Targeted Aviation Advanced Biofuels Demonstration Competition – Feasibility Study

Final report

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Executive summary

Renewable fuels of biological and non-biological origin will be an important part of the overall decarbonisation of transport. Sustainable aviation fuel (SAF), in particular, is likely to be essential to decarbonising the aviation industry given that alternatives like electrification may not be able to service medium-long haul flights.

Globally, there is an emerging sustainable aviation fuels market. The UK currently has no production of SAF, and Government support would be needed to develop UK-based production and bridge the gap between new technologies and commercially demonstrated plants.

This study has shown that there are a range of technologies at different maturities that could produce SAF and a pool of UK and international developers that could build demonstration and commercial SAF plants in the UK. The vast majority of these technologies could deliver GHG reductions in excess of 70% in comparison with fossil kerosene. But, securing investment for these high-risk and potentially capital intensive projects (commercial plants costs are around £600M to £700M) faces a number of barriers:

- **Technology risk:** There is a high degree of technology risk for First of a Kind (FOAK) commercial plants. After starting up, these plants may not perform as well as expected, particularly during the first few years, when plants typically face reliability issues and therefore SAF production can be well below nameplate capacity. This translates into a significant economic risk, which private investors are not willing to take on or they will require a high premium for the capital they provide.
- **High capital costs of FOAK plants:** Costs for a FOAK are significantly higher compared to further plants based on the same technology which means that there is a higher cost gap to bridge and that cannot be bridged alone by the RTFO as a market mechanism.
- **Market mechanism uncertainty:** While the DfT has set a target for development fuels as part of the RTFO scheme as incentivisation for SAF production, the scheme is not yet mature enough for investors to estimate the long-term income dRTFCs could produce for SAF plants. FOAK commercial plants rely heavily on dRTFCs as an income stream to make them commercially viable, but this uncertainty over the price poses a risk to investors. In addition, recycled carbon feedstocks (e.g. non biogenic portion of MSW, steel mill off gases) are not currently included in the RTFO, though there is a consultation planned on whether to include them. The uncertainty over the outcome of this and potential changes that might result makes it difficult for plant developers to build a robust business case.

This study has also identified that both capital support for plant construction and additional policy measures to provide revenue certainty are needed to overcome the barriers above and establish SAF production in the UK. In particular, it is recommended to develop:

- A funding competition that
    1. provides capital commensurate with that required at the different project life cycle stages of a SAF plant and that cannot solely be raised from the private sector which is currently facing additional challenges from impacts of the COVID-19 pandemic.
    2. can provide the level of capital support that is required to enable private investors to co-invest in the construction of a FOAK plant. This requires Government funding that is above the level that could be supplied under State Aid (current limit €15million which corresponds to only 2% of the construction cost of a large FOAK plant). Therefore, Government should consider mechanisms which fall outside of State Aid support and can provide considerably higher levels of support, such as loan guarantees, tax credits and direct investment.
- Additional policy support measures that provide revenue certainty to investors to give them confidence that they will make a return on their investment. Given that dRTFCs are a critical part of a SAF plant's revenue stream long-term visibility of the dRTFC price is needed, which could be achieved through measures such as a floor price.

Although substantial Government intervention is needed, the development of a SAF industry in the UK could support substantial UK low carbon growth. A high level analysis indicates that this could generate between £700m and £1,660m in GVA, with potentially half of this being generated from the export of IP and the provision of engineering services. This industry could create between 5,000 and 11,000 green jobs, and furthermore, replacing imported kerosene with domestically produced SAF would increase fuel security and have a net positive impact on the UK's balance of payments.

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Glossary

Abbreviation	Definition
ABDC	Advanced biofuels demonstration competition
CAAFI	Commercial Aviation Alternative Fuels Initiative
DfT	Department for Transport
F4C	Future Fuels for Flight and Freight Competition
FOAK	First of a kind (Commercial Plant)
SAF	Sustainable aviation fuels
RTFO	Renewable Transport Fuel Obligation
(d)RTFCs	(development) Renewable Transport Fuel Certificates

1 Introduction

The Government has an important role to play in increasing UK production and deployment of advanced renewable/sustainable fuels of biological and non-biological origin, and in unlocking their potential benefits to the UK; such fuels will be an important part of the overall decarbonisation of transport. The Renewable Transport Fuels Obligation (RTFO), in particular through the development fuels sub-target, incentivises the demand for advanced renewable/sustainable fuels. Since 2014, the Department for Transport (DfT) has launched two competitions, the Advanced Biofuels Demonstration Competition (ABDC)[1] and the Future Fuels for Flight and Freight Competition (F4C)[2], to provide additional grant funding support to demonstration and early stage advanced renewable fuels plants. These sustainable fuels continue to need greater support to reach the market and benefit the UK, due to the higher technical and commercial risks involved.

Aviation in particular will continue to be heavily reliant on a kerosene type fuel and the emissions from the sector are expected to continue to rise globally. Sustainable aviation fuel (SAF), a fossil kerosene substitute, will be needed if the sector is to decarbonise, given that the alternatives will be unable to service medium-long haul flights (e.g. electrification) or are at least 10 to 20 years away from realisation (e.g. hydrogen). In 2018, the UK consumed 16.18Mtoe (million tonnes of oil equivalent) of aviation fuel[3], highlighting the required scale up of SAF production and use. In response the Government is providing additional impetus to the industry by creating the Jet Zero Council in June 2020. The Jet Zero Council will bring together leaders from aviation, environmental groups and government and is charged with making net-zero emissions possible for future flights. Support in this sector has now become even more important given the large impacts it has experienced during the coronavirus (COVID-19) pandemic.

To further help the production and deployment of sustainable aviation fuels DfT wishes to explore the feasibility and benefits of a third competition targeting sustainable aviation fuels, specifically fuels that meet the relevant ASTM/DefStan standard and so may be blended with existing aviation fuels at up to 50%. The ambition of a third targeted competition will be to provide support to help de-risk investments through grants and / or other support mechanisms to pave the way for first-of-a-kind commercial scale plants in the UK.

The aim of this study was to analyse the feasibility, design, support mechanisms and benefits of such a new competition. It builds on the 2014 and 2017 studies that supported the development, launch and management of the ABDC and F4C, respectively, and also on the lessons learned from both competitions, especially in relation to competition design and support mechanisms.

The specific objectives of the study were to:

- Determine the **feasibility of a competition** by assessing:
    - the status of sustainable aviation fuel production technologies, their barriers and needs
    - the type of support that could enable and accelerate their deployment and how this could form part of a competition
    - the potential interest in a competition and hypothetical projects and
    - the business case for deployment in the UK
- Provide the information necessary to DfT to **design and launch a competition** focused on sustainable aviation fuels which:
    - builds on the feasibility assessment and lessons learned from the ABDC and F4C
    - includes eligibility and selection criteria on feedstocks, production methods and GHG savings
    - details potential alternative funding structures, for example loan guarantees or a grant/loan combination.

The report is organised as follows:

[1] https://www.gov.uk/government/speeches/advanced-biofuels-demonstration-competition
[2] https://ee.ricardo.com/transport/case-studies/f4c
[3] https://www.ons.gov.uk/economy/environmentalaccounts/datasets/ukenvironmentalaccountsfuelusebytype

- Section 2 provides an overview of potential advanced renewable fuel pathways
- Section 3 investigates possible funding structures for a competition
- Section 4 discusses feasibility and a potential design of such a competition
- Section 5 sets out the business case for Government investment taking into account the design suggested in Section 4
- Section 6 sets out further work required and recommendations to take the competition forward.

2 Potential advanced renewable fuel pathways

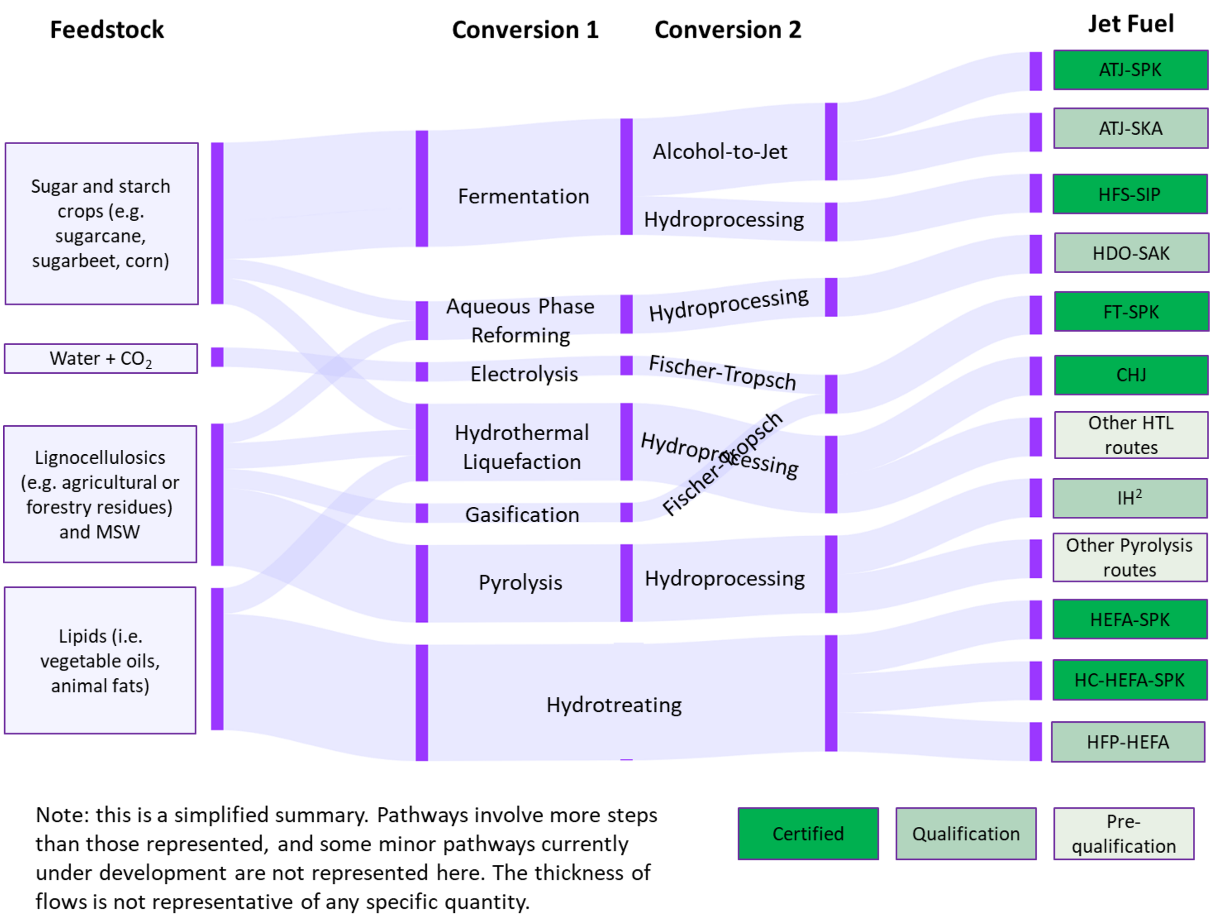
In this section, we provide an overview for each of the SAF production pathways of the technology, main technology and plant developers, their key challenges and potential GHG savings. This provides the basis for assessing the pool of potential applicants to the competition, and the type of plant they may be likely to want to build. For the purposes of understanding what pathways may be of most interest to the design of a possible future aviation-focused competition, it is important to understand that unlike other end-use sectors such as road or marine transport, all aviation fuel must currently be certified via the ASTM's D4054 certification process in order for it to be used in commercial aircraft. Given the time and cost involved in this process, whether a pathway has already been certified, or whether it has demonstrated a serious interest in becoming certified, is a key factor in assessing whether project developers using a particular technology are likely to bid or not, and whether they need to clear the later stages of the qualification process in order to produce commercial jet fuel.

Therefore, we have grouped production pathways as:

- Certified: Pathways that have successfully completed the certification process and whose fuels can be used today
- Qualification stage: Pathways that are currently going through the certification process
- Pre-Qualification stage: Pathways that have not yet entered the certification process, but have shown preliminary interest in doing so

A schematic showing the certification status of production pathways is shown in Figure 1.

Figure 1: Certification status of SAF production pathways



TRL is also an important factor in assessing the pool of potential competition entrants, as it indicates the scale of plant that a developer is likely to build. In some cases, there is a positive correlation between

TRL and the stage of the certification process they are at, i.e. pathways which are at a high TRL are far along the certification process. In other cases, however, even high TRL technologies may be at a relatively early stage in the certification process. The TRL of each pathway is discussed in their respective fuel pathway sections.

2.1 Certified pathways

2.1.1 Summary of certified pathways

There are eight different types of certified SAF production pathways, with two of them approved in 2020. This indicates continued interest in SAF development, which has increased in recent years. Table 1 and Figure 2 summarise the status of certified SAF pathways, their technology maturity and the main players involved. More details on each pathway are described in their respective sub-sections.

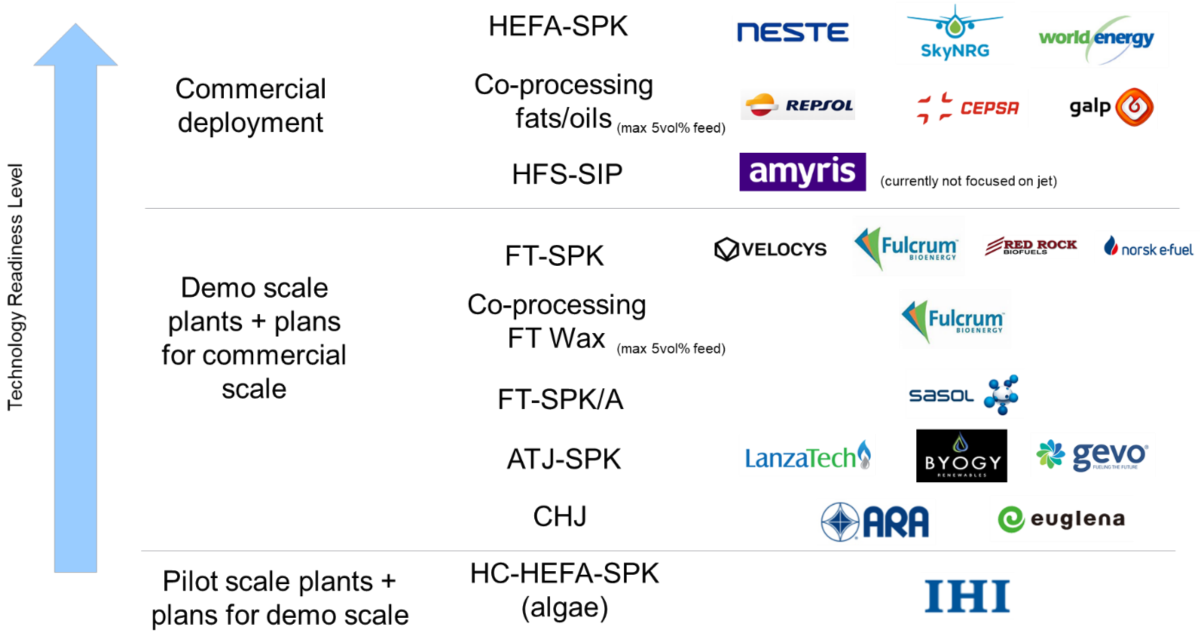
Table 1: Certified SAF pathways

ASTM fuel name	Year of certification	Feedstock	Maximum blend level	TRL	Main players
Fischer-Tropsch - Synthetic paraffinic kerosene (FT-SPK)	2009	MSW, agricultural and forest residues, energy crops	50%	5-6	RedRock Biofuels, Fulcrum, Velocys
Hydroprocessed Esters & Fatty Acids - Synthetic paraffinic kerosene (HEFA-SPK)	2011	Vegetable and animal lipids	50%	8	World Energy, Neste, SkyNRG
Hydroprocessing of Fermented Sugars - Synthetic Iso-Paraffinic fuels (HFS-SIP)	2014	Sugars	10%	7-8 (conventional sugars) 5 (cellulosic sugars)	Amyris, Total
Fischer-Tropsch - Synthetic paraffinic kerosene with added aromatics (FT-SPK/A)	2015	MSW, agricultural and forest residues, energy crops	50%	5-6	Sasol, Rentech
Alcohol-to-Jet Synthetic Paraffinic Kerosene (ATJ-SPK)	2016 (updated in 2018 to include more feedstocks and higher blend)	Starches, sugars, cellulosic biomass	50%	5-6	Lanzatech, Gevo, Byogy
Co-processing of up to 5 vol% oils and fats in a refinery to produce kerosene	2018	Vegetable and animal lipids	5% (refinery input)[4]	8-9	CEPSA, Galp, Repsol, Chevron, BP, Phillips 66
Catalytic Hydrothermolysis Synthesized Kerosene (CHJ)	2020	Vegetable and animal lipids	50%	6	ARA, Euglena

[4] Limit is 5% by volume of refinery input, whereas for other biojet fuels the blend limit is in terms of biojet blending percentage in fossil kerosene

ASTM fuel name	Year of certification	Feedstock	Maximum blend level	TRL	Main players
Hydrocarbon-hydroprocessed Esters and Fatty acids (HC-HEFA-SPK)	2020	Micro-algae	10%	5	IHI
Co-processing of up to 5 vol% FT waxes from MSW	2020	MSW	5% (refinery input)Error! Bookmark not defined.	6	Fulcrum Bioenergy

Figure 2: Summary of players across certified pathways



Only two pathways (HEFA-SPK and co-processing of vegetable oils in a refinery) have reached commercial technology maturity. It is recommended that these pathways are not included in the list of eligible technologies, as providing funding for these technologies would not fit the aim of helping to de-risk investment in ‘first of a kind’ (FOAK) commercial SAF plants.

Aside from these two pathways, the pathways that are experiencing the highest interest and industry activity are the ATJ and FT pathways, both of which feature multiple industrial players which could be capable of building FOAK commercial plants. For the ATJ pathway, Lanzatech are building a large demonstration unit, and for FT, multiple FOAK commercial plants are now under construction, all in the US. In the UK, Velocys (FT) and Lanzatech (ATJ) are the players at the most advanced stage of commercialisation and progressed to Stage 1 of the last F4C competition. Therefore, applicants for FOAK commercial plants are likely to use these technologies. UK based developers who previously applied for F4C funding also predominantly focused on developing FT technology.

Hydroprocessed Fermented Sugars (HFS-SIP) is a pathway that was certified in 2014 by Amyris, but no recent activity in jet fuel production has been recorded. Amyris seems to have shifted their focus to the biochemicals market. In 2020, three new pathways have been added to the ASTM annex: Catalytic Hydrothermolysis (CHJ), HEFA from algae (HC-HEFA-SPK) and co-processing of FT waxes from MSW. CHJ and HC-HEFA-SPK are at an early stage of development and are being developed by single players. FT pathways are relatively more mature, but FT waxes from MSW have never been co-processed in existing refineries at commercial scale before.

Reflections on certified pathways

Of the pathways that can produce fuels that can be used in today's commercial aircraft, there are some technologies at higher levels of technology readiness which could build FOAK commercial plants (e.g. AtJ, FT-SPK), and some which could build demonstration scale plants (e.g. CHJ, HC-HEFA-SPK). The competition would likely receive applicants in both these categories.

2.1.2 Alcohol to Jet Synthetic Paraffinic Kerosene (ATJ-SPK)

Alcohol to Jet Synthetic Paraffinic Kerosene (ATJ-SPK) is a process which turns alcohols (C2 to C5) into aviation fuel. In practice the alcohols used are ethanol and iso-butanol. The process consists of several steps: dehydration, oligomerisation, hydrogenation, and distillation. AtJ is a developing pathway currently at TRL 5-6, but it is largely based on technology used in the oil and chemicals industry and could therefore progress quickly. The advantage of this pathway is that it can transform alcohols from various origins into high-quality fuel. However, the alcohols need to be derived from biomass feedstocks usually through a fermentation process. This preliminary step is characterised by low energy yields, thus negatively affecting the overall yield of the conversion from biomass to jet fuel. This, combined with the high capital cost of equipment, makes SAF production via ATJ relatively expensive.

Key players and projects in the ATJ-SPK pathway are given in Table 2

- Lanzatech and Byogy are the leading technology developers. Both Lanzatech and Byogy use a similar process of dehydration, oligomerisation and hydrogenation. Both of them have multiple plants planned but none of these are at a commercial stage.
- Lanzatech has already engaged with the UK biofuel industry and with the UK government, having participated and reached Stage 2 of the F4C competition, in which it is planning construction of an 82 thousand tonne/year demonstration plant in the UK.
- Ekobenz is the only player operating a commercial plant. Although they produce mainly gasoline, the process could potentially produce jet fuel.
- Gevo is active in jet fuel production from iso-butanol derived from corn. Recently Gevo has teamed up with Viva Energy, an Australian fuel supplier, to produce road and jet fuel from regionally sourced feedstock in Australia[5].

Table 2: ATJ-SPK players and projects

Developer	Tech licensor/s	Partner/s	Plant Location	Maturity	Prod-uction capacity* (ktonne/ year)	Plant Status**	Products	Start-up date
Lanzatech	Lanzatech/ LanzaJet	Virgin Atlantic, Boeing	UK	FOAK Commercial	824	Planned	Jet	2024
	Lanzatech/ LanzaJet	ANA (offtake), Suncor (equity+offtake), Mitsui (equity), US DoE (grants)	Soperton, Georgia, USA	Demonstration	30	Planned	Jet, diesel	2022
	PNNL	US DoE	Soperton, Georgia, USA	Pilot	9	Operational	Jet	2012

[5] https://biofuels-news.com/news/australias-viva-energy-to-produce-biofuels-from-regionally-sourced-feedstocks/

Developer	Tech licensor/s	Partner/s	Plant Location	Maturity	Prod-uction capacity* (ktonne/ year)	Plant Status**	Products	Start-up date
Byogy	Byogy & Petron (ethanol to ethylene), Avapco (ethanol production)	US DoE	Thomaston, Georgia, USA	Demonstration	2	Planned	Jet, diesel	
	Byogy	Na	Australia	Demonstration	0.374	Planned	Jet, diesel	
Gevo	Gevo	Air Total, Avfuel	Silsbee, Texas, USA	Demonstration	0.228	Operational	Jet	2011
Swedish Biofuels	Swedish Biofuels	KTH	Stockholm, Sweden	Pilot	Na	Operational	Jet	2011
Ekobenz	Ekobenz, Howden, Dickow, Samsom, API Schmidt	Na	Bogumiłów, Poland	FOAK Commercial	23	Operational	Gasoline	2018

* Figures refer to total liquid fuel output, i.e. sum of multiple fuel fractions. Assumed average fuel density of 0.8 kg/litre

** 'Operational' refers to plants which are either operational or in commissioning, 'planned' refers to plants which are either planned or under construction

The main challenges in this pathway at the moment are:

- The oligomerisation catalyst used for the alcohol to jet step is sensitive to certain contaminants in the ethanol feed.
- Relatively high hydrogen consumption associated with the hydrogenation step.
- The opportunity cost of ethanol in the road transport sector demands higher incentives for SAF. Namely, the additional cost of producing jet fuel from ethanol via the ATJ process is not justified by high enough revenues from selling jet fuel. On the other hand, selling ethanol as a biofuel for the road transport sector is more incentivised.

2.1.3 Hydroprocessed Esters and Fatty Acids Synthetic Paraffinic Kerosene (HEFA-SPK)

Hydroprocessed Esters and Fatty Acids Synthetic Paraffinic Kerosene (HEFA-SPK) is a jet fuel produced through hydro-treatment of vegetable oils and animal fats. HEFA is the most mature SAF pathway and it is already at commercial production stage (TRL 8). Because of its maturity and simplicity compared to other pathways, HEFA technology can produce advanced biofuel at lower cost. The main limitation of this pathway is feedstock availability. UCO and tallow are limited resources, while virgin vegetable oil is currently absorbed by FAME production. New feedstocks such as camelina and carinata crops are currently under scrutiny for their potential to provide additional resource, whilst meeting sustainable criteria.

The number and size of the plants producing hydrotreated fuels from vegetable oils are larger compared to other SAF pathways. However, most of these plants are not dedicated to jet fuel production, but are optimised for primary production of renewable diesel, which is referred as Hydrotreated Vegetable Oil (HVO). HEFA is obtained by further processing HVO through an additional hydro-cracking step. Whilst technically, few modifications to HVO plants are required to produce HEFA, only one operational plant worldwide is currently optimised for HEFA production (i.e. World Energy's biorefinery in California).

There are several companies and plants producing HVO at commercial scale and in some cases jet-range molecules are produced as by-products. However, given the scope of this study, in this section we focus only on players who are known to produce some quantity of HEFA-SPK. World Energy became the largest HEFA producer globally after acquiring AltAir's refinery in California, which is optimised for jet fuel production. Neste is the largest HVO producer with multiple operational refineries and the largest HEFA producer in Europe. Most of Neste's HEFA is produced in Finland but they are planning additional jet fuel production through the extension of their refinery in Singapore. SkyNRG is planning a greenfield plant in the Netherlands which will be optimised for jet fuel production.

Key challenges:

- Availability of sustainable feedstock.
- Despite being the lowest cost SAF, HEFA-SPK is still three to five times more expensive than fossil jet (pre-COVID-19). This is partly due to the hydrogen consumption of this process, which is relatively high.

Table 3: HEFA players and projects

Developer/s	Tech licensor/s	Partner/s	Plant Location	Maturity	Production capacity* (ktonne/ year)	Plant Status**	Product/s	Start-up date
Neste	Neste (NEXBTL)	American Airlines, BP, Alaska Airlines	Porvoo (1&2), Finland	Commercial	430	Operational	Jet, diesel	Porvoo 1: 2007 Porvoo 2: 2009
			Singapore 1	Commercial	710	Operational	Diesel	2010
			Singapore 2	Commercial	590	Planned	Jet, diesel	2022
World Energy	Honeywell UOP/Eni (Ecofining™)	United Airlines, World Fuel, Air BP, SkyNRG, SAS, KLM, Finnair	Paramount refinery, California, USA	Commercial	753	Operational	Jet	2016. The extension will be operational in 2022
SkyNRG	Haldor Topsoe (HydroFlex™)	KLM, Shell	Delfzijl, Netherlands	Commercial	115	Planned	Jet	2022
Eni	Honeywell UOP/Eni (Ecofining™)	Hera (feedstock supply)	Venice, Italy	Commercial	420	Operational	Diesel, Jet	2019
		Na	Gela, Italy	Commercial	600	Operational	Diesel, Jet	2014. with extension operational in 2021
ECB Group	Honeywell UOP/Eni (Ecofining™), Crown Iron Works	Acciona (EPC)	Villeta, Paraguay	Commercial	928	Planned	Jet, diesel	2022
Zhenhai Refining and Chemical	Sinopec	Na	Ningbo, Zhejiang Province, China	Commercial	30	Operational	Jet	2019

* Figures refer to total liquid fuel output, i.e. sum of multiple fuel fractions. Assumed average fuel density of 0.8 kg/litre

** 'Operational' refers to plants which are either operational or in commissioning, 'planned' refers to plants which are either planned or under construction

2.1.3.1 Co-processing of lipids in refinery

Co-processing of oils and fats is effectively the same pathway as HEFA/HVO, except that the biogenic feedstock is blended with fossil distillates. Co-processing consists of the simultaneous transformation of biogenic feedstocks and intermediate petroleum distillates in existing petroleum refinery process units to produce renewable hydrocarbon fuels. Co-processing therefore largely utilises existing refining, transport and storage infrastructure, avoiding the need for investment in new bio-refinery units and the infrastructure to support them. Despite being an already mature pathway (TRL 8-9) the blending of biogenic feedstock is limited to 5% by volume. This limitation is dictated by the ASTM certification and blending up to 10% would be technically feasible without major process modifications. Blending percentages higher than 10% require additional adjustments to refinery equipment and operations[6].

Several petroleum oil refiners have trialled lipids co-processing in their refineries including Chevron, BP, and Phillips 66[7]. A subset of them went a step further and integrated lipids co-processing into their operations. Examples of these companies are Cepsa and Repsol in Spain, Galp in Portugal, Total in France, Preem in Sweden and ConocoPhillips at its refinery in Ireland[8]. However, it should be pointed out that most of the oils currently being co-processed are virgin vegetable oils (palm or soybean oil), with only a small share of waste oils and fats.

2.1.4 Hydroprocessed Fermented Sugars to Synthetic Isoparaffins (HFS-SIP)

Hydroprocessed Fermented Sugars to Synthetic Isoparaffins (HFS-SIP) is a type of SAF produced via fermentation of sugary biomass which can be blended with fossil kerosene up to a maximum of 10%. There are different pathways to produce SAF through direct sugar fermentation. The pathway that produces HFS-SIP was developed by Amyris and is based on genetically modified yeasts which consume sugars and excrete long-chain liquid alkenes (e.g. farnesene). Other pathways are based on other types of bacteria which produce short-chain gaseous alkenes (e.g. isobutene).

Currently, HFS-SIP is based on conventional sugar feedstocks, although cellulosic sugars have been tested. HFS-SIP production using conventional sugar feedstocks are at TRL 7-8, while the same processes based on cellulosic feedstocks are at TRL 5.

Amyris' technology is based on aerobic fermentation of sugars to produce farnesene which is then converted into farnesane, a molecule that can be used as a drop-in jet fuel. Amyris constructed a commercial-scale plant in Brazil producing farnesene from sugarcane (which was sold to DSM in 2017[9]). Originally Amyris' operations were focussed on fuel production and they established a joint venture with Total, which got their farnesane certified as a jet fuel in 2014. However, more recently Amyris interests have shifted away from fuels and focussed on farnesene for the chemicals and pharmaceutical markets[10]. This choice was driven by two main reasons. The first is that specialty chemicals are usually higher value products than fuels. The second is that Amyris' process for converting lignocellulosic sugars into jet fuel is characterised by low overall efficiency. This translates into high operational costs making HFS-SIP one of the most expensive SAF pathways.

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[6] Concawe, 2019, "Refinery 2050: Conceptual Assessment", PDF page 32, https://www.concawe.eu/wp-content/uploads/Rpt_19-9.pdf
[7] 2015, http://www.caafi.org/resources/pdf/CoProcessing_of_HEFA_Feedstocks_with_Petroleum_Hydrocarbons_for_Jet_Production_June192015.pdf, http://www.caafi.org/resources/pdf/2.5_Enabling_Lipids.pdf
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[10] BiofuelsDigest, July 2018, http://www.biofuelsdigest.com/bdigest/2018/07/11/amyris-same-as-it-never-was/

Table 4: HFS-SIP players and projects

Developer/s	Tech licensor/s	Partners	Plant Location	Maturity	Production capacity* (ktonne/ year)	Plant Status**	Product/s	Start-up date
JV Amyris Total	Amyris	Cathay Pacific (off-taker)	Brotas, Brazil (acquired by Royal DSM in 2017)	FOAK Commercial	33	Operational	Farnesene (originally for upgrading to jet fuel, now as biochemical)	2012

* Figures refer to total liquid fuel output, i.e. sum of multiple fuel fractions. Assumed average fuel density of 0.8 kg/litre

** 'Operational' refers to plants which are either operational or in commissioning, 'planned' refers to plants which are either planned or under construction

2.1.5 Fischer-Tropsch Synthetic Paraffinic Kerosene (FT-SPK)

There are two Fischer-Tropsch (FT) pathways certified under ASTM D4054 Annex A1. FT-SPK was certified in 2009 and can be blended with fossil jet fuel up to a maximum of 50%. FT-SPK/A which was certified in 2015 for blends up to 50%, contains aromatics offering a spectrum of molecules more similar to fossil jet fuel.

The intermediate product in FT pathways is syngas. Syngas can be produced in several different ways, one of which is gasification of biomass and wastes and one of which is combining hydrogen produced via electrolysis with a stream of carbon dioxide. This latter pathway is called Power-to-Liquids with Fischer-Tropsch synthesis (PtL FT). Jet fuel produced via PtL FT is certified under Annex A1 provided that iron or cobalt catalysts are used in the FT synthesis[11].

2.1.5.1 Gasification with FT synthesis (Gas+FT)

The gasification with Fischer-Tropsch synthesis process (Gas+FT) transforms lignocellulosic biomass or solid waste into road and aviation fuels. This process was developed from coal-to-liquid gasification, which is a mature technology, but the process based on biomass is still a developing technology at TRL 6-7. The Gas+FT process tolerates heterogenous feedstocks (with appropriate pre-treatment equipment) and benefits from technology maturity of the individual steps of the process. Major disadvantages of Gas+FT are that it has good techno-economic performance only at large scales and it is very energy-consuming. Additionally, high purity requirements for syngas in the FT process complicate the syngas clean-up phase, increasing cost.

Table 5: Gasification FT players and projects

Developer/s	Tech licensor/s	Partners	Plant Location	Maturity	Production capacity* (ktonne/ year)	Plant Status**	Product/s	Start-up date
Fulcrum BioEnergy	TRI (gasifier), BP/Johnson Matthey (FT), Marathon Petroleum (FT upgrading)	Offtakers: Cathay Pacific, United Airlines, Air BP, World Fuel Services	Nevada, USA	FOAK commercial	32	Planned	Jet fuel, diesel	2020
	TRI (gasifier)		Indiana, USA	Commercial	100	Planned	Jet fuel, diesel	2022
Red Rock Biofuels	TCG (gasifier), Velocys (FT)	Offtakers: FedEx Express,	Lakeview, Oregon	FOAK commercial	46	Planned	Jet fuel, diesel	2020

[11] D7566 specification, Annex1, article A1.4.1.1

Developer/s	Tech licensor/s	Partners	Plant Location	Maturity	Production capacity* (ktonne/ year)	Plant Status**	Product/s	Start-up date
		Southwest Airlines						
Velocys	TRI (gasifier), Velocys (FT)	Offtakers: British Airways, Shell	Immingham, UK	FOAK Commercial	48	Planned	Jet fuel, diesel	2025
	TRI (gasifier), Velocys (FT), Haldor Topsoe (FT upgrading)	Oxy Low Carbon Ventures (CO_2 capture)	Natchez, Mississippi, USA	Commercial	91	Planned	Diesel, jet fuel	2023
Sunshine Kaidi New Energy Group	Kaidi AlterNRG (gasifier), Rentech (FT)	Spinverse (consulting)	Kemi, Finland	Commercial	225	Planned	Diesel, jet fuel	N/A
Expander Energy	Expander Energy	Vanderwell (biomass supplier)	Slave Lake, Alberta	Demonstration	5.6 (stage 1), 23.2 (stage 2)	Planned	Diesel, jet fuel	2021
Total	ThyssenKrupp (gasifier), Axens (syngas cleanup)	IFP Energies Nouvelles, Avril	Dunkirk, France	Demonstration	0.6	Planned	Jet fuel, diesel	2020
Frontline Bioenergy	Frontline Bioenergy	SGC Energia, Stanley Consultants, and Delphi Engineering and Construction	Iowa, USA	Pilot	0.041	Operational	Diesel, jet fuel	2010

* Figures refer to total liquid fuel output, i.e. sum of multiple fuel fractions. Assumed average fuel density of 0.8 kg/litre

** 'Operational' refers to plants which are either operational or in commissioning, 'planned' refers to plants which are either planned or under construction

Velocys and Fulcrum BioEnergy are most actively developing large new gasification + Fischer-Tropsch plants. Velocys are now planning to build a FOAK plant in the UK and have received funding to support project development activities through the F4C competition. Fulcrum BioEnergy is a US player in fuel production from MSW and they are building their FOAK plant (Sierra BioFuels) in Nevada. Expander Energy, Sunshine Kaidi and Red Rock Biofuels also have plants planned. The availability of feedstocks suited to gasification (such as woody biomass and an increasing interest in municipal solid waste), and the location of policy-supported market demand, has led to North America and Northern Europe being the main regions for project development for this pathway.

Challenges for the Gas+FT process include

- Syngas clean-up; this is the most challenging step.
- FT wax upgrading is expensive if done on-site.
- The selectivity of the process is low and a maximum of about 50% of the FT products is jet fuel. The rest is made up of light gases and heavier hydrocarbon waxes that can be partially upgraded to jet fuel.

A strength of several of the companies involved in this pathway is that they bring experience of the technology components from other applications. Velocys (technology supplier to Red Rock Biofuels) for example have deployed their FT reactor at a gas-to-liquids plant and TRI and ThyssenKrupp have operated large-scale biomass gasifiers. However, there is still a lack of expertise in the integration of these component technologies at scale, including the necessary syngas clean-up and conditioning steps that lie between gasification and FT synthesis steps – most of the actors have been previously focused on one of the technology components.

The final upgrading of FT waxes to finished jet and diesel products can happen either on-site or ex-situ by transporting the waxes to a separate refinery. The second case could benefit from cost savings by avoiding the installation of additional upgrading infrastructure.

2.1.5.2 Power to Liquids with FT synthesis (PtL FT)

The Power-to-Liquid with Fischer-Tropsch (PtL FT) pathway enables the production of fuels combining a carbon source with a hydrogen stream produced via electrolysis. Therefore, this pathway is based on three "feedstocks": electricity, water and a source of CO_2. Provided that the electricity has low-carbon origins, this technology can produce fuels with very low carbon emissions (5 gCO_2e/MJ or less[12]). PtL FT also represents an option for the utilisation of CO_2 waste streams from industrial processes. The main drawbacks of this technology are the high operational cost due to high electricity consumption and the high capital cost of the equipment. PtL FT jet is certified under ASTM Annex A1 provided that the FT process employs iron or cobalt catalysts (which is also valid for Gas FT). In accordance to this certification it can be blended with fossil jet fuel up to 50%.

Only a handful of developers and projects are currently active (Table 6). They are all concentrated in Europe and all the projects are at pilot or demonstration scale. The main players are Sunfire and Nordic Blue Crude who have both planned construction of 8,000 tonne/year plants in Norway. Most PtL FT plants include e-jet as a product alongside other products, and only two projects (EDL and GP2J) are primarily designed to supply aviation fuel.

Table 6: Power to Liquids FT players and projects

Developer/s	Tech licensor/s	Partner/s	Plant Location	Maturity	Production capacity* (tonne/year)	Plant Status**	Product/s	Start-up date
Copenhagen Airports	Na	Maersk, DSV Panalpina, DFDS, SAS, Ørsted	Copenhagen, Denmark	FOAK Commercial	Stage 1: 2k Stage 2: 38k Stage 3: 250k	Planned	Jet, road diesel, marine gas oil, methanol	Stage 1: 2023 Stage 2: 2027 Stage 3: 2030
Norsk e-fuel	Sunfire (HT co-electrolysis), Climeworks (DAC)	Paul Wurth, Valinor (Wind power)	Norway, Herøya	FOAK Commercial	8,000	Planned	FT wax to be upgraded to Jet, diesel fuel	2023
Nordic Blue Crude	Na	NTNU, Enova, SkyNRG, Audi, Mobil Den Hartog	Norway, Herøya	FOAK Commercial	8,000	Planned	FT wax to be upgraded to Jet, diesel fuel	2022
Repsol	Na	Petronor, Energy Agency of the Basque Government	Spain, Bilbao	FOAK Commercial	2,300	Planned	FT wax to be upgraded to Jet, diesel fuel	N/A

12 Malins, C., 2017, What role is there for electrofuel technologies in European transport's low carbon future?, https://www.transportenvironment.org/sites/te/files/publications/2017_11_Cerulogy_study_What_role_electrofuels_final_0.pdf

Developer/s	Tech licensor/s	Partner/s	Plant Location	Maturity	Production capacity* (tonne/year)	Plant Status**	Product/s	Start-up date
EDL Anlagenbau Gesellschaft	Sunfire (HT co-electrolysis), Climeworks (DACC), INERATEC (FT synthesis)	Schiphol, The Hague airport, SkyNRG	Netherlands, Rotterdam	Demonstration	292	Planned	FT wax to be upgraded to Jet fuel	Plan announced in 2019
Sunfire	Sunfire (HT co-electrolysis), Climework (DACC), INERATEC (FT synthesis)	Kopernikus project: Karlsruhe Inst Tech (KIT), German gov	Germany, Karlsruhe	Demonstration	58	Planned	FT wax to be upgraded to Gasoline, jet fuel, Diesel	2019
Soletair	VTT (DACC), INERATEC (FT Synthesis)	LUT, ABB, ENE Solar System	Finland, Lappeenranta	Pilot	0.6	Operational	FT wax to be upgraded to Gasoline	2017
Technical University of Hamburg	Na	GP2J project: DOW, BP (FT wax off-taker), DLR, Hamburg airport, Airbus	Germany, Stade	Demonstration	Na	Planned	FT wax to be upgraded to Jet fuel, diesel	Construction scheduled from 2022
BP	Na	Uniper, Fraunhofer ISI	Germany, Lingen	Demonstration	Na	Planned	FT wax to be upgraded to Gasoline, jet, diesel	N/A

* Figures refer to total liquid fuel output, i.e. sum of multiple fuel fractions. Assumed average fuel density of 0.8 kg/litre

** 'Operational' refers to plants which are either operational or in commissioning, 'planned' refers to plants which are either planned or under construction

Challenges for the PtL FT pathway include:

- High operational cost due to high electricity consumption.
- High capital cost due to expensive equipment unit cost, especially at small scale.
- Low technology maturity of process components (e.g. co-electrolyser or reverse water gas shift reactor).
- Disparity between the commercial scale for the electrolyser and the FT element of the plant
- FT wax upgrading is expensive if done on-site.
- The selectivity of the process is low and a maximum of about 50% of the FT products is jet fuel. The rest is made up of light gases and heavier hydrocarbon waxes that can be partially upgraded to jet fuel.

Without subsidies, electrofuels are unlikely to be economically viable compared to fossil jet fuel; the only situation in which this situation might be reversed was if there were very high crude oil prices and very low-cost renewable electricity. In the near-term such favourable macroeconomic conditions are very unlikely to materialise and PtL fuels are likely to remain significantly more expensive than fossil fuels.

2.1.5.3 Fischer-Tropsch Synthetic Paraffinic Kerosene with Aromatics (FT-SPK/A)

FT-SPK/A is a jet fuel produced through the same process and using the same feedstocks as FT-SPK but integrating an additional step: the alkylation of light aromatics (primarily benzene). Through alkylation, aromatic compounds are produced and blended into the fuel to provide a full spectrum of molecules found in typical petroleum-based jet fuel, rather than just paraffins. A minimum content of aromatics is required in jet fuels to ensure the swelling of jet engine seals.

This fuel was certified in 2015 for blending with fossil jet up to 50% by volume. The qualification process taskforce was led by Sasol, the South-African company that pioneered FT technologies and gasification of coal. No recent activity has been recorded in the FT-SPK/A pathway from Sasol or other players. A possible reason is that the cost of adding the alkylation step to provide aromatic content to the fuel (i.e. production of FT-SPK/A) is not justified if the blending limit is the same as the version without aromatics (i.e. FT-SPK).

2.1.5.4 Co-processing of FT waxes from MSW

Aviation fuels derived via co-processing FT waxes produced from gasification of MSW have been approved in July 2020 as a new SAF pathway[13]. More precisely, this pathway is an addition to Annex A1 of ASTM D1655 as the resulting SAF produced is FT-SPK. The pathway consists of gasification of MSW followed by conversion of the syngas to liquid products (i.e. long hydrocarbon chains called “waxes”) via the Fischer-Tropsch process, and co-processing the FT waxes in an existing refinery to produce aviation fuel. Currently, the maximum quantity of FT waxes that can be fed to refinery operations is 5% of the total refinery feedstock. This pathway has been proposed and pursued by Fulcrum Bioenergy who is currently constructing their FOAK commercial plant (Sierra BioFuels) in Nevada, US.

2.1.6 Catalytic Hydrothermolysis Synthesized Kerosene (CHJ)

The Catalytic Hydrothermolysis Synthesized Kerosene pathway (CHJ) is a recent addition to ASTM D7566 Annexes and was officially approved in January 2020 with maximum blending of 50%. The CHJ process (based on hydrothermal liquefaction technology) consists of three main steps. In the first step clean free fatty acid (FFA) oil from the processing of waste oils is converted into a bio-crude oil inside the catalytic hydrothermolysis reactor. In the second step, the bio-crude oil undergoes hydrotreating and is converted into a mixture of several different hydrocarbons. Finally, this mixture is separated through distillation into single fractions (diesel, jet, gasoline). Research has shown that through the CH process, SAF can be produced from a variety of triglyceride-based feedstocks such as soybean oil, jatropha oil, camelina oil, carinata oil, and tung oil[14].

Applied Research Associates (ARA) and Chevron Lummus Global (CLG) are the developers of the CHJ pathway, and they named the SAF produced through this process ReadiJet™. The name with which ARA and CLG have patented their conversion technology is Biofuels ISOCONVERSION (BIC)[15]. They are now planning to scale up this technology in the United States and Japan. In the United States, multiple projects are in an engineering phase, and Euglena Corporation has completed construction of its integrated demonstration facility in Japan with the intent to deliver CHJ for commercial flights during the Olympic Games in Tokyo[16]. Euglena is partnering with All Nippon Airways as a jet fuel off-taker and

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[13] https://www.ainonline.com/aviation-news/business-aviation/2020-07-06/astm-approves-new-sustainable-jet-fuel-process

[14] https://www.greencarcongress.com/2020/02/2020-0201-astmchj.html

[15] http://www.readifuels.com/CLG-fuel-commercialization.html

[16] https://www.greencarcongress.com/2018/11/20181102-euglena.html

Isuzu Motors for the diesel fraction. Euglena is planning to build their FOAK plant and start commercial production by 2025[17].

Because the CH process uses waste or virgin vegetable oils, it faces similar challenges as the HEFA/HVO pathway regarding feedstock availability and sustainability. Additionally, the technology is still at an early stage and the fuel production cost is high relative to fossil jet[18].

Table 7: CHJ players and projects

Developer	Tech licensor/s	Partner/s	Plant Location	Maturity	Total capacity* (ktonne/ year)	Plant Status**	Product/s	Start-up date
ARA	ARA, CLG (Biofuels ISOCONVERSION™)	Chevron Lummus Global (CLG)	USA	Demonstration	4.642	Operational	Jet, diesel	2014
Euglena	ARA, CLG (Biofuels ISOCONVERSION™)	ANA (jet fuel off-take), Isuzu Motors (diesel off-take)	Yokohama, Japan	Demonstration	0.232	Operational	Jet, diesel	2020

* Figures refer to total liquid fuel output, i.e. sum of multiple fuel fractions. Assumed average fuel density of 0.8 kg/litre

** 'Operational' refers to plants which are either operational or in commissioning, 'planned' refers to plants which are either planned or under construction

2.1.7 Hydrocarbon-hydroprocessed Esters and Fatty acids (HC-HEFA-SPK)

Hydrocarbon-hydroprocessed Esters and Fatty acids (HC-HEFA-SPK) is the name of the latest fuel addition to ASTM D7566 Annexes, approved in May 2020[19]. This is a HEFA-type fuel derived from micro-algae. The process to produce HC-HEFA-SPK is identical to the standard HEFA-SPK with the addition of a pre-treatment step. Micro-algae containing oils are first dried, and then the oil content is extracted using a solvent. The oil extracted then undergoes hydrotreating as in the standard HEFA process. IHI Corporation is developing this pathway based on a specific type of micro-algae called "Botryococcus braunii". This species of micro-algae is particularly suitable for fuel production because it offers high oil yields compared to other types of feedstocks.

IHI Corporation is based in Japan and started R&D activities in 2011. Today their technology is at pilot scale with a project in Saraburi (Thailand) integrating algae cultivation and conversion into jet fuel. The project is developed in collaboration with Kobe University[20] and Siam Cement, a Thai cement producer. The company is now looking at expanding production to an industrial scale in the next ten years[21]. IHI have also begun work with Showa Shell Sekiyu K.K. to identify issues associated with developing an integrated bio jet fuel supply scheme based on blending of IHI's HC-HEFA-SPK with Showa Shell' Sekiyu K.K.'s petroleum-based jet, and develop solutions to solve any problems identified.

The main challenges associated with micro-algae cultivation are the long-term stability and productivity of the crop, the overall process economics, and GHG emissions. Cultivation of micro-algae has relatively high energy consumption and associated GHG emissions if that energy is based on fossil sources[19].

[17] Euglena, 2017, https://www.icef-forum.org/platform/speakers/2017/topic3/ICEF2017_CS2-2_Korehiro_Odate_fin.pdf
[18] Table A5, p99, https://www.nrel.gov/docs/fy16osti/66291.pdf
[19] Green Car Congress, May 2020, https://www.greencarcongress.com/2020/05/20200514-ihi.html
[20] IHI, November 2017, press release, https://www.ihi.co.jp/en/all_news/2017/other/2017-11-06/index.html
[21] IHI, March 2019, "Development of sustainable bio jet fuel derived from Microalgae", https://www.nedo.go.jp/content/100889561.pdf

Table 8: HC-HEFA players and projects

Developer/s	Tech licensor/s	Partner/s	Plant Location	Maturity	Total capacity* (ktonne/year)	Plant Status**	Product/s	Start-up date
IHI	IHI, Chitose Lab, Kobe University	Chitose Lab, Kobe University	Saraburi, Thailand	Pilot	Na	Operational	Jet, diesel	2017

* Figures refer to total liquid fuel output, i.e. sum of multiple fuel fractions. Assumed average fuel density of 0.8 kg/litre

** 'Operational' refers to plants which are either operational or in commissioning, 'planned' refers to plants which are either planned or under construction

2.2 Qualification stage pathways

2.2.1 Summary of Qualification Stage Pathways

There are currently four pathways going through the ASTM qualification process.

Hydro-deoxygenation Synthetic Aromatic Kerosene (HDO-SAK) is a pathway pursued by Virent and based on sugary biomass, but their technology is at a relatively early stage. From information on recent company activity, it appears that Virent's interests are now more focussed on bio-chemicals production rather than jet fuel.

High Freeze Point HEFA (HFP-HEFA) is a pathway at TRL8-9 and is based on the conversion of oils and fats. It could potentially make large volumes of SAF available in a short time, if it was approved, because this fuel is very similar to HEFA and HVO, and only relatively minor modifications to HVO plants would be required to produce HFP-HEFA. If activity is measured by number of active players, this is the most active pathway among those in qualification stage given the large number of HVO/HEFA producers compared to other pathways. However, HFP-HEFA is still in Phase 1 after having entered the qualification process in 2015. This highlights a slow progress of the certification of this pathway. Boeing, together with Neste, are leading the taskforce for its certification but many HVO producers have vested interests in the approval of this fuel because the certification of HFP-HEFA would open-up an additional market for their fuel at a limited cost. Given that the technology to produce this fuel is already mature, it is not recommended that this pathway is considered to be eligible for the competition.

Integrated Hydropyrolysis (IH^2) is a process converting lignocellulosic biomass or MSW into finished fuels. The technology is at demonstration stage and is being developed by Shell. Moderate activity is ongoing in this pathway with Shell financially supporting Biozin for the construction of a FOAK plant in Norway. It is important to note that Shell has not announced plans to play a leading role in developing plants using this technology; rather, it appears to be only licensing the technology, and providing some additional support to licensees. If licensees of this technology were to apply to the competition, they would probably apply to build a FOAK commercial plant.

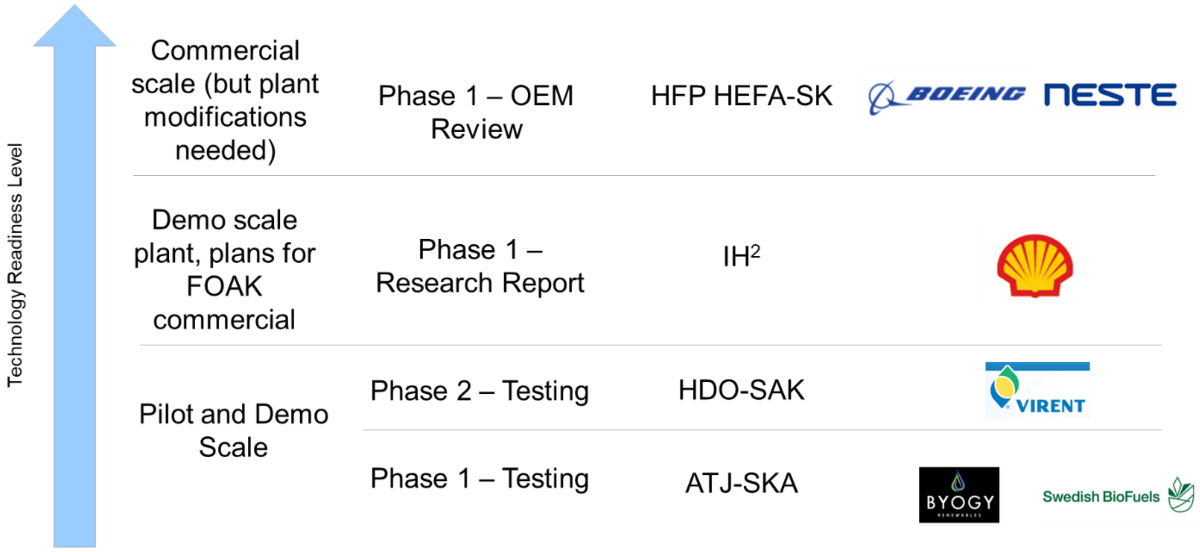
Alcohol-to-Jet Synthetic Kerosene with Aromatics (ATJ-SKA) is a variation of the already certified ATJ process that has the potential to not be subject to a maximum blending limit. Swedish Biofuels and Byogy are involved in this pathway but no public announcements have been made in the last couple of years.

Table 9 and Figure 3 summarise the status of qualification SAF pathways, their technology maturity and the main players involved.

Table 9: Status of SAF pathways at qualification stage

ASTM Progress	Pathway	Feedstock	TRL	Task Force Lead
Phase 2 – Testing	Hydro-deoxygenation Synthetic Aromatic Kerosene (HDO-SAK)	Sugars and/or cellulosics	5-6 (conventional sugars) 4-5 (cellulosic sugars)	Virent
Phase 1 – OEM Review	High Freeze Point Hydroprocessed Esters and Fatty Acids Synthetic Kerosene (HFP HEFA-SK)	Renewable fats oils and greases	8	Boeing
Phase 1 – Research Report	Integrated Hydropyrolysis and Hydroconversion (IH^2)	Lignocellulosics and/or MSW	6	Shell
Phase 1 – Testing	Alcohol-to-Jet Synthetic Kerosene with Aromatics (ATJ-SKA)	Sugars and/or lignocellulosics	5-6	Byogy, Swedish Biofuels

Figure 3: Summary of players across qualification stage pathways



Reflections on qualification stage pathways

Compared to the certified pathways, there are fewer technologies and fewer players who would be interested in building FOAK commercial plants, and their level of technology readiness is slightly less mature.

2.2.2 Hydro-deoxygenation Synthetic Aromatic Kerosene (HDO-SAK)

Hydro-deoxygenation Synthetic Aromatic Kerosene (HDO-SAK) is produced using a technology also known as Aqueous Phase Reforming (APR). The APR process converts lignocellulosic and sugary biomass into road and aviation fuels. APR based on conventional sugars is at TRL 5-6, while the cellulosic-sugars one is at TRL 4-5. A wide range of sugars can be used as feedstocks. One advantage of APR is that unlike other reforming processes it does not require water removal. However, the pathway does require a substantial amount of hydrogen supply and solid-free sugars. These two characteristics make the capital and operational cost of APR relatively high compared to other SAF pathways.

Virent is the only player in the APR pathway. The company was bought by Tesoro Corporation in 2016, but it still exists as a separate sub-entity[22]. Virent focusses on converting plant-based sugars into hydrocarbons via the aqueous phase reforming process followed by catalytic upgrading. Their patented technology is known as BioForming®. Virent has partnered with Shell for gasoline and jet fuel production, and with Toray and Coca Cola for bio-based Polyethylene terephthalate (Bio-PET) for use as a packaging material. Although APR is a fuel pathway, there appears to be more recent interest in moving into biochemicals production (where profit margins are potentially higher) than in transport biofuels. For example, Virent has recently partnered with BP and Johnson Matthey to further advance the commercialisation of BioForming® for production of bio-paraxylene[23].

The main technical barriers affecting APR are the low selectivity to liquid hydrocarbons, the short catalyst lifetime due to deactivation and coking, and the low yields when using lignocellulosic sugars due to a less homogenous feedstock and the presence of impurities[24].

Table 10: HDO-SAK players and projects

Developer/s	Tech licensor/s	Partner/s	Plant Location	Maturity	Production capacity* (tonne/ year)	Plant Status**	Product/s	Start-up date
Virent	Virent	Marathon Petroleum, Johnson Matthey, BP	Madison, Wisconsin, USA	Pilot	25	Operational	BioFormate®, a mixture of molecules with a high aromatic composition	2010

* Figures refer to total liquid fuel output, i.e. sum of multiple fuel fractions. Assumed average fuel density of 0.8 kg/litre

** 'Operational' refers to plants which are either operational or in commissioning, 'planned' refers to plants which are either planned or under construction

2.2.3 High Freeze Point HEFA (HFP-HEFA)

High Freeze Point HEFA (HFP-HEFA), also known as HEFA+, is a fuel produced through the same process of hydrotreating vegetable and animal lipids as HEFA-SPK. The physical difference between HEFA-SPK and HEFA+ is the length of the molecule chain. HEFA+ molecules are longer than HEFA-SPK, which is what leads to the higher freezing point of HEFA+. The fact that HEFA+ molecules are longer implies that less processing (hydro-isomerisation) is required for this fuel, giving it a production cost advantage over HEFA-SPK. Despite being a technologically mature pathway (TRL 8, the same as HEFA-SPK), HFP-HEFA certification is currently in "Phase 1 – OEM review". Testing is focussing on determining the maximum blend with fossil jet fuel that still guarantees a sufficiently low freeze point.

Today there are no commercial producers of HEFA+, but if this fuel achieved ASTM certification it could potentially be produced at any plant currently producing HVO[25]. This means that with the right market and policy conditions in place, if this fuel was approved large volumes of HEFA+ could start to be supplied in a relatively short time. Relatively small adjustments to an HVO refinery would be required to optimise the process for HEFA+ production, highlighting the fact that this pathway has few technology development needs.

[22] Nb. Tesoro was renamed Andeavor in August 2017, and Andeavor was acquired by Marathon Petroleum in April 2018. Virent still operates as a brand, so here we continue here to refer to Virent.
[23] Virent is partnering with BP for production of bio-paraxylene. Virent, 4 March 2019, https://www.virent.com/news/bp-partners-with-virent-and-johnson-matthey/
[24] IRENA, 2016, "Advanced Liquid Biofuels", https://bit.ly/2A0gnbM
[25] ICCT, 2018, "Policy and Environmental Implications of Using HEFA+ for Aviation", https://theicct.org/sites/default/files/publications/Green-Diesel-Aviation_ICCT-Working-Paper_20180321_vF.pdf

One of the supporters of this fuel there is Neste who promote the high level of maturity and price advantage of HEFA+ compared to other SAFs. Many other HVO players can be considered as potential HEFA+ suppliers including Diamond Green Diesel, Renewable Energy Group (REGI), UPM Biofuels, Total, CEPSA, and Sinopec.

2.2.4 Integrated Hydropyrolysis (IH2)

The integrated hydropyrolysis and hydroconversion process (IH^2), developed by the Gas Technologies Institute (GTI) and now sub-licensed by Shell, is a continuous thermochemical process that can produce drop-in liquid fuels from a variety of feedstocks including forestry residue, agricultural waste and mixed urban waste[26]. Unlike some other SAF production processes which require hydrogen to be produced externally and imported into the plant, this process can be designed so that its hydrogen requirements can be produced internally.

Currently, this process is at TRL 6, with a demonstration scale unit processing 5 tonne/day (dry) feedstock at Shell's Bangalore Technology Centre in India. There are plans for a first of a kind commercial scale unit to be built in Åmli, Norway, by Biozin Holding AS, a joint venture between Biozin AS (a subsidiary of Bergene Holm AS, the second-largest sawmilling and wood processing group in Norway) and Swedish oil refiner, Preem. Shell has provided financial support for the pre-engineering phase of the study[27]. There have been no other publicly announced licensees of this technology.

Despite being a promising pathway, the IH^2 process still needs to be proven at full commercial scale. Potential challenges that the process might face are high downtime due to gummy biomass residues and low catalyst life when the catalyst is mixed upfront with the biomass[28].

Table 11: Integrated Hydropyrolysis players and projects

Developer/s	Tech licensor/s	Partner/s	Plant Location	Maturity	Production capacity* (tonne/year)	Plant Status**	Product/s	Start-up date
Shell	Shell Catalysts & Technologies (ex CRI Criterion), GTI	US DoE, Zeton (EPC), KBR (EPC)	Bangalore, India	Demonstration	584	Operational	Gasoline, Jet, Diesel	2015
Biozin Holding AS	Shell Catalysts & Technologies (ex CRI Criterion), GTI	Bergene Holm (feedstock supply), Preem (off-taker), KBR (EPC)	Åmli, Norway	FOAK Commercial	96,000	Planned	Biocrude	2022

* Figures refer to total liquid fuel output, i.e. sum of multiple fuel fractions. Assumed average fuel density of 0.8 kg/litre

** 'Operational' refers to plants which are either operational or in commissioning, 'planned' refers to plants which are either planned or under construction

2.2.5 Alcohol to Jet Synthetic Kerosene with Aromatics (ATJ-SKA)

Alcohol to Jet Synthetic Kerosene with Aromatics (ATJ-SKA) is similar to ATJ-SPK but contains a higher amount of aromatic compounds, which are needed in jet fuel to ensure the swelling of seals in the jet engine. This is why ATJ-SKA if it is approved, has the potential to be directly used in aircrafts without

[26] https://www.shell.com/business-customers/catalysts-technologies/licensed-technologies/benefits-of-biofuels/ih2-technology.html
[27] https://bioenergyinternational.com/biofuels-oils/shell-to-provide-financial-support-for-norwegian-biorefinery-project
[28] https://www.biofuelsdigest.com/bdigest/2016/01/05/low-cost-drop-in-renewable-fuels-licensing-activity-is-picking-up-fast-for-ih2/

the need for blending. The fuel has entered the ASTM certification process, but it is still in Phase 1 – Testing. There are two main players involved in ATJ-SKA, Swedish Biofuel and Byogy.

Swedish Biofuel's pathway is slightly different from other ATJ pathways because it is not limited to the conversion of a single alcohol but can convert all types of alcohols. It has demonstrated conversion of both ethanol and 2,3-butanediol. This pathway is also more flexible than others as the aromatic fuel content can be adjusted as desired, ranging from almost zero to the maximum allowed by current jet fuel specifications[29,30]. Swedish Biofuel have received funding from the European Commission (BFSJ project) to design, construct and operate a demonstration plant producing 10,000 tonnes/year of which 5,000 tonnes will be jet fuel. Project partners includes Lanzatech as technology provider, Lufthansa as fuel off-taker and SCA Energy AB as biomass supplier, and SkyNRG as fuel distributor[31].

Byogy is a California-based biofuel producer who has developed its proprietary ATJ technology to convert ethanol into drop-in jet fuel or gasoline. Byogy's technology can adjust the aromatic content of jet fuel from ~0% to 30% and they are involved with Swedish Biofuel in the certification of ATJ-SKA[32]. As presented in Section 0, Byogy has a couple of demonstration plants planned but have not reached commercial scale yet.

Both players are also involved in the ATJ-SPK pathway and their plant are included in Table 2.

2.3 Pre-Qualification stage pathways

2.3.1 Summary of Pre-Qualification Stage pathways

This section includes an overview of other SAF pathways and players that have not entered the ASTM qualification process yet. The landscape of biofuel pathways suitable for jet production is vast and composed of several companies and organisations developing their own technologies. In this study, we have decided to concentrate on those companies that have recently manifested an interest in jet fuel production by engaging with aviation industry stakeholders (based on CAAFI, and the ASTM D4054 pipeline as it was in 2019) as shown in Figure 4. Some of these companies have already reached out to CAAFI and OEMs to begin the certification process. These pre-qualification stage pathways have been grouped by type of feedstock and are discussed further in the sections below.

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[29] Zschocke et. al., 2017, "High Biofuel Blends in Aviation (HBBA)", https://ec.europa.eu/energy/sites/ener/files/documents/final_report_for_publication.pdf
[30] Swedish BioFuels AB, https://ec.europa.eu/info/sites/info/files/9_angelica_hull.pdf
[31] European Commission, "Production of fully synthetic paraffinic jet fuel from wood and other biomass" (FP7 project), accessed on 11/05/2020, https://cordis.europa.eu/project/id/612763
[32] Byogy, 2016, "Renewable Fuels For All Modes of Transport", https://www.energy.gov/sites/prod/files/2016/09/f33/weiss_alternative_aviation_fuels_workshop.pdf

Figure 4: ASTM pipeline[33]

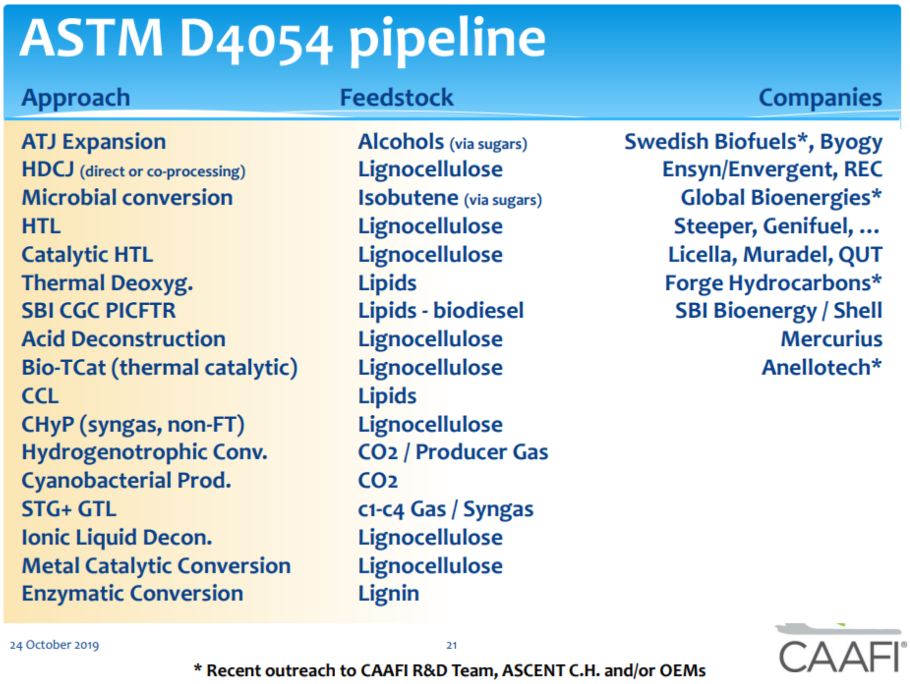
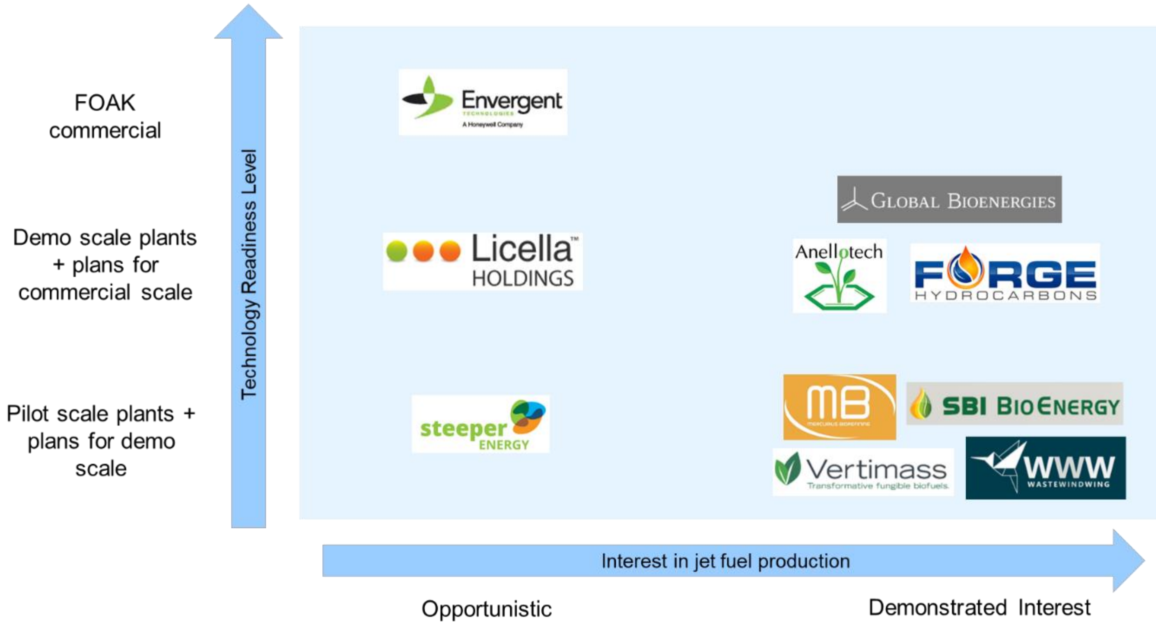


Figure 5 summarises pre-qualification SAF pathways illustrating how technology developers are distributed across technology maturity and interest in SAF production. Players are classified as "Opportunistic" when jet fuel is only mentioned as one possible output of their process. The category of "Demonstrated interest" includes organisations who have recently engaged with aviation industry stakeholders (e.g. airlines, ASTM), or when jet fuel is mentioned as one of their main products.

[33] https://www.gti.energy/wp-content/uploads/2019/10/47-tcbiomass2019-Presentation-Steve-Csonka.pdf

Figure 5: Summary of players across pathways in pre-qualification stage



Reflections on pre-qualification stage pathways

Compared to the certified pathways, there are fewer technologies and fewer players who have demonstrated an active interest in pursuing aviation fuel as their main product. These technologies are also generally at earlier stages of technology development. It is harder to assess which of these players would be interested in entering a competition.

2.3.2 Lignocellulosic pathways

2.3.2.1 Hydrothermal Liquefaction (HTL)

Hydrothermal Liquefaction (HTL) processes convert wet cellulosic biomass or wastes into an intermediate bio-crude oil which can then be upgraded to jet fuel either in-situ or transported to external refineries. There are several types of HTL processes characterised by different levels of technology maturity. The certified CHJ pathway is an example of a relatively mature HTL pathway, but others are at an earlier stage of development. HTL offers the possibility to process wet feedstocks without requiring drying. Compared to pyrolysis oils, HTL bio-crude oils have the advantages of lower water and oxygen contents, higher energy density, and greater stability.

Major technical challenges of this pathway are:

- The high temperature and pressure conditions of the process which negatively impacts both equipment capital and operational costs.
- The significant upgrading (via hydroprocessing) required to meet jet fuel specifications requires a significant amount of hydrogen (but less than pyrolysis).

There are several players involved in HTL pathways among which Steeper Energy and Licella are the most active. Other players include Genifuel, Muradel and Queensland University of Technology.

Steeper Energy is a Danish-Canadian company licensing their proprietary HTL technology called Hydrofaction™. The super-critical conditions of their process are optimised to promote high yields of bio-crude oil that can be converted into transport fuel, including jet. In 2017, Steeper announced its partnership with Silva Green Fuel, a joint venture between the Norwegian Statkraft and the Swedish Södra, to build a demonstration plant at a former pulp mill in Tofte (Norway). Steeper has licensed their

Hydrofaction™ process to Silva Green, who will employ it to convert woody residues into bio-crude oil for further upgrading to diesel, jet or marine fuel[34].

Licella is an Australian company that has developed and patented a type of catalytic HTL technology called Cat-HTR™. Licella engaged with aviation stakeholders in the past when, in 2011, they explored SAF production from woody biomass in partnership with Virgin Australia and Air New Zealand[35]. More recently, Licella has licensed their technology to ReNew ELP for the construction a FOAK commercial plant in the UK (Teeside). However, this plant is going to target the conversion of end-of-life plastic into chemical products, rather than jet fuel[36].

2.3.2.2 Hydroprocessed Depolymerized Cellulosic Jet (HDCJ)

Hydroprocessed Depolymerized Cellulosic Jet (HDCJ) is a class of processes that includes different pathways converting lignocellulosic feedstocks into liquid fuels via thermochemical reactions. Most of these pathways involve some form of pyrolysis[29].

One of the players involved in this pathway is Envergent, a joint venture between Ensyn and Honeywell UOP. Envergent is the licensor of the “Rapid Thermal Process” (RTP™) technology which converts lignocellulosic biomass into a bio-crude oil. In the RTP™ process biomass particles are fragmented and vaporised by a flow of hot sand. The vapours are subsequently quenched and condense into a bio-crude oil that is then extracted. The bio-crude needs to be upgraded to jet fuel and Envergent, with support of Honeywell UOP, is working on the integration of the upgrading process into existing refineries[37].

Ensyn has a commercial facility in Port-Cartier (Quebec) with a capacity of about 32,000 tonnes/year of bio-crude. The project was developed in collaboration with Arbec Forest Products, a timber producer who supplies sawmill residues to the plant. The technology was provided by Envergent. Part of the biocrude is sold to and co-processed in Canadian and US refineries for production of transport fuels[38]. Despite being a potential SAF producer and listed in the ASTM certification pipeline, Ensyn’s operations seem to be focussing on other fuel markets at the moment.

2.3.2.3 Other pathways

Mercurius Biorefining, a US company, is developing a novel process which converts cellulosic biomass to renewable diesel, aviation and marine fuels. Their technology is called “REnewable Acid-hydrolysis Condensation Hydrotreating” (REACH) and creates an intermediate bio-crude product through the use of catalytic hydrolysis, which is then upgraded to transport fuel through commercial hydrotreating equipment[39]. In February 2019, they received funding from the Australian government to build a pilot plant in Queensland dedicated to production of renewable jet and diesel from agricultural and forestry waste[40].

Anellotech’s patented Bio-TCat™ process produces 100% bio-based aromatic chemicals (i.e. benzene, toluene and xylene). In addition to these chemicals, Bio-TCat™ technology produces heavier aromatics products, which can be used as bio-marine fuel, or can be upgraded to make diesel or jet fuel

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[34] Steeper Energy, December 2017, press release, https://steeperenergy.com/2017/12/15/steeper-energy-announces-eur-50-6-m-dkk-377-m-advanced-biofuel-project-with-norwegian-swedish-joint-venture-silva-green-fuel-in-licensing-deal/
[35] https://www.greencarcongress.com/2011/12/licella-20111214.html
[36] https://www.greencarcongress.com/2018/08/20180816-neste.html
[37] Envergent website, accessed on 12/05/2020, https://www.envergenttech.com/technology/frequently-asked-questions/
[38] Ensyn website, accessed on 12/05/2020, http://www.ensyn.com/quebec.html
[39] Mercurius Biorefining website, accessed on 12/05/2020, https://www.mercuriusbiofuels.com/Technology.html
[40] Queensland Gov, February 2019, press release, http://statements.qld.gov.au/Statement/2019/2/13/gladstone-biorefinery-pilot-plant-gets-the-goahead

blendstocks[41]. Although Anellotech is yet to enter the ASTM certification process, they have outreached to the CAAFI R&D team to initiate the process[42].

Anellotech's bio-aromatics are currently produced using loblolly pine feedstock from the southern United States at Anellotech's T-Cat8® pilot plant in Silsbee, Texas. Commercially-viable process yields and catalyst performance have been demonstrated. As a result, they have begun planning for scale-up design and engineering of a commercial plant. Their next step is the construction of a plant with a capacity of 40,000 tonnes/year of products including C9+ aromatics to use as transport fuels[43]. Anellotech has been developing their technology in partnership with players such as Johnson Matthey, who provides the catalysts, and Axens who supports the commercialisation and licensing of Bio-TCat™.

2.3.3 Sugars pathways

One promising sugar-based SAF pathway is the ATJ variation that Vertimass is developing. Vertimass has developed a technology called "Consolidated Dehydration and Oligomerisation" (CADO) which does not require the additional hydrogenation step typically present in the back end of more established ATJ pathways. This has positive impacts on energy consumption and process economics[44].

In October 2019, the company has been awarded by the US Department of Energy up to $1.4 million to optimise their process for renewable jet production[45]. In July 2019, Vertimass completed its first technology license agreement with Alliance BioEnergy Plus in West Palm Beach (Florida), to produce renewable jet fuel along with Benzene, Toluene, Ethylbenzene, and Xylenes[46]. Although CADO is yet to enter the ASTM certification process, Vertimass is in exploratory discussions with CAAFI to get their jet fuel certified[47].

Global Bioenergies is pursuing a biological pathway to SAF production based on genetically modified bacteria converting sugars into isobutene followed by oligomerisation and hydrotreating. This pathway is similar to Amyris' and produces a type of fuel similar to HFS-SIP. The technology maturity using conventional sugar feedstocks is at TRL 7-8, while the same processes based on cellulosic feedstocks is at TRL 5. Similar to Amyris' process, the main challenges for this pathway are associated with the low efficiency of converting lignocellulosic sugars into fuels, which translates into a high feedstock cost and a high energy consumption. Global Bioenergies, based in France, is the technology owner of this pathway and operates a demonstration-scale plant in Germany (Leuna refinery) in partnership with Fraunhofer CBP. The plant capacity is 100 tonnes/year of isobutene[48]. This molecule can be further processed and transformed into different products. Global Bioenergies is targeting isododecane for the cosmetics and jet fuel market and ETBE and isooctane as gasoline additives. In 2018, the company announced their collaboration with SkyNRG on ASTM-certification of SAF produced from Global Bioenergies' iso-butene[49].

Their next step is to move to commercial scale with the construction of the IBN-One plant, a joint venture with Cristal Union and participation of L'Oréal. This plant will have a production capacity of 50,000

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[41] Anellotech website, accessed on 12/05/2020, https://www.anellotech.com/about-us
[42] https://www.gti.energy/wp-content/uploads/2019/10/47-tcbiomass2019-Presentation-Steve-Csonka.pdf
[43] BifuelsDigest, May 2019, https://www.biofuelsdigest.com/bdigest/2019/05/05/anellotechs-bio-tcat-technology-viability-confirmed-during-pilot-plant-campaign-moving-forward-with-commercialization/
[44] https://www.greencarcongress.com/2019/11/20191127-vertimass.html
[45] https://biofuels-news.com/news/vertimass-awarded-up-to-1-4-billion-to-optimise-renewable-jet-fuel/
[46] https://www.vertimass.com/vertimass-completes-first-technology-license-to-alliance-bioenergy-plus-inc/
[47] http://caafi.org/news/pdf/CAAFI_Quarterly_Q2_2019.pdf
[48] Global Bioenergies, March 2019, "High performance bio-based components for gasoline and jet fuel", https://www.nedo.go.jp/content/100890889.pdf
[49] Gloabal Bioenergies, April 2018, press release, https://www.global-bioenergies.com/global-bioenergies-and-skynrg-announce-their-collaboration-on-astm-certification-of-a-bio-isobutene-feedstock-and-conversion-process-for-the-production-of-sustainable-aviation-fuel/?lang=en

tonnes of isobutene and derivatives[48]. The final use of isobutene has not been decided yet, but a significant fraction of it could be used for jet fuel production.

2.3.4 Waste Lipids pathways

One promising pathway to create renewable jet fuel is the Lipid-to-Hydrocarbon (LTH) technology. It converts waste fats and other organic oils into hydrocarbons. This conversion is performed through a two-stage process, hydrolysis followed by pyrolysis[50], and does not require any catalyst or hydrogen.

Forge Hydrocarbons, based in Canada, is the technology owner of this pathway and has patented the technology. In 2020, the company received equity investments[51] from Shell Ventures, and a follow-on contribution from Valent Low-Carbon Technologies, adding to a prior investment from Lockhead Martin. Forge Hydrocarbons is planning to build a first-of-its kind plant with an expected annual production capacity of 27 thousand tonnes of jet, diesel and naphtha in Sombra, Ontario.

Another waste lipids pathway is being developed by SBI Bioenergy, also based in Canada. SBI uses a continuous catalytic process that converts fat, oil or grease into renewable gasoline, diesel and jet fuel that can be dropped directly into fossil fuels[52]. The pathway consists of a two-stage process converting lipids into biodiesel and glycerine first, and then upgrading the biodiesel to drop-in fuels. For both steps SBI has developed proprietary catalysts called "Continuous Green Catalysts". In 2017, Shell acquired the exclusive development and licensing rights for the SBI BioEnergy patented production process[53].

2.3.5 Municipal Solid Wastes pathways

In the UK, the WasteWindWing (WWW) project is aiming to convert MSW into jet fuel via gasification combined with methanol/DME synthesis. WWW is being developed by a team of researchers at University College London in partnership with the Royal Academy of Engineering and Heathrow airport. In 2019, this project won the British Airways "Future of Fuels Competition", a 1-year long competition to support sustainable aviation fuel innovation in the UK.

WWW has a path to commercialisation lined up. They are currently conducting a FEED study as the basis for a pilot plant to be built by 2022. To build this plant they will rely on government funding and partner with Innovate UK and ABSL as the gasification technology supplier[54].

2.4 UK applicants from previous F4C competition

In addition to the players presented in section 2, there are 12 other UK organisations who participated in the F4C competition and that submitted projects relevant to fuel production for aviation[55]. These organisations are mostly small UK technology developers (with less than 10 employees) and are distributed across various fuel pathways. Five of these projects would produce a fuel that is already certified, while the other projects involve pathways which are in the pre-qualification stage.

Among the 12 projects, the only one led by a large and established organisation is a proposal by Johnson Matthey for an FT synthesis plant. In partnership with Fulcrum Bioenergy and Advanced Plasma Power (APP), the project proposed to utilise plasma gasification of MSW at APP's demonstration plant in Swindon to produce a syngas which would subsequently be synthesised into

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[50] Green Car Congress, October 2013 : https://www.greencarcongress.com/2013/10/20131014-forge.html
[51] Globalnewswire, February 2020, https://www.globenewswire.com/news-release/2020/02/13/1984443/0/en/FORGE-announces-investment-from-Shell-Ventures-and-Valent-Low-Carbon-Technologies.html

[52] SBI Bioenergy website, accessed on 18/05/2020, https://www.sbibioenergy.com/r-d
[53] Green Car Congress, June 2017, https://www.greencarcongress.com/2017/06/20170628-shell.html
[54] IATA, 2019, "Sustainable Aviation Fuel Symposium", https://www.iata.org/contentassets/8dc7f9f4c38247ae8f007998295a37d5/safs2019-day1.pdf
[55] Velocys, Lanzatech and Fulcrum are not counted in this group despite being F4C applicants, because they have already been included in previous sections

liquid fuels via FT. Johnson Matthey and BP have licenced their FT technology to Fulcrum Bioenergy in 2018 for the realisation of Fulcrum's new Sierra BioFuels plant in the US. Two important developments have occurred with respect to this project since it was first proposed. Firstly, APP decided to focus production on synthetic natural gas (SNG) at its Swindon facility, rather than liquid fuels. Secondly, APP went into administration in 2018, but with the assistance of both a DfT loan and other match funding, a new entity, Advanced Biofuels Solutions Ltd. (ABSL), was formed to complete the project. Construction recommenced in September 2019 and much of the remaining construction work was complete at the time of writing this report.

Follow up activities conducted under this study suggest that while some of the projects continue to pursue plans to demonstrate their technology for SAF production, only two of them have made any significant advances. Others have re-focussed their business activities on energy or road fuel production.

One of the projects which received funding under the F4C competition is the one led by KEW Projects. This project has been awarded a share of £6.5 million to build plants for production of road fuel for heavy goods vehicles, but with the secondary aim of also producing aviation fuels[56]. The production process involves gasification of waste wood and RDF, thermal cracking and FT. The first plant is planned to be built at the Sustainable Energy Centre in Wednesbury.

Reflections on previous UK based applicants

Overall, the UK has a number of SMEs involved in SAF production which could apply to enter a new competition if this was designed to provide funding to meet their particular development needs.

2.5 Estimation of GHG savings

For the key pathways described above, this section provides a review of anticipated GHG emissions from the process and the GHG savings achieved in comparison with the RED II comparator. It also describes at a high level what variables affect the reported results. Note that for all fuels the GHG emissions are shown in the figures below without GHG emissions from transport and distribution of the finished fuel. These are dependent on the distance and mode of transport but are typically small. For example, emissions for transporting aviation fuel produced in the UK 300km by road from its point of production to its point of use would be around 1.2gCO_2eq./MJ [57].

It is also important to note that other climate impacts associated with aircraft, such as nitrogen oxides (NOx), soot, and water vapor, which create contrails and cirrus clouds, are outside the scope of this analysis. However, these impacts are not yet fully understood and further investigation is needed by the wider scientific community.

Summary of GHG savings

In summary, these pathways can all provide 70% GHG savings[58] in comparison with the fossil counterfactual. However, these results depend heavily on assumptions around the feedstock used, the source of electricity and CO_2 (for Power to Liquids pathways) and the production method for hydrogen used (particularly for HEFA, which uses significant amounts of hydrogen).

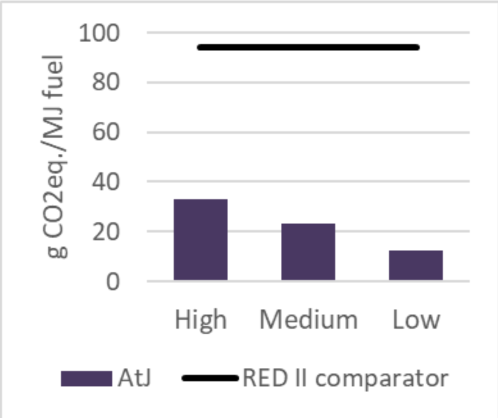
2.5.1 ATJ-SPK, ATJ-SKA

The GHG emissions savings for alcohol to jet technology pathways range between 65 – 87% compared to RED II fossil fuel comparator, strongly depending on the GHG emissions from the production of the

56 https://www.gov.uk/government/news/orange-peel-rubbish-and-fatbergs-the-fuels-behind-the-future-of-green-transport
57 JEC (2018) WtW Study v5
58 Except for the HFS-SIP route – but only one data point is available for this route

alcohol. Estimates in the literature for GHG emissions for the production of jet fuel from ethanol range from 3 $gCO_2eq./MJ$[59] to 7$gCO_2eq./MJ$[60], although there are relatively few publicly available sources which provide data on this process. Figure 6 indicates the GHG emissions from jet fuel production via a number of different alcohol production pathways, assuming GHG emissions from conversion of ethanol into jet of 5$gCO_2eq./MJ$, The high figure reflects ethanol production from corn[61], the medium figure reflects ethanol production from sugar beet[62] and the low figure reflects ethanol production via gasification and fermentation of corn stover.[63]

Figure 6: GHG savings for jet fuel production via alcohol to jet



2.5.2 HEFA-SPK, HFP-HEFA, HC-HEFA-SPK

For HEFA produced from fats and oils, the GHG emissions savings range between 53 – 89%, largely dependent on whether virgin vegetable oils or waste fats and oils are used. Figure 7 illustrates the GHG emissions of HEFA produced from rapeseed (high figure), animal fats (medium figure) and used cooking oil (low figure)[64].

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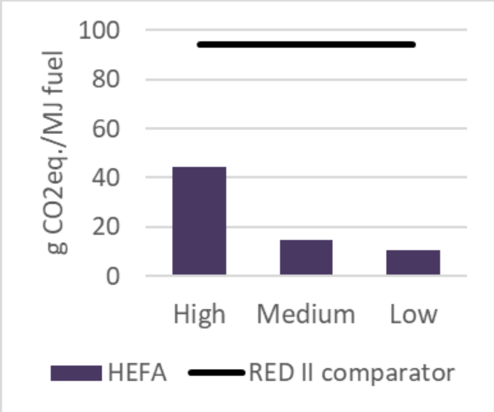
[59] Calculation based on data in GREET
[60] Hannon et al. (2019) Technoeconomic and life-cycle analysis of single-step catalytic conversion of wet ethanol into fungible fuel blendstocks, Available from: https://www.pnas.org/content/117/23/12576
[61] RED II, Available from: https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32018L2001&from=EN , Typical value for the production of corn (maize) ethanol (forest residues as process fuel in CHP plant) was used
[62] RED II, Available from: https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32018L2001&from=EN , Typical value for the production of sugar beet ethanol (with biogas from slop, natural gas as process fuel in CHP plant) was used
[63] Handler, R.M., Shonnard, D.R., Griffing, E.M., Lai, A., Palou-Rivera, I. (2015) Life cycle assessments of ethanol production via gas fermentation: anticipated greenhouse gas emissions for cellulosic and waste gas feedstocks, Industrial and Engineering Chemistry Research, 55, 12, 3253-3261, https://pubs.acs.org/doi/full/10.1021/acs.iecr.5b03215
[64] Values shown on graph are typical values from the RED II excluding transport and distribution emission

Figure 7: GHG emissions from the production of HEFA

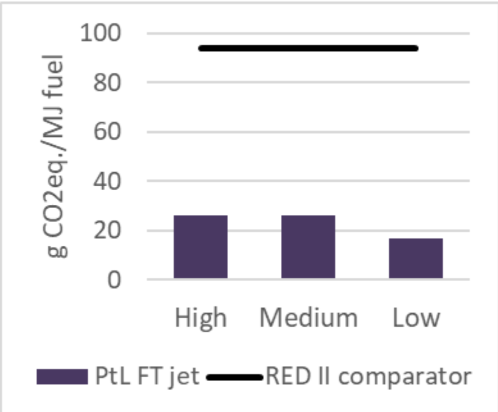


2.5.3 FT-SPK (both biomass gasification and power to liquids pathways)

For FT-SPK PtL pathways (Section 2.1.4), the level of GHG emissions savings is highly dependent on the GHG intensity of the electricity source used, and the energy used in CO_2 capture, ranging between 56 - 96% . Use of renewable electricity for PtL fuel production is critical to achieving significant GHG emissions savings. In Figure 8, the high, medium and low value all assume use of renewable electricity for hydrogen production with a GHG intensity for the electricity of 0gCO_2eq./MJ.

There can also be substantial variation in the GHG emissions from PtL FT jet production depending on the GHG emissions associated with capture and purification of CO_2 for use in the process. In Figure 8 the high value is based on direct air capture of CO_2 powered by renewable electricity and natural gas for heat.[65] The medium figure is based on CO_2 capture from cement production.[66] The low figure is based on CO_2 capture from a natural gas combined cycle gas turbine with 95% capture rate.[67] It should be noted that the GHG emissions from capture and purification of CO_2 could be substantially higher than those shown here if the energy requirements are high and fossil sources of energy are used. On the other hand, there is scope to reduce the GHG emissions from DAC compared to those shown here if renewable or waste energy sources are used for both the power and heat required.

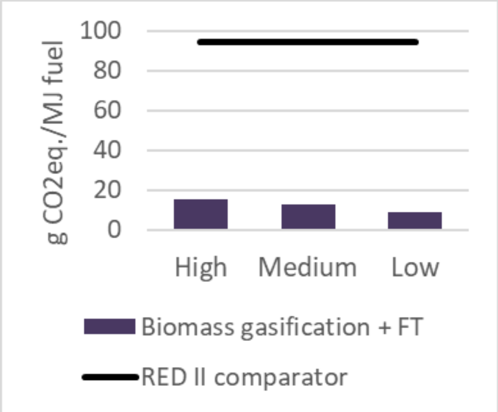
Figure 8: GHG emissions savings for power to liquid FT-SPK pathways compared to the RED II comparator



[65] Keith, D.W., Holmes, G., St Angelo, D., Heidel, K. (2018) A Process for Capturing CO_2 from the Atmosphere, Joule, 2, 1573-1594. Based on process set-up D.
[66] Voldsund et al (2019) Comparison of technologies for CO2 capture from cement production - Part 1: Technical evaluation
[67] The IEA (2019) Towards Zero Emissions, available from: https://ieaghg.org/publications/technical-reports

For FT fuels produced from biomass gasification a smaller range in GHG intensity is typically seen across the literature, with GHG emissions savings ranging between 84 – 90%. The high, medium and low values illustrated in Figure 9 reflect typical values for the production of biomass FT fuel from farmed wood (high), waste wood (medium) and black liquor gasification integrated with a pulp mill (low).[68]

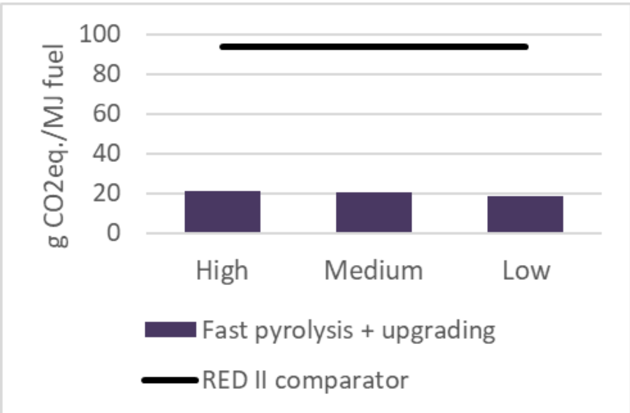
Figure 9: GHG emissions from the production of FT jet fuel via biomass gasification



2.5.4 IH2, HDCJ and other pyrolysis pathways

The GHG emissions savings of 77-80% can be achieved through fast pyrolysis and upgrading (IH2 – Section 2.2.4 , HDCJ – Section 2.3.2.2) of forest residues in comparison to the RED II comparator. Figure 10 shows the GHG emission to be around 20 gCO_2e/MJ (excluding downstream transport and distribution and refuelling) – the high value refers to a first commercial plant, with the medium and low value referring to medium and long-term technology outlook respectively[69]. The methodology used assumes no GHG emissions at point of collection for a waste feedstock. Proprietary information suggests the emissions can range from as low as 5 gCO_2e/MJ to 32 gCO_2e/MJ, depending on the technology used and co-products from the process (syngas and biochar).

Figure 10: GHG emissions for fast pyrolysis + upgrading technologies compared to RED II comparator

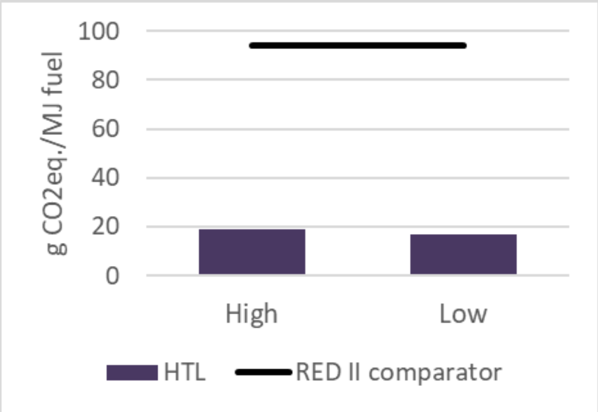


[68] RED II, Available from: https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32018L2001&from=EN , Figures used are typical values, excluding transport and distribution
[69] IRENA (2016). Innovation Outlook: Advanced Liquid Biofuels.

2.5.5 CHJ and other HTL pathways

HTL routes can achieve GHG emissions savings of between 80 – 82% compared to RED II fossil fuel comparator, similar to those achievable through pyrolysis with upgrading technology . Figure 11 shows the GHG emissions from HTL pathways (CHJ –Section 2.1.6) to be around 17 gCO_2e/MJ, (excluding downstream transport and distribution and refuelling)[70]. The high value assumes a process with ex-situ H2 production and the low value, in-situ H2 production, which has lower GHG emissions. There are currently few companies developing HTL technology, therefore there is limited data available for validation.

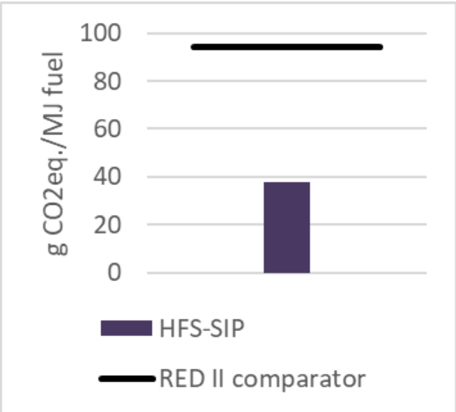
Figure 11: GHG emissions savings of HTL technology compared to RED II comparator



2.5.6 HFS-SIP

For the direct sugars to hydrocarbon process, the GHG emissions are strongly dependent on the source of the sugars. For jet fuel produced from sugar cane and used at a 10% blend level, the GHG emissions from fuel production are estimated by de Jong et al. (2017) to be 38 $gCO_2eq./MJ$ (Figure 12), a GHG emissions saving of 60%. Whilst this estimate of emissions does not meet the 70% GHG saving threshold, that does not rule out that this pathway could meet the threshold, e.g. if sugars with lower GHG emissions associated with their production were used as a feedstock.

Figure 12: GHG emissions from the production of HFS-SIP jet fuel

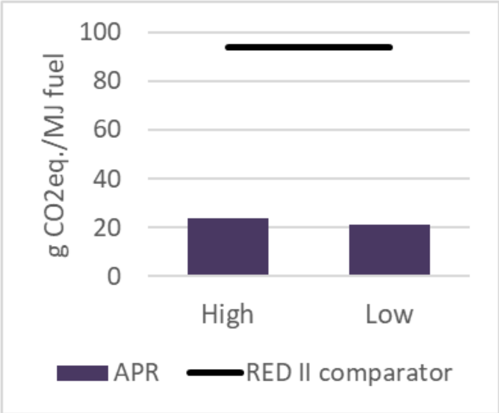


[70] De Jong et al. (2017). Life-cycle analysis of greenhouse gas emissions from renewable jet fuel production. *Biotechnology for Biofuels.10:64*. doi: 10.1186/s13068-017-0739-7

2.5.7 HDO-SAK (APR)

The GHG emissions of fuel produced via APR are fairly uncertain, as there are no examples of this process operating at above pilot scale today. Estimations from IRENA (2016)[71] are illustrated in the figure below and suggest a GHG emission saving of 74 – 78% is achievable. Both the high and the low figures reflect the production of diesel via hydrolysis + APR of agricultural residues. The high figure is a estimation of emissions in the medium-term and the low figure reflects an estimate of emissions in the long-term, due to anticipated improvements in conversion efficiency in the future.

Figure 13: GHG emissions from the production of jet fuel via APR



[71] IRENA (2016) Innovation Outlook for Advanced Liquid Biofuels, Available from: https://www.irena.org/publications/2016/Oct/Innovation-Outlook-Advanced-Liquid-Biofuels

3 Funding structures

DfT's previous sustainable fuels competitions (ABDC and F4C), used a grant support mechanism and in reviewing the lessons learned from both it is clear that grant support can provide a useful funding structure, and is well understood by other financing institutions, such as banks and investments firms. However, in this study, we have expanded the review of funding structures to examine additional options which could be considered by DfT in the design of a future competition. The following section of this report draws together evidence collected from:

- Primary research into international Sustainable Aviation Fuels funding structures
- The lessons learned review
- Investor interviews
- State Aid regulations

It also reflects on that evidence and provides links to both the business case section below, and the section on feasibility (Section 4)

3.1 International funding for sustainable aviation fuels

Research has been conducted into the various types of financial instruments that have been utilised in biofuels funding (both UK and internationally) in order to provide an insight into the types of projects that might require funding, how the financial instrument has been implemented, and the associated advantages/drawbacks of using the instrument. Some financial instruments related to non-biofuels, such as conventional fuels (e.g. kerosene) have also been considered, as well as policy instruments derived from structures that have proven effective to mobilise project finance to build and operate production capacity[72]. The latter looks to assess the feasibility of these structures in the context of sustainable aviation fuels and within this research, how these could be implemented in the UK. The research is summarised below with further details contained in Appendix B of this report.

Main funding categories identified

The financial instruments identified within this research are based on those identified by the International Civil Aviation Organisation (ICAO) in a review of instruments for financing reductions in aviation emissions[73]:

- **Grants**
  Project Development Costs, Capacity Building, Policy Development
- **Loans**
  Contingent, Concessionary, Senior Debt, Credit Line, Microfinancing
- **Bonds**
  Green, Traditional Bonds
- **Guarantees/Insurance**
- **Direct Investment**
  Government, Private Equity
- **Other Support**
  Subsidies and Incentives, Contracts, Tax Benefits, Other

A summary of each category is outlined below along with some real-world examples of funding used in sustainable aviation fuels (or non-SAF) schemes.

Grants

A grant is a non-repayable fund with a fixed maximum rate of intensity in relation to project costs (for example ABDC had a fixed maximum rate of 50% of eligible costs). The grant mechanism is well understood by other financing institutions, such as banks and investment firms and are generally

[72] https://www.atlanticcouncil.org/wp-content/uploads/2020/04/AC_SAF_0420_v8.pdf
[73] ICAO, 2017. Financing Aviation Emissions Reduction. https://www.icao.int/environmental-protection/Documents/ICAO_UNDP_GEF_FinancingLowCarbonAirportGuidance.pdf

counted as State Aid when awarded to private sector organisations seeking to develop new technologies. Section 3.4 goes into further detail regarding State Aid.

Examples of grant support in the SAF area are:

- Ongoing grant support from the Swedish Government to the Swedish Energy Agency to promote sustainable aviation fuels. The Swedish Government have agreed to finance research and development projects aiming at promoting sustainable aviation fuels, providing up to 20 million SEK (approx. £1,725,000) in 2018, 30 million SEK (approx. £2,587,000) in 2019, and 50 million SEK (approx. £4,310,000) in 2021.
- Work led by Washington State University in which the Northwest Advanced Renewables Alliance (NARA) received $40 million grant (approx. £32,122,000) from the United States Department of Agriculture (USDA) to develop a holistic approach to building a supply chain for aviation biofuel, from feedstock to education amongst future workforces. Note that the US does not have an equivalent State Aid limit to the UK, limiting grant or low-interest loan support to EUR 15 million per project.

Loans

Loans are borrowed money, typically from a bank, that will be expected to be paid back over a set period of time with interest. Loans are especially useful when the project is expected to deliver sufficient revenue stream, but the firms do not have enough liquidity to make the initial investment. Sustainability linked loans, where the loan is linked to achievement of specific sustainability targets are an alternative to traditional loans, with the market for them increasing 250 percent in 2019. In contrast to financial instruments such as Green Bonds (which provide capital for specific sustainability projects), they do not come with restrictions on how their proceeds can be used.

An example of a sustainability loan in the aviation sector is that given to JetBlue Airways, a major American low-cost airline, and the sixth largest in the USA with regards to passengers carried. The company has signed on to a new credit facility that is priced, based on its performance on environmental and social matters. The credit has been provided in the form of a sustainability linked loan through which the company has received a $550 million (approximately £443 million) from the French bank BNP Paribas. As a result, this financial incentive gives the airline the opportunity to address its sustainability and carbon commitments. However, if JetBlue fails to achieve (its predetermined environmental, social and governance targets set out by BNP Paribas, the airline will be subject to higher interest rates on the loan; conversely if it surpasses its targets interest rates will be reduced.

Bonds

A bond is a fixed income instrument that represents a loan made by an investor to a borrower, such as a company or government. By issuing a bond a company or government borrows money from an investor, who in return are paid interest on the money they've loaned.

Green bonds, or sustainable bonds are bonds that were created to fund projects that have positive environmental and/or climate benefits, including energy, transport, waste management, building construction, water and land use. Green bonds which are issued are often 'use of proceeds' or asset-linked bonds, meaning that the proceeds from these bonds are earmarked for green projects.

Green bonds used to finance sustainable aviation fuels have been utilised at the Sierra Biofuels Plant located in Nevada, USA. The project aims at producing low cost, low carbon transportation fuels, including aviation fuel and diesel, using feedstock derived from municipal solid waste. In doing this, Sierra have raised (through additional support) more than $200 million (approx. £160,800,000) in tax-exempt municipal bonds through the State of Nevada Department of Business and Industry. These bonds were labelled as 'green bonds' as a result of the environmental benefits of the project.

Guarantees/Insurance

A financial guarantee insurance is a type of financial insurance or support scheme, typically contracted by a third party (guarantor) to protect a second party (the creditor) in case someone who borrows money from them (the investor) cannot pay it back. Loan guarantees can be particularly useful for developers in order to help manage project risk and attract additional funding, either equity or debt.

The UK Guarantee Scheme (UKGS), implemented by the Infrastructure and Projects Authority (IPA) supports private investment in UK infrastructure projects. It does this by bridging the gap between equity and debt financing when normal debt providers have very expensive terms or conditions that are prohibitive. The scheme can issue up to £40 billion of guarantees and is open to at least 2026. It has already issued nine guarantees totalling £1.8 billion of Treasury-backed infrastructure bonds and loans, supporting over £4 billion worth of investment. However, the UKGS does not typically fund first of a kind projects, as the commercial risk is assessed in the same manner as any major lender. SAF plants are therefore viewed as too high risk for the loan guarantee programme to consider funding them.

In the US, the Department of Agriculture's Rural Development is currently offering loans guarantees, which are backed by the federal government, for the development, construction, and retrofitting of commercial scale biorefineries. The maximum loan amount is for 80% of project costs or $250 million (approximately £201 million) with a loan term of 20 years or the useful life of the project. These loans or loan guarantees will be provided to first of a kind commercial demonstration projects for renewable energy, with the ambition of progressing them through to the commercialisation stage. However, investor interviews have clarified, the US Government charges for this guarantee effectively make it more expensive than a commercial loan. The Fulcrum Sierra plant, having initially secured a loan guarantee under this programme, eventually changed approach and issued Green Bonds to cover their debt financing instead.

The Investment Plan for Europe, the so-called 'Juncker plan'[74] contains a pillar named the European Fund for Strategic Investments (EFSI) which provides an EU guarantee to mobilise private investment, with the European Commission working together with its strategic partner, the European Investment Bank (EIB). The next stage of the Juncker Plan from 2021-2027 has been re-branded the InvestEU Programme and aims to mobilise at least EUR 650 billion in additional investment[75]. The EIB are currently reviewing loans for biofuel projects within Europe, leveraging the loan guarantee from the EU to agree loans on commercial terms to new projects.

Direct Investment

Direct investment in the private sector or, direct equity investment refers to money that has been invested in a firm by an investor, which in legal terms, means gaining part ownership of the company. Investors directly purchase the shares/stocks of a company and recover it only when they sell their shareholdings to other investors, or when the assets of the firm are liquidated, and proceeds distributed among them after satisfying the firm's obligations. This form of investment is also linked with 'venture capital', through which investors provide direct equity to companies that have a high growth potential, in exchange for an ownership share. These companies often demonstrate innovate technology or business models that investors find attractive.

In 2016 for example, Fulcrum and BP formed a strategic partnership which included a $30 million (approximately £26 million) equity investment in Fulcrum by BP to support the development of its first plant in Nevada, USA. The aim of the plant was to produce sustainable transport fuel made from household waste. The partnership also included a 500 million gallon jet fuel offtake agreement with Air BP, the aviation division at BP, to provide 50 million gallons per year of low carbon, drop in jet fuel.

Under previous competitions (the Advanced Biofuels Demonstration Competition in particular) the question of direct equity investment by UK Government was not considered a viable option due to the likely liabilities involved in equity ownership in a very early advanced biofuels market. However, this may be an option to explore further with HM Treasury and senior DfT stakeholders, depending on DfT's current appetite for risk and liabilities, and the potential impact of significant Government investment into individual plants.

[74] https://ec.europa.eu/commission/priorities/jobs-growth-and-investment/investment-plan-europe-juncker-plan/what-investment-plan-europe_en
[75] https://ec.europa.eu/commission/priorities/jobs-growth-and-investment/investment-plan-europe-juncker-plan/whats-next-investeu-programme-2021-2027_en

Other Support

Other financial support mechanisms identified include subsidies and incentives, tax benefits, and non-government investment funds.

- **Tax benefits** were conceived to be a viable approach for incentivising the use of sustainable aviation fuels. For instance, tax credit provides a suitable incentive to produce and place renewable fuel into the market, while decreasing production costs compared to fossil fuels, and supporting investment in blending infrastructure. Currently, in the USA, financial incentives such as the Biodiesel and Renewable Diesel Blender Tax Credit provides a fuel tax credit for fuels containing biodiesel fuel. Arguably, an incentive like this targeted specifically at the production and blending of sustainable aviation fuels might overtime lower the product costs of SAF and in turn, boost the level of commercial deployment associated with SAF.
- **Non-government investment funds** are examples of mechanisms where government can input substantial investment capital without contravening State Aid rules. Two recent examples of this type of fund are the **Digital Infrastructure Investment Fund (DIIF)** and **Charging Infrastructure Investment Fund (CIIF)**. Both DIIF and CIIF involve UK Government and private sector investors contributing to an investment pot, which is then managed by an independent body, charged with making all investment award decisions. Where this is potentially less applicable to SAF is the technology risk involved, as the technologies here are either relatively cheap and replicable, or there are a large variety of market actors if any one of the technology routes fail. Even with the reduced technology risk, it took 12 months of intensive stakeholder engagement and marketing to secure 5-6 core investors alongside Government. Setting up this type of private equity fund is not likely to be feasible for SAF as there are not many investors in the market, which is at a far earlier stage than digital and charging infrastructure, and those investors tend to have close relationships with individual projects so would be less inclined to allow an independent fund manager to make decisions on funding allocation.
- **Contracts for Difference** are an investment incentivisation mechanism for low carbon electricity generation, which enable long term electricity purchasing agreements at fixed rates. This provides developers of projects with high upfront costs and long lifetimes with direct protection from volatile wholesale prices. This provides the revenue certainty needed for projects to recruit equity and debt funding for the upfront capital costs. To date, Contracts for Difference have made a significant impact on the viability of low-carbon electricity generation technologies, although they have not yet been used in the sustainable biofuel market.

Reflections on international funding structures

Overall, projects below TRL 8 are generally funded by grants matched with private sector investors. The lack of international examples of pilot plants and demonstration plants being funded using any alternative funding mechanisms supports the findings of the lessons learned review; that grant funding is the most appropriate route for these types of project.

For FOAK commercial (or indeed second/third etc) plants, there are more options for DfT to consider including loan guarantees, tax credit schemes, direct equity investment and green bonds. From the research, existing plants utilised these mechanisms for the CAPEX construction costs rather than initial feasibility/FEED studies. This again supports the findings of the lessons learned review; that grant funding may still be required to enable the initial project development stages of FOAK commercial plants. The review also showed that all FOAK commercial SAF plants to date have required some form of state involvement in the financing of the project in order to raise the upfront capital.

3.2 Key evidence from the lessons learned review

Representatives of nine current and past projects funded by ABDC and F4C provided evidence for the lessons learned review through a survey and direct interviews, see Appendix C. The key evidence relating to the funding structure for a future competition is summarised below.

Wider policy

- The RTFO is not a mature mechanism, the RTFC value is volatile and investors are worried that there is no floor price or certainty for future pricing. As dRTFCs make up 70-80% of revenue, they need certainty on this going forward.
- There is little alignment between different UK funding schemes e.g. IUK, Circular Economy Fund
- The historical failure of many large waste projects can make it difficult to raise investment
- Investors are often more interested in quick wins rather than long term projects

Competition-specific

- The State Aid maximum limit (of EUR 15 million for any one project) means Government support is only a very small proportion of total costs for anything larger than a small demonstration project
- The level of match funding required is crucial for projects of all scales. 50% grant funding intensity is seen as being too low to attract investors for pilot and demonstration scale plants
- Larger projects would value an additional funding mechanism to support FEED to further de-risk projects
- Support/funding should be more in line with project lifecycle, e.g. stage gated funding with two-to-three stages for pilot/demonstration projects and three or more stages for large scale projects
- Grant funding is best for early project stages such as feasibility and FEED
- Loan guarantees or low interest loans for construction stages are more suitable for commercial plants, and not for pilot/demonstration projects

Reflections on lessons learned evidence

It will be important to place a new competition in the context of other UK funding available at the time, with value in coordinating the launch of the competition with other cross-over funders in the area of innovation and sustainable biofuels such as IUK, Zero Waste Scotland, BEIS and Defra.

For pilot/demonstration scale projects, it appears taking the staged approach of F4C and continuing use of grant funding under Article 41 of the General Block Exemption Regulations on State Aid[76] (*Investment aid for the promotion of energy from renewable sources*) will provide the necessary funding support for potential applicants. As pilot and demonstration scale projects have little certainty over any likely revenue streams (if indeed the pilot will even continue production after confirmation of the success of the technical solution), grant funding is more appropriate than low interest loans or any other revenue-based financial mechanism.

For FOAK commercial (or indeed further) plants, the future development of the RTFO will be important to investor confidence, as will demonstration of Government's understanding of FOAK commercial plants in other countries gained through this feasibility study and any additional research on future developments in other countries (for example the construction of FOAK SAF plants funded by the EU Innovation Fund).

3.3 Key evidence drawn from investor interviews

Eight investors, representing the airline, oil and gas, banking and industrial/conglomerate sectors were interviewed during June 2020. The interviewees were asked for their views on:

- Key risks associated with investing in plants producing fuels specifically for the aviation industry, and FOAK commercial SAF plants as a specific target for a future DfT competition
- Investor pre-requisites for FOAK commercial SAF plants
- Funding mechanisms that would stimulate investment in a FOAK commercial SAF plant

[76] https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:02014R0651-20170710&from=EN

- How much support might need to come from UK Government (as a percentage of total upfront capital support)
- What other support might be needed from DfT, both within a competition and wider to incentivise investment

3.3.1 Key risks associated with investing in plants producing low carbon fuels specifically for the aviation industry

Several investors explained that investing in plants which predominantly produce SAF rather than other low carbon fuels (e.g. renewable diesel) can be highly challenging, as there is currently insufficient incentive to design plants which focus predominantly on aviation fuel:

- Marginal revenues for SAF over and above those of renewable diesel are not enough to justify the additional production costs incurred by producing SAF.
- Aviation was viewed by some investors as a cyclical industry where bankruptcy and consolidation are more common than other industries. Furthermore, there are not many airlines out there, meaning that the pool of potential customers is limited. The current COVID-19 pandemic has made this more of an issue.
- Plants which are designed to produce for jet give less flexibility in terms of the product slate (some investors preferred flexibility, to protect against policy and market uncertainty).
- Kerosene has tighter product quality requirements than diesel, and for new, FOAK commercial plants, there is a risk that sometimes off-spec product may be produced, particularly during the first few years of operation. If reliable product quality cannot be guaranteed, then this could pose problems for the quality of the overall kerosene mix in commercial pipelines. Trucking has so far been used for small scale SAF test flights but at a bigger scale this would not be economic nor practical for all airports.

However, some investors did state that from a strategic perspective, aviation is an attractive destination for such fuels – particularly as road transport market for liquid fuels shrinks as electrification penetrates further.

3.3.2 Specific risks associated with investing in FOAK commercial SAF plants:

Revenue uncertainty was stated as a key risk by every single investor interviewed. The main issue stated was the current lack of visibility on dRTFC prices which creates a significant degree of revenue uncertainty for investors. Many stated that revenue certainty is absolutely essential for a positive investment decision to be made. Furthermore, the RTFO is due to end in 2032. Even though this is 12 years away, given time required to develop projects, and the lifetime of a plant, this time horizon may not be sufficient to give the certainty that investors need.

The majority of stakeholders stressed that there is a high degree of technology risk for FOAK commercial plants. After starting up, these plants rarely perform as well as expected, particularly during the first few years, when plants typically face reliability issues and therefore SAF production can be well below nameplate capacity. This translates into a significant economic risk for investors, as the revenue (predominantly derived from dRTFC credits) is directly proportional to the amount of fuel produced by the plant. Furthermore, developers often need to build plants at larger capacities, to benefit from economies of scale. However, this often means scaling up many times from demonstration scale, which brings significant technical risk with it.

Some stakeholders shared a view that they see higher regulatory complexity in the UK compared to some of its counterparts, particularly relating to obtaining planning permission. They explained that the Environment Agency could be seen to be too cautious when approaching novel plants/processes. Delays in the planning permission process leads not only to uncertainty, but also to project delays, which translates into higher project costs.

Lastly, feedstock supply was viewed as another key risk. Without secure, long-term contracts in place, investors may be hesitant to invest. Furthermore, there is considerable uncertainty over which feedstocks may qualify for policy support (currently, the non-biogenic content of MSW is not eligible for RTFCs).

3.3.3 Pre-requisites from developers needed to give investors confidence

Given the significant risks associated with FOAK commercial plants described above, investors have a number of key pre-requisites in terms of identifying suitable companies and projects to invest in.

Firstly, some investors stressed the importance of demonstration scale activity having already been carried out, to prove the concept, gather useable process data and show a clear path to commercial operations. A clear, well documented history of the performance of the integrated process (not just its constituent parts) was seen as being key to evidence this activity.

In terms of the team, a management team with a demonstrable track record in previous large scale development projects is seen as key in giving confidence to investors. Furthermore, a team with a stable leadership that has been committed to the company for an extended period of time is seen as being positive.

In addition, investors explained that the presence of co-investors was also key in giving additional confidence. When a potential investor sees other existing investors already on board, this gives additional confidence, given that these existing investors will have already carried out their own technical and commercial due diligence, and are happy with the risks identified. Airlines explained that they see Oil and Gas companies as key partners not just from a financial point of view, but also in helping to perform due diligence on the developer's technology. There was consensus that it is extremely hard for banks to finance FOAK commercial plants, due to feedstock and product price volatility, as well as significant technology risks. If they were to invest, it is unlikely that one bank would provide all the finance and would expect other banks to join them.

Having feedstock agreements in place (for a sufficient amount, for the long term, and at low cost) and a good site with strong transport links, permits in place and good relationships with local stakeholders, were also seen as being key to attracting partners.

From a strategic perspective, some interviewees wanted to see that developers had a clear plan for further deployment beyond the FOAK commercial plant, and from a sustainability perspective, some wanted to find partners whose sustainability goals were strongly aligned with their own.

3.3.4 Funding mechanisms that would stimulate investment in a FOAK commercial SAF plant

Overall, there were mixed views from investors on which funding mechanisms would be most suitable for this competition. There are various advantages and disadvantages of each, with the key points summarised below:

- **Loan Guarantees:** Generally, interviewees agreed that in theory, these should help to attract co-investors to provide capital for the construction of FOAK commercial SAF plants. However, several used the example of the US to explain that thus far, this has not been proven in practice and that it may not be as attractive as it appears to be at face value. For example, Fulcrum's Sierra Biofuels plant did win approval for a Loan Guarantee from the USDA, however, in the end they raised capital through Tax Exempt Green Bonds. Whilst loan guarantees are available to SAF plants in the US, the terms of the loan are not favourable in comparison with commercial loans, as a fee is charged for providing the guarantee, which adds significant cost to the loan. Other interviewees felt that the conditions attached to certain guarantees were often not realistic for a project developer to meet. Therefore, if a Loan Guarantee scheme is to be put in place to complement this competition, it is recommended that the specific conditions and costs associated with it are considered carefully.
- **Grants:** This was seen as the simplest mechanism, and was welcomed by all, but interviewees appreciated that the Government may not wish to hand out large grants. Several investors commented that grants would be most appropriate to fund project development activities e.g. feasibility, FEED studies.
- **Tax Exempt Green Bonds:** Tax exempt green bonds have been successful in the US, with Fulcrum's Sierra plant having raised capital through this mechanism. Not only is the tax incentive attractive to investors, but its rate of return is more attractive than similar infrastructure bonds.

- **Equity position:** Several investors thought that if the Government was to take an equity position in the project, this would play an important role in helping a project to raise debt finance, particularly as smaller developers can find it hard to raise debt. One interviewee suggested that if the Government were to provide equity for a demonstration unit, it could come with an option for the Government to invest in the commercialisation stage, which would provide a way for the Government to have a continued interest in the development and deployment of the technology.

Aside from the type of funding mechanism, two other key points were made about what features could be introduced to make them more effective:

- **Additional support during the first few years of operation:** Given the reliability challenges that investors expect FOAK plants to have during the first few years of operation, several interviewees suggested some kind of additional support during this period would provide additional confidence to investors. The type of support was not specified, but additional revenue support to offset reduced revenues resulting from potential plant reliability issues would likely be welcomed.
- **Minimising downside risk:** Given the above-mentioned reliability risks, and the perception of policy uncertainty, investors suggested that introducing features into certain funding mechanisms to minimise downside risks to investors could be seen as being attractive. An example of a low interest loan, where the principal does not need to be paid back if the project return is not positive, was suggested, however it is important to note that this particular example would contravene State Aid rules.

Another key takeaway message was that the above funding mechanisms, on their own, will likely not be enough to incentivise investment. Interviewees stressed the need for projects to have revenue certainty in addition to the above funding, with suggested revenue stabilisation mechanisms explained in Section 3.3.7.

3.3.5 How much support might need to come from UK Government

Given that the costs of a FOAK commercial SAF plant are expected to be on the order of £700m+, investors all agreed that a significant budget is needed to be provided by Government.

In terms of the funding percentage provided by Government for the construction of a FOAK commercial plant, the responses varied from 10 to 50%, with several explaining that this depends on the investor's risk appetite and what policy support is in place. Most responses suggested a level of around 20-30% would be appropriate, which we have subsequently used in the business case analysis in Section 5.2.

3.3.6 Other non-financial support from the government during a competition:

It was suggested that cross-departmental alignment (e.g. between DfT and BEIS) on their combined SAF strategy could provide greater clarity to investors. As part of this, it was suggested that having a representative to engage with successful competition applicants on possible policy changes and other regulatory issues could enable the project development process to be smoother.

Given that several interviewees explained that the planning permission process was seen to be quite challenging, it was suggested that the government could provide support to developers through the planning permission and other regulatory processes.

3.3.7 Government support outside a competition to enable investment:

For FOAK commercial SAF plants, around 70-80% of project revenue is dependent on policy support mechanisms such as dRTFCs. Therefore, long term visibility on such policy support mechanisms was seen as being as important as funding support provided through the competition.

The majority of interviewees expressed the concern that there is no long term price visibility on dRTFCs. Some measures that have been suggested were:

- Price floor to minimise downside risks to investors.
- If a price floor is not possible, some kind of mechanism to give price visibility for the first five years of the plant's lifetime - particularly given that these plants have low availability during this period.

- Another modification to the RTFO was suggested wherein if certificates trade below a certain percentage of the buyout price, this would trigger an increase in the blending obligation, which would drive up the price of dRTFCs.
- Providing clear visibility in the long term for which fuels will be eligible for dRTFCs, as incumbents or prospective investors see a potential risk from other lower-cost entrants depressing the dRTFC value.
- Some viewed RTFO expiring in 2032 as being positive compared to other countries. However, others commented that this is not a sufficiently long term view, given that projects will take several years to develop, and that projects are often viewed with a lifespan of 20+years

Some interviewees also suggested alternative support measures for FOAK SAF plants:

- In the eyes of several investors, Contracts for Difference (CfDs) have been successful in providing revenue certainty to investors in renewable power. It was suggested that a similar mechanism for SAF could also provide this revenue certainty. To mitigate the reliability risks at the beginning of a plant's lifetime, it was suggested that the level of revenue support could be higher at initial stages and then decline towards end of the project (taking account cost reduction through learning).
- A SAF mandate was suggested as an alternative to current situation, where aviation can opt in to RTFO. Some interviewees explained that with the current system being on an opt in basis, for an investor looking to maximise their return on investment, it essentially becomes an economic decision to produce road diesel or jet, which for most plants, will lead to prioritisation of diesel production.
- It was suggested that the Royal Air Force (RAF) could consider purchasing SAF, based on the experience in the US wherein the US Military has engaged in offtake agreements and performed tests in their hardware.

3.3.8 Summary and investor perspectives on the UK

Despite the challenges mentioned above, the majority of investors are interested in SAF. However, in their eyes, the key question is whether to invest in SAF production in the UK or in other countries. Overall, several investors explained that the UK is seen as not being a particularly easy place to invest in intermediate to large scale plants (generally seen as fine for small scale investments). Many of the interviewees were global investors and explained that capital will be deployed where there is a conducive policy environment to support investment.

Reflections on investor views

FOAK commercial SAF plants will not be straightforward to fund and will need Government support to move forward. The most important message from investors was that these projects will need both (a) funding support for plant construction and (b) revenue support to secure investment, for the UK to be viewed as an attractive environment for investment. Having one in place without the other is not likely to be sufficient to de-risk such projects for potential investors.

In terms of funding support, this could be achieved in a number of ways (e.g. loan guarantees, equity investments, tax credits) with each potentially having their own advantages and disadvantages.

In terms of revenue support, the key message is that long term certainty on revenue is needed in order to incentivise investors to provide capital for plant construction.

3.4 State Aid regulations

The European Commission's State Aid regulation[77] is designed to prevent Government funding from causing unfair competitive advantages within a given market. The review of the State Aid regulation had three aims:

[77] https://ec.europa.eu/competition/state_aid/legislation/block.html

1. Confirm, as far as possible, the likely position regarding State Aid regulations from January 2021
2. Confirm whether there are any opportunities within the General Block Exemption Regulations to award funding of more than EUR 15m to a single project for sustainable biofuel production
3. Confirm any other options for DfT to award larger sums of public funding to sustainable biofuel plants

Brexit

With the UK on course to complete the transition period after leaving the European Union at the end of 2020, it will be important to understand the potential impacts on public funding rules in the context of a new DfT competition likely to be launched in 2021. Under the Withdrawal Agreement there is no change to State Aid rules until after the end of the transition period on 31 Dec 2020. From January 2021, the UK's competition authority, the Competition and Markets Authority (CMA), would become responsible for monitoring aid that affects trade between Great Britain and the EU[78]. On the assumption that State Aid requirements and limits would persist the review focussed on the limitations of the relevant Articles of the current State Aid regulations.

Required limits within the General Block Exemption Regulations (GBERs)

In designing a funding scheme to support demonstration projects, there are a number of routes available that will comply with State Aid legislation, including block exemptions and a full notification procedure, which is known as an individual exemption.

General Block Exemption Regulations (GBERs) provide a list of specific conditions under which Member States may launch a funding scheme without being required to complete the full notification procedure. Provided the block exemption conditions are met, the programme manager may simply notify the Commission via a retrospective transparency notice. In the event of a very large individual award being made, a notification must still be made to the Commission – even when the scheme under which the award has been made satisfies all of the requirements of GBER.

The majority of innovation competitions delivered by DfT and BEIS over the past decade have been funded via the GBERs. In particular, ABDC and F4C utilised Article 41 of the GBER for investment aid for the promotion of energy from renewables. This allows a grant intensity of up to 100% within a maximum cap of EUR 15million. The table below provides an overview of all exemptions under the GBER that could potentially be relevant to projects funded by a new competition.

[78] However, according to the Withdrawal Agreement, state intervention that affects trade in goods between Northern Ireland and the EU would remain subject to EU State Aid rules, including enforcement by the Commission and the European Court of Justice. This distinction has the potential to lead to legal disputes, with measures such as a government grant scheme open to all UK businesses potentially falling under both regimes.

Figure 14: State Aid exemption options for a new innovation-focussed competition

Article and title	Scope & Eligible Costs	Maximum aid intensity	Aid intensity uplifts	Maximum Threshold
25 – Aid for research and development projects.	(b) **experimental development** (meaning acquiring, combining, shaping and using existing scientific, technological, business and other relevant knowledge and skills with the aim of developing new or improved products, processes or services. This may include development of commercially usable prototypes);	Experimental development: 25%	+ 10% for medium-sized enterprises; + 20% for small enterprises. + 15% if one of the following conditions apply: - if the project involves effective collaboration (see Art 25(6)(b)(i) for more details); or - if the results are widely disseminated (see Art 25(6)(b)(ii) for more details)	Experimental research: 15m Euros per recipient, per project
Article 41 – investment aid for the promotion of energy from renewables	Eligible Costs – the extra investment costs to promote the production of energy from renewable source. Restrictions apply regarding biofuels which must use sustainable feedstocks that are non-food-based.	Aid intensity may be set by the funder subject to the process being a competitive application	+ 20% for small undertakings; + 10% for medium-sized undertakings. + 15% for Assisted Area (a); 5% for Assisted Area (c).	15m Euros per recipient, per project.

Article 41 (investment aid for the promotion of energy from renewables) is the most relevant exemption for a future SAF competition, as it contains specific provisions for biofuel production from sustainable feedstocks and covers all aspects of project delivery from feasibility to commissioning of the completed plant. Within the review, there were no opportunities identified to award higher levels of funding either via grants or low interest loans to projects within a competition operating under the GBERs.

Options outside of the GBERs

Regarding the use of State Aid routes for grant funding and low interest loans, much depends on the timescale for development and launch of a scheme. Longer term programmes (such as those run by the Carbon Trust, TSB and ETI) have all applied for a specific full State Aid exemption using the full notification procedure which allows for maximum control over the design of the scheme but requires in-depth justification of the requirement for market intervention. Within UK Government Departments, BEIS, Defra and DfT have all used State Aid General Block Exemption Regulations to deliver grant funding schemes with a shorter lead-time.

If it is not possible to comply with all the conditions of a block exemption, the program manager must apply for an individual exemption using the full notification procedure which can take at least three to six months for approval with the EU. With the upcoming change of State Aid authority from the EU to the CMA it is difficult to predict the likely timescale needed for an individual exemption, particularly if there is a 'no deal' Brexit.

Reflections on State Aid implications

It remains likely that the UK will continue to implement direct government support in a similar manner to current State Aid regulations, which means that DfT would not be able to award grants at the levels seen in US examples of FOAK commercial SAF funding (e.g. US$80m to Fulcrum) as this would breach State Aid limits.

Article 41 remains the most viable route for funding pilot and demonstration SAF plants in particular. There is logic in utilising Article 41 for FOAK commercial SAF plants, particularly during feasibility and FEED stages where the limitations on funding amount (max EUR 15m) would still allow substantial input to project development costs. For the construction phase of a FOAK commercial SAF plant, a grant or low interest loan via Article 41 would possibly only amount to 1-2% of the total capital cost so would have very limited impact on the financing of a project.

4 Feasibility

4.1 Bidder profile, number of bidders, and target TRL

In this section, the aim is to assess whether there will be a sufficient number of potential applicants to the competition, and what scale of plant these applicants would likely aim to build.

In section 2 an overview of different aviation fuel pathways, their certification status and the relevant players was presented. These players and their technologies span across different levels of maturity. This is an important dimension to analyse in order to design a competition that can provide adequate funding to a portfolio of heterogenous projects.

To support this analysis, the players considered in Section 2 across all the pathways, have been grouped in two categories according to their development plans based on their current technology maturity:

- *Early commercial stage applicants*. This category includes all those players who have at least one operational (or operated) demonstration plant. Some of the players in this group already have plans for construction of FOAK commercial plants, and if they decided to participate in the competition, they would likely apply for funding for FOAK commercial plants. The corresponding TRL for this group is 6-7.
- *Demonstration and pilot stage applicants*. This category includes all those players who have no operational (or operated) demonstration plants but do have one or more operational pilot plants. Some of the players in this group already have plans for construction of demonstration plants, and if they decided to participate in the competition they would likely apply for funding for large pilot or demonstration scale plants. The corresponding TRL for this group is 5.

Technology and project developers who already have operational plants at commercial stage have been excluded from this feasibility analysis. This means that all HEFA and lipids co-processing players have been excluded since their technology is now established and beyond FOAK commercial stage, and as stated previously, it is recommended they are excluded from the competition, as they could be supported by other policy mechanisms.

The result of the analysis is summarised in Table 12. Figures are based on the best of our knowledge of fuel producers and technology developers who are relevant to SAF production, at the time of writing.

Estimating the likelihood of these organisations participating in the competition is not straightforward and has a high degree of uncertainty. There are several factors driving the final decision to participate in a competition from the perspective of these players, and regardless of the attractiveness of the competition prize, there are a number of decision factors that are outside of DfT's control. Examples of these decision factors are:

- Relevance to current or future business strategy. The most likely bidders are fuel producers who are already involved in SAF production at pilot or demonstration stage and want to scale-up their technology. Fuel producers who are mainly targeting the road transport sector might be less interested in joining the competition.
- Existing business relationships with UK partners. Having already established partnerships with UK players across the fuel value chain (e.g. feedstock suppliers, fuel suppliers, airlines) is highly important, particularly for FOAK commercial plants.
- Spare organisational capacity. Many of these organisations are relatively small in size and if they are already committed to several projects, they might not have spare resources to dedicate to committing to additional projects.
- Existing competition. The competitor landscape plays a role in the chances of success from individual players' perspective. Some players might decide not to bid depending on known competitor engagement.
- Opportunity options. Other funding opportunities might be concurrently available in other countries which might diminish the interest of potential bidders to the DfT competition.

Assessing the likelihood of participation according to these criteria for each organisation is difficult based on publicly available information only. However, business relevance (the first bullet listed above) is arguably one of the most important criteria and could be inferred by companies' activity and announcements relevant to aviation fuel production. All the organisations considered in this study have a certain degree of interest in aviation fuel production and many of them are targeting aviation fuels as their main market.

Therefore, the full list of potential project developers considered in Section 2 has been filtered by considering their level of interest in aviation fuel production in order to provide an estimate of the number of likely bidders in both groups. A few small-scale projects are led by universities, and these have been excluded from the potential bidders list.

Based on these assumptions, the breakdown of likely bidders is summarised in Table 12.

Table 12: Players breakdown according to their technology maturity

Group	All players	Likely bidders	TRL	Group description	Examples of pathways	Examples of key players
Early commercial applicants	22	20	6-7	At least 1 operational demonstration plant	ATJ-SPK, FT-SPK, CHJ	Velocys, Fulcrum, ARA
Demonstration and pilot applicants	30	24	5	No operational demonstration plants	HC-HEFA, ATJ-SKA, Other ATJ	IHI, Swedish Biofuels, Vertimass
Total	53	45				

Reflections on potential bidders

A total of about 45 players have been identified to be likely applicants. They are roughly equally split across the two groups, but slightly more players could apply for demonstration and pilot scale plants.

This analysis therefore indicates that there could be a relatively large pool of potential applicants looking to develop pilot, demonstration and FOAK commercial SAF plants in the UK, should the competition offer the right incentives.

4.2 Funding mechanism

From the known information on potential applicants and projects that could apply to a new SAF-focussed competition, the two key funding mechanisms of most relevance to the feasibility of that competition are:

1. **State Aid compliant grants**: This is a well-known funding mechanism, understood by developers, investors and lenders, and is suitable for feasibility and FEED funding (due to risk of failure) ahead of capital funding for construction. However, as noted in other sections of this study, grant funding alone will be too low value to have a significant effect on financing the construction of a FOAK commercial plant.
2. **Loan Guarantees for FOAK commercial construction costs**: This would effectively see DfT taking on the risk of project failure, with full acceptance that the entire value of the loan may need to be written off. This is balanced with the reward of released funds to re-invest in future if the project is successful. Potential debt and equity investors both saw loan guarantees as a vital element of the financing of FOAK commercial plants.

Other potential funding mechanisms for FOAK commercial past the limits of State Aid (EUR 15million per project), which could prove feasible with more extensive investigation, include:

- **Direct equity investment**, whereby DfT would seek 30-40% equity stake in each FOAK commercial project. The EIB recommended this route as an efficient mechanism to enable projects, although this would require internal consultation as to the level of risk and liability acceptable to DfT. It would also require consultation with project developers who may prefer to leverage debt financing over equity financing. However, with the cash reserves of 'traditional' investors in SAF (e.g. airlines and oil and gas companies) currently impacted by COVID-19, there may be more appetite in the market for DfT to act as an equity investor. This mechanism could stand as an alternative to a loan guarantee for FOAK commercial plant but has not been modelled in the Business Case section of this report.
- **Tax credits,** which already exist in the UK. Currently, in the USA, financial incentives such as the Biodiesel and Renewable Diesel Blender Tax Credit provides a fuel tax credit for fuels containing biodiesel fuel. Arguably, an incentive like this targeted specifically at the production and blending of sustainable aviation fuels might overtime lower the product costs of SAF and in turn, boost the level of commercial deployment associated with SAF.
- **Green bonds**, which have been successful in the US, with Fulcrum's Sierra plant having raised capital through this mechanism. However, in a recent statement to the press[79] the head of the UK's Debt Management Office, Robert Stheeman, told the Financial Times he is sceptical that issuing green bonds would be cost effective because it could prove difficult to create a big and liquid market. "One of the natural ways you minimise cost is you try and ensure all your bonds are as liquid as possible," he said. "In our case that usually means building up benchmarks to £20-30bn size. Smaller one-off bonds tend to fragment that process and the market is not necessarily willing to pay a liquidity premium for those smaller bonds." So, there may be specific challenges in raising green bonds for sustainable aviation fuel in a UK context.

We strongly recommend these options are discussed further with senior DfT stakeholders.

As a key piece of feedback from the lessons learned review and investor interviews, it is important to note that securing the investment financing often hinges on the securing of the feedstock supply and confidence in future revenue streams. Therefore, a strong recommendation from this feasibility study is for DfT to consider options regarding revenue support alongside options for investment support.

Reflections on funding mechanism recommendations

Funding for pilot and demonstration projects is relatively clear cut and does not deviate from previous DfT competitions.

There are however other options for DfT to consider regarding FOAK commercial plants, which should be discussed further with key stakeholders within DfT in light of the recent announcements around 'Jet Zero' and the importance of sustainable aviation fuels in the near future. There are clear signals from FOAK commercial developers and investors that loan guarantees for FOAK commercial plants would be viewed favourably.

4.3 Potential competition design

Within the initial specifications of this feasibility study, we were asked to review the feasibility of a potential competition to pave the way for sustainable aviation fuel production in the UK, with a budget ranging from £50m to £500m. In order to do that Section 5 of this report (Business Case) looks at different variations of budget and outcome based on the following outline competition design.

[79] https://www.ft.com/content/b0b31764-3932-11ea-a6d3-9a26f8c3cba4?segmentId=bf7fa2fd-67ee-cdfa-8261-b2a3edbdf916

Figure 15: Potential competition design

TRL 5 Small pilot ⟷ **TRL 8** First commercial plant → Commercial deployment

	Proposed Stream 1 (pilot & demo)	Proposed Stream 2 (FOAK Commercial)
Qualification	Outline proposal – single page summary stage gate	
Stage 1 Feasibility	• Grant funded £250k max • Max 100% of eligible costs • 6 months to complete	• Grant funded £5m max • Max 100% of eligible costs • 9 months to complete
Stage 2 FEED	• Grant funded £750k max • Max 75% of eligible costs • 12 months to complete	• Grant funded £5m max • Max 50% of eligible costs • 24 months to complete
Stage 3 Construction	• Grant funded EUR 15m max minus Stage 1 & 2 funding • Max 60% of eligible costs • 36 months to complete	• Grant funded EUR 15m max minus Stage 1 & 2 funding • Loan guarantee up to 30% of CAPEX (capped at £200m) • Credit rating of applicants of key importance in funding award

The structure of the proposed competition design is broken down into streams and stages:

1. Two streams of funding, with different funding mechanisms

   Stream 1 (pilot & demonstration) would function much like the current F4C competition with all funding based on grant support, which has been successful in attracting proposals for pilot and demonstration scale projects. This feasibility study has identified a need for these types of projects to be further supported in order to pave the way for SAF production in the UK, as well as confirmed a pool of potential and interested bidders. Funding for feasibility, FEED and construction (capital) stages of pilot and demonstration plants have been proposed within the allowable State Aid limits.

   Stream 2 (FOAK commercial) tackles some of the learning from F4C, which was not designed to support FOAK commercial plant, and the feedback from project developers and investors regarding the type of support they would view as most beneficial to the sector. This stream would access grant funding in a similar manner to Stream 1, with a significant additional funding mechanism to support the upfront capital needed to pave the way for FOAK commercial plants in the UK.

   It is important to note that different budget scenarios would affect the feasibility of the two-stream competition design. In section 5.2 of this report, changes to the budget between £50m and £500m are examined for their impact on the likely outputs. For example, at £50m it is unlikely that any FOAK commercial plants could be supported past the FEED study.

2. Four stages of the competition: these are illustrated in Figure 16: Four stages of the competition.

Figure 16: Four stages of the competition

Stage 0 Qualification

- This addresses feedback from previous competition participants that preparing and submitting proposals requires significant investment from project developers without clear indication of their likely success.
- Adding a short-form single page qualification stage would allow potential bidders to submit a rapid response regarding their planned project, helping to quickly identify projects that may fall out of scope, prove too high risk for support at this stage, or lack sufficient credibility for DfT support. It would also help DfT to focus their necessary technical and commercial expert support for the main assessments.

Stage 1 Feasibility & pre-FEED

- It is proposed that both streams receive significant grant support for feasibility studies due to the potential likelihood of failure or a negative outcome of the study. There are fewer investors operating in this area, and it remains a barrier to development of new technologies.
- This is achievable within State Aid limits by utilising GBER Article 41 (10(c)) which allows for aid granted in a competitive bidding process to be awarded up to 100% of the eligible costs. As the feasibility funding would then form part of the full completed project, it is the view of DfT Legal (see F4C feasibility study) that feasibility studies for advanced biofuel plants can be funded using Article 41.
- Recognising the different cost scales and time needed for delivery of these studies has led to recommending differentiated caps on grant awards between the two streams, based on the average costs of feasibility studies within the two streams.

Stage 2 FEED studies

- This is proposed at a lower rate of grant intensity for both streams, reflecting the expectation that developers and investors would start to take on some of the risk of project failure, with no expectation of any revenues as a result of this work.
- Recognising the different cost scales and time needed for delivery of these studies has led to recommending differentiated caps on grant awards between the two streams, based on the average costs of FEED studies within the two streams.
- Within this design, it is possible for projects in stream 1 (pilot & demonstration) to move from feasibility to construction if a FEED study is not neccesary for the scale of plant being built.

Stage 3 Construction

- For stream 1 (pilot & demonstration) projects, the maximum awarded would be EUR 15 million minus the grant awarded at Stage 1 & 2. This is again consistent with F4C and allowable under State Aid regulations. A key learning from ABDC and F4C was that 50% intensity was still insufficient to attract investors without any substantial revenue streams being in place post-construction. We have suggested 60% as a maximum intensity that still places expectations on investors to shoulder some of the risks in reward for their equity in a novel technology.
- For stream 2 (FOAK commercial) in addition to accessing the 'balance' of the EUR 15 million cap, it is proposed that projects are able to apply for a loan guarantee for up to 30% of the upfront capital, capped at a maximum of £200 million. This proposed funding intensity is derived from investor interviews, and is consistent with European-level loan guarantees being made available for advanced biofuel plans under the 'Junker plan', maintaining the UK's competitiveness as a location for SAF developers to invest.

4.4 Risks to successful delivery of the competition

In this section, potential risks to the successful delivery of the competition have been assessed at a high level, based on the findings presented elsewhere in the report. Note that we have focused mainly on those risks specific to this particular competition and those which we have examined in this work, rather than generic risks e.g. cost overruns which whilst relevant are not as crucial in terms of the decisions that DfT would need to make in the near term regarding competition design and possible funding mechanisms. These risks have been divided into four categories: bidder, funding, policy, and competition design related.

4.4.1 Bidder-related risks

Figure 17 provides a summary of the bidder related risks to the competition. Overall, there should be a sufficient number of bidders entering both the FOAK commercial stream and the pilot/demonstration stream. Furthermore, particularly for the FOAK commercial stream, these players have track records that indicate that they would likely enter with high quality applications. It is worth noting however, that there is a perception risk that this competition may not be providing additional value compared to support already provided in the F4C competition, if projects similar to those proposed by Velocys or Lanzatech also emerge as being successful applicants to this competition.

Figure 17: Bidder related risks

Risk Category	Risk Description	Impact	Severity	Probability	Mitigating measure
Bidders	Low number of potential applicants – FOAK commercial	Insufficient number Of bidders	High	Low – there are sufficient number of players who could develop FOAK	None needed
	Low credibility of bidders – FOAK commercial	Bidders rejected early on	High	Low – developers are already developing large demo and FOAK commercial plants elsewhere	
	Insufficient number of credible bidders – pilot/demo	Insufficient number of bidders	High	Low – there are sufficient number of players who could develop pilot/demo	
	Low credibility of bidders – pilot/demo	Bidders rejected early on	High	Medium – earlier stage developers tend to have less track record	
	Insufficient differentiation vs previous entries	Perception that competition has not provided additional value	Medium	Low for pilot / demo Medium for FOAK (may get projects similar to Velocys or Lanzatech)	Clear communication strategy on competition aims

4.4.2 Funding related risks

As shown in Figure 18, funding related risks to the successful delivery of the competition can be split into those relating to government funding mechanisms and those related to private sector funding. As discussed previously, State Aid limitations, and the current unavailability of loan guarantees for relatively high risk technologies, currently mean that it could be difficult to provide the necessary scale of funding to enable the construction of FOAK commercial SAF plants in the UK. To mitigate this, DfT could consider the other mechanisms suggested in Section 4.2.

Another key risk for FOAK commercial plants is that two key types of partners are needed to develop these, airlines and oil and gas companies, have both been hit particularly hard by the current COVID-19 crisis, and therefore, particularly for airlines, it is questionable whether they have the financial resources to help support a FOAK commercial plant going forward, without significant government support.

Figure 18: Funding related risks

Risk Category	Risk Description	Impact	Severity	Probability	Mitigating measure
Government funding	Overall pot size is too small / funding intensities too low	Low number of FOAK entrants, or FOAK entrants only enter to receive support for feasibility and FEED stages	High for FOAK Low for pilot/demo	Unclear	Additional support through other policy support mechanisms
	State aid rules mean that government support is capped at £15m		High for FOAK Medium for demo Low for pilot	High – state aid limitations will likely remain post Brexit	
	UK Loan Guarantee Scheme not available to applicants		High for FOAK – if no alternatives are available	Very High	Consider developing an equity fund for SAF or DfT standalone loan guarantee
Private funding	Lack of Airline funding/support	FOAK developers fail to get match funding, particularly for the FEED + construction stages. Money spent supporting earlier project phases may be seen to be wasted	High for FOAK (Airlines are key offtake partners and investors)	Very High – COVID-19	Provide support to airlines conditional on green investment
	Lack of Oil and gas funding/support		High for FOAK (O&G companies are key offtake partners and investors)	High – COVID-19	Additional support through other policy support mechanisms
	Lack of Banks / other investor funding		High	High – most banks unlikely to lend due to high risk	

4.4.3 Policy related risks

As discussed previously, particularly for FOAK commercial plants, having revenue certainty is key to giving investors confidence in providing capital for the construction of these plants. The perception of key stakeholders is that there is a lack of visibility on the long term dRTFC price, meaning that this is a key risk for investors, even if government support was made available through this competition. Giving more visibility to the long term dRTFC price, or an alternative mechanism to provide long term revenue stability (e.g. Contracts for Difference), were noted as key requirements by both project developers and investors alike, as summarised in Figure 19.

Figure 19: Policy related risks

Risk Category	Risk Description	Impact	Severity	Probability	Mitigating measure
Government policy support	Developers' lack of visibility of dRTFC price floor	FOAK developers fail to get match funding, particularly for the FEED + construction stages. Money spent supporting earlier project phases may be seen to be wasted	Very high for FOAK Low for pilot/demo	High – many stakeholders feel that without changes, RTFC price visibility will remain low	Consider floor price or alternative mechanism to give revenue certainty to projects

4.4.4 Competition design related risks

This study proposes that any competition has different streams suited to different plant scales, and stages that more closely align with actual project lifecycles, which should maximise the chances of successful applicants progressing through to plant construction (Figure 19). Other key risks can also be minimised, such as those related to a proper and fair assessment process. There are also learnings from previous competitions that can help in designing a future competition more effectively; these have been detailed in Section 3.2.

Figure 20: Competition design related risks

Competition Structure / Running Competition	Competition design not suitable for different plant scales and stage of project	Applicants who enter are unable to progress to plant construction	High	Low	Competition should have different streams for different plant scales and stages match project lifecycle
	Technical and economic risks of applicants not properly assessed	Funding not given to best applicants or proposals of not sufficiently high standard	High	Low	Ensure team running the competition has correct prior experience and competencies

5 Business case

5.1 UK value and job analysis of a UK based SAF industry to 2040

The aim of the analysis in this section is to determine the potential benefit to the UK economy in terms of the gross value added (GVA)[80] and job creation[81] which could arise from establishing a UK based SAF industry to 2040. The deployment of SAF production in the UK would expand revenue generation and GVA, thus creating jobs. Further, supporting the development of knowledge and innovation could diversify the UK's revenue streams, allowing for UK businesses to tap into the global market, through IP (e.g. licensing revenue) and services (e.g. engineering). Based on the 2019 Sustainable Aviation UK Fuels Roadmap[82] and previous Bioenergy Technology Innovation Needs Assessment work for BEIS[83], a simple set of calculations and assumptions has been developed to estimate the potential value to the UK of the deployment of sustainable aviation fuel plants. This approach is similar to that used in the Future Fuels for Flight and Freight Study (F4C) feasibility study.

Deployment scenarios for the production of SAF in the UK were based on the Sustainable Aviation UK Roadmap (2019). The time frame for the Sustainable Aviation UK Roadmap was 2020 – 2035. However, due to the recent ramifications of the global pandemic, Covid-19, the timeframe has been shifted to 2025 – 2040.

Given the deployment scenarios are meant to reflect the potential production of sustainable aviation fuel, all fuel types were included, regardless of their current certification status. The fuel production technologies were grouped into the following pathway categories:

- Alcohol to jet
- Gasification + Fischer-Tropsch
- Pyrolysis
- Direct sugars to hydrocarbons (aerobic fermentation)
- Hydrotreated oils and fats (including both standalone hydrotreatment and co-processing in a refinery)
- Power-to-liquids with Fischer-Tropsch
- Other thermo-chemical (hydrothermal liquefaction and aqueous phase reforming)

HEFA is not considered a development fuel under the RTFO therefore, unless this changes or other support is aimed at HEFA, it is unlikely any new HEFA plant would be located in the UK. Therefore, HEFA production in the UK was excluded from the analysis.

The Sustainable Aviation UK roadmap employed a 'bottom-up' methodology to estimate the potential deployment of the SAF production technologies listed above. It is based on current deployment numbers, as well as future deployment plans stated in the public domain. Considering the degree of variation expected, a slow and fast growth scenario was modelled reflecting differences in:

- Project timeline: how long it takes to build and commission each plant.
- Initiation rate of projects: How many commercial projects can be started each year, e.g. via technology licences.
- Launch-point: Feasible time frame between a previous project starting and the next project.

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[80] Gross Added Value (GVA) is the measure of the value of goods and services produced in an area, industry, or sector of an economy
[81] Job creation is measured assuming an average GVA per worker, encompassing both direct UK jobs and indirect UK jobs as a result of the UK's share of the accessible global market
[82] Sustainable Aviation UK (2020) Sustainable Aviation Fuels Road-Map. Available from: https://www.sustainableaviation.co.uk/wp-content/uploads/2020/02/SustainableAviation_FuelReport_20200231.pdf
[83] (2012) Bioenergy Technology Innovation Needs Assessment (TINA). Available from: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/593451/TINABioenergySummaryReport20120918vPublished.pdf

- Success rate: How many of these plants and developers might fail/be unsuccessful?

Given that SAF production activity to-date has been focused in Europe and North America, the UK share of global SAF production capacity was estimated as a ratio between the UK population and the sum of EU-28, United States, Canada and Mexico, at a value of 6.6% in 2040. Furthermore, in many of the pathways included in the analysis, both diesel and jet fuel are produced. Given the focus of this study, the deployment model reflects an "aviation optimised" pathway, in which the plants maximise the production of jet fuel in preference to diesel.

There is currently no SAF production in the UK. Velocys' Altalto plant and Lanzatech's ATJ FOAK plants, if successful, will come online mid-2020s, with a combined capacity of 120 ktonnes/year (5 PJ/annum). By 2040, UK SAF production could amount to between 400 – 950 ktonnes/yr (17 – 42 PJ/annum), for 5 – 14 commercial plants, under the slow and fast growth aviation-optimised scenarios respectively.

The turnover from SAF production was calculated by assuming the price of SAF is equal to the price of fossil kerosene plus the buy-out price of two development fuels RTFCs (45.45£/GJ)[84]. In the short-to-medium term, this could be a reflection of the revenue support needed for SAF production. However, as the UK SAF industry matures and the cost of production reduces, the level of revenue support needed will probably decrease, in the long-term. Due to the current global climate, and uncertain oil prices, the slow and fast growth scenarios were run based on two different Brent Crude Oil prices, 40 USD/bbl and 60 USD/bbl, to reflect differing levels of financial recovery for oil prices. In June 2020, BP predicted that the oil price was likely to average out at 55 USD/bbl by 2050[85]. A premium of 15.5 USD/bbl was assumed to calculate the fossil jet fuel price, based on historic trends in the difference between oil and jet fuel price[86], resulting in an estimated SAF price of 53.1 – 55.8 £/GJ (including two development RTFCs), meaning the turnover of the SAF is highly dependent on the value of dRTFCs. The UK annual turnover figures for 2040 under the slow and fast growth, aviation-optimised scenario are illustrated in Table 13, within this, feedstock is estimated to account for around 35%, technology 60% and distribution 5%. The difference in turnover between the two oil prices is relatively small, showing that most of the turnover is driven by the dRTFCs.

Table 13: Turnover in £m from UK SAF production by 2040

	Turnover (£m/annum)	
Oil Price (USD/bbl)	Slow Growth	Fast Growth
40	927.2	2,220.1
60	975.5	2,335.1

The turnover figures were used to estimate the Gross Value Added (GVA) to the UK economy across the supply chain based on a methodology used in the Bioenergy TINA, which was also used in the F4C feasibility study. Under this methodology, an assumption is made on the GVA share of the market for each component of the SAF production chain: feedstock, technology, distribution. For each component a certain percentage is assumed to be available to foreign companies, which allows the estimation of the GVA value that remains within the UK domestic market. It is also likely that the UK could capture value from the production of SAF elsewhere in the world, for example through the supply of technology components and engineering services related to the design and development of conversion technology. These opportunities align with the UK's strengths, as suggested by Velocys' Bayou plant in Mississippi, United States; whilst this Bayou project is focussing on road transport fuel, it makes use of Velocys' FT technology which is also being used in their UK project – Altalto. Therefore, Velocys is an example of

[84] RTFO Year 11 Guidance, Available from: https://www.gov.uk/government/publications/renewable-transportfuel-obligation-rtfo-guidance-year-11 ; The value of two development RTFCs is used because a qualifying fuel made from wastes and residues qualifies for two development RTFCs
[85] BBC (2020) Available from: https://www.bbc.co.uk/news/business-53047894
[86] IATA (2020) Available from: https://www.iata.org/en/publications/economics/fuel-monitor/

how the UK can capture value from the global market, through exportable, protectable IP. This additional value is captured in the GVA calculations through assuming a proportion of the global SAF market (excluding the UK) is a result of contributions from the UK (e.g. through providing a technology licenses). Therefore, the total UK GVA from the development of a SAF industry includes UK GVA from UK fuel production and UK GVA from non-UK fuel production, which could range from £706 million to £1,664 million as shown in Table 14, with 42 – 44% as a direct result of the UK market, and 56-58% as a result of non-UK fuel production. The majority of GVA from non-UK fuel production arises from the contribution of technology largely driven by the exportable IP and provision of technology services.

Table 14: Gross Value Added (GVA) under a slow and fast growth of a UK-based SAF industry to 2040

		Oil Price – 40 USD/bbl		Oil Price – 60 USD/bbl	
	Unit	Slow Growth	Fast Growth	Slow Growth	Fast Growth
UK GVA from domestic fuel production	£m/annum	293.0	701.6	308.2	737.9
UK GVA from non-domestic fuel production	£m/annum	412.7	880.6	434.1	926.3
Total UK GVA	£m/annum	705.7	1,582.2	742.2	1,664.2

The UK currently imports around 80% of its aviation fuel demand, therefore it was assumed that any SAF production in the UK would directly replace imported kerosene, thus displacement effects were not considered in the GVA calculations. Replacing imported kerosene with domestically produced SAF would increase fuel security and have a net positive impact on the UK's balance of payments. Under the fast growth scenario, the production of 950 ktonnes/annum of aviation fuel domestically in the UK, replacing imported fossil kerosene, would have a positive impact on the balance of payments of £320m to £435m dependent on oil price.

To estimate the potential job creation, an average GVA per worker in the non-manufacturing production sector, of £144,000 was used (ONS, 2015)[87]. Therefore, the development of a SAF industry in the UK could support between 4,900 and 11,500 UK jobs. Of this, 2,000 to 5,100 are associated with domestic SAF fuel production.

This analysis shows that there is the potential for significant GVA and jobs to be added to the UK. However, it is important to note that this is a simplistic analysis and is contingent on whether planned projects go ahead which depends on factors such as developers successfully demonstrating their technology, financial requirements being met and scaling up of the processes (i.e. to progress from pilot to larger scale).

5.2 Impact of the competition on GVA and jobs

In this section, an analysis was carried out to look at the potential impact of the competition itself, in terms of GVA and jobs that result from the construction of SAF plants that this competition could support. This part of the analysis therefore only considers GVA and jobs associated with the plants supported by the competition, as opposed to the wider GVA and jobs creation in the UK resulting from deployment of SAF in the UK and globally to 2040 (previous section)

[87] ONS (2015) Available from: https://www.ons.gov.uk/economy/economicoutputandproductivity/productivitymeasures/articles/labourproductivitymeasuresfromtheannualbusinesssurvey/2006to2015

To calculate the potential impact of the competition an optimisation algorithm was developed, using a linear program modeler in Python. The algorithm works to maximise the SAF production given a certain competition budget and specified funding intensities. Maximising SAF production was chosen as the objective for the algorithm because revenue is a function of SAF production and subsequently GVA from the domestic UK market and job creation are a function of revenue. Given the overarching aim of this part of the study is to assess potential impact to the UK economy that could arise from the competition, maximising SAF production was deemed the most suitable objective function of the algorithm. Lower bounds were imposed in the algorithm to ensure that at least one pilot and one demonstration plant are funded to avoid a scenario in which only a FOAK unit is supported.

The SAF production calculated is based upon the number of plants and scale of plants built, which is dependent on two key user defined inputs: the funding budget and the funding intensity, both of which are described in more detail bellow. Other important inputs to the algorithm include the typical plant size for pilot, demonstration and FOAK-scale projects. These inputs were estimated based on existing or planned SAF plants, alongside their capital cost, based upon information available in the public domain. From this, a cost per unit of fuel produced is found. Note that the algorithm prioritises SAF production from supporting FOAK projects due to FOAK having the lowest cost per unit capacity of SAF. Table 15 shows the algorithm's key inputs[88]. It is important to note that Brent Crude oil price of 60 USD/bbl was assumed in calculating the GVA, which in light of the current climate, should be viewed as a best-case scenario. However, the price of oil does not dictate the results in terms of total SAF production and number of plants supported.

Table 15: Key inputs used in the impact of the competition algorithm

Project scale	Capacity (tonnes/ annum)	Feasibility (£m)	FEED (£m)	Construction Cost (£m)	Cost per unit capacity (£m/tonne)
Pilot	41.2	0.03	0.07	5	0.12
Demonstration	1,648	0.24	1	35	0.02
FOAK	89,278	5	10	713	0.01

The two major variables considered in this analysis are:

(1) Total funding budget: three budgets were considered - £50m, £250m, £500m
(2) The funding intensity: the proportion of required funds supported by DfT.

Both these variables were written into the algorithm as financial constraints, which the solution must adhere to.

The funding intensity was disaggregated into contributions for feasibility study (Stage 1), FEED study (Stage 2) and plant capital (Stage 3, construction). Pilot and demonstration plants are likely to require a higher intensity of support from the government due to difficulty in securing funding from private investors for novel processes. However, a major constraint in government funding of individual plants

[88] Feasibility costs for pilot and demonstration were based on the ratio of capital cost to feasibility cost calculated from the assumption that the feasibility cost of FOAK units is £5m. This is based on Velocys' Altalto plant. Available from:

https://www.velocys.com/wp-content/uploads/2019/07/Announcement-of-Velocys-fund-raise-15-July-2019.pdf

FEED costs for FOAK projects was based on stakeholder engagement. The FEED cost for demonstration plants is expected to be in the range of £0.5-1.0m – the upper end reflecting more novel technologies. For pilot plants the ratio of capital cost to FEED cost for FOAK was used to scaled to estimate a cost of FEED.

is that the total amount for one project (including all stages of the project lifecycle from feasibility through to construction) cannot exceed the State Aid limit of 15 million EUR. Funding for feasibility, FEED and construction (capital) stages of pilot and demonstration plants have been set within these State Aid limits, as has funding for feasibility and FEED stages of FOAK plants. In this analysis, the funding intensity for constructing FOAK projects, based on feedback from investor interviews is varied between 20% and 30%. The State Aid limit is roughly equivalent to the FOAK feasibility and FEED costs, corresponding to just 1.8% of the construction costs of a FOAK. Therefore, the required funding for FOAK construction stage surpasses the State Aid limit, and thus for the purposes of this preliminary analysis, is assumed to have been provided through a mechanism that does not contravene State Aid rules and therefore the funding of FOAK construction stage is still considered within the total funding budget.

The results in this report must be viewed as illustrative. The algorithm is not probabilistic (does not account for the likelihood of a plant getting built, which could vary with government-backed funding intensity), nor does the algorithm take into account impacts of using different funding mechanisms (i.e. whether the funding is provided in the form of a grant or a loan guarantee). The primary objective of the results is to illustrate to DfT the impact of funding intensity and total budget of the competition, and to serve as a starting point for more detailed discussion around competition design.

Given that the budget constraint is affected predominantly by the funding intensity provided for FOAK commercial plants, two scenarios were considered, (A) and (B), in which the capital funding intensity of FOAK projects is varied, with 20% for FOAK in Scenario A and 30% in Scenario B. The results of the modelling shown in Figure 21 and Table 16 allows for a number of observations to be made:

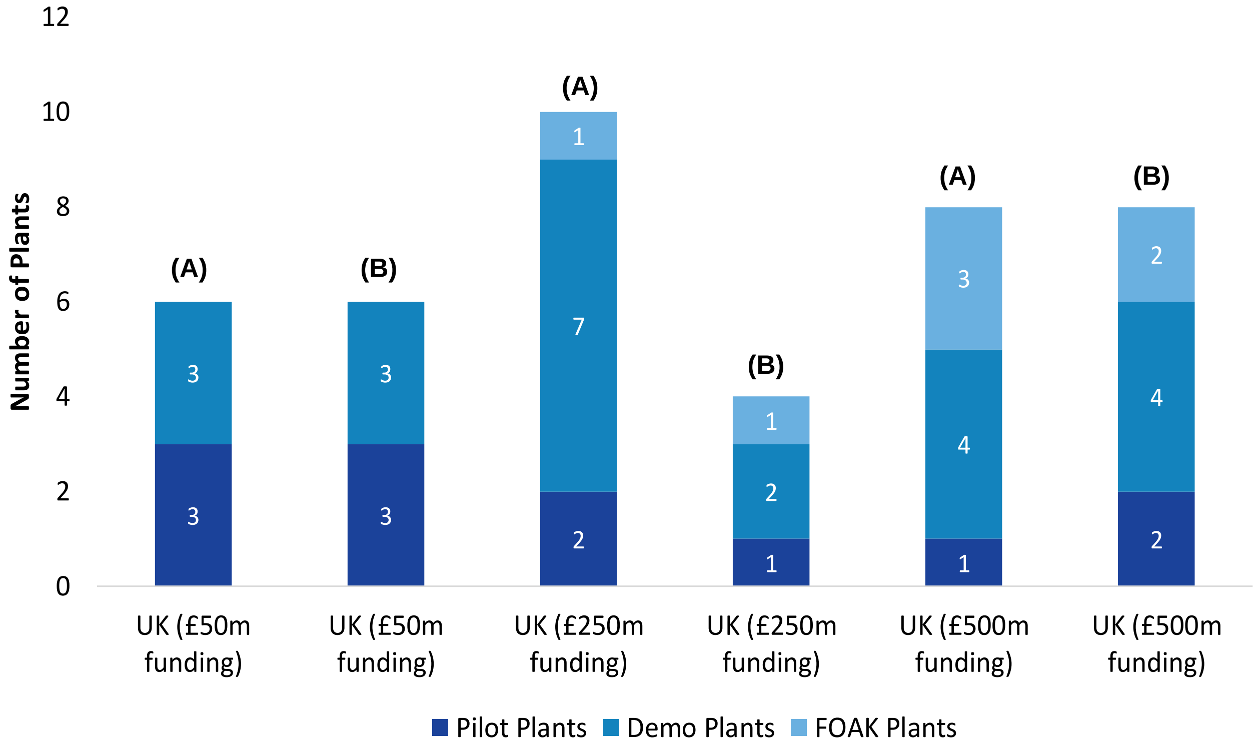
- Firstly, with a budget limit of £50m, a FOAK plant is unlikely to be supported. This suggests £50m funding bracket would have to be limited to pilot and demonstration projects, with the aim of developing R&D. While this does not allow for sizable SAF production, it could promote innovation and exportable IP, which is not captured by this calculation. Furthermore, Table 16 indicates the potential job creation, although as in the analysis, the number of jobs is assumed to be proportional to the scale of the plants, the number of jobs created by pilot and demonstration plants is probably underestimated.
- In funding was £250m, one FOAK plant can be supported under both Scenarios. However, in Scenario A, a higher number of pilot and demonstration plants can be supported, due as the lower funding intensity means that £70m less of funding is given to the FOAK plant. As with the £50m funding budget, this outcome emphasises that GVA alone is not necessarily the best metric for assessing value to the UK. Scenario A has the potential to contribute much more to the UK through supporting five more demonstration plants than in Scenario B, stimulating higher levels of R&D and innovation. However, in terms of GVA Scenario A only results in an additional £6m.
- Finally, for a funding budget of £500m, two or three FOAK plants could be supported, depending on the capital cost funding intensity. The difference of one FOAK plant between Scenario A and Scenario B could result in significantly different impacts to the UK economy, in terms of GVA; for 20% capital funding, three FOAK plants could be supported and result in a GVA £222m per annum, compared to a scenario where the capital funding is 30%, in which case only 2 FOAK plants could be supported, generating £143m of GVA per annum (Table 16). Furthermore, the level of job creation is highly dependent on the number of FOAK projects supported, with Scenario A yielding around 500 additional jobs (approximately 1,500 in total) compared to Scenario B as a result of the additional FOAK project supported.

Table 16: Key performance metrics for Scenario A and Scenario B of the direct impact of the competition analysis, for three funding brackets: £50m, £250m, £500m

	Scenario A – FOAK capital funding intensity 20%			Scenario B – FOAK capital funding intensity 30%		
	£50m	£250m	£500m	£50m	£250m	£500m
No. Pilot Plants	3	2	1	3	1	2
Funding for Pilot Plants (£m)	9.3	6.2	3.1	9.3	3.1	6.2
No. Demo Plants	3	7	4	3	2	4
Funding for Demo Plants (£m)	40.0	93.2	53.3	40.0	26.6	53.3
No. FOAK Plants	-	1	3	-	1	2
Funding for FOAK Plants (£m)	-	147.6	442.9	-	218.9	437.3
SAF production (tonnes/annum)	5,068	100,896	247,466	5,068	92,615	185,230
GVA (£m/annum)	3.9	77.8	221.6	3.9	71.4	142.8
Job creation (UK direct jobs)	27*	540	1469	27*	496	992

**Likely an underestimate due to the calculation of number of jobs being proportional to the scale of the plant.*

Figure 21: Graph illustrating the number of plants supported under different DfT budgets and funding intensities



Note: Scenario A corresponds to a funding intensity of 20% for capital costs of a FOAK project; Scenario B corresponds to a funding intensity of 30% for capital costs of a FOAK project.

Reflections on the impact of the competition analysis

The key conclusion to draw from this illustrative example, is that total funding budget and funding intensity levels have a significant influence on the outcome of the competition in terms of number and types of plants supported, and value to the UK economy in terms of GVA and job creation.

Some further considerations include:

- Whether to assess value of pilot and demonstration plants to the UK economy in a way other than domestic GVA, as the benefits of supporting plants at this level are not accurately reflected in GVA.
- The implications on the level of funding provided by the DfT for FOAK projects on the amount of capital that needs to be raised by private investors and therefore the likelihood of investment. Whether it is feasible for companies to raise 80% of capital through private investors, particularly given current macroeconomic conditions, will need to be investigated further, and will likely also be highly dependent on the availability of policy mechanisms which provide sufficient long-term revenue support.
- The level of funding support that needs to be provided by this competition will be highly dependent on level of revenue support available through dRTFCs. As mentioned previously, this is not a probabilistic calculation and does not consider the likelihood of a plant being built, based on the level of revenue support through dRTFCs.

6 Summary and recommendations for further work

In summary:

1. Sustainable aviation fuel (SAF) is a major route to decarbonisation for the UK aviation industry given that the alternatives will be unable to service medium-long haul flights (e.g. electrification) or are at least 10 to 20 years away from realisation (e.g. hydrogen).
2. Globally, there is an emerging sustainable aviation fuels market. The UK currently has no production of SAF at commercial scale. Government input is needed to 'level up' the UK's position and bridge the gap between new technologies and commercially demonstrated plants.
3. There is a large opportunity for Government action to leverage substantial UK low carbon growth and green jobs in the sector, all supporting the Jet Zero agenda for post-COVID 19 economic recovery.
4. There are a range of technologies at different maturities that could produce SAF and a large and credible pool of bidders that could enter a competition to build plants in the UK. Broadly these can be grouped into pilot and demonstration scale projects, and first of a kind (FOAK) commercial projects.

Pilot and demonstration scale projects:

5. Some technologies that utilise novel feedstocks are still at demonstration scale. It is still important to fund these to provide future security of supply across a range of feedstocks. State Aid-compliant grants that support a large proportion of costs are a necessary funding mechanism for pre-commercial technologies (typically £5m to £25m per plant).

FOAK commercial projects:

6. DfT's aim of paving the way for FOAK commercial plants in the UK will need to involve substantial amounts of funding as each plant has a very high upfront investment cost (in the order of £700m per plant).
7. The current environment (post-COVID-19) presents major challenges for FOAK commercial plants, particularly where airlines and oil & gas companies would be major investors.
8. The most important message from investors was that these projects will need both capital and revenue support in order to secure investment as they see high levels of risk in technology failure and SAF revenues in comparison to other revenue streams.
9. The level of capital support that is required for FOAK projects is above the level that could be supplied under State Aid. With the State Aid limit being €15million, this corresponds to roughly 2% of the construction cost of a large FOAK plant, which would likely not be enough to incentivise private investment. Therefore, Government should consider mechanisms which fall outside of State Aid support and can provide considerably higher levels of support, such as loan guarantees, tax credits and direct investment.
10. Government should also strongly consider revenue support to give the certainty that investors need in funding these plants.

We recommend the following next steps for DfT to undertake:

- Funding
  - Consult DfT Legal and Finance to discuss the feasibility of the different alternative funding mechanisms identified through the study such as loan guarantees, tax credits, green bonds and equity investment. This may also require further stakeholder consultation with Treasury in due course.
- Policy
  - DfT to review how they can provide plant developers and investors with better long-term visibility of dRTFCs.
  - Investigate if other mechanisms such as CfDs could be implemented to further help developers build a stable business case.
  - Integrate the cross Government low carbon economy strategy and the recently announced Jet Zero council.

- DfT Business Case
    - Based on the outcomes of funding and policy discussions DfT will need to finalise its business case and set a budget for the competition.
- Detailed competition design
    - Once DfT has set its budget and knows which funding mechanisms it could employ, the scope of the funding programme, eligibility and assessment criteria, and stakeholder communications will need to be elaborated.

Appendices

A1 Appendix A TRL definitions

TRL	Type of plant	Description
1	-	Basic principle observed
2	-	Technology concept formulated
3	Lab	Experimental proof of concept
4	Lab	Technology validated in lab
5	Pilot	Technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)
6	Demonstration	Technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)
7	Demonstration	System prototype demonstration in operational environment
8	FOAK Commercial	System complete and qualified
9	Commercial	Actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies)

Source: HORIZON 2020 – WORK PROGRAMME 2014-2015
General Annexes Page 1 of 1 Extract from Part 19 - Commission Decision C(2014)4995
https://ec.europa.eu/research/participants/data/ref/h2020/wp/2014_2015/annexes/h2020-wp1415-annex-g-trl_en.pdf

A2 Appendix B Summary of funding mechanism research

Appendix B
Financial Instrument

Click here to download Appendix B – Summary of funding mechanism

A3 Appendix C Lessons learned

A3.1 Methodology

The first phase of work consisted of a review of the lessons learned from ABDC and F4C. The review focussed on:

- The design of the competitions and
- The type and level of funding available.

As part of the review we specifically considered:

- Whether the lessons taken from ABDC around re-structuring the F4C into two phases worked well or not and if the additional support provided during Stage One was valued by grantees and provided benefits to them.
- If funding needs to be further restructured (for example, looking at level of funding available, modularising projects for funding) and in addition, if other funding mechanisms may have been more beneficial to grantees.
- Where support was most needed across both competitions, both during the application and also the grant phases.
- Whether there were any common areas of challenge, and whether any contractual conditions caused particular burdens on projects.

The following stakeholder activities were undertaken to gain a broad range of views from internal (delivery team, DfT, ABDC/F4CProgramme Board) and external (F4C applicants and grantees) stakeholders:

- A joint online call with current and past members of the ABDC and F4C delivery teams in Ricardo and E4tech,
- A joint online call with DfT's low carbon fuels delivery team and the Programme Board DfT have convened for both the ABDC and F4C,
- Individual calls with current grantees[89] of the F4C scheme and selected applicants to Stage 1 of F4C and
- An email survey to applicants[90] to Stage 1 of F4C.

A3.2 Findings

The following provides a summary of the findings from the different stakeholder activities. The findings have been grouped into:

- Barriers to SAF production
- Competition Design

A3.2.1 Barriers to SAF production

The following issues were identified as barriers to SAF production in the UK:

A3.2.1.1 Policy related barriers

- While the DfT have launched the RTFO scheme as a reward mechanism for SAF production, the scheme is not yet mature enough for investors to estimate the income RTFCs and dRTFCs could produce for SAF plants. There is currently no trading history available and the RTFO does not provide a mechanism to guarantee a floor price for SAFs. First of a kind demonstration/commercial plants rely on RTFCs as income stream to make the plant

[89] Only those that are proposing to produce SAF
[90] Only those that are proposing to produce SAF. Only 4 of the 11 applicants contacted responded to the survey.

commercially viable, but this uncertainty over the price poses a risk to outside investors. As an alternative a mechanism, whereby Government would pay the difference between the current market price and the price needed to make a SAF plant commercially viable, was suggested by one of the stakeholders to help make the business case to investors.

- The UK Government is currently undertaking a consultation of the RTFO. The uncertainty over the outcome and potential changes makes it difficult for plant developers to build a robust business case and poses some risks. For example, DfT have considered to change the RTFO so that biomethane from anaerobic digestion converted into hydrogen through a steam methane reformer is no longer eligible, which may have unintended consequences for some developers who wish to use the hydrogen for their fuel production process.
- Treatment of mixed waste within the RTFO: The RTFO currently only rewards the biogenic fraction of MSW. Stakeholders suggested that DfT could also reward SAF producers for the non-biogenic waste conversion if it can be demonstrated that the CO_2 savings are achieved from using the residual waste. This could be used as a transitional arrangement in the next 10 to 15 years for example. This would make a huge different to developers using mixed waste as feedstock. One example listed by stakeholders was the implementation of a low carbon fuels standard that is technology agnostic and related to overall carbon intensity of fuels.
- The RTFO does currently not include industrial waste emissions as feedstocks. This is particularly relevant for the interim production of ethanol, which can in turn be converted to jet fuel. Industrial waste emissions are more easily available and also available in larger quantities than ethanol produced from other under the RTFO eligible feedstocks.
- The current RTFO does not encourage developers to achieve higher GHG savings that what is currently set out in RTFO. Higher GHG savings add costs disproportionately to the plant construction budget. The government could incentivise developers to aim for higher GHG savings through a supplementary payment for each addition 1% of reduction. One way to achieve this may be through combination with CCS.
- One stakeholder commented that many airlines are looking to purchase offsets from abroad to meet their CORSIA targets rather than invest directly in local projects to reduce their carbon emissions. The Government could enable UK airlines and airports to be able to claim carbon offsets for waste to advanced fuel projects undertaken in the UK to meet CORSIA targets for which there are a number of relevant carbon methodologies that can be used for such thermal-chemical/chemical recycling technologies including conversion to transport fuels that can be approved with VERRA or Gold Standard (e.g. https://verra.org/the-verified-carbon-standard-program-has-been-accepted-to-supply-carbon-credits-under-corsia/).
- One stakeholder commented that there is currently not enough incentive to use waste as feedstocks despite incineration being the less efficient technology solution.
- One stakeholder stated that even if there is funding to get a small number of plants built, the longer term policy framework (e.g. Carbon price) is critical to ensuring a financially viable SAF industry.

A3.2.1.2 Barriers related to securing funding

- Securing investment for these high-risk and potentially quite costly projects (commercial plants costs are around £600M-£700M) has been named as a barrier to SAF production by all stakeholders. In particular the following aspects have been stated:
    - Government support is needed to help de-risk projects so that they become investment ready and also to further educate the investment community about the benefits of such projects. There have been lots of waste projects/commercial plants that failed over the last few years; cost overruns, court cases, there is the risk that projects do not go through FEED.
    - State Aid is capping Government support at EUR 15million. Commercial plant projects would benefit from no or a higher funding cap.
    - The current UK loan guarantee scheme for infrastructure projects states as one of the criteria that a commercial bank/investor must be willing to fund the project. However, project developers would want access to a loan guarantee scheme because

commercial banks/investors feel that the risk to them is too high and therefore would not provide a loan.
  - Current support mechanisms from different Government departments are not as closely aligned as possible regarding requirements for applicants.

A3.2.2 Competition design

A3.2.2.1 What worked well

The following elements of the competition were identified as **working well:**

- Both the ABDC and F4C competitions were well received by industry, demonstrating Government engagement and support in the sector.
- Stakeholders felt that the application process for both stages of the F4C was commensurate with the level of funding available and grantees commented positively on the support provided by the delivery partners during both application stages.
- DfT stated that the initial interest in the F4C and the portfolio of projects selected for Stage 2 met their requirements and that both the ABDC and the F4C were contribution to DfT's KPIs such as job and apprenticeship creation and intellectual property creation.
- Stakeholders stated that the Stage 1 F4C eligibility criteria were reasonable, with the exception of plant commissioning by March 2021 for commercial plants and that the range for TRL should have been broader. Applicants had issues with meeting all Stage 2 criteria prior to the submission deadline.
- Internal stakeholders felt that the delivery team had put in place a robust evaluation process for both stages of the F4C, but that during Stage 2 further emphasis should have been placed on the technical solution and project implementation. DfT and other Government stakeholders also commented that the level of due diligence applied to the applications was appropriate as Government is investing tax payers' money and cannot be seen to be supporting projects that may fail in due course.
- Stakeholders agreed that a grant was the best mechanism to support the pre-construction activities and for funding the construction of demonstration plants. SMEs in particular rely on grant funding for their projects, with regular claim intervals as available under ABDC and F4C.
- Grantees welcomed the tailored additional support provided by the delivery partners during Stage 1 and Stage 2 of the F4C and valued in particular the support in calculation GHG emissions and the support provided by the Monitoring Officers.

A3.2.2.2 Further improvements

The following **improvements** were identified by stakeholders. There were notable differences for demonstration plants and commercial plants for some aspects, which have been separated out below:

- Internal stakeholders suggested that a higher level of support during the Stage 1 application phase might have been beneficial to further improve the quality of applications and it was discussed if a pre-application questionnaire in the form of Expression of Interest application may be useful. In addition, it was noted that more tailored sub-questions in the application form may also enable applicants to present the arguments and evidence more succinctly.
- F4C applicants commented on the different models used for calculating the GHG reductions and that the provision of a GHG model as part of the application process would have been beneficial to create a level playing field for all applicants.
- F4C Stage 1 funding provided between 50% and 100% of up to £500k grant funding for activities including feasibility studies, planning, GHG calculations, securing match funding and FEED studies. Stakeholders noted that the allocated six months funding period was not enough to obtain planning or conduct a FEED study, nor was the funding sufficient for a FEED study for a commercial plant.
- One stakeholder commented that they were unsure how much money to ask for despite the guidance provided as they felt a higher budget may have been evaluated less favourably.
- Stakeholders commented that F4C was trying to accommodate both demonstration and commercial plants, but that the scheme had been designed to be more suitable to

demonstration plants. Stakeholders welcomed the idea of providing different funding streams for demonstration plants and commercial plants with different funding mechanisms.

- Internal stakeholders commented that the competition timescales should not be dictated by DfT funding cycles but should be appropriately designed for the type of competition.
- Stakeholders suggested that funding should be released against stage gates/milestones instead of dispersing funds for the full construction phase.
- F4C grantees stated that it has been difficult to secure the required Heads of Terms for the Stage 2 applications as offtake and demand for feedstock were too far in the future to already agree prices in the HoTs.
- F4C grantees also stated that it has been difficult to secure the full funding, in particular for the commercial plants, prior to the Stage 2 application deadline as further work was required to further de-risk the projects before investors may be willing to invest. In addition, the reduction in funding intensity also caused problems for the SME grantees. One grantee suggested to assess applications on their technical and commercial merit and award a conditional offer, after which applicants would be asked to fully secure the match-funding. This approach had also been discussed as a possible option during internal stakeholder discussions.

- *Demonstration Plants*
    - Stakeholders suggested that up to 80% grant funding should have been made available to projects building demonstration plants. From the ABDC experience in particular, demonstration plant developers have found it difficult to secure the required 50% of match funding and any cost overruns. This was also confirmed by the F4C demonstration project, that we interviewed. This is largely due to the fact that demonstration plants will generally not generate any profits.
    - It was therefore also suggested by stakeholders that the grant funding should not stop at plant competition, but also cover running the plant to prove fuel quality.
    - Unsuccessful applicants to the F4C scheme report two years after the Stage 1 application deadline that they are still looking for investment for the projects. Interim funding has mainly been provided as private investment by company owners/shareholders.

- *Commercial Plants*
    - Stakeholders welcomed the idea of the introduction of a further, interim stage to fund FEED or other pre-construction engineering activities. The preferred funding mechanism for this was a Government grant to help to further de-risk the project prior to seeking funding for plant construction.
    - The F4C provided up to 50% grant funding for Stage 2, which was capped at £8m per project, which was not sufficient for building a commercial plant. It was, however, also noted that Government funding added value to the project no matter what level of funding as it demonstrated commitment from Government to the project and helped in securing match funding.
    - Stakeholders thought that low interest loans or guarantees would be appropriate mechanisms to support commercial plant construction.

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