nomenclature

A	Set of alternative jet fuel business cases
j	Alternative jet fuel criteria
d_j	Performance difference between competing AJF business cases
p_j	Preference function
$P(a,b)$	Aggregated preference index
$P(b,a)$	Inverse aggregated preference index
ι_j	Indifference threshold to determine choice negligibility
α_j	Distance to decision indifference
β_j	Distance to decision preference
π_j	Preference threshold to imply preferred choice
w_j	Importance coefficients of criteria
ϕ^+(a)	Positive outranking flows for technology a
ϕ^-(a)	Negative outranking flows for technology a

1. Introduction

In response to global climate change, the UK government has committed to achieve at least 80% greenhouse gas (GHG) emissions reduction by 2050 against the 1990 baseline. The transportation sector remains one of the major sources of emissions, and the energy consumption in transport creates a significant problem of energy dependency as it relies to a large extent on petroleum. Industries and researchers are continuously devising and improving sustainable low carbon technology solutions on road vehicles, while less attention has been paid for

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other transport modes (e.g., aviation and HGV sectors) which are difficult to decarbonize. Yet, the aviation sector is one of the most rapidly growing transport sectors and the increased environmental impacts are concerning.[2]

One of the most viable options to decarbonize the aviation industry is to develop "drop-in" alternative jet fuels (AJFs) which can substitute fossil fuels without modifying existing aircraft technology [1]. Electrifications of commercial flights while currently being explored are arguably infeasible at this moment in time. Most studies tend to measure the effectiveness of AJFs via a qualitative approach, or cost-benefit analysis (CBA) or minimizing carbon reductions. For instance, [2] summarizes advantages and issues related to aviation-grade algae biofuel which is classed as the latest (third) generation of biofuel feedstocks. [3] quantifies and compares the costs of production of six AJF pathways using consistent financial and technical assumptions.

Governments support production of AJFs and airlines are keen to consume AJFs [1]. Figure 1 shows a list of airline companies used alternative jet fuels in test commercial flights for the period of 2008 to 2018 – see IATA [4].[3] However, the availability and cost of AJFs, immature supply chains and potential disruption required to alter established operational practices are significant barriers for large AJFs in-takes for airline companies [1]. Energy companies require more benefit in switching and/or investing in risky high capital costs bio-energy production technologies. Consequently, it is important to identify the most effective AJFs that can be acceptable to all stakeholders rather than those with the best CBA or which are best at mitigating carbon emissions. A methodology is required which can systematically consider often-divergent perspectives of stakeholders ranging from end-users to investors who are potentially involved in delivering and consuming AJFs [5].

Fig.1. Alternative fuels for test flights and commercial flights between 2008-2018 [IATA]

In this paper, we design a hybrid multi-criteria decision-making analysis (MCDA)-based methodological framework to assess competing AJFs technology options. Furthermore, we focus on identifying the key barriers that affect the commercial development, deployment and consumption of AJFs based on both prior literature and stakeholder engagements. Our proposed framework provides an in-depth understanding of contrasting technology advantages (e.g., reduced CO_2 emissions, stakeholders' interest) and drawbacks (e.g., low degree of technology maturity, high investment cost, high operating and maintenance costs, low production volumes); with comparisons on individual criteria and the entire criteria set. By focusing on motives, attitudes and stakeholders rather than merely the technical and economic aspects of AJFs, our paper makes a new contribution to the field. We also discuss potential policies and incentives on encouraging research and development, and investment in UK based bio-refineries.

The rest of the report is organized as follows. Section 2 presents the frameworks that have been designed. Section 3 reports and discusses our empirical results. Section 4 concludes the paper.

2. MCDA Framework

In seeking to assess the relative performance of AJFs, we use an MCDA-based framework methodology. Note that MCDA is a generic framework and as such implementation of our specific evaluation of relative performance of AJFs requires several key decisions to be made.

2.1. Stakeholder Analysis and Preference Gathering

One of the key challenges in assessing AJFs is to identify and use criteria which have credibility among, and reflect the differing perspectives of, a potentially diverse group of stakeholders. Therefore, we first performed a stakeholder analysis to identify relevant parties who have a vested interest and potential influence to accelerate the development and deployment of AJFs.

We have classified them into different categories depending on the nature of their businesses/organizations – see Fig.2. For example, key government and other bodies such as Knowledge Transfer Network (KTN) special interest groups on sustainable aviation (SA SIG); IATA; Roundtable on Sustainable Biomaterials (RSB),

[2] For example, the International Civil Aviation Organization (ICAO) forecasted that by 2050 aviation emissions could grow by a further 300-700% compared to 2005.
[3] Four airports (e.g., LA, Bergen, Oslo, Stockholm) with regularly supply of AJFs, and eight airlines (e.g., United; JetBlue; Cathay) have concluded long-term off-take agreements with biofuel suppliers using AJFs. [4]

Transport of Scotland; key technology companies such as Johnson Matthey; Future Blends; Velocys; Shanxi Lu'an Ltd; China Huaneng Group. We are engaging with various stakeholders to gather their views and preferences on issues related to AJFs via different channels (e.g., conferences; workshops; seminars; site visits).

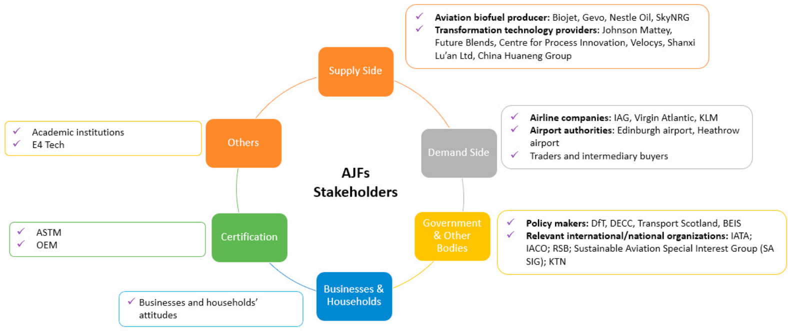

Fig.2. Alternative Jet Fuels Stakeholders

First, what are the alternative jet fuels technologies to be assessed? We evaluate 6 potential alternative jet fuel production pathways for which data are available in peer-reviewed literature: Gasification with FT synthesis; Fast pyrolysis and hydroprocessing (FPH); Aqueous phase processing (APP); Hydroprocessed Esters and Fatty Acids (HEFA); Advanced fermentation (AF); Hydrothermal liquefaction (HTL) [1,2,3,6,7] – see Table 1. We consider different feedstocks and obtain insights by studying leading developers on the specific pathways.

Table 1: Potential Alternative Jet Fuel Production Pathways.

Pathway	Feedstock
Gasification + FT Synthesis	Waste
Fast pyrolysis and hydroprocessing (FPH)	Corn stover
Aqueous phase processing (APP)	Woody biomass
Hydroprocessed Esters and Fatty Acids (HEFA)	Soybean oil, tallow, yellow grease
Advanced fermentation (AF)	Corn grain, sugarcane, herbaceous biomass
Hydrothermal liquefaction (HTL)	Woody biomass

Second, what are the criteria and how to measure them? To generate and define a list of criteria, we have reviewed the relevant literature and consulted industrial experts in 3 workshops. In sum, we have identified a final list of 10 criteria and their corresponding measures. We have broadly divided them into the following four aspects; namely, financial, environmental, technical, and social dimensions – see Table 2 for detailed definitions.

Third, what are the relative importance of criteria? Another important task is to find out the relative importance for each criterion. Several methods could be used to generate weights for each criterion, such as Max100, Min100, point allocation method, and the Analytic Hierarchy Process (AHP). In this study, we have opted for the AHP approach to compute the vector of criteria weights to fully reflect stakeholders' views and opinions. In first the stage, we construct a qualitative judgement on the relative importance of each criterion with respect to each sub-criterion. We then translate these qualitative judgements into numerical scales from 1 to 9 and compute the criterion weights. In addition, we use an equal weighting scheme as a benchmark to check how sensitive or robust rankings of strategies are to decision makers' preferences.

Table 2: Description of criteria used in evaluating AJFs

	Criteria	Definition
Financial	**Investment Cost**	This criterion refers to the additional investment required to provide a business as usual scenario on the standard production of jet fuel. This can include but is not limited to technology, specialist services, advice and consultancy, construction of physical structures and transport structures to support production of AJFs.
	Running Cost	Running costs consists of both operation and maintenance costs required over business as usual scenario. To be more specific, the operating costs is determined as a percentage of the investment cost to reflect the size of the operation. This also include the cost for acquiring and processing the relevant feedstocks.
	Revenues	Total revenues would potentially generate from selling fuel products such as LPG, naphtha, middle distillates, gasoline, heavy oil.
Environmental	**CO2 Emissions Savings**	Measured by the net CO2 emissions savings compared to conventional petroleum jet fuel technologies.
Technical	**Pathway Efficiency**	Refers to the production rate of jet fuel based upon required resources.
	Technology Maturity	Technological maturity of the process pathway based upon technological readiness (TRL)level (1-9). Calculated via weakest link theory i.e., the technology within the process with the lowest TRL level.
	Transferability	This criterion refers to the extent to which a specific AJF technology could be transferred for use in a different environment. Decision makers were invited to identify hurdles transferability might face, and potential opportunities.
Social	**Stakeholders' Interest**	It is important to gather the views and opinions from various stakeholders (e.g., airline companies; government bodies; energy companies) regarding to their interests and concerns to a specific AJF technology.
	Wealth and Job Creation	This criterion is measured by the extent to which the implementation of a specific alternative jet fuel production plant would generate wealth and jobs.

2.2. MCDA method

In this study, we use of a hybrid MCDA method which include AHP and Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE) II methods. Note that PROMETHEE II is an outranking method capable of accommodating conflicting criteria, as well as any mix of quantitative and qualitative measures of such criteria. The basic principle of PROMETHEE II is based on pair-wise comparisons of competing AJFs on each criterion, where a criterion could either be maximized or minimized [5, 8].

The main steps of the integrated PROMETHEE II method can be summarized as follows:

Step 1: Compute the weighted averages of weights or relative importance coefficients of n criteria, say w_j over k experts, by using the *AHP method*:

$$\overline{w}_j = \frac{1}{K}\sum_{j=1}^{K} w_j \tag{1}$$

Step 2: For each criterion j, we choose the preference function p_j as follows:

$$p_j(d_j) = \begin{cases} 0, & if \;\; d_j \le \iota_j \\ \frac{d_j - \iota_j}{\pi_j - \iota_j}, & if \; \iota_j < d_j \le \pi_j \\ 1, & if \;\; d_j > \pi_j \end{cases} \tag{2}$$

where d_j denotes the difference in performance with respect to criterion j between a pair of competing AJFs; ι_j is the indifference threshold and any difference smaller or equal to this threshold is considered as negligible by the decision maker; π_j is the preference threshold and implies strict preference; any difference in-between implies hesitation, and we assign a score accordingly.

Step 3: For each criterion j, we use the appropriate threshold elicitation method to determine indifference and preference thresholds as functions of the range of values of the corresponding measure, as follows:

$$\iota_j = \alpha_j \times (\max_{\alpha \in A}\{g_j(a)\} - \min_{\alpha \in A}\{g_j(a)\}); \quad \alpha_j \in (0,1) \quad (3)$$

$$\pi_j = \beta_j \times (\max_{\alpha \in A}\{g_j(a)\} - \min_{\alpha \in A}\{g_j(a)\}); \beta_j \in (0,1) \quad (4)$$

where A denotes the set of AJFs. Note that α_j and β_j reflect percentages of the range of values taken by criterion j that would lead to indifference and preference situations, respectively. Depends on the nature of application, we can set them the values according to the literature. Note that if we set them to zero for a specific criterion, then it provides an absolute discriminating power: that is, any difference matters, regardless of its magnitude. On the other hand, we can set non-zero values for of α_j and β_j to provide a non-absolute or nuanced discriminating power in which differences within a small range are essentially not meaningful.

Step 4. Compute preference indices for each pair of alternatives, as follows:

$$P(a,b) = \sum_{j=1}^{m} w_j \times P_j(a,b); \; P(b,a) = \sum_{j=1}^{m} w_j \times P_j(a,b) \quad (5)$$

where $P(a,b)$ is the aggregated preference index and expresses to what extent a is preferred to b over all the criteria; while $P(b,a)$ expresses to what extent b is preferred to a.

Step 5. Compute the positive and negative outranking flows for each alternative, say $\phi^+(\text{a})$ and $\phi^-(\text{a})$ respectively, as follows:

$$\phi^+(\text{a}) = \frac{1}{n-1}\sum_{b \in A\setminus\{\alpha\}} P(a,b); \; \phi^-(\text{a}) = \frac{1}{n-1}\sum_{b \in A\setminus\{\alpha\}} P(b,a) \quad (6)$$

Step 6. Compute the net outranking flow for each alternative:

$$\phi(a) = \phi^+(\text{a}) - \phi^-(\text{a}) \quad (7)$$

Step 7. Use the net outranking flows computed in the previous step to define a binary outranking relation, say S, as follows:

$$\alpha \text{ S } \text{b} \Leftrightarrow \phi(a) \geq \phi(b) \quad (8)$$

3. Preliminary Results

In this session, we report some preliminary results based on using data from [3] under three simple criteria: investment costs; running costs and revenues. Table 3 provides the simple multi-criteria ranking produced by the integrated PROMTHEE II method.

First, we focus on low investment costs scheme for those commercially motivated stakeholders who prefer with a low capital investment costs over the remaining aspects in prioritizing what makes a good investment in AJFs productions pathways – see the first three columns of Table 3. This resulted in the following simple weight vector [0.5;0.3;0.2]. We obtained the net outranking flow score ($\phi(a)$), which is the net score between positive and negative outranking flows. Recall that a positive outranking flow of an AJF measures the extent to which it outranks (better than) other AJFs, whereas a negative outranking flow of an AJF indicates the extent to which it is outranked by (worse than) other AJFs. Obviously, the higher the net flow score, the better the AJF pathway performs in relation to other options. Our results revealed that the HEFA using yellow grease is ranked the first, with the highest net outranking flow $\phi(a)$ of 0.5027, whereas the AF using herbaceous biomass is ranked the last with the lowest ϕ of -0.7996.

Table 3: Preliminary Results

Low Investment Costs Scheme			Equal Weight Scheme		
Rank	**Pathways + Feedstocks**	$\phi(a)$	**Rank**	**Pathways + Feedstocks**	$\phi(a)$
1	HEFA using yellow grease	0.5027	1	FPH using corn stove	0.4044
2	HEFA using tallow	0.3774	2	HEFA using yellow grease	0.3429
3	FPH using corn stove	0.3258	3	AF using sugarcane	0.2416
4	HEFA using soybean	0.2063	4	HEFA using tallow	0.2062
5	AF using sugarcane	0.1968	5	Gasification/FT Synthesis using Waste	0.1630
6	Gasification/FT Synthesis using waste	0.0978	6	HEFA using soybean	0.0106
7	AF using corn grain	-0.0467	7	AF using corn grain	-0.0890
8	APP using woody biomass	0.3444	8	APP using woody biomass	-0.0741
9	HTL using woody biomass	-0.5162	9	HTL using woody biomass	-0.5254
10	AF using herbaceous biomass	-0.7996	10	AF using herbaceous biomass	-0.7602

To check to what extent, the preference of decision makers will affect the results reported earlier, we consider a neutral scenario in which we assume that each criterion is equally important; thus, the weighting vector is simply [0.33; 0.33; 0.33]. The right panel of Table 3 provides the rankings based on an equal weighting scheme. We find that by altering the weights to an equal weighting scheme, the rankings of the best and worst performing technologies did not change much.

However, nowadays AJFs still plays a very minor role in relation to the conventional kerosene jet fuels. The key barriers for large-scale commercial development and consumptions of AJFs including large price gap between conventional kerosene jet fuels and bio-jet fuels; immature supply chains; feedstocks availability and costs; and policy frameworks [1,4,9,10]. For example, for HEFA fuels, feedstock costs accounts for a significant proportion of total costs, and a high proportion of used cooking oil is already been used for biodiesel production [9].

4. Conclusions

In this paper, we proposed a hybrid MCDA-based framework to evaluate a range of competing AJFs. Our analysis constitutes various criteria and different forms of data and relations, to compare different AJFs and to reflect the multiple interests and priorities of numerous stakeholders. Our work adds value to understand the technology development to date, technical barriers to commercialization, other development drivers such as the availability and willingness of financial institutions to finance, businesses to invest in AJFs productions and its supply chains in the UK, policy support and regulation, in addition to commercialization and scale-up potentials. We hope our findings can enable relevant government body to assess the potential policy and incentives on commercialization barriers and increase investment, and to understand how policy can be shaped to support continued development and investment in potential UK biorefineries.

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